Incorporation of Embodied Energy into Building Energy-Efficiency Codes: A Pathway to Life-Cycle Net-Zero Energy Building in Australia

By

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Table of Contents

Abstract

This thesis aims to demonstrate the importance of incorporating embodied energy into the building energy efficiency regulations (BEERs) of Australia. This study commences with conducting a comprehensive literature review of studies that employ a life cycle energy assessment (LCEA) approach in evaluating the total energy performance of buildings. As a result, sixty-six studies have been analysed with respect to the methodological approaches taken for defining system boundary conditions. It is shown that the current trend of LCEA application in residential buildings suffers from significant inaccuracies due to incomplete definitions of system boundary conditions. The findings form the base for developing a comprehensive framework through which the system boundary definition for calculations of embodied and operational energies can be standardized.

Further, this study quantifies the significance of embodied energy associated with Australian BEERs by assessing the total life cycle energy performance of more than 2,300 design scenarios of a residential building – reflecting a range of performance from standard 6-star buildings to highly energy-efficient buildings. The results revealed that the proportion of embodied energy significantly increases from 20–40% to 50–75% in transitioning from standard 6.0-star buildings to highly energy-efficient buildings. This finding underlines the necessity of including the embodied energy impacts into the BEERs when moving towards energy neutrality in the residential building sector.

This study also puts forward a comprehensive framework based on the findings of a literature review examination that enables incorporating embodied energy into BEERs by standardising system boundary definitions in LCEA analysis. The framework developed in the research consists of six distinctive dimensions i.e., temporal, physical, methodological, hypothetical, spatial, and functional. These dimensions encapsulate 15 components collectively, including 'stages of building life cycle', 'building components and systems', 'elements beyond building scales', 'method for assessment of embodied energy', 'background database for embodied energy assessment', 'type of energy', 'unit of measurement', 'parameters contributing to operational energy assessment', 'method for assessment of operational energy', 'assumptions', 'building lifespan', 'climate', 'building site location', 'building type', and 'density'.

The proposed framework possesses two key characteristics. First, its application facilitates defining the conditions of a system boundary within a transparent context. This consequently

leads to improved reliability of obtained LCEA results for decision-making purposes since any particular conditions (e.g., truncation or assumption) are considered in establishing the boundaries of a system. Second, the use of a framework will also provide a meaningful basis for cross comparison of cases within a global context, which allows identification of best practices for the design of buildings with low life-cycle energy use.

The study application of the proposed framework has been demonstrated by analysing the LCEA performance of a case study building in Adelaide and cross comparing the results with a case study building retrieved from literature and located in Melbourne. The results have indicated the capability of the framework for maintaining transparency in establishing a system boundary in an LCEA analysis, as well as a standardized basis for cross-comparison of cases. The study concludes with recommending potential measures for future developments of Australian BEERs.

In summary, the implications of this research underscore the need for future generations of Australian BEERs to consider reduction of buildings' embodied energy impacts as a requirement for realizing net-zero energy or carbon in the built environment. The implementation of this approach can positively contribute to reducing the use of energy (or carbon)-intensive products in the residential building sector, limiting their impacts on national carbon emissions while encouraging cleaner production of construction products. On a broader scale, this study contributes to improving the current procedures for standardisation of LCEA analysis by proposing a framework that introduces six distinctive dimensions. The outcomes of this research are expected to assist policymakers with including embodied energy into current BEERs.

Statement of originality

I, Hossein Omrany, certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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Date: 27/09/2021

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Summary of abbreviations

BEERs	Building Energy Efficiency Regulations
NatHERS	Nationwide House Energy Rating Scheme
NGS	National Greenhouse Strategy
BCA	Building Codes of Australia
NCC	National Construction Codes
TLEB	Trajectory for Low Energy Buildings
ZEBs	Zero Energy Buildings
ZCBs	Zero Carbon Buildings
NZEB	Net-Zero Energy Buildings
nZEB	nearly Zero-Energy Buildings
LCEA	Life Cycle Energy Assessment
LCA	Life Cycle Assessment
EOL	End of lifecycle
NSGA-II	Non-Dominated Sorting Genetic Algorithm II
PV	Photovoltaic
IEA	International Energy Agency
ABCB	Australian Building Codes Board
ktoe	Kilotonnes of Oil Equivalent
EIA	U.S. Energy Information Administration
OECD	Organization for Economic Cooperation and Development
HVAC	Heating, Ventilation, and Air Conditioning
GHG	Greenhouse Gas
IECC	International Energy Conservation Code
EJ	Exajoules
GJ	Gigajoule
EPBD	Energy Performance of Buildings Directive
EPiC	Environmental Performance in Construction

List of figures (Excluding figures in papers)

List of tables (Excluding tables in papers)

Chapter 1. Introduction

The Australian residential sector is undergoing a major housing boom with approximately 200,000 new buildings being constructed each year (Schmidt et al., 2020a), and considerably more are required annually to accommodate the projected population growth of nearly 40 million by 2050 (Australian Bureau of Statistics, 2017). In this regard, the building energy efficiency regulations (BEERs) play a significant role in minimising energy usage in the building sector by imposing minimum requirements on buildings' operational energy consumption. In 2003, Australia introduced its first set of mandatory national energy efficiency regulations with a focus on reducing thermal loads – namely heating and cooling loads – while excluding the embodied energy impacts of building designs (NCC, 2019). This country now intends to transition its building sector toward zero energy (or carbon) building by increasing the minimum energy efficiency requirements for both new and retrofitted buildings. This transition will be facilitated via employing the current building regulatory system in Australia. Nevertheless, this study argues that the achievement of zero energy building using the current BEERs may never be truly realised owing to the limited coverage of these regulations. Therefore, the overarching aim of this research is to promote the incorporation of building embodied energy impacts into the current BEERs of Australia.

This chapter begins by providing an introductory background of the BEERs currently in use in Australia. Further, the research problem and gaps in knowledge will be highlighted along with elaboration on the research aims and objectives, research scope, research methodology, and significance of the research.

1.1 Introductory background of Australian building codes

The implementation of national mandatory energy efficiency standards in Australia began in 2003, although the policy path has a much longer history. The practice of building energy conservation as a voluntary action was supported by the government through the 1970s and 1980s (Berry and Marker, 2015), but it was not until 1988 that the Australian government opted to establish energy efficiency standards for residential and commercial buildings across different states. This occurred because of the commitment Australia made to the resolutions of the 1988 Toronto Conference, i.e., "*The Changing Atmosphere: Implications for Global Security*" (Berry and Marker, 2015).

In 1989,The Australian government initiated a holistic examination of building regulatory systems and processes via a Building Regulation Review Taskforce, which led to establishing a funding commitment in 1990 to create model codes for energy-efficient residential and non-residential buildings with a completion goal of December 1993, and the development of a Nationwide House Energy Rating Scheme (NatHERS) to help promote climate-appropriate designs (Berry and Marker, 2015).

The importance of energy efficiency standards for housing and commercial buildings was recognised as a part of the 1998 National Greenhouse Strategy (NGS) (NCC, 2019). An option outlined in the NGS was to introduce measures into the Building Codes of Australia – now called National Construction Codes (NCC) – to "decrease greenhouse gas emissions by efficiently using energy" (NCC PP. 372, 2019). On 19 July 2000, an agreement was reached between the Commonwealth Government and the State and Territory Governments to develop a comprehensive national energy-efficiency provisions that can regulate energy usage in residential and commercial buildings. Upon the incorporation of industry's perspective, the Commonwealth Government further revealed its intention of launching a new strategy consisting of two essential components: i) promoting energy efficiency measures by industry, and ii) establishing minimum mandatory requirements in the Building Codes of Australia (BCA) (NCC, 2019). Later, on the 5th of January 2001, the development of energy efficiency measures for inclusion into the BCA was decided as the result of an agreement between the Australian Greenhouse Office and the Australian Building Codes Board. This agreement was supported by the industry due to its potential for phasing out worst practices and providing a level playing field.

In 2003, energy efficiency regulations were introduced into the BCA for the first time, with the scope limited to housing. Ever since its enforcement, the energy efficiency requirements of BCA only account for the thermal loads of a building design, namely heating and cooling loads, and exclude the energy consumption caused by other parameters such as lighting, ventilation, electrical appliances and cooking (NCC, 2019).

The compliance of energy efficiency performance is generally demonstrated using two methods: (i) proposal of an alternative solution (i.e., verification-using-a-reference-building), and (ii) a deemed-to-satisfy approach (NCC, 2019). The first method is labour and knowledge intensive, and mainly applied in the assessment of housing stock (Daniel et al., 2017). The deemed-to-satisfy approach is more widely used, and it offers two methods to substantiate compliance: (i) elemental regulations, and (ii) energy star rating. The first option specifies R-values for different building components and determines glazing and ventilation requirements. The second option, energy star rating, requires a building design to obtain a certain star rating out of a maximum rating of 10 stars by using certain simulation software accredited by the NatHERS (NatHERS, 2021). The NatHERS is a performance-based rating system established to rate dwellings based on their annual thermal performances (i.e., only heating and cooling loads) (NatHERS, 2021). A 10-star rating indicates that the dwelling would need nearly no additional heating and cooling in order to retain indoor comfort level. The energy star rating is the most common method being used to meet the minimum energy efficiency requirements of the NCC (NatHERS, 2021).

These regulations were further expanded to include other building classifications in 2006, along with increasing the stringency for dwellings to a target of 5.0 stars (NCC, 2019). In 2010, the minimum mandatory thermal requirements were increased to the equivalent of 6.0 stars for houses and apartments (NCC, 2019). Currently, all new buildings need to meet certain thermal requirements equivalent to 6.0 stars in order to substantiate their compliance with the energy efficiency regulations, except in Northern Territory (NatHERS, 2021) where the minimum star rating for new dwellings or retrofitting existing buildings is 5-star, 3.5-star for new apartments, and there is no energy efficiency requirements for commercial buildings (Building and energy efficiency, 2021).

Despite the gradual increase of minimum mandatory thermal requirements over recent years, studies argue that the current building regulatory standards of Australia are less effective compared to those set by other countries. Hence, strong calls for increasing minimum mandatory thermal requirements have been raised (Moore et al., 2019; Moore et al., 2014; Moore et al., 2011; Doyon and Moore, 2020; Clune et al., 2012; Moore and Holdsworth, 2019; Horne and Hayles, 2008; Daniel et al., 2015).

Horne and Hayles (2008) showed that housing regulations stipulated by North America, the UK and Europe for comparable climatic conditions were on average 55% more effective than Australian regulations. Horne et al. (2005) also demonstrated that a 5-star rated building in Australia may underperform by 1.8–2.5 stars compared to the average international levels of performance. In recent research, Moore et al. (2019) investigated more than 187,000 certificates issued by NatHERS between 2016 and 2018 in order to analyse the response to market desires and the regulatory environment. The results revealed that 81.7% of dwellings were merely designed to meet minimum standards, while 98.5% fell below the economic and environmental optimum. It was shown that only 1.5% of new dwellings were constructed to optimum economic and energy performance. Moore et al. (2019) further recommend a significant increase of minimum regulatory standards by 7.0 to 8.0 stars if Australia is to realise a low energy or low carbon housing sector by 2050.

Australia now aims to further strengthen its measures toward minimising energy consumption in residential buildings. In February 2019, the ‘Trajectory for Low Energy Buildings’ (TLEB) was endorsed by the Council of Australian Governments as a national plan to realize zero energy and carbon-ready buildings by 2030 (Figure 1.1) (Trajectory for Low Energy Buildings, 2019b). The TLEB aims to identify opportunities for energy efficiency improvements throughout the building system, from thermal performance to appliance energy usage and renewable energy generation (Trajectory for Low Energy Buildings, 2019b). The principal purpose of TLEB is to materialise the concept of zero energy (and carbon) ready buildings in Australia through building codes. To this end, the minimum mandatory thermal requirements for new buildings would be increased to 6.5 stars equivalent in tropical and temperate climates, and 7.0 stars equivalent in colder climates. This increase is set to be periodically implemented in 2022 and 2025.

Figure 1.1 An overview of the TLEB in Australia (TLEB, 2019a)

The TLEB characterises zero energy buildings (ZEBs) and/or zero carbon buildings (ZCBs) thus,: "*zero energy (and carbon) ready buildings have an energy efficient thermal shell and appliances, have sufficiently low energy use and have the relevant set-up so they are "ready" to achieve net zero energy (and carbon) usage, if they are combined with renewable or decarbonised energy systems on-site or off-site*" (TLEB, 2019c). As indicated, the TLEB aims to achieve the state of energy (and carbon) neutrality in the Australian building sector by focusing on three main domains: i) increasing energy efficiency of building shells so that newly built buildings will consume extremely low energy during their operations, ii) supporting the use of energy efficient heating and cooling appliances or systems, and iii) advocating the integration of renewable energy systems (e.g., photovoltaic, or solar panels) to generate energy on-site and/or off-side. Figure 1.2 illustrates the components that fall within the scope of TLEB for realising zero energy (and carbon) buildings.

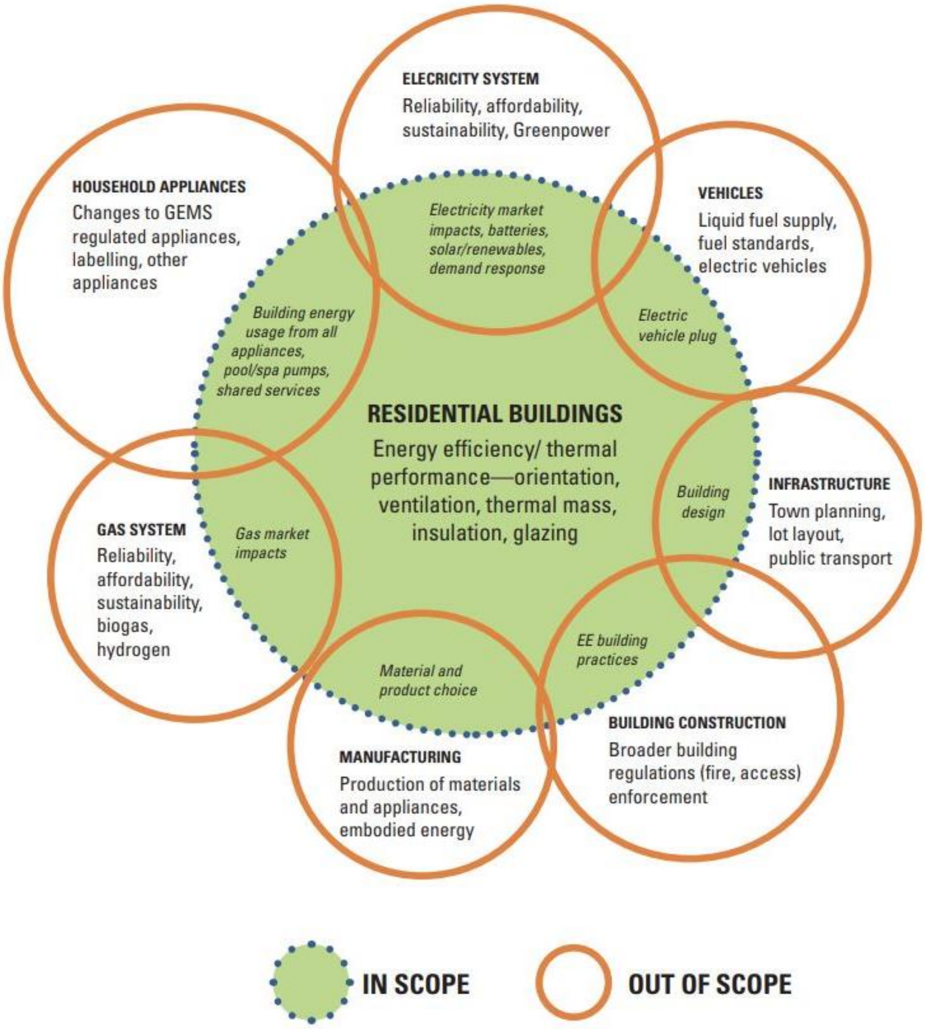

Figure 1.2. Components fall within the scope of TLEB for increasing energy efficiency (TLEB, 2019c)

Despite the promising outlook of TLEB, the primary focus is placed on the minimisation of operational energy while the embodied energy impacts associated with building designs are excluded. Embodied energy is defined as the amount of energy utilised in material production (i.e. extraction of raw materials and material manufacturing), assembly (i.e. construction/installation), replacement and maintenance, end-of-life processes and transportation required between any of these steps (IEA, 2016; Dixit et al., 2013; Dixit et al., 2012; Venkatraj and Dixit, 2021). The main focus of this study lies in addressing the limited approach of current policies promoting energy efficiency in the residential sector of Australia. It argues that the adoption of such a limited approach may cause energy consumption or carbon emissions to simply move from one stage of building life cycle to another, failing to yield net zero energy use throughout the entire building life cycle.

Previous studies have highlighted the importance of incorporating embodied energy into the BEERs by investigating the magnitude of embodied energy in the context of buildings with high energy efficiency in Australia (Crawford et al., 2016; Stephan et al., 2012; Crawford, 2011). For instance, Crawford et al. (Crawford et al., 2016) evaluated the life cycle primary energy impacts of two residential buildings with high energy efficiency performance located in Melbourne and Brisbane, Australia. The calculation of operational energy was carried out only considering the impacts of thermal operational energy, namely heating and cooling loads. The results revealed that embodied energy constituted 89% and 97% of the total life cycle energy demands in Melbourne and Brisbane, respectively. This underlines the significance of embodied energy, and the need to include it in BEERs, especially for energy-efficient buildings where the demands for space heating and cooling are minimal.

The consideration of both embodied and operational energies, or the so-called 'life cycle energy' by the current BEERs, is challenging due to the numerous processes and variables involved. This is despite the fact that over the years, several international standards and frameworks have been developed aiming to standardise the process of computing buildings' embodied energy in conjunction with operational energy such as ISO14040:2006 (ISO, 2006) or the European frameworks developed by the Technical Committee TC350, for example EN 15978:2011 (EN 15978, 2011). Nonetheless, the pathways for incorporating embodied energy into the current BEERs are still unclear. The comprehensive literature review carried out by this research, as presented later in chapters 3 and 4, revealed that the current trend of assessing total life cycle energy performance (LCEA), that is accounting for the impacts of both operational and embodied energies in residential buildings, suffers from significant inaccuracy accruing from incomplete definitions of the system boundary, in tandem with the lack of consensus on measurements of operational and embodied energies.

Based on the above background, the aim of this study is to facilitate the transition of the Australian building sector towards net-zero energy by proposing a comprehensive framework that enables the current BEERs to account for the impacts of both operational and embodied energies. In this regard, the main objectives of this study are to:

(1) Identify the main attributes causing variations in life cycle energy assessments;
(2) Investigate the impacts of embodied energy associated with building energy efficiency codes of Australia; and
(3) Propose a comprehensive framework that assists the current BEERs of Australia to account for total life cycle energy impacts of residential buildings.

The study makes two main contributions to the field:

- Firstly, this study is the first of its kind that specifically researches embodied energy impacts associated with Australian energy efficiency regulations across the star ratings, from standard 6-star buildings to highly energy-efficient buildings; and
- Secondly, it complements the current standards and frameworks by proposing a comprehensive framework for standardising life cycle energy assessments for residential buildings.

1.2 Statement of the research problem

1.2.1 Identifying the principal contributors causing variations in life cycle energy assessment

In recent years, the literature has witnessed a growing body of research demonstrating the significance of embodied energy attributed to buildings with high energy-efficiency performance. However, this surge of research has been unable to alter the mindset of policymakers about the necessity of abating buildings' embodied impacts when planning for the enhancement of sustainability in the built environment (Säynäjoki et al., 2017). Many studies have attempted to encourage the incorporation of embodied energy into BEERs by increasing the accuracy of embodied energy calculation methods (Crawford, 2008; Crawford, 2011; Treloar, 1997); investigating challenges for inclusion of embodied energy into BEERs from the perspectives of building professionals (Chan, 2019; Davies et al., 2014); or integrating building information modelling techniques with the life cycle assessment (LCA) approach and building codes (Cavalliere et al., 2019; Hollberg et al., 2020). Nevertheless, the impacts of embodied energy are being widely ignored by BEERs in most countries (Pomponi and Moncaster, 2018). The main reason for such an exclusion resides with the complexity of BEERs in accounting for the impacts of both operational and embodied energies due to the various processes and parameters involved.

Over recent years, several international standards and frameworks have been developed to standardise the process of calculating LCA and LCEA (e.g. ISO14040:2006 (International Organization for Standardization, 2006) or EN 15978:2011 (EN 15978, 2011). However, the findings of recent studies report great variations in the results of LCEA and LCA analyses (Venkatraj and Dixit, 2021; Pan and Teng, 2021; Omrany et al., 2021; Omrany et al., 2020). For instance, Pan and Teng (2021) conducted a literature review analysis of 244 case studies, aiming to quantify potential variations in embodied energy calculations. To this end, they quantified the effects of parameters influencing measurement of embodied energy within the context of life cycle assessment such as building service life, methods for calculation of embodied energy, data source, and components considered for embodied energy estimations. The results showed that significant variations may stem from the choice of method for embodied energy assessment, for example a 200% increase from process-based to hybrid method.

Although Pan and Teng (2021) managed to quantify the impacts of a number of factors with potential impacts on LCEA results, the scope of their assessment was limited to embodied energy calculations and omitted parameters that can affect operational energy such as methods to compute operational energy or variables that should be considered toward this end. Moreover, several parameters such as climatic conditions, assumptions, type of energy (i.e., primary, or secondary energy), building site location (i.e., city, suburb, regional and remote) were not taken into consideration by previous studies. These parameters can impact LCEA or LCA results by influencing the calculations of either embodied energy or operational energy. For instance, Sandin et al. (2013) tested the effects of assumptions made at the end of lifecycle stage on the LCA comparisons of two alternative roof construction elements, namely glue-laminated wooden beams, and steel frames. The results indicated that the assumptions can significantly influence the LCA comparison of the two construction components in four ways – whether the end of life is be included in the assessment, whether recycling or incineration is assumed in the disposal of glulam beams, whether the modelling of disposal is based on consequential or attributional approach and the type of technology that is assumed to be utilised.

In addition, the varied approaches to account for the effects of parameters that influence the assessments of embodied energy, as well as operational energy, can be critical in varying LCEA results (Omrany et al., 2021; Omrany et al., 2020). This can be seen in the findings of Pan and Teng (2021) which found that unclear descriptions of system boundaries for including cradle-to-gate and cradle-to-end of construction embodied energy may cause a 9.2% variation in the achieved results.

In another study, Venkatraj and Dixit (2021) examined the potential effects of utilising different methods for embodied energy calculation (i.e., process-based, aggregated, and disaggregated input-output based hybrid) in varying LCEA results. The findings showed that the values calculated via aggregated and disaggregated input-output-based hybrid were respectively140%

and 305% higher in comparison with process-based method. This indicates that the choice of methods for estimating the impacts of embodied energy can be determinative in causing variations of LCEA results.

Previous research has endeavoured to explore sources of variations with a focus given only to the calculation of buildings' embodied impacts (Dixit et al., 2013; Dixit et al., 2012). Devising a framework capable of accounting for the total energy and environmental impacts of buildings requires developing a thorough understanding of parameters that can impact LCEA (or LCA) assessments. Despite the attempts undertaken, there is still a need to comprehensively investigate the key parameters causing variations in LCEA results by examining the methodological approaches of current studies towards quantification of embodied and operational energies.

1.2.2 Investigating the embodied energy impacts of Australian BEERs

Previous studies have underlined the significance of embodied energy associated with buildings in Australia. These studies can be categorised into two major groups based on their approaches toward the assessment of buildings' embodied impacts.

Firstly, there are studies that have utilised embodied energy assessment as a tool for decision-making purposes (Aye et al., 2012; Stephan and Crawford, 2016; Lawania and Biswas, 2018; Sartori et al., 2021). For instance, Lawania and Biswas (2018) employed a life cycle assessment approach in order to identify locations where low-carbon houses can be designed. To this end, they have investigated the possibility of designing low-carbon dwellings in 18 regional locations in Western Australia. The outcome singled out location-specific hotspots for low-carbon housing design in Western Australia. In another study, Aye et al. (2012) endeavoured to demonstrate the potential environmental benefits of prefabrication construction systems in comparison with conventional methods by quantifying the embodied energy of modular prefabricated steel and timber multi-residential buildings.

Secondly, there are a group of studies aiming to increase the accuracy of measuring LCEA – that is, including both operational and embodied energies (Stephan et al., 2012; Stephan et al., 2013; Crawford, 2014; Stephan and Crawford, 2014; Stephan and Athanassiadis, 2017; Schmidt et al., 2020b; Li et al., 2021). The primary focus of such studies is to highlight the underestimated magnitude of embodied energy impacts and to showcase the significance of embodied energy via different approaches. For instance, Stephan et al. (2012) and Stephan et al. (2013) formulated a comprehensive framework to account for the embodied energy requirements at both building and city scales. The outcomes of both studies commonly showed that embodied energy may constitute a significant portion of total building life cycle energy consumption. In another study, Crawford (2014) assessed total life cycle energy usage of a residential building in Melbourne using real data collected from the energy bills of the building for calculation of operational energy. To compute embodied energy, an input-output hybrid methodology was used due to its capacity for calculating higher values for embodied energy. The employment of this approach, using real data for calculation of operational energy in lieu of simulation approach, and using the hybrid method for estimation of embodied energy, led to achieving a much more reliable and comprehensive understanding of the total energy demands, as conclusively stated by Crawford (2014).

Despite the growing body of literature, there is a lack of studies that have specifically researched the life cycle energy repercussions associated with increasing building energy efficiency requirements in accordance with the Australian NCC. Most research has focused on showcasing the magnitude of embodied energy within the context of total life cycle energy performance without specifically quantifying the association between BEERs and embodied energy impacts. In other words, it remains unclear how much energy usage in residential buildings has been overlooked by the current BEERs due to excluding the impacts of embodied energy. Presently, the BEERs being implemented in Australia presents an incomplete picture of energy consumption in buildings because it ignores embodied energy. The transition towards net zero energy calls for the inclusion of embodied energy assessment in existing BEERs. Yet, little is known regarding how this inclusion can be achieved, and how it will impact the current approaches and rating scales of BEERs. As such, addressing this gap may be of utmost importance in terms of generating new insights for the future development of NCC.

1.2.3 Proposing a comprehensive framework to account for total life cycle energy impacts

The absence of a standardised framework for defining system boundaries is commonly considered as a principal contributor to varying LCEA results (Pan et al., 2018; Pan and Teng, 2021; Omrany et al., 2021; Pan, 2014; Moncaster et al., 2018). This is reflected in the findings' of Pomponi et al. (2018) who assigned three independent environmental assessors with five projects to calculate their respective life cycle environmental impacts – a total of fifteen detailed assessments. The findings reported significant discrepancies in the final results even when the initial information available to the assessors was the same.

The importance of system boundary definition was first noted by Sartori and Hestnes (2007) through analysing 60 cases. Recent studies have also attested to the key role of system boundary definition in deriving variations and identified multiple reasons for such phenomena, for example varied definitions of physical and temporal boundaries the use of different methods for measuring embodied and operational energies; buildings' geographic locations, data source, and data quality; or manufacturing technology (Pan et al., 2018; Pan and Teng, 2021; Omrany et al., 2021; Pan, 2014; Moncaster et al., 2018). For instance, Moncaster et al. (2018) identified three major categories that contribute to varying results in embodied energy analysis, namely "temporal differences in the stages considered"; "spatial differences in the material boundaries" and "physical disparities in the data coefficients".

Despite the significance of system boundary definition in determining the quality of LCEA results, a limited number of studies have been undertaken to standardise system boundary definition. Hammond and Jones (2010) introduced a four-level regression model for the description of a system boundary. The first level accounts for all of the energy inputs used directly during processes such as construction, prefabrication, maintenance, replacement, demolition, and disposal in order to produce a product. The second level of the regression model promotes the inclusion of energy consumption sequestered into main and all upstream and downstream processes of materials and product manufacturing. The third level captures the amounts of energy use embedded in the production, delivery, and installation of machines that are utilised to manufacture materials, as well as on- and off-site construction processes. The final level represents the amount of energy expelled during the main, upstream, and downstream production processes of manufacturing machinery that in turn produces the machine of third level regression. Although the proposed model endeavours to disentangle the energy inputs used at each stage of a building's life cycle, it fails to capture various data requirements for buildings' environmental assessment. These include: methods for calculation of embodied and operational energies; data source; assumptions; climate; building lifespan; building location; and, building density and building type.

Likewise, Fay (1999) presented the same ideas about defining system boundary conditions composed of multiple levels. A similar boundary condition was demonstrated by Herendeen (1998) through analysing the life cycle energy in car production. The results showed that 90%

of the energy is consumed during the process of producing the constituents of car materials such as steel, plastic, glass, etc., whereas only 10% of energy consumption relates to car manufacturing plants. Dixit et al. (2013) also proposed a conceptual framework based on a comprehensive literature review and synthesising the opinions in the relevant literature on system boundary definition. The proposed framework primarily elaborated on the temporal and physical boundaries of a system being researched and omitted parameters that can influence LCEA results such as building operational energy analysis (i.e., methods of calculation, and variables for analysis), including such things as building location, building density, building type, climate, assumptions.

Stephan et al. (2012) also presented a comprehensive framework of a system boundary to capture the energy requirements at both building and urban scales. The framework accounts for operational and embodied energy usage of buildings, as well as embodied impacts related to nearby infrastructure and occupant transport energy. Although the framework promotes the integration of energy flows between embodied, operational, and transport requirements, it does not provide tailored data requirements for different dimensions of system boundaries such as climate, method selection for computation of embodied and operational energies, source of data, building density or building type.

In another research project, Pan (2006) proposed a theoretical framework to assist multi-criteria decision making in selecting off-site construction technologies. The framework captures four aspects of system boundaries – ontology, epistemology, methodology, and axiology. Pan's framework enables the theoretical investigation of system boundaries defined in previous studies of LCA and carbon emissions. Later, Pan (2014) developed a conceptual model consisting of eight boundaries – "the policy timeframe, building lifecycle, geographic, climatic, stakeholder, sector, density, and institutional boundaries". This framework provides the possibility of cross comparison of different cases within a harmonised context. Nonetheless, the life cycle boundary of the framework only elaborates on the temporal dimension of the system boundary without providing detailed information on other facets such as parameters that can affect operational energy, for example, methods to compute operational energy or variables that should be considered toward this end, databases for calculation of embodied energy, type of energy (i.e., primary, or secondary energy), or assumptions.

Satola et al. (2021) conducted a comprehensive investigation of 13 voluntary frameworks from 11 countries within the context of the project IEA EBC Annex 72 on "Assessing Life Cycle

Related Environmental Impacts Caused by Buildings". Upon performing this investigation, a framework was proposed encompassing a number of methodological options including system boundaries for both operational and embodied GHG emissions, the type of GHG emission factor for electricity use, the approach to the "time" aspect, and the possibilities for compensating GHG emission. Despite the attempts undertaken, several important components of system boundary are still missing such as the necessity of acknowledging assumptions, spatial requirements, e.g., climate and building site location, as well as functional aspects of system boundary, e.g., building type and density.

The frameworks developed by the reviewed studies fall short of capturing all the dimensions involved in defining system boundaries. The majority aimed at simplifying the temporal and physical dimensions. This highlights the need for a much more comprehensive framework when aiming for the incorporation of embodied impacts into BEERs. The comprehensiveness of such a framework can assist policymakers to set certain requirements and standards for each dimension of the framework at national or regional scales.

1.3 Gaps in knowledge and research questions

Based on the analysis above, the gaps of knowledge relating to the incorporation of embodied energy into the current building energy codes can be summarised as follows:

- First, accounting for the impacts of embodied energy in tandem with operational energy requires a thorough understanding of the parameters that may cause variations in the results of LCEA. Currently, there is a dearth of research exploring factors with potential impacts on LCEA results.
- Second, Australia aims to strengthen its measures towards minimizing energy consumption in residential buildings. However, there is a lack of study investigating the significance of embodied energy impacts associated with increasing energy efficiency of buildings in Australia.
- Third, there is no comprehensive framework that can capture all the dimensions involved in establishing system boundaries when assessing life cycle energy performance.

In response to the gaps in knowledge outlined above, this research intends to first identify variables that lead to variations in LCEA results through conducting a comprehensive analysis of the literature. To address the second gap, this study demonstrates the potential impacts of embodied energy attributing to the building energy-efficiency codes of Australia by analysing various cases of residential buildings via a simulation approach. Further, a comprehensive framework will be proposed based on the findings from the literature review in order to standardise the assessment of embodied energy in combination with operational energy. The application of this framework in assessing the life cycle energy of buildings will be also tested.

Hence, the three main research questions (RQ) to be answered in this study are:

RQ1: What are the main attributes causing variations in LCEA results?

The primary step to account for the impacts of embodied energy is to understand the key parameters attributing to the calculations of both embodied and operational energies that may lead to variations in LCEA results. The answer to this question will facilitate the development of a framework to regulate the incorporation of embodied energy into BEERs.

RQ2: To what extent does the exclusion of embodied energy from the energy efficiency regulations impact the transition of Australian residential buildings toward net-zero energy?

This question contains one important sub-question: *can the continued exclusion of embodied energy from the energy efficiency regulations effectively lead to reducing energy consumption in Australian residential buildings?* This question seeks an answer to the magnitude of embodied energy in the context of Australian energy-efficiency building codes. The answer to this question may potentially instigate the need for rethinking the concept of building energy rating systems in Australia by accounting for the embodied impacts of building designs.

RQ3: How can the embodied energy be incorporated into BEERs?

Despite the increasing attention being paid toward the significance of embodied energy, the pathways for inclusion of embodied energy in the current BEERs are still ambiguous. This research question attempts to assist Australian BEERs to account for the impacts of both embodied and operational energies via developing a comprehensive framework.

1.4 Research aim and objectives

The aim of this study resides with facilitating the transition of the Australian building sector towards life cycle net-zero energy by proposing a comprehensive framework that enables the current BEERs to account for the impacts of both operational and embodied energies. This transition should further lead to minimising the use of energy (or carbon)-intensive products in the building sector and limiting their impacts on the national carbon emissions while encouraging cleaner production of construction products.

The objectives of this study are as follows:

- **Objective 1: To identify the key attributes causing variations in LCEA results.**
    - Many standards and frameworks have been developed over the years aiming to harmonise the LCEA assessment of buildings. Yet, the findings of recent studies indicate significant variations in the results amongst the studies due to different approaches employed in carrying out the LCEA assessments. This, in turn, leads to compromising confidence in using LCEA approach at the policy level. Therefore, this objective aims to identify the principal parameters leading to variation in the results of LCEA assessment.

- **Objective 2: To investigate the impacts of embodied energy associated with building energy efficiency codes of Australia.**
    - This objective aims to examine the significance of embodied impacts linked with Australian energy efficiency building codes. The realisation of this objective would demonstrate the limited scope of current Australian BEERs for achieving energy efficiency in the residential building sector, which will further highlight the necessity of minimising embodied energy when increasing the thermal performance of buildings.

- **Objective 3: To propose a comprehensive framework that assists the current BEERs of Australia to account for total life cycle energy impacts of residential buildings.**
    - The focus of current BEERs is primarily placed on minimising operational energy. This limited scope of attention fails to yield a total life cycle net-zero energy in the residential building sector. Hence, it is incumbent upon the new building codes to extend their relative scopes to include embodied impacts. The achievement of this objective aims to facilitate the incorporation of embodied

impacts into BEERs by developing a comprehensive framework that enables establishing system boundary conditions within a standardised context.

1.5 Research scope

The scope of this research is limited to residential buildings in Australia due to the higher share of this sector in energy consumption. A recent report issued by the Department of Industry, Science, Energy and Resources revealed that the residential sector consumed 460.90 Petajoules of energy in 2018 – 128.30 Petajoules more than non-residential buildings (Australian Energy Update, 2020). In addition, this research calculates embodied and operational energies using primary energy, since this contains higher energy in comparison with the delivered energy (Venkatraj and Dixit, 2021). Further details on limitations concerned with realising each objective are provided in the respective chapters.

1.6 Research methodology

The overall methodological approach of the study is illustrated in Figure 1.3. The primary step towards developing a holistic framework that can account for the impacts of both operational and embodied energies is to identify the parameters with potential effects on the final results of LCEA research.

To meet the first objective, comprehensive literature review analyses were conducted to investigate publication materials relating to the application of LCEA in residential buildings published between 1996 and 2020. The searching exercises were carried out through various scholarly databases such as Web of Science, ProQuest, and Scopus. Multiple filters were also considered in order to eliminate publications that fell outside the scope of this study. More than sixty studies were identified with more than 240 case studies being represented from over 15 countries. The retrieved studies were then analysed with respect to their approach toward defining the system boundary conditions for LCEA. Details on the analysis of literature review can be found in chapters 3 and 4.

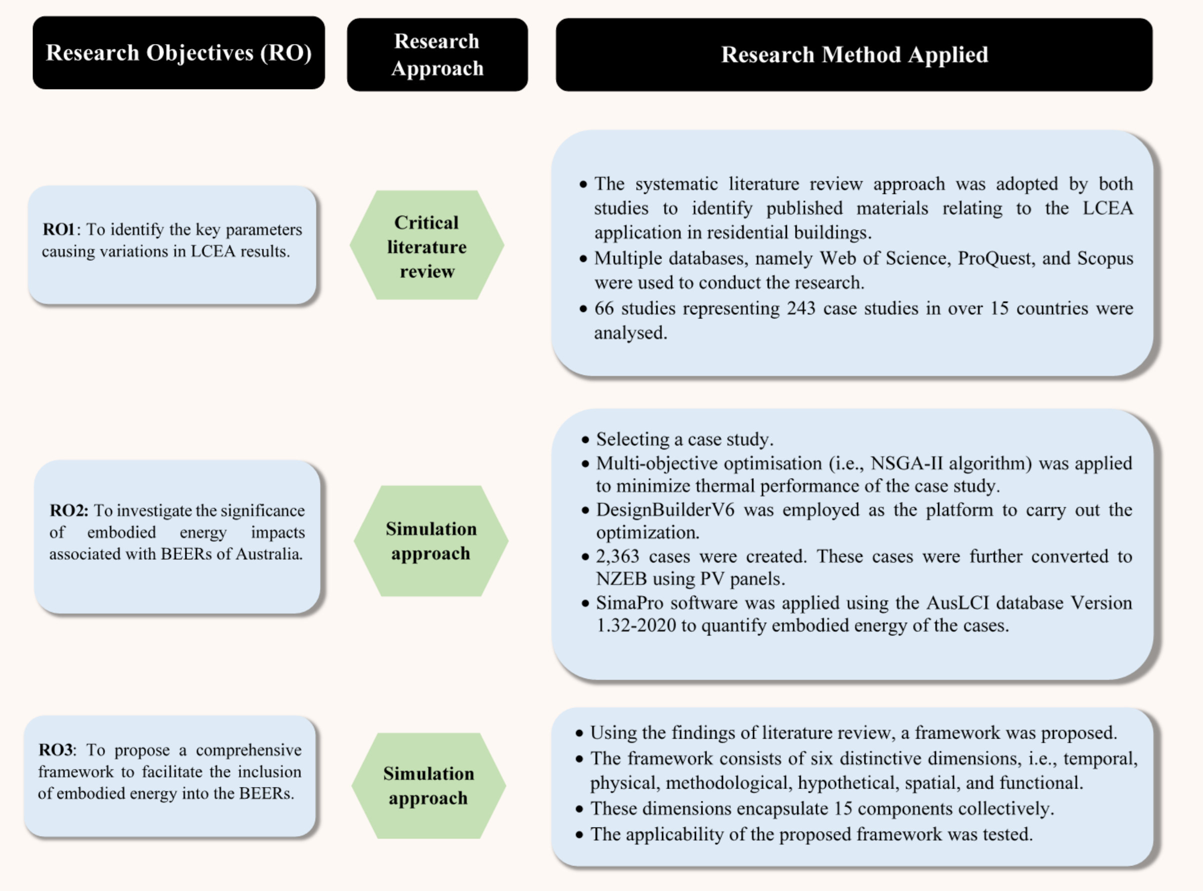

Figure 1.3 Research approach

The second objective is to evaluate the embodied energy impacts linked to BEERs. To this end, a case study was selected that could satisfy two primary conditions: first, it needed to be the most common type of residential building in Australia so that the results would have broader implications; and second, it needed to meet the minimum mandatory thermal requirement determined by the NatHERS rating scheme in accordance with the reference year of 2020. Hence, a single-storey detached building was selected as the case study. It is also noteworthy to mention that detached dwellings comprise 69% of the total housing stock in Australia (Schmidt, et al., 2020). The thermal performance – heating and cooling loads – of the building was then evaluated using AccuRate software in order to ensure that the selected building met the requirement of the NatHERS rating system. Afterwards, the heating and cooling loads of the case study were subjected to minimisation through employing a multi-objective approach using ten groups of design variables. The optimisation was carried out using Non-Dominated Sorting Genetic Algorithm II (NSGA-II) within the platform of DesignBuilderV6.

The results obtained from optimisation offered over 4500 derivatives of the case study with each one having a different design configuration. These cases were ranked using the NatHERS rating system, and those rated less than 6-Star rating were phased out. This led to downsizing the cases to 2,363 design configurations, with each one representing a unique design of a single-storey detached building. Thereafter, these cases were converted into NZEB by adding Photovoltaic (PV) panels to zero out their thermal loads. The last step involved calculating embodied energy impacts of each case via SimaPro software and using the AusLCI database Version 1.32-2020 as the background life cycle inventory database. The total life cycle energy usage was then computed by adding thermal loads and embodied energy of each case. The realisation of this objective may have implications for TLEB (TLEB, 2019b), instigating the need for rethinking the concept of building energy rating systems in Australia by accounting for the embodied impacts of building designs. Further details are provided in Chapter 5.

The third objective of this study was met by proposing a comprehensive framework to assist with incorporating embodied energy into BEERs by standardising system boundary definitions. This framework consists of 15 components identified by analysing the literature, and further consolidated into six distinguished dimensions including temporal, physical, methodological, hypothetical, spatial, and functional.

The proposed framework possesses two key characteristics. First its application facilitates defining the conditions of a system boundary within a transparent context. This consequently leads to increased reliability of obtained LCEA results for decision-making purposes since any particular conditions (e.g., truncation or assumption) considered in establishing the boundaries of a system under study can be revealed. Second, the use of a framework can also provide a meaningful basis for cross comparison of cases within a global context. This characteristic can assist in identifying best practices for the design of buildings with low life cycle energy use performance.

The applicability of the proposed framework was demonstrated using two case studies. The first case study was a single-storey detached building located in Adelaide, Australia that utilised PV panels in order to zero out its annual energy demands. The second case study was a single-storey building in Melbourne, Australia constructed according to the NCC. The latter was retrieved from literature in order to demonstrate the capacity of the proposed framework for cross comparison of cases. It is noteworthy to mention that both cases represent of the bulk of new dwellings that are currently being constructed across Australia. Chapter 6 provides details on the descriptions of the case studies and development process of the framework, as well as implementation of the framework.

1.7 Significance of the research

The significance of this research is threefold:

- First, this study identifies key parameters with potential impacts on causing variations in LCEA analysis. To date, most of the existing research has focused on identifying variables that affect embodied energy calculations. Nevertheless, no study has yet been comprehensive enough to solicit all the parameters associated with the measurements of both embodied energy and operational energy. The creation of such an understanding can pave the way towards devising a framework through which embodied energy can be incorporated into current BEERs.
- Second, the research substantiates the need for rethinking the concept of a building energy rating system in Australia. Since the initiation of Australian BEERs, the scope of these regulations has been always limited to minimising thermal loads (i.e., heating and cooling) of buildings. The current regulatory standards impose minimum requirements for thermal performance of new and renovated buildings. These requirements have been gradually increased over the years, and now the aim is to further strengthen the stringency of thermal requirements within the next few years. Nevertheless, the transition of Australian residential sector toward net zero energy via the current BEERs may be unfeasible due to their limited scope in excluding the impacts of embodied energy. The extent to which energy usage in residential buildings is being ignored due to the exclusion of embodied energy is still unclear. Correspondingly, this study investigates embodied energy relating to the BEERs across various star-rated buildings, ranging from standard 6-star buildings to highly energy-efficient buildings. Meeting this objective unveils the significance of embodied energy impacts corollary to Australian BEERs. This, in turn, will determine a need for future versions of BEERs to account for the impacts of embodied energy in combination with operational energy.
- Third, this research proposes a comprehensive framework that enables incorporation of embodied impacts into the current building codes of Australia. The proposed framework facilitates definition of system boundary conditions within six distinctive

dimensions, promoting the possibility for policymakers to set requirements for inclusion of embodied energy into BEERs at national or regional levels.

1.8 Thesis organisation

This thesis is structured as a “thesis by publications”, which means, according to The University of Adelaide’s Graduate Centre (2021), it “may include publications that have been published and/or accepted and/ or submitted for publication and/or unpublished and unsubmitted work written in a manuscript style”. This thesis includes four published manuscripts, presented as Chapters 3, 4, 5 and 6. The first manuscript (Chapter 3) mainly aims to provide a comprehensive review of the literature, whereas the other three manuscripts (Chapters 4, 5 and 6) each corresponds to one of the three research questions. Figure 1.4 provides an overview of the thesis structure. This thesis consists of eight chapters.

Chapter 1 (*Introduction*) presents an introductory background of the study and states the research problems and gaps in knowledge as well as research questions, research aims and objectives, research scope, research methodology and significance of the research.

Chapter 2 (*Background literature*) provides an overview of the need for having energy efficiency requirements in building codes. This section details further into investigating the rationale behind implementing BEERs, elaborating on different compliance approaches for enforcement of BEERs and development and implementation of BEERs. This section also discusses the need for reducing embodied energy impacts when transitioning toward zero energy.

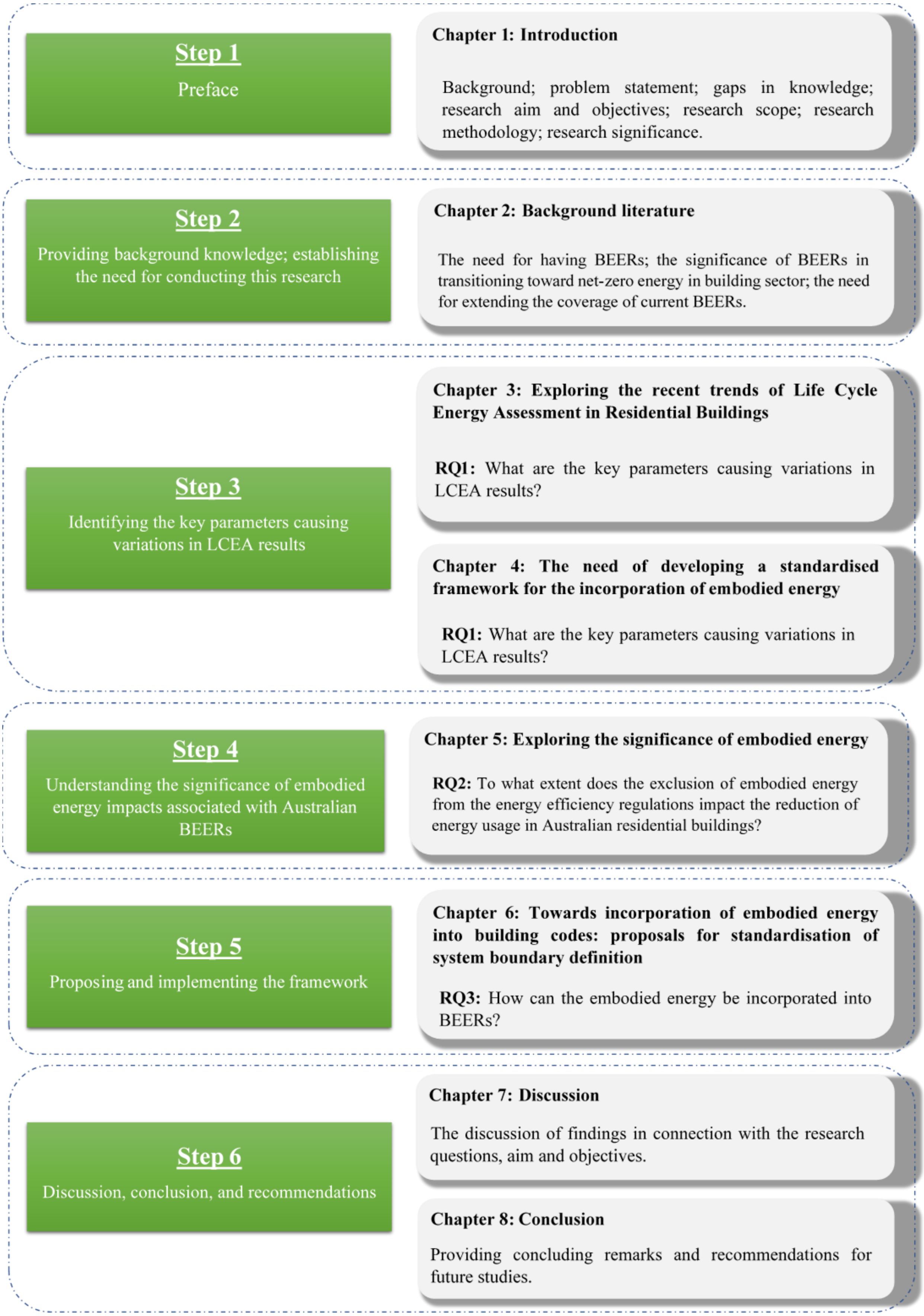

Figure 1.4 An overview of the thesis structure

Chapter 3 (*Results: part I*) provides a literature review analysis carried out by this study in order to capture the recent trend of LCEA assessment in residential buildings. This chapter presents a published paper:

> **Omrany, H**., Soebarto, V., Sharifi, E., & Soltani, A. (2020). Application of life cycle energy assessment in residential buildings: a critical review of recent trends. *Sustainability*, 12(1), 351. DOI: https://doi.org/10.3390/su12010351.

Chapter 4 (*Results: part II*) provides details on a comprehensive literature review analysis performed by this study in order to solicit the key parameters causing variations in LCEA results. This chapter presents a published paper:

> **Omrany, H.**, Soebarto, V., Zuo, J., Sharifi, E., & Chang, R. (2021). What leads to variations in the results of life-cycle energy assessment? An evidence-based framework for residential buildings. *Energy and Built Environment*, 2(4), 392-405. DOI: https://doi.org/10.1016/j.enbenv.2020.09.005.

Chapter 5 (*Results: part III*) presents details on how embodied energy impacts relating to energy efficiency building codes of Australia were examined. This chapter presents a published paper:

> **Omrany, H.,** Soebarto, V., & Ghaffarianhoseini, A. (2021). Rethinking the concept of building energy rating system in Australia: a pathway to life-cycle net-zero energy building design. *Architectural Science Review*, 1-15. DOI: https://doi.org/10.1080/00038628.2021.1911783.

Chapter 6 (*Results: part IV*) furnishes details of the framework developed by this study in order to streamline the process of incorporating embodied impacts into BEERs. This chapter presents a published paper:

> **Omrany, H.,** Soebarto, V., Zuo, J., & Chang, R. (2021). A Comprehensive Framework for Standardising System Boundary Definition in Life Cycle Energy Assessments. *Buildings*, 11(6), 230. DOI: https://doi.org/10.3390/buildings11060230.

Chapter 7 (*Discussion*) presents the discussion of the results and recommended measures for future research.

Chapter 8 (*Conclusions*) concludes the thesis by highlighting the contribution of this research to the current body of knowledge.

Chapter 2. Background literature

Buildings accounted for the largest share of global final energy consumption and CO_2 emissions in 2019 (IEA, 2021a; United Nations Environment Programme, 2020). Recently, the United Nations Environment Programme issued a report stating that the energy used by buildings, including building operations and construction, amounted to 130 Exajoule (35%) globally in 2019, with 38% of energy-related CO_2 emissions (United Nations Environment Programme, 2020). The energy usage in the building sector is projected to double by 2050 if appropriate measures are not taken (Nejat et al., 2015). Hence, it is essential to plan for the future intensification of energy demands in the building sector by developing building energy efficiency regulations (BEERs) that can effectively mitigate the environmental impacts of buildings. This section aims to discuss the importance of BEERs in transitioning the building sector toward zero energy, and the need for including embodied energy into the current building codes in order to achieve life-cycle net-zero energy in the building sector.

2.1 Notions and definitions

This section aims to enunciate the key terminologies used in this study, namely 'building', 'energy' and 'building energy efficiency regulations'. In addition, it will explain the logic for limiting the scope of the study to the residential sector and the use of energy as a measure to describe building performance.

2.1.1 Building

The Webster's Dictionary defines a building as "*a usually roofed and walled structure built for permanent use (as for a dwelling)*" (Webster's Dictionary, 2021). In a more comprehensive definition, the Organisation for Economic and Co-operation Development defines a building as (OECD, 2002): "*any independent free-standing structure comprising one or more rooms or other spaces, covered by a roof, enclosed with external walls or dividing walls which extend from the foundations to the roof, and intended for residential, agricultural, industrial, commercial, cultural, etc., purposes*."

In these definitions, a building is perceived as a physical entity with the combination of several structural elements which provides a secure settlement for its occupants. However, a building can be more than a physical entity – sociologists believe that buildings represent qualities such as identity and memory. Architects may also point out significances such as cultural values and potency being embodied by buildings. Urban planners might see buildings as the 'bricks' of the urban fabric. Hence, a building is a complex object that can be perceived and defined differently. In this thesis, a building is defined as an assembly of various materials that create a physical barrier through which indoor and outdoor spaces are separated to enhance users' comfort, and which may include the use of heating and cooling systems.

Buildings can also be differentiated based on their functions. There are two general building classifications: residential and non-residential, with each having its own sub-categories. In this regard, the Building Code of Australia (BCA) categorises buildings into ten different categories (Table 2.1) (Building classification, 2021).

Table 2.1. Building classification in accordance to BCA (Australian Energy Update, 2020)

Category	Building class	Building sub-class	Description
Residential	Class 1	Class 1a	A single detached dwelling, or a group of dwellings each being a building, separated by a fire-resisting wall including a row house, terrace house, town house or villa unit.
		Class 1b	A boarding house, guest house, hostel, or a residence with a total area of all floors not exceeding 300m^2 and ordinarily not occupied by more than 12 people. These buildings should not be located above or below another dwelling or another Class of building other than a private garage.
	Class 2		Class 2 refers to apartment buildings. Typically, these buildings are multi-unit residential buildings where people live above and below each other. Class 2 buildings may also be single storey attached dwellings where there is a common space below. For example, two dwellings above a common basement or carpark.
	Class 3		Class 3 includes buildings other than Class 1 or Class 2 buildings, or a Class 4 part of a building. Class 3 buildings are a common place of long term or transient living for a number of unrelated people such as a boarding house, guest house, hostel or backpackers. Class 3 buildings may also be "care-type" facilities (such as accommodation buildings for children, the elderly, or people with a disability) which are not Class 9 buildings.
	Class 4		Class 4 refers to buildings that are sole dwellings or residence within buildings with non-residential nature. An example of a Class 4 part of a building would be a caretaker's residence in a storage facility. A Class 4 part can only be located in a Class 5 to 9 building.
Non-residential	Class 5		An office building used for professional or commercial purposes, excluding buildings of Class 6, 7, 8 or 9.
	Class 6		A shop or buildings allocated for the sale of goods by retail, or the supply of services direct to the public. Example: café, restaurant, kiosk, hairdressers, showroom, or service station.
	Class 7	Class 7a	A building which is a car park.
		Class 7b	A building which is for storage or display of goods or produce for sale by wholesale.

Class 8		A factory can best represent buildings in Class 8. It is a building constructed for the production, assembling, altering, repairing, packing, finishing, or cleaning of goods. Class 8 buildings can also be used to carry a process or handicraft for the purposes of trade, sale, or gain. A laboratory is also a Class 8 building, even though it may be small.
Class 9	Class 9a	A health care building, including those parts of the building set aside as a laboratory.
	Class 9b	An assembly building, including a trade workshop, laboratory, or the like, in a primary or secondary school, but excluding any other parts of the building that are of another class.
	Class 9c	An aged care building.
Class 10	Class 10a	A private garage, carport, shed or the like.
	Class 10b	A structure being a fence, mast, antenna, retaining or free-standing wall, swimming pool or the like.
	Class 10c	A private bushfire shelters.

In Australia, residential buildings contribute significantly to overall energy consumption. The recent report on Australian energy consumption issued by the Department of Industry, Science, Energy and Resources affirms the significance of the Australian residential sector in consuming energy in 2018-19 (Australian Energy Update, 2020). Table 2.2 shows that residential sector is the fifth major contributor to the total Australian energy consumption, using 460.90 PJ energy, which is more than non-residential buildings. This figure includes the amount of energy produced from rooftop solar photovoltaic panels and energy received from the grid.

Table 2.2. Energy consumption in Australia, by sector

Sector	**2018–19**		**Average annual growth**	
	PJ*	**share (Per cent)**	**2018–19 (Per cent)**	**10 years (Per cent)**
Transport	1,748.4	28.2	1.6	1.8
Electricity supply	1,591.7	25.7	-1.8	-1.1
Manufacturing	1,050.2	16.9	-2.7	-2.0
Mining	812.4	13.1	11.3	9.1
Residential	460.9	7.4	0.5	0.4
Commercial	332.6	5.4	-0.4	1.8
Agriculture	103.1	1.7	-12.3	0.8
Construction	24.3	0.4	-6.2	-0.5
Water and waste	16.5	0.3	8.8	2.8
Other	55.8	0.9	-0.6	-3.3
Total	6,196.0	100.0	0.6	0.7

Note: Petajoules

Australia is witnessing a tremendous housing boom, with over 200,000 new dwellings being built each year (Building Approvals, 2020). However, much more will be required to support the predicted population expansion of over 40 million by 2050 (Population Projections, 2018). This underlines the significant untapped opportunity for the sector to tackle the issue of climate change by minimising energy use. Hence, this thesis focuses on residential buildings.

2.1.2 Energy

Energy comes from the Greek word *Ενεργεια* which means 'put to work' and it constitutes a basis for the definition of energy: the "*ability of matter or radiation to do work because of its motion, its mass, or its electric charge, etc...*" (Online Etymology Dicitionary). Energy can thus be interpreted as the capacity to carry out work according to various criteria. Modern societies are heavily reliant on energy to procure services. In this regard, the source of energy supply may have profound impacts on the built environment.

Based on the report of International Energy Agency (IEA) in 2018, 81.21% of the world's energy demands were supplied through fossil fuels including coal, natural gas, and oil (IEA, 2021c). The combustion of fossil fuels is a known contributor to introducing CO_2 into the atmosphere. Also in 2018, 99.3% of the CO_2 generated was due to burning fossil fuels (IEA, 2021b). The emissions of this gas contribute directly to the phenomenon of global warming and climate change.

The use of fossil fuels to generate energy also leads to the depletion of natural resources since they are not renewable. As such, energy can be considered as an appropriate indicator to measure the environmental performance of buildings because: i) it is a universal metric for quantitative evaluation of a process or a phenomenon, and ii) it is directly attributed to the CO_2 emissions and global warming. Therefore, this thesis uses energy as the environmental indicator to measure buildings' performance.

There are two general types of energy, namely delivered energy and primary energy. The delivered energy refers to the amounts of energy supplied to the building (e.g., electricity and heat etc.) considering the efficiency rates of end-use systems in buildings (Omrany et al., 2021; Omrany et al., 2020). Primary energy denotes total energy required to generate "a final energy service, including all fuel inputs and losses along the energy chain" (Gustavsson and Joelsson, 2010). These energies are basically incomparable though related, hence measurements and comparisons of buildings' energy performance should be carried out using either primary or delivered energy (Dixit et al., 2010; Dixit et al., 2012; Dixit et al., 2013), otherwise, the results could be ambiguous and misleading (Dixit et al., 2012; Dixit et al., 2013; Dixit, 2017).

Primary energy usually contains higher energy compared to the delivered energy (Omrany et al., 2020); the latter is typically one third of the primary energy due to the losses from the source to the site (Dixit et al., 2012). For instance, Pears (1996) showed that the use of primary energy for measuring embodied energy of building materials can potentially lead to achieving higher values of between 30–40%. Therefore, it is widely recommended that primary energy should be used when considering both embodied energy and operational energy (Dixit et al., 2010; Dixit et al., 2012; Dixit et al., 2013; Dixit, 2017; Omrany et al., 2020). Thus, this research measures embodied and operational energies using primary energy.

2.1.3 Building energy efficiency regulations

The building energy efficiency regulations (BEERs) refer to a set of codes developed to reduce buildings' energy usage via legislating standards for building construction. GlobalABC characterises BEERs as the "*locally adapted bioclimatic design principles to optimise passive design*" (GlobalABC, 2019). These regulations primarily aim to increase the energy efficiency of buildings by imposing minimum requirements on building components such as insulation levels and glazing performance (Rodríguez-Soria et al., 2014). So far 136 countries have adopted mandatory and/or voluntary building regulations in an attempt to comply with the Paris Agreement, under which countries have committed to maintaining the increase of global temperature well below 2 degrees, and preferably no more than 1.5 degrees by the end of the century (Figure 2.1) (GlobalABC, 2019).

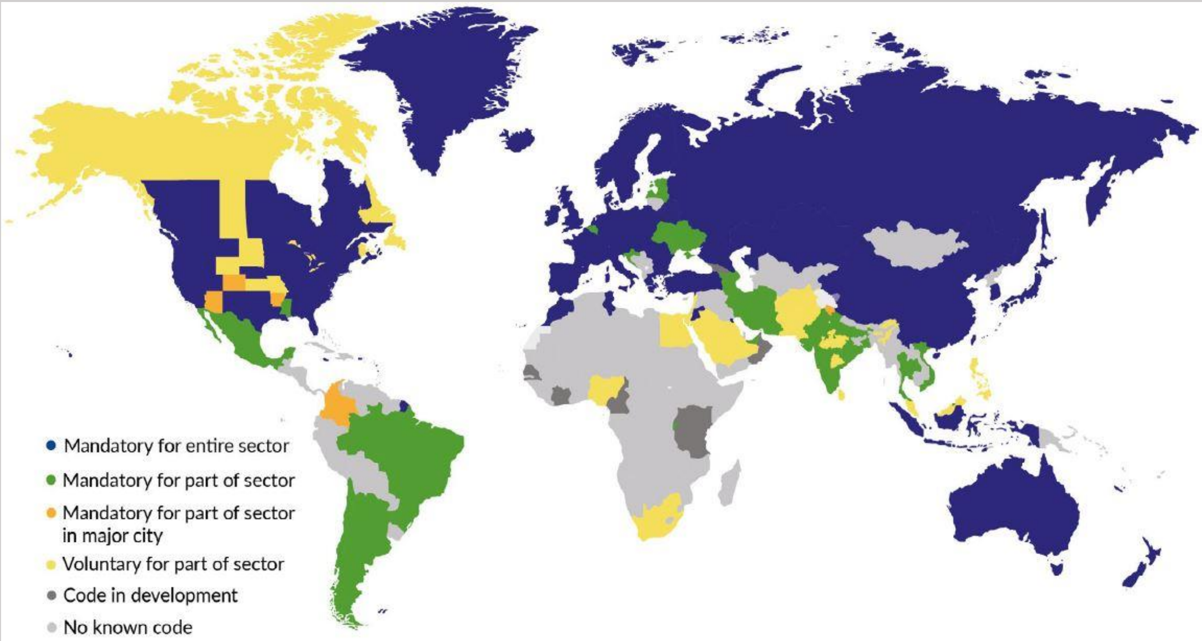

Figure 2. 1. Implementation of building energy codes. Sourced from: GlobalABC/IEA/UNEP (2019) (GlobalABC, 2019)

Australia is among the countries that have implemented compulsory requirements for the thermal performance of new and retrofitted buildings. These requirements are determined through the National Construction Code (NCC) series which is comprised of three volumes including the Building Code of Australia (Volumes 1 and 2) and Plumbing Code of Australia (Volume 3). The Australian Building Codes Board (ABCB) is the entity that is responsible for developing and maintaining the NCC through consultations with representatives of the building industry and broader community.

The ABCB is a joint initiative representing the three levels of government in Australia, that is, federal, state or territory and local. The ABCB ensures that a uniform set of national building standards is in place through the NCC, by imposing 'minimum essential requirements' for structure, fire resistance, access and egress, services and equipment, energy performance, and indoor conditions. Regarding energy performance, the minimum requirements are set by the NCC as guided by the Council of Australian Governments and the ABCB under the Building Act.

The current BEERs for residential buildings in Australia are reiterated through the Nationwide House Energy Rating Scheme (NatHERS). The NatHERS is a performance-based rating system that has been developed to rate and evaluate the energy performance of buildings (NatHERS-Accredited Software, 2019). The NatHERS provides guidelines for the calculation of buildings' energy performance via accredited third-party software, such as AccuRate, FirstRate5, BERS Pro, and HERO (NatHERS-Accredited Software, 2019). The results achieved through the NatHERS scheme are ranked across 'star' rating bands that range from 1 star (the least performing) to 10 stars (the best performing) (NatHERS Star Band Criteria). The 10-star buildings are nearly zero-energy buildings (nZEB) or net-zero energy buildings (NZEB) in some States, and they require almost no mechanical air-conditioning systems to provide heating and cooling. The thermal performance required by each star band is adjusted based on climatic conditions within a specific location. NatHERS divides Australia into 69 different climate zones. Figure 2.2 illustrates different star bands for the capital cities of Australia.

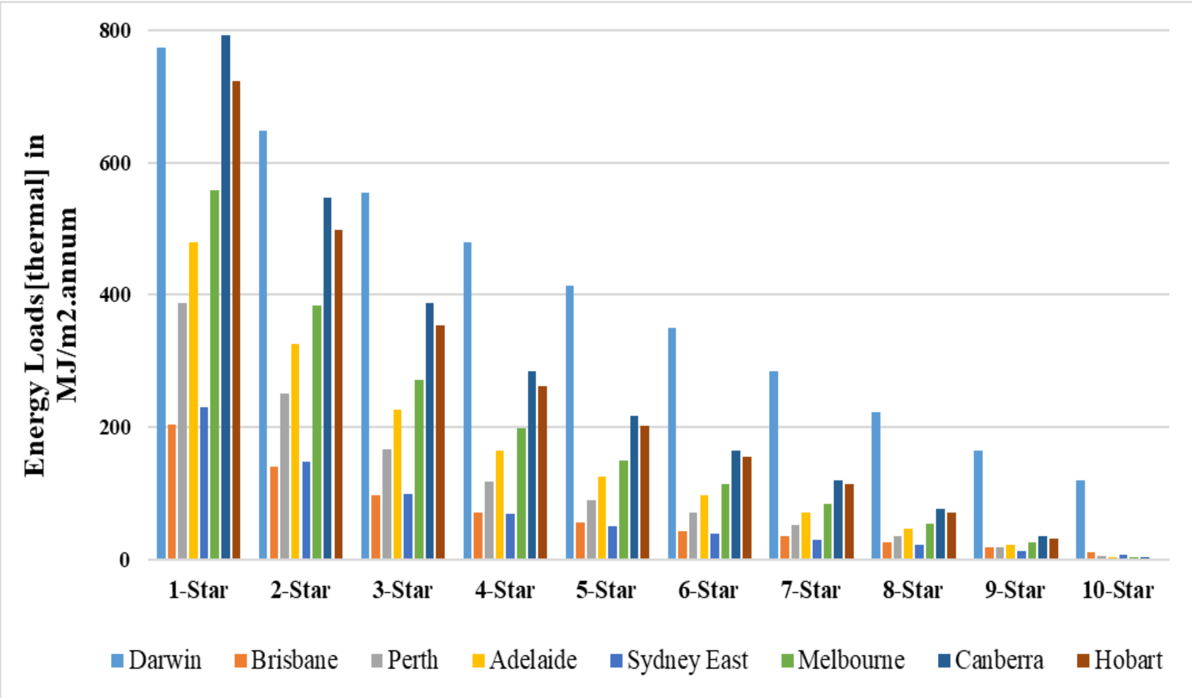

Figure 2.2. NatHERS Star Band Criteria (Energy Loads [thermal] in MJ/m^2.annum)) (NatHERS Star Band Criteria). The requirements are illustrated for the reference year of 2010.

In general, the establishment of minimum energy performance has had positive impacts on energy efficiency in the building sector of Australia. Prior to the introduction of policy requirements for minimum housing insulation in 1990, the average star-rating performance of dwellings was 1.0 star (Moore and Holdsworth, 2019). This was later increased to an average of 2.2 stars once these requirements were introduced (Moore and Holdsworth, 2019). Currently, all new and retrofitted residential buildings need to obtain a 6-star energy rating in order to comply with BEERs (except in Northern Territory where the minimum requirement is 5-star). However, there has been strong demand for increasing minimum mandatory requirements for buildings' thermal performance over the years (Moore et al., 2019; Moore et al., 2014; Doyon and Moore, 2020). Indeed, the TLEB has been recently developed to envisage Australia's national plan for realising the state of energy neutrality in the building sector (TLEB, 2019). TLEB aims to gradually increase the minimum mandatory requirements set by BEERs for new and retrofitted buildings. In this sense, the BEERs will be used as a vehicle to deliver zero energy and carbon-ready buildings. This research aims to draw attention to the limited coverage of current Australian energy-efficient building codes, promoting the incorporation of embodied energy into current BEERs of Australia in tandem with operational energy.

2.1.4 Net-zero energy buildings (NZEBs)

The concept of NZEBs has gained momentum over the recent decades because of its capacity to curtail energy consumption and CO_2 emissions in the built environment (Mlecnik, et al. 2011). Ever since, many terms have been emerged to describe NZEBs and are often used interchangeably in the literature. Torcellini et al. (2006) stated that the unit applied in the definitions of NZEBs can be influenced by i) the project's goals, ii) the investor's intention and purpose, iii) concerns about climate change and reduction of GHG emissions, and iv) energy cost. Hence, they presented four different definitions for NZEBs including i) Net-Zero Site Energy Building, ii) Net-Zero Source Energy Building, iii) Net-Zero Energy Cost Building, and iv) Net-Zero Energy Emissions Building.

The definition of Net-Zero Site Energy Building refers to a building that can generate as much energy as it utilises via renewable sources installed on site (Torcellini et al. 2006). Examples of these installations are roof-mounted PV or solar hot water collectors. These buildings are less vulnerable to the external fluctuations that may affect generation and delivery of energy to buildings. Nevertheless, the definition of Net-Zero Site Energy Building fails to differentiate the values of various fuels at the source. For instance, this definition recognises one unit of electricity energy used at the site as equivalent to one energy unit of natural gas at the site, though electricity is more valuable at the source.

Another definition of NZEBs is the Net-Zero Source Energy Buildings that refer to buildings that can produce as much energy as they consume at the source (Torcellini et al. 2006). In this definition, the total source energy of a building is calculated by summing the imported and exported energy that are multiplied by appropriate site-to-source energy factors. Despite complexity that the use of conversion factors may cause, the achieved results in this definition will be more accurate.

The Net-Zero Energy Cost Building is a building that receives as much financial credit for exporting energy to the grid as it is charged on the utility bills (Torcellini et al. 2006). The amounts of energy expelled to the grid must balance energy, distribution, peak demands, taxes, and metering charges for electricity and gas use. Finally, the Net-Zero Energy Emissions Building is defined as a building that generates at least as much emissions-free renewable energy as it uses from emissions-producing energy sources (Torcellini et al. 2006). Similar to net zero source energy building, this definition also has difficulties concerned with uncertainty in determining the generation source of electricity. In another approach, Kilkis (2007) argued that the metric of balance in definitions presented for NZEBs should address both quantity and quality of energy in order to evaluate total environmental impacts of buildings. Hence, the term 'net zero exergy building' was proposed and defined as '*a building, which has a total annual sum of zero exergy transfer across the building-district boundary in a district energy system, during all electric and any other transfer that is taking place in a certain period of time*' (pp 3) (Kilkis 2007).

In addition, there are other terms often appear in the literature to describe concepts similar to NZEBs such as 'nearly zero energy building'. This term is defined as a highly energy-efficient building that is capable of covering its required energy, to a large extent, through renewable sources generated on-site or nearby (D'Agostino and Mazzarella, 2019). This definition is now being implemented by Energy Performance of Buildings Directive recast, a policy framework focused on reducing energy consumption in the European building sector. Another term appeared to describe NZEBs is "zero energy ready" (or net zero ready). Targets are established by policymakers promoting the harvest of renewable energy to offset household energy demands. However, this approach is not always economically viable or sometimes regulatory rules for utility interconnection may not be mature or cost-effective. Hence, the term of "zero energy ready" (or net zero ready) is used to support construction of buildings with low energy demands, while having proper structural and electrical infrastructures to be equipped with renewable systems (IPEEC, 2018). However, these buildings are not required to have renewable systems at the time of construction.

Considering the variety of definitions for NZEB and the risk of using them interchangeably, this thesis intends to adopt the definition of Net-Zero Source Energy Building and uses appropriate conversion factors in order to account for energy sources.

2.2 The need for energy efficiency requirements in building codes

2.2.1 Energy use in residential buildings

The total energy consumption of the residential sector increased globally by 38% between 1990 and 2018, reaching 2,109,205 kilotonnes of oil equivalent (ktoe) in 2018 which is the highest level ever recorded (IEA, 2018). The increase of energy consumption in this sector is attributed to reasons such as the increase in world population, improved access to energy in developing countries, use of energy-consuming devices and rapid growth in global building floor areas. The residential sector also contributes significantly to global CO_2 emissions due to its heavy reliance on fossil fuels for supplying energy. Figure 2.3 shows that fossil fuels including natural gas, oil products, and coal constitute more than 81% of the energy supply, whereas only 2% of energy demands were supplied via renewable energy, an increase of only 1.5% in 2018 compared to 1990. This underlines the opportunities to curb dependency on fossil fuels by investing more in renewables to supply energy in this sector.

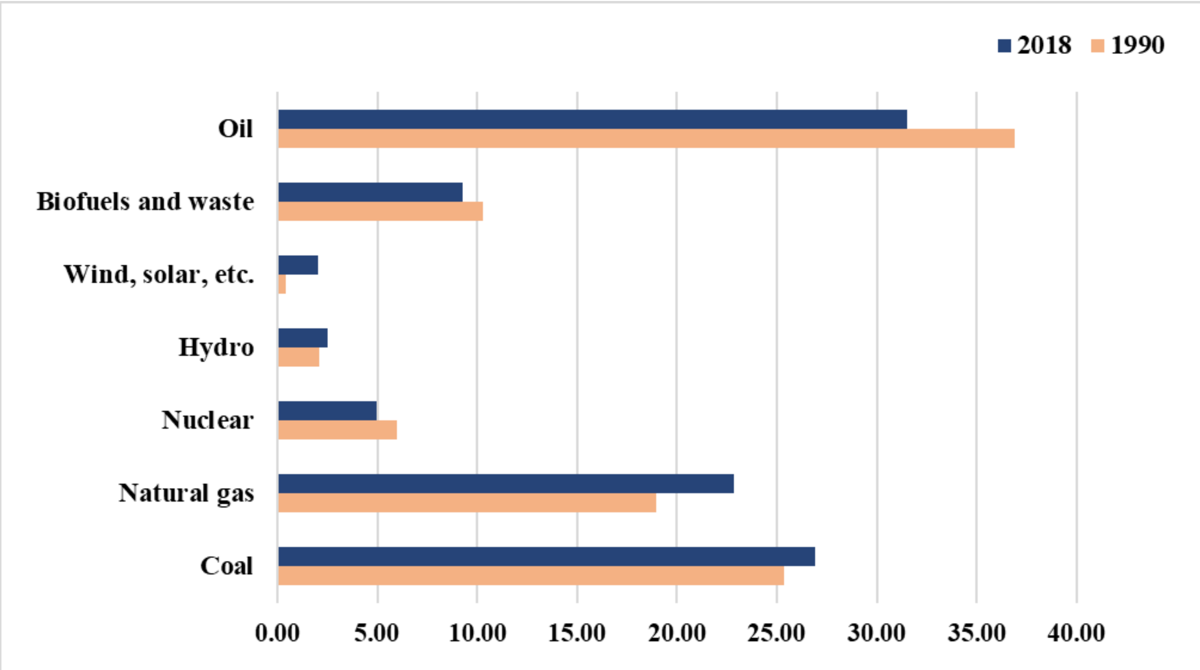

Figure 2.3.Main sources of energy supply in percentage. Sourced from IEA (IEA, 2021b)

Figure 2.4 presents the share of residential sector energy consumption compared to the total energy consumption worldwide compared with other sectors in 2018. It can be seen that more than 21% of the total global energy is used in this sector. This makes the residential sector the third-largest contributor to global energy usage after transport and industry (IEA, 2018). Most of the energy used in the residential sector is attributed to space heating, as shown in Figure 2.4. Electrical appliances and water heating are the other key contributors to energy use in the residential sector.

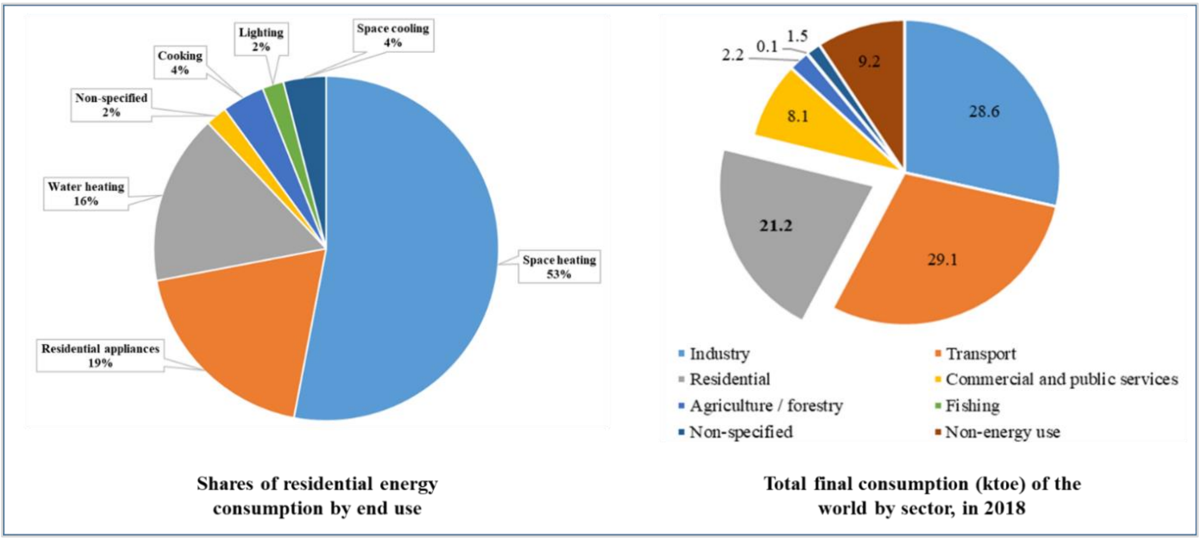

Figure 2.4. Energy consumption by use in residential sector (left), and final energy consumption of the world in 2018 (right) (IEA, 2018)

The pattern of household energy use may vary amongst countries depending on various factors, such as energy mix, types and levels of energy services provided in buildings. For instance, low and lower-middle income countries are more dependent on solid fuels (e.g., mostly biomass) whereas high-income countries rely on network-supplied energy such as electricity, natural gas, and district heating (in cold climates) (Liu et al., 2010). Hence, high-income countries are consuming more energy than low-income countries once they are compared based on per capita energy use.

Climate is another factor that can greatly influence household energy usage in residential buildings. For instance, nearly 64% of the overall energy consumption in 27 European countries was used for space heating in 2018 (Energy consumption in EU households, 2018), whereas space heating only accounts for 35% of the overall energy usage in the Australian residential sector (Australia 2018 Review, 2018). Therefore, the coverage of energy efficiency building codes differs among countries. In Australia, for instance, energy efficiency building codes mainly focus on the minimisation of operational thermal loads of buildings since these typically represent the largest contribution to the delivered energy demand.

The need to extend the coverage of building energy efficiency codes now can be emphasised considering the impending intensification of energy demands in the next decades driven by population growth, urbanisation, and increased standards of living. The U.S. Energy Information Administration (EIA) has projected that the energy usage associated with buildings will grow in Organization for Economic Cooperation and Development (OECD) countries by 1.3% per year on average from 2018 to 2050 (The U.S. Energy Information Administration, 2019). Further, EIA projects that the growth rate of energy usage in non-affiliated OECD countries would be more than 2% per year (The U.S. Energy Information Administration, 2019). Hence, building codes can play an important role in mitigating energy usage in residential buildings.

2.2.2 The rationale for implementing building energy efficiency regulations (BEERs)

Buildings' lifetimes may stretch over hundreds of years and thus, decisions undertaken at the early stages of building design can directly impact buildings' energy consumption performances over much of their lifetimes. The first and foremost benefit of enforcing BEERs is to spur the reduction of energy consumption in the building sector, as well as minimising concomitant carbon emissions. The implementation of BEERs may potentially have several other co-benefits in addition to combating climate change, such as lower energy bills for consumers, improved energy security, health and comfort, and a lower need for energy subsidies (Evans et al., 2017; Evans et al., 2018). Hence, many countries have now introduced codes and regulations imposing minimum levels of energy efficiency on constructing new buildings or retrofitting existing buildings. Nevertheless, the full achievement of building energy code's benefits, including their role in climate change mitigation, depends on code implementation during building design and construction.

2.2.3 Development and implementation of BEERs

The development of BEERs requires collating and analysing a wide variety of data. The following activities are recognised as the main steps to be taken toward the development of BEERs (Liu et al., 2010):

- Identification of relevant examples from other locations: comprehensive survey analyses of international BEECs are required in order to identify the most suitable BEERs.
- Development of local base case building: investigating current building stock in order to determine base case buildings that can be utilised as benchmarks for development

and appraisal of building code requirements. This requires significant data collection of building stock such as energy use profile of current buildings, building typologies, climate data, information about equipment and materials that are available locally, as well as their associated costs.

- Estimation of energy-saving and cost-effectiveness of the base case buildings: the energy efficiency performance of the base case buildings as well as their attributed costs should be estimated early during the development process using different means such as simulation. In parallel, the opinions and professional judgments of construction experts should be used at the early stage of the BEER development and adoption process in order to assure the soundness of the BEERs.
- Drafting, reviews, and revisions of code document: BEERs should contain detailed documentation including technical data such as equipment ratings or tables of default values, explicit standard requirements, including compliance forms (that are easy for inspectors to check) and alternate compliance options. In the case of performance-based compliance, suitable simulation software with validated calculation engines should be developed. In addition, certain provisions for continued BEER maintenance and regular code revision and updates should be made.
- Engagement of stakeholders for public review: the early involvement of key stakeholders facilitates the identification of any potential issues attributing to the implementation of BEERs and resolving them prior to finalising the codes. This will increase the possibility that the stakeholders would embrace the implementation of these codes.

Upon the incorporation of public review, the BEERs would be legally adopted as voluntary or mandatory codes (Liu et al., 2010; Bartlett et al., 2003; Conover et al., 2011). In this regard, there are certain concerns that need to be addressed for the further development of BEERs. The level of simplicity and flexibility of the building codes should be decided. Whether the new building codes should allow architects and designers to practise prescriptive and performance-based compliance paths should be determined (Liu et al., 2010). Provisions for acceptance of innovation should also be embedded into the BEERs in order to increase the resilience of building codes toward the dynamics of new emerging technologies. Furthermore, the adoption of prescriptive and performance-based approaches for implementing BEERs should be roughly equivalent so that possibilities for existing loopholes can be minimised (Liu et al., 2010). In addition, the requirements specified by BEERs should be beneficial for the whole of society

(Liu et al., 2010; Bartlett et al., 2003; Conover et al., 2011). In another words, the costs of BEERs implementation should be balanced by the energy-saving potentials as well as other associated benefits over the building's lifetime. Hence, lifecycle cost analysis should be performed with the aim of identifying measures that have the highest financial impact on saving energy.

The development and implementation of building codes should take place in collaboration with a solid institutional infrastructure (Liu et al., 2010). In this regard, it is important to have a unit directly affiliated to a governmental agency/unit that would be in charge of code development and enforcement. Consultants with a variety of expertise should be constantly engaged to provide constructive feedback on the development and enforcement of BEERs by analysing the market. The structure of the codes' implementation should also be responsive in such a way that allows for improvements of the existing system in place by incorporating feedback received from public reviews.

2.2.4 Compliance approaches for enforcement of BEERs

The policies that enforce energy efficiency can be generally grouped into three different categories – sticks, tambourines, and carrots (Azevedo et al., 2013). In the context of building sector, "sticks" represent regulations, codes, and standards through which mandatory requirements for benchmarking metrics for best practices can be determined (Hu et al., 2020). "Tambourines" provide a basis to educate the public regarding the compliance requirements and energy efficiency strategies through informational tools such as capacity building, labelling, and awareness-raising campaigns (Hu et al., 2020). "Carrots" offer supplementary advantages such as rebates and subsidies with the aim to stimulate outstanding building performance via either innovative technological approaches or curtailment practices (e.g., conservative occupants' behaviours) (Hu et al., 2020). Regarding the enforcement of BEERs (i.e., "sticks"), the choice of compliance is often prescriptive or performance-based (Liu et al., 2010).

The prescriptive approach usually determines the minimum requirements for thermal performance of specific building components, for example, maximum U-values for external walls, roofs, windows as well as specifying minimum energy efficiency requirements for HVAC systems, lighting systems, or water heaters. Prescriptive BEERs are easy for builders and designers to apply since they provide transparent instructions and require relatively less information and expertise. This approach is also easier for reviewers and examiners, particularly if the applied equipment and materials could be certified and tested. The prescriptive approach can also be more convenient for product manufacturers because it provides a solid baseline for them to refine their products or retool their product lines (Liu et al., 2010). However, the prescriptive approach has been criticised due to its lack of capacity to promote innovation in the construction industry and its inflexibility for optimising construction costs (Foliente, 2000). Hence, many countries around the world have either introduced performance-based building regulations or are in the process of doing so.

The performance-based approach facilitates regulating the whole building performance, enabling designers to employ optimisation solutions in correspondence to the particular circumstances (Liu et al., 2010). This approach also enables practitioners to utilise innovative products in building construction. The Council for Research and Innovation in Building and Construction defined the concept of performance-based approach as "*the performance approach is, first and foremost, the practice of thinking and working in terms of ends rather than means. It is concerned with what a building is required to do, and not with prescribing how it is to be constructed*" (Meacham et al., 2005). Performance-based regulations usually set certain levels for the overall annual energy performance (or energy budget) of targeted buildings. This approach also specifies standardised methodology to compute sub-energy budgets attributed to different usage of energy in buildings such as lighting, space heating, and cooling, as well as domestic hot water. To ease the process of compliance check, computerised tools are usually developed adopting the standardised methodologies (e.g., calculation methods).

In spite of descriptive BEERs, the performance-based approach focuses on the outcomes envisaged for a building and less on individual materials, assemblies, construction, and installations (Meacham, 2009). Performance-based regulation achieves this by including specific statements of policy priorities and goals that represent societal expectations and preferences, along with functional statements, organisational standards and performance criteria that are used to illustrate the achievement of functional (societal, political) goals and objectives (Meacham, 2009). Nonetheless, there are certain concerns related to the application of performance-based BEERs. For instance, this approach is more complex compared to prescriptive BEERs since substantiating the compliance of a building's performance with energy efficiency regulations usually requires performing computerised calculations. This in turn, makes the process of checking and validation more difficult, as building control staff need to have a certain expertise in order to appraise the data and calculations.

2.3 Toward zero energy buildings using BEERs

The earliest version of building codes dates back to Babylonian Hammurabi's law (1750 BC) (McFann, 2012). The Codes of Hammurabi entailed 282 laws written in cuneiform on an eight-foot-tall stone slab and it was publicly displayed (McFann, 2012). The laws numbered 229 to 233 related to the construction of buildings. While today's building codes aim to promote safety, energy efficiency and occupant's health, Hammurabi's codes dealt with the consequences of building failures. For instance, law number 229 stipulated that "a builder builds a house for someone, and does not construct it properly, and the house which he built falls and kills its owner then the builder shall be put to death" (McFann, 2012). The focus of modern building codes changed from specifying conditions for poor construction to mandating requirements in response to disasters such as fires or earthquakes. An early example of modern building codes is the London Building Act of 1844 in which conditions for improving drainage were specified, along with maintaining sufficient width of streets to ensure proper ventilation as well as regulating explosive and other such detrimental works (McFann, 2012).

In the twentieth century, governments began incorporating energy regulations, first into existing building codes and subsequently in a separate supplementary document typically referred to as "building energy codes". Building energy codes have evolved over time in response to national priorities. After the Second World War, health issues caused by poor insulation in cold climates instigated the initial movement toward regulating buildings' thermal conditions (IEA, 2013). In the 1960s, an increase in standards of living and demands for a higher indoor comfort made it necessary for countries to increase insulation requirements for buildings. Later, the oil crisis of 1973–1974 accelerated the development of energy building codes in most countries with the aim to reduce energy use (IEA, 2013).

In the 1990s, the stringency for energy requirements was further strengthened due to concerns relating to climate change and resource depletion. Nowadays, attempts are being undertaken worldwide to minimise energy consumption in the building sector by launching schemes to support the design and construction of highly energy-efficient buildings such as low-energy, nearly zero-energy buildings (nZEB), or net-zero energy buildings (NZEB). Table 2.3 tabulates a number of these initiatives that are stimulating the increase of energy efficiency in the building sector.

Table 2.3. Target and definitions for zero energy/carbon buildings

Source	Country	Target	Target year	Definition
Energy Performance in Buildings Directive (2010)	EU	All new EU buildings to be nearly zero energy.	2021	Defines nZEB as a "building that has a very high energy performance … The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby."
		All new public buildings must be nearly zero energy.	2019	
Energy Policies of IEA Countries: The UK 2012 Review (2012) (DCLG, 2009)	UK	All new-built dwellings must be zero carbon.	2016	Defines a Zero Carbon Home as a building that has "net emissions of carbon dioxide (CO_2) from all energy use in the home including internal lighting, heating, hot water service, air conditioning and mechanical ventilation" as well as "all other energy use (that is, energy used for computers, machinery or other processes carried out day to day in the building)" over the whole year.
Belgium federal government, definition of Zero-Energy House (Mlecnik et al., 2011; Belgium Review, 2016)	Belgium	Near-zero energy for all new buildings	2020	Defines a zero-energy house (ZEH) as a building compliant with the conditions for a passive house, whilst the "residual energy demand for space heating and cooling can be fully compensated by renewable energy produced on site".
US federal government (Crawley et al., 2009)	US	Zero energy for 50% of US commercial buildings	2040	Defines a "zero net energy commercial building" as a building that requires "a greatly reduced quantity of energy to operate to meet the balance of energy needs from sources of energy that do not produce GHGs" and "in a manner that will result in no net emissions of GHGs, whilst still being economically viable".
		All US commercial buildings	2050	
U.S Department of Energy (2015)	US	NA	NA	Defines a ZEB as "an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy".

NASA, Net Zero Energy Buildings Roadmap (Pless et al., 2014)	US	All new NASA buildings	2020	Defines an NZEB as "one that first sets an aggressive energy use intensity goal for the building in project planning. It then meets the reduced demand goal through energy efficiency approaches and technologies. Lastly, it adds renewable energy in a prioritised manner, using building-associated, emission-free sources first, to offset the annual conventional energy use required at the building."
CSIRO (Riedy et al., 2011)	Australia	NA	NA	Defines a ZEH as "a detached residential building that does not produce or release any CO_2 or other GHGs to the atmosphere as a direct or indirect result of the consumption and utilisation of energy in the house or on the site".
Energy Council (Trajectory for low energy buildings, 2019)	Australia	NA	NA	Defines: "zero energy (and carbon) ready buildings have an energy efficient thermal shell and appliances, have sufficiently low energy use and have the relevant set-up so they are 'ready' to achieve net zero energy (and carbon) usage, if they are combined with renewable or decarbonised energy systems on-site or off-site".
Ministry of Economy, Trade and Industry (IEA, 2010; METI, 2015)	Japan	Zero emissions in standard newly constructed houses	2050	Defines an NZEB as "a building whose annual net consumption of primary energy is zero".
World Green Building Council (WGBC, 2018)	NA	NA	NA	Defines a Net Zero Carbon Building as a highly energy-efficient building where "the amount of carbon dioxide emissions released on an annual basis is zero or negative". This building is fully powered from on-site and/or off-site renewable energy sources and offsets.

In most countries, BEERs are commonly utilised to fulfill the targets set for realising zero or nearly zero-energy buildings. For instance, the Energy Performance of Buildings Directive (EPBD) requires that all the new buildings in Europe must be nZEB from 31 December 2020, while new public buildings have needed to be nZEB since 31 December 2018 (Energy Performance in Buildings Directive, 2010). Correspondingly, European countries must adjust their BEERs to properly meet the EPBD requirements. This indicates the importance of BEERs for energy efficiency meeting targets in the building sector. The focus of these regulations is on minimising the amount of energy consumed in thermal (i.e., heating and cooling) and non-thermal loads (i.e., domestic hot water, electrical appliances and equipment, ventilation, lighting, and cooking) within a particular period of time. This approach is reflected in the definitions given for nZEBs or NZEBs, as tabulated in Table 2.3.

Nevertheless, recent research has argued that the current approach of BEERs fails to reduce the total energy usage of buildings since these regulations exclude the impacts of embodied energy (Crawford et al., 2016; Omrany et al., 2020; Omrany et al., 2021; Pomponi and Moncaster, 2018). The argument is that reduction of operational energy can be addressed once the building is constructed by using energy-efficient appliances and equipment. However, any attempt to reduce embodied energy after construction provokes an additional increase of embodied energy. Hence, it is imperative for the BEERs to not only consider the importance of reducing operational energy, but also decrease embodied impacts in building designs.

2.3.1 The effects of building codes on saving operational energy

The implementation of BEERs is commonly agreed to be an effective mechanism to reduce CO_2 emissions related to buildings' operations in the medium term (Evans et al., 2017; Evans et al., 2018). For instance, reports generated by International Energy Agency (IEA) indicate that the enforcement of building codes by the member countries led to saving 6-22% of average annual energy consumption associated with buildings (IEA, 2013). Yu et al. (2014) also stated that the implementation of building codes in China may potentially contribute to minimising CO_2 emissions associated with building sector by 13-22%to 2100. The enforcement of building energy-efficiency codes can be particularly important for countries dealing with housing booms such as China, India, and Australia.

Wang et al. (2019) estimated the effects of implementing Chinese BEERs using survey data collected from 1128 households in Chongqing, China. The effectiveness of building energy-efficiency codes was evaluated at two levels – the 50%- BEER (low level) and the 65%- BEER (high level) through applying the propensity scores matching method. The results showed that the enforcement of 65%- BEERs and 50%- BEERs can decrease energy use intensity (kWh/m2/year) including cooling and heating electricity by 41% and 38% respectively.

Wang et al. (2019) noted a performance gap between the amount of energy savings calculated during the design stage of a building and actual operation energy savings. Hence, they recommend the inclusion of outcome-based compliance pathways into the current BEERs system. In addition, it is suggested that databases containing energy consumption of buildings should be developed in China as a measure to support developing building energy codes and performance evaluation.

In another study, Xu et al. (2013) studied the potential of different energy efficiency standards, namely China local, China national, and UK standards for energy savings in hot summer and cold winter zones in the Chinese residential sector and public buildings. To this end, energy simulation tool eQuest was employed to analyse building end-use energy. The findings indicated that the adoption of Chinese national standards can offer 31.5% energy savings for the residential sector compared to the existing situation, while the local and UK standards brought energy savings equivalent to 45.0% and 53.4% respectively. For public buildings, the corresponding energy saving potentials were 62.8%, 67.4%, and 75.9% for national, local, and UK standards respectively.

A study on Indian building codes showed that adequate application of building regulations can bring annual energy savings equivalent to 17–42%, depending on the building type (Tulsyan et al., 2013). Likewise, Yu et al. (2017) underlined the significance of building codes in Gujarat, India for saving energy. Their study showed that building codes can reduce electricity consumption by 20% in 2050. Tulsyan et al. (2013) analysed the capacity of Indian energy efficiency building codes for saving energy in Jaipur of six different building types using a simulation approach. The results showed that the proper implementation of energy-efficiency codes may bring 44 kWh/m^2/year energy savings for government buildings, whereas potential energy savings for private offices were 128 kWh/m^2/year. They also predicted that 12,475 MWh/year potential energy savings can be achieved for commercial buildings within the next five years if energy efficiency building codes were implemented.

Lee and Yik (2002) carried out a comprehensive study analysing the design characteristics of 22 commercial buildings in Hong Kong. The results indicated that the implementation of regulatory building standards, coupled with voluntary schemes can lead to achieving energy savings ranging between 8% to more than 30%.

Lee and Chen (2008) benchmarked energy-efficiency codes of China against HK-BEAM using a case study. The benchmark was done by accounting for seven criteria that were common between the two building codes including indoor design temperature, envelope features (i.e., heat transfer coefficients of roof, wall, and windows, shading coefficient, window-to-wall ratios, and overall thermal transfer values), occupation densities, infiltration, lighting power intensities, small power intensities and air conditioner (AC) features. The simulated results revealed that the case study designed in accordance with the Chinese building codes was 51.1% better in consuming energy compared to when the case was designed according to HK-BEAM. The findings also indicated that building energy use of a typical building designed based on the building codes can be most influenced by AC operation hours, indoor design temperature, coefficient of performance of the room air-conditioners units, as well as envelope attributes.

Fayaz and Kari (2009) benchmarked Iranian building energy-efficiency Code 19 against ISO 9164, EN 832, German regulation, TS 825 of Turkey, and China's GB 50189 in order to show how these codes and standards account for national characteristics. To this end, they assessed five cases of residential buildings in Iran against Iranian Code 19, as well as Turkish standard TS 825. The results suggest that Code 19 was able to efficiently calculate characteristics of building envelopes. However, further improvements in the areas of ventilation, gains from internal and solar sources were needed.

Livingston et al. (2014) showed the achievement of 106 million tonnes of oil equivalent in cumulative energy savings between 1992 and 2012 in the United States. Koirala et al. (2013) assessed the potential of International Energy Conservation Code (IECC) 2003 and IECC 2006 for saving energy in the US residential sector. The results indicated that the implementation of building codes can save approximately 1.8 % of electricity, 1.3 % of natural gas, and 2.8 % of heating oil coupled with reducing 7.54 million metric tons of CO_2 per year.

In recent research, Koirala and Bohara (2020) estimated the effects of implementing US energy efficiency policy in the residential sector of 48 states between 1970 and 2017 using a Dynamic Panel Data model coupled with a two-step Generalized Method of Moments technique. The results found that energy efficiency codes had the ability to save 8.6 % in energy consumption in the residential sector.

In another study, Novan et al. (2017) investigated hourly electricity consumption for 158,112 houses in Sacramento, California aiming to analyse the effectiveness of energy efficiency codes implemented in 1978 for the first time. The results revealed that houses built after 1978 consumed 8% to 13% less electricity for cooling compared to those constructed prior to 1978.

Jacobsen and Kotchen (2013) also evaluated the effects of increased stringency in building energy-efficiency codes of Florida by using utility billing data collected from households constructed under different energy code regimes. The results showed that the increased stringency in building energy-efficiency codes may reduce electricity and natural gas consumption respectively by 4% and 6%. The average social and private payback periods were estimated to be in the range of 3.5 and 6.4 years.

Kim et al. (2020) conducted research to identify possible measures to strengthen the prescriptive and performance criteria for enhancing market acceptance of the building energy codes in Korea. To this end, the potential for energy savings driven by the prescriptive criteria that had been improved in the past were initially analysed. Thereafter, several measures for future reinforcement of building codes in Korea were suggested based on an analysis of the collected energy performance parameters and cost data. The results showed that energy-efficiency requirements for office buildings and school buildings can be strengthened by approximately 5% to 15%.

Song and Choi (2012) investigated the effects of a newly enforced building code in Korea on energy consumption in residential buildings through field measurements and simulation. The building regulation allows the remodelling of balcony spaces to be used as a living space in residential buildings. The results showed that heating and cooling loads can be 39% and 22% higher for units without balcony space compared to those with balcony space. The assessment also indicated that the implementation of such a regulation may eventually lead to considerable energy loss on the national scale and the ratio will be 0.3% of the final energy use in Korea.

This review shows that the adoption of BEERs can potentially lead to the enhancement of energy efficiency in the building sector by minimising operational energy usage. However, recent studies have raised concerns about the limited scope of these policies as they only account for the impacts of operational energy and tend to exclude embodied energy (Pomponi and Moncaster, 2018; Crawford et al., 2016). Pomponi and Moncaster (2018) stated that without immediate action, embodied energy would become the 'second wave' of environmental concern relating to buildings' performance. Therefore, there is a need of extending the current scope of BEERs to include embodied energy impacts.

2.3.2 The necessity of extending the coverage of BEERs

Most of the developed countries began implementing BEERs for residential and non-residential buildings as a response to the first oil crisis in the mid-1970s (Liu et al., 2010). The enforcement of these regulations was carried out in most countries at national and state levels.

Prior to the mid-1990s, there were only a few countries in Southeast Asia that had some forms of voluntary codes for commercial buildings. A survey conducted in 1994 showed that only 15 countries, including 11 developing and four transitioning countries, had formulated either voluntary or mandatory BEERs for residential and/or non-residential buildings (Janda and Busch, 1994).

Since then, the number of countries employing BEERs has increased significantly. For instance, a report on the global status of BEERs implementation in 2007 listed 37 countries that had introduced BEERs (Janda, 2009). The most recent report shows that 136 countries have reflected on the importance of energy efficiency measures in buildings (United Nations Environment Programme, 2020), indicating a significant improvement in supporting energy efficiency over recent decades. Nevertheless, the building sector is still known as one of the major contributors to global energy usage and CO_2 emissions.

The total overall energy use in this sector increased from 118 Exajoules (EJ) in 2010 to approximately 130 EJ in 2019 (United Nations Environment Programme, 2020). This increase lies mainly with the fastest-growing demands for building energy services such as space cooling and heating, appliances, and electric plug-loads as driving factors in energy consumption. In this regard, the coverage of energy efficiency policy plays an important role in minimizing energy use in the sector.

The coverage refers to the scope of BEERs in defining the parameters impacting on energy consumption in buildings. The 2018 review on the global status of BEERs implementation shows that the current policies regulating energy efficiency only cover 35% of the buildings' energy use, a minor enhancement from the coverage of 34% in 2017 (Figure 2.5) (Worldwide building energy efficiency coverage, 2018). This means that a large percentage of annual operating energy usage of buildings is not being addressed via BEERs.

Lighting coverage appears to become saturated at 83% of energy consumption covered by policies in 2018. This may be attributed to the major global policy shift of phasing out incandescent lamps and replacing them with LED lighting. In 2019, the sales of LED lamps reached an exceptional sales record of more than 10 billion units including both luminaires and light sources (i.e., bulbs, tubes, modules) (Report on global lighting by International Energy Agency, 2020). The vast deployment of LEDs driven by their relatively higher energy efficiency performance has led LED sales to exceed that of fluorescent lamps in residential buildings. The efficacy of typical LEDs available in the residential market is in the range of 100 lumens per watt (lm/W) depending on the model (e.g., directional, non-directional, tubular), whereas the average efficacies for compact fluorescent and halogen lamps are approximately 60 lm/W and 20 lm/W, respectively (Report on global lighting by International Energy Agency, 2020).

On the other hand, electrical appliances not only received scant attention (with only 31% of policy coverage), but also saw a 1% drop compared to the preceding year. This indicates untapped opportunities for future policies to improve energy efficiency in the building sector by tightening stringency for electrical appliances.

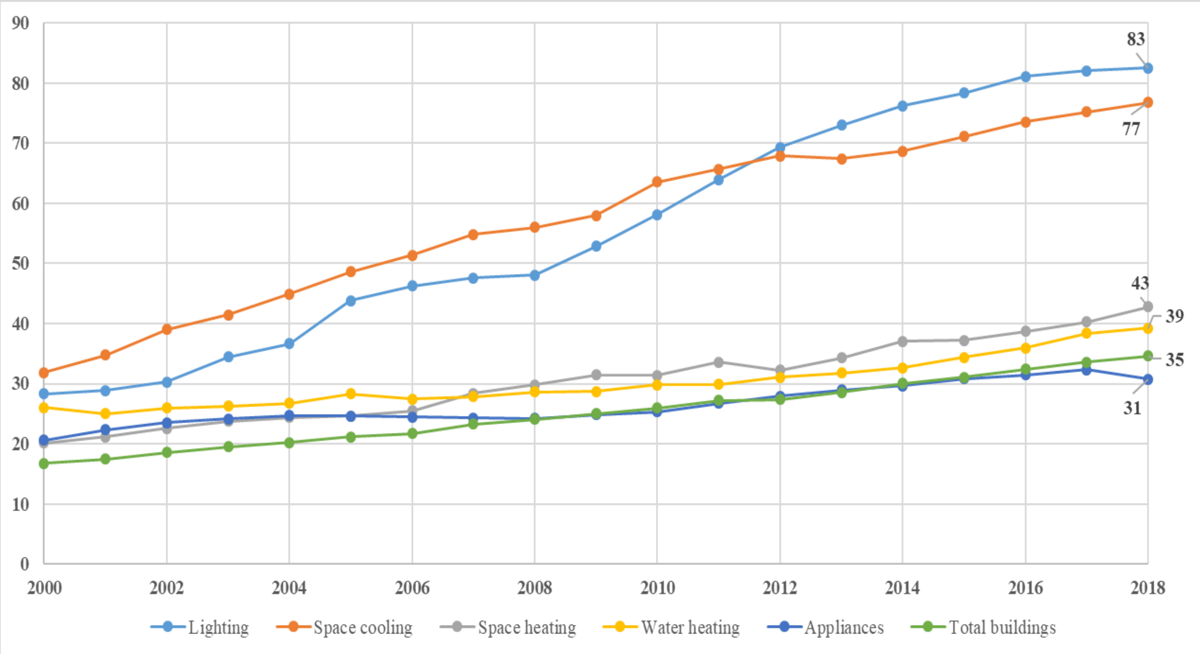

Figure 2.5. Policy coverage of total final energy consumption in buildings, 2000-2018. Reproduced from (Worldwide building energy efficiency coverage, 2018)

The coverage of building energy regulations can also be discussed in terms of the extent to which they account for the impacts of operational and embodied energies. Table 2.4 shows the coverage of BEERs that are being implemented in a number of countries. As indicated, lighting and electrical appliances received less attention compared to other parameters. In other words, the major focus of BEERs is placed on minimising energy consumption caused by space heating, space cooling, domestic water heating, and ventilation, while lighting and appliances are being commonly excluded in residential buildings. This exclusion could be due to the difficulty in checking BEERs compliance as energy use of lighting and electrical appliances over an entire year are hard to capture via software packages.

Amongst all the countries using BEERs, the Netherlands is one of the few that include the impacts of embodied energy relating to construction materials in BEERs (Building Decree, 2012). Other countries have also taken their initial steps towards this end including France (French Ministry of Sustainable Housing, 2017), Finland (Kuittinen and le Roux, 2018), Norway (Norwegian Standard NS 3720, 2018), Denmark (Danish Government Strategy for the Circular Economy, 2018; Frivillig Baeredygtighetsklasse i bygningsreglementet, 2018), and Sweden (Boverket Klimatdeklaration Av Byggnader, 2018) but this is yet to be fully reflected in their BEERs.

Table 2.4. Coverage of BEERs for residential buildings in different countries

Country	Coverage of BEERs							Reference
	Lighting	**Space cooling**	**Space heating**	**Water heating**	**Appliances**	**Ventilation**	**Embodied energy**	
Australia		▲	▲					National Constructions Code: Guide to Volume two
UK	▲	▲	▲	▲		▲		Standard Assessment Procedure for Energy Rating of Dwellings (SAP, 2014); Reduced Data Standard Assessment Procedure (Reduced Data SAP for existing dwellings, 2019).
California-US		▲	▲	▲		▲		Residential Compliance Manual of California Building Energy Efficiency Standards; Chapter 8: Performance Method (Residential Compliance Manual, 2019).
Germany		▲	▲	▲		▲		Energy Conservation Regulations reported by International Energy Agency (Energy Conservation Regulations, 2019); The European portal for energy efficiency in Buildings (The European portal for energy efficiency in Buildings, 2009)

Norway	▲	▲	▲	▲		▲		Regulations on technical requirements for buildings (Building Technical Regulations, 2016); International Energy Agency (The Planning and Buildings Act, 2016).
Netherlands		▲	▲	▲		▲	▲	Building Decree 2012 (Building Decree, 2012)
Japan	▲	▲	▲	▲	▲	▲		Building Energy Efficiency Act reported by International Energy Agency (Building Energy Efficiency Act, 2019); Overview of the Act on the Improvement of Energy Consumption Performance of Buildings (An Overview of Building Energy Efficiency Act, 2016)

NB: ▲ included in the policy coverage.

The Netherlands has recently strengthened its measures toward realising zero energy in the building sector. Starting from 1 January 2021, all new buildings needed to be nearly zero-energy (nZEB) as a result of compliance with EPBD requirements. The Building Decree 2012 stipulates safety, health, usability, energy efficiency and the environment requirements for building, refurbishment, rebuilding, demolition, and occupancy of a building (Building Decree, 2012). Section 5.2 of Building Decree 2012 titled "Environment, New Structures", requires that the environmental impacts (i.e., GHG emissions and resource depletion) associated with the structural elements of a residential function or an office building with a total usable area exceeding 100 m^2 must be quantified. The environmental burden of construction materials are required to be calculated following "Environmental Performance Calculation Method for Buildings and Civil Works" standards (Determination Method, 2019).

In parallel, the National Environmental Database (Nationale Milieudatabase) was developed to provide a standardised process for computing the environmental performance of buildings and civil engineering works in the Dutch context (National Environmental Database, 2020). This database supplies environmental information relating to products and activities that are calculated according to the Determination Method. In addition, several software tools have been developed to facilitate the calculation process (National Environmental Database-Validated calculation tools). These tools enable practitioners to readily calculate the environmental impacts of buildings via linking models to the database.

Despite the promising measures taken by the government of the Netherlands, no restriction has been set on the amount of embodied energy associated with the used construction materials. In other words, the current regulatory system of Netherland building jurisdictions only demands that builders calculate the environmental loads of their buildings with no cap imposed on the maximum/minimum values for the environmental performance of buildings. This requirement aims to encourage the use of materials with the lowest environmental impacts.

The subsequent step in the Netherlands should be to introduce mandatory requirements for the total environmental performance of buildings. This approach has been advocated by previous studies. For instance, Chan (2019) examined the environmental benefits of regulatory requirements specified by Hong Kong jurisdictions on the energy efficiency performance of building designs. To this end, a survey was conducted on the design and construction of 240 fully air-conditioned buildings constructed between 1986 and 2017, which produced data on the trends of building designs and constructions over 32 years. As a result, a number of changes were made to the building codes in Hong Kong. Chan then employed EnergyPlus simulation software in order to examine the effectiveness of these changes on both the operational and embodied energy of buildings. The results showed that the implementation of current energy-efficiency regulation in Hong Kong may lead to the reduction of both embodied and operational energy. It is also advised that policymakers should incorporate an assessment phase into the development of building regulations to investigate the environmental effects of proposed regulatory requirements on building energy efficiency prior to finalisation.

In another study, Stephan and Crawford (2016) investigated the relationship between house size and life cycle energy demands with the aim of informing future building energy-efficiency regulations in Australia. A typical detached house in Melbourne was selected, and its floor area was parametrically changed from 100 to 392 m^2 for four different household sizes. The initial and recurrent embodied energy demands correlated to each altered case were calculated and summed with operational energy over 50 years. The results showed that the life cycle energy demand increased at a slower rate compared to house size – hence, the expression of energy-efficiency performance per m^2 may favour large houses whereas these buildings require more energy. The study conclusively stated that BEERs should account for embodied energy, plus they should reconsider energy intensity thresholds for house size and use multiple functional units to measure efficiency.

2.4 Summary

This chapter has provided an overview of the current trends of energy consumption in residential buildings and discussed the key role of building energy efficiency regulations in reducing energy consumption. It has shown that the adoption of current BEERs can potentially lead to minimizing energy consumption in buildings. However, the net reduction of total life cycle energy consumption cannot be achieved due to the limited scope of these regulations. The majority of BEERs being implemented in different countries tend to exclude the impacts of embodied energy. This approach results in the omission of a considerable portion of energy usage that is embedded in upstream and downstream stages of buildings' life cycles. Hence, there is a necessity of extending the coverage of current BEERs to include the impacts of embodied energy.

Chapter 3. Exploring the Recent Trends of Life Cycle Energy Assessment in Residential Buildings

3.1 Introduction

The impacts of embodied energy are being widely excluded from the frame of building energy efficiency regulations in most countries. The main reason for the exclusion is because of inconsistencies in life cycle energy assessments (LCEA) – evaluating the total environmental burdens of buildings by considering the impacts of embodied energy in combination with operational energy. This inconsistency leads to variations in the results of LCEA, which may further compromise the reliability of the achieved results for decision-making purposes. This chapter conducts a scoping literature review, examining methodological approaches of studies published over the last decade (i.e., 2010 until December 2019), toward analyzing the total LCEA of residential buildings. The outcome of this chapter is to provide an updated understanding of the current trends in employing LCEAs in residential buildings.

3.2 List of manuscripts

This part of the research has been produced as a journal article, published in the journal of *Sustainability*:

Omrany, H., Soebarto, V., Sharifi, E., & Soltani, A. (2020). Application of Life Cycle Energy Assessment in Residential Buildings: A Critical Review of Recent Trends. *Sustainability*, 12(1), 351. DOI: https://doi.org/10.3390/su12010351.

The paper is presented here in a reformatted version for consistency of the thesis presentation. The accepted manuscript can be found in Appendix I.

Statement of Authorship

Title of Paper	Application of Life Cycle Energy Assessment in Residential Buildings: A Critical Review of Recent Trends
Publication Status	☑ Published ☐ Accepted for Publication ☐ Submitted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details	Omrany, Hossein, Veronica Soebarto, Ehsan Sharifi, and Ali Soltani. "Application of life cycle energy assessment in residential buildings: a critical review of recent trends." Sustainability 12, no. 1 (2020): 351. DOI: https://doi.org/10.3390/su12010351

Principal Author

Name of Principal Author (Candidate)	Hossein Omrany		
Contribution to the Paper	Conceptualization, methodology, collecting the data (literature materials), data analysis, and writing—original draft preparation.		
Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	15/08/2021

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Veronica Soebarto		
Contribution to the Paper	Methodology, review & editting, supervision.		
Signature	Professor Veronica Soebarto — Digitally signed by Professor Veronica Soebarto	Date	21/09/2021

Name of Co-Author	Ehsan Sharifi		
Contribution to the Paper	Review & editting.		
Signature		Date	16/8/2021

Please cut and paste additional co-author panels here as required.

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Ali Soltani		
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Signature		Date	

Please cut and paste additional co-author panels here as required.

3.3 Application of Life Cycle Energy Assessment in Residential Buildings: A Critical Review of Recent Trends

Abstract: Residential buildings are responsible for a considerable portion of energy consumption and greenhouse gas emissions worldwide. Correspondingly, many attempts have been made across the world to minimize energy consumption in this sector via regulations and building codes. The focus of these regulations has mainly been on reducing operational energy use, whereas the impacts of buildings' embodied energy are frequently excluded. In recent years, there has been a growing interest in analyzing the energy performance of buildings via a life cycle energy assessment (LCEA) approach. The increasing amount of research has however caused the issue of a variation in results presented by LCEA studies, in which apparently similar case studies exhibited different results. This paper aims to identify the main sources of variation in LCEA studies by critically analyzing 26 studies representing 86 cases in 12 countries. The findings indicate that the current trend of LCEA application in residential buildings suffers from significant inaccuracy accruing from incomplete definitions of the system boundary, in tandem with the lack of consensus on measurements of operational and embodied energies. The findings call for a comprehensive framework through which system boundary definition for calculations of embodied and operational energies can be standardized.

Keywords: life cycle energy assessment; life cycle assessment; residential buildings; energy efficiency; sustainability.

1. Introduction

The residential sector is responsible for consuming 27% of energy and emitting 17% of the greenhouse gas (GHG) emissions worldwide [1, 2]. This percentage differs between countries due to varying climatic conditions, energy requirements, social and economic situations, and the availability of main energy resources [3]. Due to the significance of this sector in mitigating global climate change, considerable efforts have been undertaken across many countries to reduce energy consumption in residential buildings by legislating various regulations and building codes. These regulations are mainly in place to minimize the environmental impacts associated with energy use from heating, cooling, and lighting [4]. However, recent studies have shown the reduction of building operational energy use can lead to an increase in total building life cycle energy use due to increasing the embodied energy from the building components [5–8]. Therefore, research into investigating embodied energy using the life cycle energy assessment (LCEA) approach has been increasing in recent years, with numerous detailed case studies of individual buildings developed by academics.

The LCEA is a simplified version of the life cycle assessment (LCA), which only accounts for energy inputs at different stages of the life cycle, including both embodied energy and operational energy [9]. The increasing amount of research has however caused an issue of variations in results presented by LCEA studies, in which apparently similar case studies exhibited different results. To date, a plethora of studies have been conducted exploring reasons for variations in the results of LCEA studies [4,10–13]. For instance, Dixit et al. [10] identified key parameters which can lead to varying results in embodied energy analysis, namely system boundary definitions, the methods used for measurement of embodied energy, geography, the type of energy (i.e., primary or secondary energy), age and source of data, data completeness, manufacturing technology, feedstock energy considerations, and temporal representativeness.

The majority of the conducted studies only looked at parameters with potential influence on calculating embodied energy, whereas variations can also be induced from the measurement of building operational energy. Therefore, there is currently a lack of studies adopting a comprehensive approach to seek possible sources of variations throughout the entire process of LCEA analysis while including both operational and embodied energy measurements. To address this gap, the literature relating to the LCEA application in residential buildings has been reviewed with the aim to identify causes of variations in performing LCEA analysis. To this end, we limited the scope of our paper to examining studies published from 2010 onwards. This facilitated the possibility to capture the most up-to-date trends of LCEA application in residential buildings. The identified studies were then analyzed based on their definitions of system boundaries, and methods were applied to estimate embodied energy and operational energy, as well as to interpret the results achieved.

2. An Overview of Life Cycle Energy Assessment (LCEA)

The LCA is an approach for identifying and assessing the environmental impacts of products, services, or processes throughout their entire life cycles, namely extracting raw materials, processing and manufacturing, operation, and end-of-life (EOL) [14–18]. The first sets of LCA standards were established during 1997–2000 by the International Organization for Standardization (ISO), leading to the ISO standards 14040, 14041, 14042, and 14043 [19]. In 2006, the updates to these standards were finalized in which the previous versions were amalgamated into ISO 14040 and 14044 [20,21]. The major feature of an ISO standard is a four-step iterative framework, including a goal and scope definition, inventory analysis, life-cycle impact assessment (LCIA), and interpretation (Figure 1).

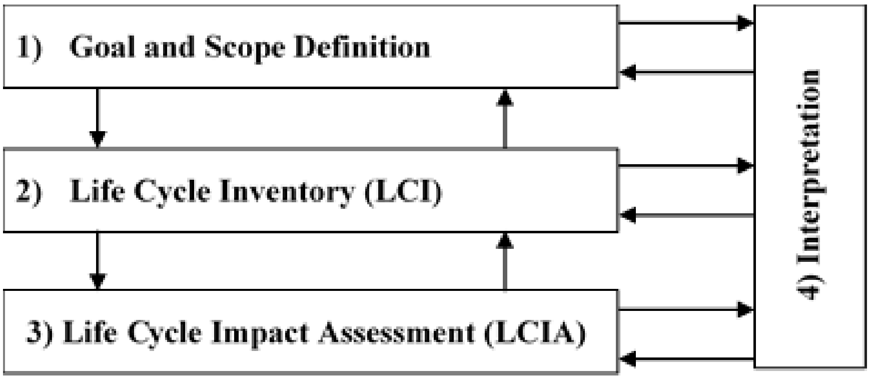

Figure 1. The Life Cycle Assessment (LCA) framework based on International Organization for Standardization (ISO) standard [22].

The first step to perform an LCA analysis is to establish the goals and scope of the study, which encompass defining system boundaries and functional units, as well as determining the quality criteria for inventory data. The life-cycle inventory (LCI) analysis refers to the procedure of collecting data and synthesizing information pertaining to the physical material and energy flows in different stages of the product life cycle. The LCIA is the stage where the environmental impacts of various material and energy flows are quantified and assigned to different environmental impact categories. At the end, the achieved results are finalized for conclusion, recommendation, and decision-making purposes.

The LCEA focuses on the evaluation of energy inputs for different phases of the life cycle [9]. Figure 2 demonstrates the system boundary for performing a whole LCEA study, consisting of raw material extraction, material processing and manufacturing, transportation of materials to the construction site, the process of construction, installation, and erection, building operations and its maintenance, and demolition. The life cycle energy of buildings can be sub-divided into embodied and operational energy.

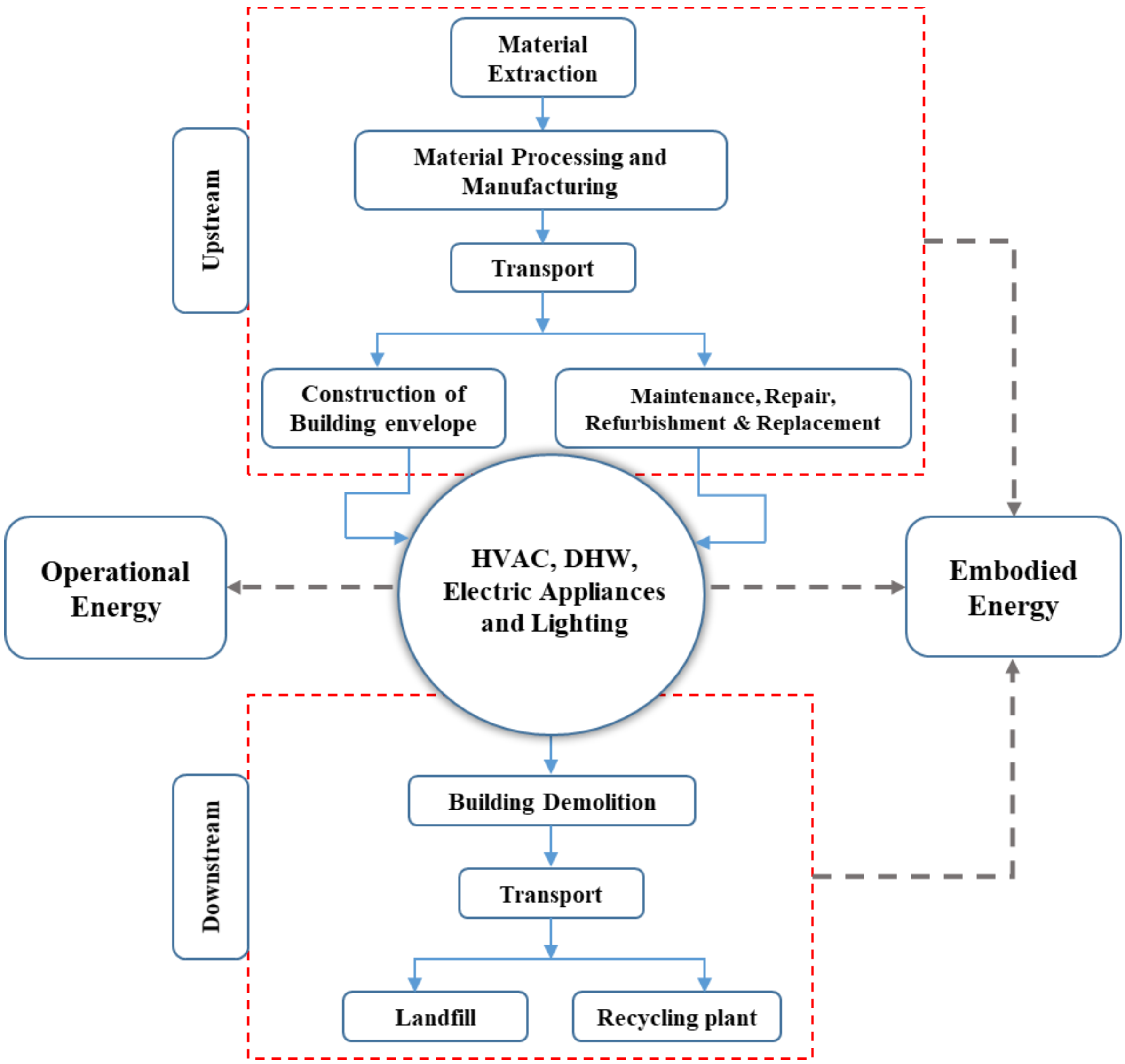

Figure 2. Building life cycle energy (adapted from reference [23]).

Operational energy refers to the amounts of energy consumed in the forms of heating and cooling, domestic hot water (DHW), electrical appliances and equipment, ventilation, lighting, and cooking in order to retain the indoor comfort conditions [24]. The share of operational energy to the total building life cycle energy use is usually higher than the embodied energy [14,23]. As a result, the minimization of this energy has been the focus of many policy-driven schemes developed in different countries to support the construction of energy-efficient buildings.

Embodied energy refers to energy used to extract and refine raw materials, manufacture materials, assemble components, conduct on-site construction, complete EOL processes, and carry out any transportation required between any of these steps [14,15]. Overall, embodied energy can be divided into:

- Initial embodied energy: refers to the quantity of energy incurred for the initial construction of the building including extracting raw materials, processing the extracted materials, and transporting building materials to construction sites and on-site construction and installation.
- Recurring embodied energy: refers to the total amounts of energy embodied in the materials used for maintaining and rehabilitating a building during its life span.
- EOL: refers to the amounts of energy required to demolish the building and to transport the resulted wastages to landfill sites and/or recycling plants.

The LCEA is, therefore, the sum of embodied energy and operational energy of a building. The reliability of results depends on the completeness and accuracy of the data and the robustness of the methodology applied to carry out an LCEA analysis. The following section elaborates on the research methodology used in this paper.

3. Materials and Methods

This paper analyzed instances of the LCEA application in residential buildings using a systematic literature review. The review considered publication materials from various academic databases, namely Scopus, Google Scholar, and Web of Science. The application of multiple search engines to investigate the body of literature covers the weaknesses of one source by using the strength of others [25,26]. The approach to conducting the review consists of three main steps.

During the first step, all LCA-related scholarly research publications (more than 300 papers) from 2010 onwards related to the LCA application in residential buildings were identified based on a comprehensive keyword searching exercise (Table 1).

Table 1. Keywords used in the research approach.

Keywords applied at the first stage
Life cycle assessment; sustainability assessment; life cycle energy assessment; operational and embodied energy; life cycle environmental assessment; building energy performance; life cycle assessment tools; building energy consumption; building environmental emissions; sustainable construction; life cycle inventory; sustainable building design; building embodied emissions.

During the second stage, the titles and abstracts of the identified documents were screened to make an initial judgment about the aptness of the publications for inclusion. Here, the key criteria considered for further analyzing the retrieved materials were i) the studies must apply LCEA, and ii) the focus of assessment must be on residential buildings. Also, the studies that were not peer-reviewed or written in English were excluded. In addition, we only accounted for the studies that considered primary energy to perform LCEA analysis. The evaluation of building energy performance can be implemented considering either primary or secondary (delivered) energy. In general, these two cannot be directly compared as they contain different quantities of energy. The energy delivered for end-use contains lower amounts of energy than the actual quantities of primary energy utilized to generate and distribute secondary energy. Thus, the impacts of buildings' life cycle energy use on the built environment can be better represented by using primary energy [11].

During the third stage, the selection process was controlled qualitatively by checking the content of all publication materials in order to ensure that only those corresponding to the scope of this paper were chosen for detailed examination. At this stage, studies with a sole focus on investigating embodied energy were not selected for examination, as they were not holistic in their approaches for appraisal of a building's life cycle energy performance. Analogously, studies with unavailable data on buildings' life cycle energy uses were also excluded from further analysis. It is noteworthy to mention that this survey accounted for all types of residential buildings including conventional and low-energy use buildings (e.g., passive buildings, net zero energy building, nearly zero energy buildings), high-rise buildings, as well as buildings located in rural and urban areas. As a result, 26 papers representing 86 case studies across 12 countries were selected. This paper considers different versions of a similar building investigated in one source, as case studies. The following sections provide a detailed analysis of the case studies.

4. Analysis and Results

This section aims to discuss the findings of the reviewed studies. The detailed list of analysis can be found in Appendices A and B.

4.1. System Boundary Definition

The system boundary refers to a set of variables that delineate the boundary of a particular system and distinguish it from other systems in an environment [12]. The approaches of the reviewed studies to defining system boundaries were analyzed with respect to excluding stage(s) from the building's life cycle, building components considered for embodied energy calculation, parameters considered for operational energy calculations, building life span, and the key assumptions.

4.1.1. Stages Excluded

As indicated in Figure 2, the stages of a building life cycle include raw material extraction, material processing and manufacturing, transport, on-site construction and installation, operational phase, and EOL. A whole LCEA study refers to an assessment which accounts for the analysis of energy usage while considering all stages of building life cycle.

The review shows that only 27% of the studies performed a whole LCEA analysis, while others neglected the impacts of certain stages on total building energy use. It was found that 50% of the studies excluded the EOL from the system boundaries, which is mainly justified due to its minor contribution to the total building life cycle energy use or the lack of clarity on the deconstruction practices after the end of building life service [5,6,27–35]. Amongst those which considered energy consumption at the EOL, studies usually avoided performing detailed analysis to unveil energy usage at this stage. For instance, Crawford [36] added 1% of the total building energy demands in order to account for the energy usage at the EOL stage. Similarly, Devi and Palaniappan [37] added an amount equal to 3% of the total building life cycle energy use to help consider energy usage at the EOL stage. In addition, 'replacement and maintenance' (recurrent embodied energy) has been a subject of exclusion for 27% of the reviewed studies [27,31,37–41] despite the significant effects that this phase may have on the total building life cycle energy use. Studies reported the recurrent embodied energy may represent up to 31% of a total building's embodied energy [30]. In another study, Crawford [36] demonstrated the impacts of recurrent embodied energy can constitute up to 22% of total building life cycle energy demands. Moreover, 'on-site construction', and 'transport' were excluded from system boundaries by 15% and 4% of the reviewed studies, respectively.

4.1.2. Building Components Considered for Measurement of Embodied Energy

The review shows the studies were inconsistent in accounting for the impacts of embodied energy pertaining to building components and systems (Table 2). From Table 2, it can be understood that there is a consensus on considering embodied energy impacts associated with main building components, namely the building envelope (i.e., external walls, roof, and floor).

However, the definition of system boundary differs amongst the reviewed studies concerning inclusion of the impacts of embodied energy related to building systems and installations as well as furniture, appliances, and fixtures.

Table 2. Different approaches toward the assessment of building embodied energy

Author(s)	Building components	Furniture/fixtures/ appliances	Elements beyond building scale
Aye et al. [27]	Columns and beams, external and internal walls, external cladding, ceiling, roof, floor, doors and windows, floor tiling, staircase.	NA	NA
Gustavsson et al. [38]	Foundation, floor structure, roof, external and internal walls, doors and windows, balconies, stairs.	Interior fixtures	NA
Dodoo and Gustavsson [42]	Foundation, floor, roof, external and internal walls, insulation, doors and windows, balconies, stairs.	NA	NA
Ramesh et al. [28]	Exterior walls, roof and floor, insulation.	NA	NA
Stephan and Stephan [30]	Exterior walls, roof, floor, building structure, insulation, building systems.	NA	Urban infrastructure, occupants' transport
Atmaca and Atmaca [43]	External and internal walls, doors and windows, roof, floor, wall and roof tiles, insulation, building structure, foundation, façade (plastering, painting).	NA	NA
Rossi et al. [44]	Basement slab, external and internal walls, roof and floor.	NA	NA
Stephan et al. [6]	Building structure and sub-structure, external and internal walls, finishings, floor, roof, foundation, systems (piping and wiring), doors and windows, insulations.	Carpet, fixtures	Urban infrastructure, occupants' transport
Cellura et al. [45]	Electrical systems, solar thermal system, Photovoltaic (PV) systems, air handling unit, thermal plant, domestic hot water (DHW) plant, building sub-structure, external and internal walls, building structure, roof and floor, foundation.	NA	NA
Stephan et al. [5]	Building structure and sub-structure, external and internal walls, finishings, floor, roof, foundation, systems (piping and wiring), doors and windows, insulations.	NA	Urban infrastructure (i.e., roads, power lines, water and gas distribution, and sewage)

Crawford [36]	External walls, roof and floor, doors and windows, paint, building structure, insulation, foundation.	Finishes, appliances, carpet, fitout	NA
Pinky Devi and Palaniappan [31]	External walls, roof and floor, building structural frames, systems (plumbing, firefighting and wiring), painting and plastering, foundation.	NA	NA
Paulsen and Sposto [46]	External and internal walls, painting and plastering, roof and floor, ceiling, windows, indoor and external doors.	NA	NA
Devi and Palaniappan [37]	Building envelope, structural frames/concreting work, finishing (plastering, painting and tiling), doors and windows, sanitary installations, systems (plumbing and water pipes) and steel work (tubes for atrium glazing and stainless steel accessories).	NA	NA
Bastos et al. [33]	External and internal walls, floor, roof, staircases, building structures, windows, external and internal doors.	NA	NA
Ramesh et al. [29]	External walls, roof, widows, PV panels, wind turbine, wiring and installation.	NA	NA
Zhan et al. [47]	External walls, floor, roof, foundation, finishing (plastering, painting and tiling), building structure.	NA	NA
Iyer-Raniga and Wong [48]	Foundations, columns, upper floors, staircases, roof, external and internal walls, windows, external and internal doors, floor and ceiling finishes.	NA	NA
Dodoo et al. [39]	External and internal walls, intermediate floor and ceiling, roof, foundation, windows and doors, elevator and stair, services and installations, finishes.	NA	NA
Tettey et al. [40]	Building structure, external and internal walls, floor, insulation and finishes, foundation, windows.	NA	NA
Mehta et al. [35]	Building structure, external walls, foundation, roof, floor, and painting.	NA	NA
Zhu et al. [41]	External walls, precast façade, staircase, slab, balcony, painting, windows, finishes.	NA	NA

Bastos et al. [32]	External and internal walls, wooden and concrete floors, staircase, roof, windows, foundations, external and internal doors.	NA	Occupants' transport
Goggins et al. [49]	External walls, foundations and floors, roof, chimney, stairs, PV panels, ventilation systems.	NA	NA
Kristjansdottir et al. [50]	PV system, space-heating system, external and internal walls, foundation, windows and external doors, roof, insulation.	NA	NA
Mistretta et al. [51]	Blinds, electrical system, solar thermal system, PV system, air handling unit, thermal plant, DHW plant, building frame, external and internal walls, support structures, roof, foundations.	NA	NA

Studies also pointed out the possibility of extending their system boundaries to include parameters beyond building elements [5,6,30]. Stephan et al. [5] put forward a framework to account for the impacts of embodied and operational energy of a building while considering the embodied energy of nearby infrastructure (i.e., roads, power lines, water and gas distribution, and sewage) and the transport energy of its occupants. In this framework, they calculated the embodied energy of surrounding infrastructures using process-based hybrid analysis. To do this, the embodied energy of each form of infrastructure was calculated based on the infrastructure density in m/km^2 and attributed to the building based on the population density and the number of users as per Equation (1):

$$LCEE_{if} = \sum_{i=1}^{I} \left(LCEE_i \times D_i \times \frac{NO}{PD} \right) \quad (1)$$

where $LCEE_{if}$ is the life cycle embodied energy of infrastructure in GJ, LCEEi is the life cycle embodied energy of infrastructure i in GJ/m, D_i is the density of infrastructure i in m/km^2, NO is the number of occupants in the building, and PD is population density in $inhabitants/km^2$. Additionally, they accounted for the energy used as the result of occupants' mobility. They applied this framework to analyze the life cycle energy usage of two buildings located in Australia and Belgium. The results showed the users' transport constituted 25.4% and 33.8% of the total building life cycle energy demands in a Belgian passive house and an Australian building, respectively. In another study, Stephan and Stephan [30] estimated the life cycle energy use of a residential building in Lebanon considering the energy embodied in users' transport, including both direct and indirect energy requirements. The direct energy refers to mobility process itself i.e., using fuel in the engine of a car, whereas indirect energy refers to all the processes supporting mobility, such as car registration, insurance, manufacturing the car itself, etc. The life cycle transport energy demand of the building's occupants ($LCTE_b$) was calculated by multiplying the energy intensity of transport modes used in Lebanon (i.e., gasoline cars) by the average traveling distance of occupants using Equation (2):

$$LCTE_b = UL_b \times \sum_{c=1}^{C}(DCI_c + IEI_c) \times ATD_c \qquad 1) \ (2)$$

where: $LCTE_b$ = Life cycle transport energy demand of the occupants of building b, in GJ; UL_b = Useful life of building b, in years; DEI_c = Direct energy intensity of car c, in GJ/km; IEI_c = Indirect energy intensity of car c, in GJ/km; and ATD_c = Average annual travel distance of car c, in km. The results showed the building life cycle energy demand of the building was dominated by transport energy with a share of 49%, followed by operational and embodied energy with the shares of 33 and 18%, respectively.

From the review, it can be realized that the studies differ according to their approaches for excluding certain stages of building life cycle and measuring embodied energy associated with building components. It was found that the exclusion of building life cycle stages occurs mainly due to the perceived minor impacts of these stages on the total building life cycle energy demand or the uncertainties relating to the fate of building materials at the end of building life. In addition, the reviewed studies were inconsistent in assessing the embodied energy of building components. Although most of the studies only accounted for embodied energy related to building components, the possibility of including embodied energies of parameters such as urban infrastructure or occupants' mobility was also suggested by a number of studies.

4.1.3. Parameters Considered for Operational Energy Measurement

The operational energy measurement depends on the extent to which parameters (i.e., heating and cooling, DHW, electrical appliances and equipment, ventilation, lighting, and cooking) are considered for assessment. From the review, it was found that 27% of the reviewed studies accounted for the impacts of all contributors [5,29,30,32,33,35,36]. It was also revealed that 62% of the studies excluded the impacts of cooking on operational energy use, followed by DHW (38%), electrical appliances (35%), lighting (27%), and ventilation (23%). The exclusion of each parameter can influence total building life cycle energy demands by affecting the proportions of operational energy and embodied energy [52,53]. For instance, Gustavsson and Joelsson [52] showed the share of embodied energy in the total building's life cycle energy use was reduced from 33% to 25% when the scope of the study was extended from only space heating to including the energy associated with household electricity, DHW, and ventilation.

Although none of the reviewed studies has given justifications, their exclusions can be related to the minor influence that each of these parameters could have on operational energy use.

4.1.4. Building Life Span

The life span assumed by the reviewed studies ranged from 50 to 100, with the most commonly used life span of 50 years (Table 3). The assumption of building life span can directly influence the share of both embodied and operational energy. This factor can impact the contribution of embodied energy to the total building life cycle energy consumption by affecting recurrent embodied energy [54,55]. The operational energy can also be influenced by the assumption of building life span as the increase of building life span leads to increasing operational energy, whereas assuming a short life span may result in increasing embodied energy over the building's life cycle owing to more frequent substitution of the whole building [56]. In a study, Rauf and Crawford [55] investigated the relation between a building's life span and its embodied energy by using a comprehensive hybrid embodied energy assessment technique. The results unveiled that extending the building's life span from 50 to 150 can result in reducing the life cycle embodied energy demands of the building by 29%.

Table 3. Frequency of building life span.

Building life span	Frequency of use
50 years	15
60 years	2
70 years	3
75 years	3
80 years	1
100 years	3*
Total	27

Note: Gustavsson et al. [38] considered two life spans: 50 and 100.

4.1.5. Assumptions

The assumptions are of the utmost importance in conducting LCEA studies due to their effects on the completeness and accuracy of the achieved results [19]. It was found that the assumptions made by the reviewed studies were associated with different phases of the building life cycle, including the initial, on-site construction, operation, replacement and maintenance, and EOL stages (Table 4).

The first group of assumptions involved the operation stage. It was noted that the estimation of a building's operational energy is commonly carried out for one year, and then the achieved figure has been multiplied by the number of years in which the LCEA study is conducted. Studies assumed that operational energy use would remain unchanged during the entire course of assessment. Although making such an assumption was only declared by a number of authors (as citied in Table 4), it can be mentioned that all the reviewed studies have made a similar assumption. Assuming a constant operational energy consumption implies that the building would have a constant schedule for heating and cooling systems, there would be unchanged patterns of occupancy (e.g., family size or behaviors), or heating and cooling systems would not be subject to depreciation. In another study, Iyer-Raniga and Wong [48] assumed that the resource mix used to supply electricity of the building would be unaltered during 100 years of building operation, despite hefty investments being made globally to promote utilizing renewable energy sources.

Table 4. Overview of the assumptions made by the reviewed studies.

Stage of building life cycle targeted	Assumption	Reference
Operation phase	The schedule for operating heating and cooling systems is assumed to remain unchanged during the entire course of life cycle assessment; The detailed occupational schedules and gains are not considered; The efficiency of heat pump system is assumed to be constant over time; The annual operating energy is assumed to remain consistent in throughout the entire building life span; The effects of climate change and occupants' behaviors in the future are not taken into consideration; The resource mix supplying electricity to the buildings is assumed to be static;	[27–29,33,42]
Initial embodied energy	Australian database of construction materials is used to calculate the embodied energy; Australian input–output-based hybrid embodied energy intensities are used for a case study located in Belgium; Using I–O data relating to production stage that occurred over a decade ago;	[6,30,36,43,48]

Embodied energy of on-site construction	All the manufacturing processes are assumed to be undertaken in one place; The primary energy used for on-site construction is assumed to be 80 kWh/m2; The primary energy used for on-site construction is assumed to be 4% of the material production primary energy; 80 and 160 kWh/m2 are assumed for the on-site energy consumption of wood and concrete building systems respectively;	[38–40]
Embodied energy of replacement and refurbishment	The structural elements of the building are assumed to have the same service life as the house; The embodied energy associated with replacement, refurbishment and repair of materials and products are assumed to be 5% every 10 years; The replacement lifetimes of construction materials in US are used for LCEA of buildings in Australia; The standard construction methods and materials are assumed to remain the same during the entire building life span;	[43,44,48]
Embodied energy of EOL	5% waste of material is assumed during construction; 90% of the wood-based demolition materials are assumed to be recovered while 10% decays into atmosphere; Only one type of fuel is assumed to be used for transporting the wastages; To account for the contribution of EOL stage, 1% of the total life cycle energy demand is summed to the final achieved figure; The embodied energy associated with EOL is assumed to be 3% of the total building life cycle energy demand; The primary energy use for demolition of wood and concrete are assumed to be 10 and 20 kWh/m2 respectively; All of the materials are assumed to be landfilled at the EOL stage; It is assumed that demolition energy will not exceed 10 kWh/m^2	[36–40,42,43]

The second group contains assumptions related to the estimation of initial embodied energy. Due to the lack of available and reliable data, studies applied databases from other countries in order to calculate embodied energy. For instance, Stephan and Stephan [30] used an Australian database containing embodied energy coefficients for building materials to calculate the embodied energy of a residential building in Lebanon. In another study, Stephan et al. [6] used Australian input–output-based hybrid embodied energy intensities to estimate the embodied energy of a passive building in Belgium. Likewise, Devi and Palaniappan [37] used the Inventory of Carbon and Energy (ICE), which is a database developed in the EU, to estimate the embodied energy of a residential building in India. This assumption may potentially compromise the quality of LCEA results due to inherent differences between the two countries, e.g., different economic sectors (in case of developing input–output matrix) or different construction practices and technologies. The justification given for making such assumptions is commonly related to the absence of a locally developed database.

Assumptions are also made to estimate embodied energy associated with on-site construction, replacement and refurbishment, and EOL stages. Gustavsson et al. [38] assumed primary energy used for on-site construction of an eight-story wood framed apartment is 80 kWh/m2. Dodoo et al. [39] also assumed that on-site construction embodied energy is equivalent to 4% of the material production primary energy. As shown in Table 4, assumptions were made on replacement and refurbishment of the buildings. Atmaca and Atmaca [43] assumed that the standard construction methods and practices would be unchanged during the entire building life span. The substitution of building materials during the use phase of the building with the exact same material is another assumption, which is not commonly specified but has been utilized by the majority of the LCEA studies. For this assumption, construction materials would be replaced by similar materials with the same energy intensities. Regarding to the EOL stage, studies assumed different shares of energy consumptions [36,37,39]. For instance, Devi and Palaniappan [37] assumed that this stage consumes 3% of the total building life cycle energy demand. Dodoo et al. [39] also assumed the demolition at the EOL stage would not exceed 10 kWh/m^2.

The majority of these assumptions were made to mitigate the complexity involved in embodied energy calculation or due to the lack of reliable data. Considering the potential impacts of assumptions on results, it can be recommended for LCEA studies to clearly mention assumptions while justifying their contextual applicability and appropriateness. Moreover, assessing the impacts of each assumption on the LCEA results could be an interesting topic for future research.

4.2. The Assessment of Embodied Energy

The embodied energy assessment commences with obtaining qualitative and quantitative data for each unit process that will be included within the system boundaries. For buildings, these data are collected by investigating technical specifications or drawings of buildings, site surveys or using contractor records. A similar approach was undertaken by the reviewed studies to collect the required data. For instance, Gustavsson et al. [38] used construction drawings and personal communication with staff of the construction industries to obtain the total quantities of building materials.

Once the required data are collected, the method to quantify embodied energy needs to be determined. Three major approaches are commonly used for the calculation of embodied energy, including the process-based approach, economic input-output (I-O) approach, and input-output-based hybrid approach. The process-based is a traditional approach, which is preferred when the physical flow of goods and services can be easily identified and traced. However, this method may become overwhelmingly complicated when inputs and outputs are numerous [43]. Moreover, it is prone to errors induced by the subjective removal of the iterative effect from the upstream production system [41]. Alternatively, the economic I-O approach follows a top-down approach and treats the whole economy as the boundary of analysis in order to arrive at consistent boundary definitions between studies. The economic I-O is based on the flow of materials in an economic structure aiming to determine the amount of primary energy required to produce a specific product or service. Although the application of this approach rectifies the incompleteness of the system boundary for capturing the upstream effects, it still lacks product-specific data. Hence, an I-O based hybrid approach was proposed to combine both process-based and economic I-O approaches and therefore cover the inputs from the entire upstream supply chain [57].

From the review, it was found that 62% of the reviewed studies applied the process-based approach to assess embodied energy, while 27% utilized the I-O based hybrid approach. Furthermore, 11% of the reviewed studies did not discuss their approaches for measurement of embodied energy. The magnitude of estimates achieved by the reviewed studies for embodied energy largely depends on the approach used for the calculation of this energy. Studies with the I-O based hybrid approach were more likely to obtain a high value for embodied energy since this approach captures energy usage embedded in both upstream and downstream stages of the building life cycle [7,30,57].

To calculate embodied energy associated with building materials, a background database containing datasets that represent technical and economic context must be selected. From the review, it was found the required background data were retrieved from two primary sources: ‘literature’, and publicly or commercially available databases (Table 5). The ‘literature’ refers to the embodied energy coefficients of previously published LCEA studies. Overall, 19% of the reviewed studies solely relied on the literature for calculating embodied energy. The mere reliance on literature may potentially compromise the quality of the achieved results, since the background databases are not representative of the building’s regional contexts (construction technology, climatic conditions, etc.).

In addition, several databases including both process-based and I-O based hybrid databases were employed for calculation of buildings’ embodied energy (Table 5). The findings indicate that 50% of the studies used generic international databases, namely ICE, Building for Environmental and Economic Sustainability (BEES), SimaPro, and Ecoinvent. Other process-based databases such as the Chinese Life Cycle Database (CLCD) and Australian National Life Cycle Inventory Database (AusLCI) were also used by the reviewed studies to acquire process specific data in order to form I-O hybrid databases [27,30,36,41].

Table 5. Databases applied by reviewed studies.

Database	**Developer**	**Data coverage**	**Access**	**Boundary**	**LCI method**
SimaPro	PRe' Consultants, Netherlands	Ecoinvent, US LCI, Danish input-output database, Dutch input-output database, LCA food database, Industry data	Licensed access	Cradle-to-grave	Process-based and I-O method
Ecoinvent	Ecoinvent centre, Swiss	General products and processes including energy, transport, building materials, chemicals, washing agents, paper and board, agriculture, waste management, international data	Licensed access	Cradle-to-gate	Process-based method
ICE	Bath University, UK	Construction and building materials, EU, mostly UK data	Publicly available	Cradle-to-gate	Process-based method
AusLCI	Building Product Innovation Council, Australia	Building and construction materials and products, Building product maintenance and replacement life data, Australian data	Publicly available	Cradle-to-grave	Process-based method
BEES	National Institute of Standards and Technology (U.S.)	Construction and building materials, mostly U.S. data	Publicly available	Cradle-to-grave	Process-based method
Database of Embodied Energy and Water Values for Materials	The University of Melbourne	Construction and building materials, Australian data	Publicly available	Cradle-to-grave	I-O based hybrid method
CLCD	Sichuan University, China; IKE Environmental Technology CO., Ltd., China	Materials and chemicals, energy carriers, transport, and waste management, China	Publicly available	Cradle-to-gate	Process-based method

From the review, it became evident that the studies differ significantly with respect to their approaches for calculating buildings' embodied energy. These variations stem from different types of methods and databases applied by the reviewed studies to assess buildings' embodied energy, combined with excluding a stage(s) of building life span, considering embodied energies associated with different building components, assuming different building life spans, and various assumptions attributing values to embodied energy calculations.

4.3. The Assessment of Operational Energy

Operational energy is commonly known for having the highest share of energy consumption in a building's life cycle [14,23]. Although previous studies attempted to draw a solid conclusion of a building's operational energy by juxtaposing different case studies [9,14,23,58–60], cross-comparison cannot be implemented in reality due to the varying approaches of studies for measuring operational energy. As previously mentioned, system boundary definition is a critical factor in calculating operational energy, as it involves including parameters with a potential influence on how operational energy use is determined. In addition, methods applied to calculate buildings' operational energy is another important variable leading to variations in LCEA results. Based on the review, methods utilized by the studies to calculate buildings' operational energy usage are categorized into four groups:

Using the actual records of building energy usage collected from utility bills, or energy audit exercises. The review found that 12% of the studies used this method to calculate the operational energy. Using this approach enables researchers to take into consideration all types of energy consumed in buildings including heating, cooling, lighting, DHW, cooking, and appliances. For instance, Atmaca and Atmaca [43] and Mehta et al. [35] used energy bills to estimate building operational energy use. Employing this method provides the ability to capture the dynamics of occupants' behaviors on energy consumption within a year. However, the application of this method can only supply an aggregated figure of building energy consumption, while failing to present a detailed breakdown of energy by use. This would potentially prevent decision makers from identifying the hot spots of energy consumption in building and providing solutions for energy reduction.

Using energy simulation software. It was found that 44% of the reviewed studies applied simulation software packages to estimate optional energy use. These software packages are commonly capable of producing detailed data on the annual energy consumption of buildings. Although the application of simulation software may ease the process of estimating operational energy, the accuracy of results achieved via simulation software can still be improved. One way to approach this challenge is to calibrate the simulation model to fit the real energy performance of the existing building. In addition, the impacts of users' behaviors on energy usage can be better taken into consideration. The two possible approaches to better account for the impacts of users' behaviors on energy use in buildings are deterministic and stochastic statistical approaches [61]. The deterministic approach refers to defining different scenarios for users' behaviors ranging from 'energy saving' to 'wasteful' behavior scenarios in respect to using energy in building e.g., DHW, on an hourly basis throughout the year. In addition, sensitivity analysis can be applied for the same purpose where sufficient data on users' behaviors are unavailable. Alternatively, the stochastic statistical model can be used to predict the users' attendance and activity in the building for inclusion into a simulation. In this model, relevant data should be collected through literature and national sociological investigations.

Static equations. Another method used by the reviewed studies (22%) for estimating operational energy was static equations [5,6,30,46,47]. In a study, Stephan et al. [5] estimated the operational energy of a residential building using Equation (3):

$$LCOPE_b = UL_b \times \sum_{e=1}^{E} (1 - SF_e) \times \frac{OPE_e}{n_e} \quad (3)$$

where $LCOPE_b$ is the life cycle primary operational energy of the building b in GJ, UL_b is the useful life of the building b, SF_e is the solar fraction for the end-use e, OPE_e is the yearly operational final energy demand of the end-use e in GJ, and $\eta e$is the average efficiency of the end-use e. The annual operational energy uses for heating and cooling were estimated by applying Equation (4):

$$OPE_h = HDH \times [U_b \times A_{ht} + (1 - \eta_{HR}) \times SV_{ht}] \quad (4)$$

where OPE_h is the operational final heating energy demand in kWh, HDH is the thousands of heating degree hours for the building site in Kh, U_b is the average heat transfer coefficient for the building in $W/(m^2K)$, A_{ht} is the area of heat transfer in m^2, ηHR is the efficiency of the heat recovery system if present, and V_{ht} is the ventilation heat transfer in W/K. The cooling energy demand was also calculated using Equation (4) by substituting the cooling degree hours for the heating degree hours. The ventilation energy demand was achieved by using Equation (5):

$$OPEv = V \times H \times P \quad (5)$$

where OPEv is the operational final ventilation energy in kWh, V is the ventilated volume in m3, H is the thousands of hours of mechanical ventilation per year, and P is the average fan power in W/m^3. The energy demands for DHW, appliances, and cooking were determined by multiplying regional per capita averages by the number of users in the house. Lighting was calculated by multiplying average annual energy usage per m2 by the usable floor area of the building. The average regional energy consumption data were then gained by using records published by governmental bodies. The final energy demands achieved were converted into primary energy applying appropriate conversion factors. Equation (3) also accounted for situations where solar systems are installed. In this case, solar fractions should be deduced from the final energy consumption of related end-uses. However, using this method can be time-consuming once the aim is to optimize a building design through parametric analysis. In addition, this method fails to capture buildings' thermal history when calculating cooling and heating loads e.g., time delay between heat absorptance and heat release by enclosing components of a room.

Miscellaneous. Other methods have been also used by the reviewed studies for calculating operational energy. For instance, Cellura et al. [45] monitored the annual energy consumption of a building in order to have an accurate estimate of the building operational energy use. Similarly, Devi and Palaniappan [37] monitored buildings' energy consumption for 21 months and then used the data for estimation of operational energy. In another study, Bastos et al. [32,33] estimated the operational energy consumptions while considering the ratio between residential electricity use and natural gas or LPG provided by the Lisbon Energy Matrix, which provides estimates of energy use in Lisbon building stock using 2002 data.

Similar to embodied energy, the approaches for calculation of operational energy also differed across the reviewed studies in two major aspects; i) accounting for the impacts of parameters contributing to operational energy use and ii) the approaches applied for calculation of operational energy use. The varied approaches for calculations of both embodied energy and operational energy may significantly influence the accuracy and completeness of the results reported by LCEA studies.

4.4. Interpretation

The final stage of an LCEA study is 'interpretation' in which the results of the analyses are discussed and recommendations are accordingly given. The interpretation of each LCEA study is unique, corresponding to the particular goal and defined system boundaries. The ISO 14044 recommends performing different types of ‘evaluations’ including a completeness check, sensitivity check, and consistency check in order to provide assurance of the robustness of the achieved results [20]. The completeness check refers to the process in which the completeness of all relevant information and data required for the interpretation is checked. The sensitivity analysis means that the reliability of the results and conclusions should be checked by determining how they are affected by uncertainties in the data, allocation methods, calculations of category indicator results, etc. The consistency check refers to the process in which the assumptions, methods, and data should be checked for whether they are consistent with the goal and scope of the study.

From the review, it was realized that three methods were commonly utilized by the reviewed studies as a means of ‘evaluation’: sensitivity analysis, uncertainty analysis, and discussion of limitations. In regards to sensitivity analysis, 31% of the studies applied this method to test the influence of inventory data parameters. For instance, Rossi et al. [44] assessed the impacts of climate and the energy mix on total building life cycle energy demands. Dodoo et al. [39] also tested the influence of insulation choices, building life span, air infiltration rates, and ventilation heat recovery (VHR) efficiency. The building life service is another parameter which has been subject to sensitivity analysis by studies [37,48]. Pinky Devi and Palaniappan [31] considered the influence of service life and efficiency in building operations on the total building life cycle energy use. Regarding the uncertainty analysis, 19% of the reviewed studies used this method. Gustavsson et al. [38] performed a qualitative uncertainty analysis, while Stephan and Stephan [30], Stephan et al. [5], and Stephan et al. [6] used the interval analysis method to quantitatively compute the uncertainty in embodied energy figures. Finally, 31% of the reviewed studies discussed the inherent limitations involving their research. Overall, no study performed all of the aforementioned evaluation methods, five studies included two of them [30,31,44,48,50], and ten studies did not consider performing any evaluation [27–29,41,42,45–47,49,51].

In addition to ISO 14044’s recommendation of a number of evaluations in order to assure the quality of results, other standards and guidelines have suggested certain measures to be taken at the interpretation stage. The EN 15978 introduced some rules to maintain the quality of final research, namely involving data validation [61]. Furthermore, EeBGuide recommends carrying out an uncertainty analysis, and where it is relevant, modeling an alternative scenario for each life cycle stage of a building [61].

4.5. Reuse and Recycling Potentials

The reuse and recycling potential refers to the process in which the benefits and loads from materials and energy beyond the assessed building's system boundary are captured [61]. It was found that eight studies considered processes associated with recycling potentials of building materials [27,38–40,42,45,49,51]. They considered reusing materials such as biomass residues during the production stage [47–49,55] and on the construction site [39] as well as recycling building materials such as concrete, steel, and wood at the EOL stage [47–49,55]. Table 6 shows the amounts of energy saved at the production, construction, and EOL stages of a building life cycle, along with representing the percentage of energy saved throughout the entire building life cycle by recycling or reusing materials (detailed data on energy saving were available for five studies).

Table 6. The reuse, recovery, and recycling potential for reducing total building life cycle energy use across the building life cycle (kWh/m^2.annuam).

Reference	Case study ID	Energy recovered at production stage	Energy recovered at construction stage	Energy recovered at EOL stage	Total energy recovered	Total energy saved (%)
Gustavsson et al. [38]	CS 4	23.64	NA	11.42	35.06	17.84
Dodoo and Gustavsson [42]	CS 5	7.78	NA	7.92	15.70	5.36
	CS 6	7.78	NA	7.92	15.70	7.27
	CS 7	7.78	NA	7.92	15.70	7.79
	CS 8	8.0	NA	8.06	16.06	6.05
	CS 9	8.0	NA	8.06	16.06	7.77
	CS10	8.0	NA	8.06	16.06	8.22
Cellura et al. [45]	CS23	NA	NA	19.01	19.01	9.14
Dodoo et al. [39]	CS 62	20.92	1.44	11.80	34.16	15.70
	CS 63	20.22	1.26	10.90	32.38	9.54
	CS 64	10.18	1.10	9.04	20.32	9.04
	CS 65	20.92	1.44	11.80	34.16	14.88
	CS 66	20.22	1.26	10.90	32.38	15.02
	CS 67	10.18	1.10	9.04	20.32	9.54
Tettey et al. [40]	CS 68	1.92	NA	5.63	7.55	4.90
	CS 69	20.98	NA	10.67	31.65	21.24
	CS 70	8.075	NA	6.30	14.38	9.75
	CS 71	1.92	NA	5.63	7.55	8.55
	CS 72	8.53	NA	6.57	15.10	18.37

Reusing and recycling building materials has already been suggested as an effective strategy to mitigate energy use in the building life cycle by decreasing embodied energy [8,62]. Based on Table 6, it can be observed that this strategy led to the reduction of total building life cycle energy use by the range of 5% to 22%.

5. Methodological Challenges

The overall methodological trends of the reviewed studies are shown in Table 7. As indicated, the present application of LCEA in residential buildings suffers from 'incompleteness' in defining system boundaries, and has 'ambiguity' in terms of measuring embodied energy and operational energy. Regarding 'incompleteness', it was realized the majority of the reviewed studies tended to exclude certain stages of the building life cycle from system boundaries. The impacts of energy consumed at the EOL were commonly discounted, with the reasoning that this stage may contribute negligibly to the total life cycle energy use of buildings. This approach not only leads to truncating system boundaries, but also deprives studies of the beneficial potential of reusing or recycling building materials at this stage.

Table 7. Overall trends of methodological aspects compiled from the reviewed studies

Methodological aspects	Overall trends of reviewed studies for LCEA application
Stages of building life cycle excluded	50% excluded EOL; 27% replacement and maintenance; 15% excluded on-site construction; 4% excluded transport.
Elements proposed for inclusion within system boundary	Three studies accounted for the inclusion of user's mobility over building life cycle; three studies accounted for the embodied energy of infrastructure on which buildings rely for receiving energy.
Building life span	58% of the reviewed studies considered 50 years as the life span.
Assumptions	All stages have been subject to assumptions.
Reuse, recovery, and recycling potential	31% of the reviewed studies considered recycling and reusing building materials.
The approach used for quantification of embodied energy	62% used process-based approach and 27% applied I-O based hybrid approach.
Database applied for estimating embodied energy	50% used generic international databases; 19% relied on the literature to retrieve embodied energy coefficients.
Contributors considered when estimating operational energy	62% excluded cooking; 38% excluded DHW; 35% excluded electrical appliances; 27% excluded lighting; and 23% excluded ventilation.
Methods used for estimation of operational energy	44% used software; 22% used static equations; 12% used energy bills. Other methods were also used such as monitoring energy consumption and using the national average of energy use for building stock.
Interpretation	31% used sensitivity analysis; 19% used uncertainty analysis; 31% discussed the limitations of these approaches. 19% used two methods.

Geographical context	50% focused on Europe; 31% on Asia; 15% on Australia; 4% on South America.

Furthermore, the extent of the inclusion of embodied energy impacts associated with building components and systems was unclear. Some studies limited their scopes of assessment to analyzing building elements (e.g., the building envelope) while there were studies which endeavored to include the embodied energy of urban infrastructure and occupants' mobility within the system boundaries. Likewise, the extent of the inclusion of parameters contributing to buildings' operational energy use varied across the reviewed studies. Only seven studies accounted for all of the parameters [5,29,30,32,33,35,36], whereas others excluded the impacts of a number of parameters. The lack of consensus on measurements of operational and embodied energies was also noted among the reviewed studies. The diversity in methods applied for calculating embodied and operational energies can affect the completeness and accuracy of the LCEA results while limiting cross comparability of the analyzed case studies. Apart from technical characteristics of LCEA analysis, the difference in geographic contexts of the reviewed studies was another source of variation in aspects of climatic conditions, quality of raw materials, production processes, economic data, processes of delivered energy generation, transport distances, energy use (fuel) in transport, and labor [10].

Despite the promising outlook of LCEA applications, the current state of this research area is plagued by inaccuracies accruing from incomplete definitions of system boundaries, coupled with ambiguous approaches for calculating embodied and operational energies. Hence, the process of decision-making can be affected due to inaccurate and incomplete results reported by LCEA studies. The inaccurate results can also influence the successful implementation of environmental practices, namely eco-labeling, through which users are informed about the environmental characteristics of buildings. Furthermore, the inconsistencies shown in Table 7 that exist throughout the entire process of LCEA analysis makes cross-comparison of the case studies impossible. Cross-comparison is important in developing an advanced knowledge about LCEA applications in residential buildings within a global context.

The diversity in applying LCEA signifies the necessity of developing a framework to standardize system boundaries, while providing guidelines on the measurements of operational and embodied energies. Previous studies endorsed a similar need to develop a standardized framework for the measurement of buildings' embodied energy [13]. However, the findings of this study showed that variations could also be induced from the measurement of operational energy. Therefore, there is a need to develop a much comprehensive framework to account for the buildings' environmental impacts, which would consider both embodied and operational energies.

6. Conclusion

This paper reviewed the current trend of LCEA application in residential buildings using a systematic literature review. Notwithstanding the extensiveness of the collected data and synthetic process of analyzing their embedded information relevant to the study's objectives, a number of limitations can be highlighted. First, the process of data collection and content analysis has been limited to the search engines, databases, and applied research terms. Moreover, the scope of the paper was limited to analyzing materials published from 2010 onwards, aiming to obtain an up-to-date understanding the use of LCEA for residential buildings. Despite the highlighted limitations, this paper managed to identify 26 papers representing 86 case studies across 12 countries. The analysis of the case studies enabled this paper to capture the most recent trends of utilizing LCEA for residential buildings.

The review shows the LCEA application for residential buildings is yet to be fully-fledged in providing accurate and complete results for decision-making purposes. This review shows the current trend of utilizing LCEA is suffering from an incomplete definition of system boundaries, combined with the ambiguous approaches for calculating embodied and operational energies. These limitations can further lead to affecting the process of decision-making while limiting the cross-comparability of the case studies. The necessity of developing a framework for standardization of system boundary definition in embodied energy measurement has been already highlighted by previous studies [13]. The findings of this study call for a comprehensive framework in which system boundary definitions for assessments of both embodied energy and operational energy can be standardized, while providing guidelines on methods for measuring these energies.

7. Future Study

This paper is a part of an ongoing project that aims to develop a conceptual framework to which the energy consumption of residential buildings throughout their entire building life cycles can be taken into consideration in a systematic and comparable approach. The next step for this research is to develop the framework based on the findings of this paper, and then validate its feasibility by assessing case studies.

Appendix A. Studies utilized LCEA in residential buildings

Authors	Country	Size (M^2)	System boundary				LCI	LCIA	Interpretation
			Stage(s) excluded	Life span (Yrs)	Operational energy	Assumptions			
Aye et al. [27]	Australia	3,943	EOL and replacement & maintenance	**50**	Heating and cooling	The schedule for operating heating and cooling systems is assumed constant; The detailed occupational schedules and gains are not considered; The efficiency of heat pump system is assumed to consistent over time.	Input–output–based hybrid approach is used; Input–output data is taken from the Australian National Accounts, combined with energy intensity factors by fuel type; Process specific data are retrieved from SimaPro Australian database	TRNSYS simulation software is used to estimate the building operational energy; The materials' quantities are multiplied by their respective embodied energy intensities, and summed.	None
Gustavsson et al. [38]	Sweden	3,374	Replacement & maintenance	50 and 100	Heating, DHW, household electricity, and electricity for facility management purposes.	The primary energy used for on-site construction is assumed 80 kWh/m^2; 5% waste of material is assumed during construction; 90% of the wood-based demolition materials are assumed to be recovered.	Process-based approach is used; Detailed info acquired from the manufacturers of building materials; Literature is used to obtain required embodied energy intensities of building materials	ENORM and ENSYST software are used to estimate the operational energy; The materials' quantities are multiplied by their respective embodied energy intensities, and summed	UA
Dodoo and Gustavsson [42]	Sweden	1,190	None	50	Heating, DHW, electricity for ventilation fans and pump, and electricity for household.	The efficiency of heating systems is assumed to be 85% and consistent throughout the entire building life span; It is assumed that 90% of concrete, wood and steel materials would be recovered at EOL.	Process-based approach is used; Literature is used for obtaining primary data on embodied energy.	VIP + software is used to estimate the operational energy; ENSYST is used to calculate the final energy for the operation activities; The embodied energy calculation is carried out multiplying the unit values by the area of each building element.	None
Ramesh et al. [28]	India	85.5	Construction and EOL	75	Heating, cooling, DHW, ventilation, household appliances and lighting.	The annual operating energy is assumed to remain constant throughout the entire building life span; The effects of climate change and occupants' behaviors in the future are not taken into consideration.	The approach to quantifying the embodied energy is not specified; Literature is used for obtaining primary data on embodied energy	DesignBuilder software is used to estimate the operational energy; The embodied energy calculation is carried out multiplying the unit values by the area of each building element and summed.	None
Stephan and Stephan [30]	Lebanon	904	EOL	50	Heating, cooling, ventilation, lighting, DHW, cooking and appliances	Australian database of construction materials is used to calculate the embodied energy; The embodied energy of infrastructures used to deliver energy to the building and life cycle transport energy demand of the building's occupants are considered.	Input–output–based hybrid approach is used; Hybrid database of construction materials developed by [63]; Process specific data are obtained from manufacturers.	DEROB-LTH software is used to calculate the heating and cooling loads; Equation is applied to calculate operational energy of DHW, ventilation, cooking, appliances and lighting; The embodied energy is calculated by multiplying the quantity of materials by their relevant embodied energy coefficient.	UA, DL

Authors	Country	Size (M^2)	System boundary				LCI	LCIA	Interpretation
			Stage(s) excluded	Life span (Yrs)	Operational energy	Assumptions			
Atmaca and Atmaca [43]	Turkey	Urban area (6,760) and rural area (1,320)	None	50	Heating, cooling, DHW, lighting, appliances, cooking	The standard construction methods and materials are assumed to remain the same during the entire building life span; The structural elements of the building are assumed to have the same service life as the house; All the manufacturing processes are assumed to be undertaken in one place; Only one type of fuel is assumed to be used for transporting the wastages.	Process-based approach is used; Literature and Inventory of Carbon and Energy (ICE) Version 2.0 are used to obtain embodied energy of building materials.	The actual energy consumption records obtained from utility bills and questionnaires are used for estimation of building operational energy; The embodied energy calculation is carried out multiplying the unit values by the area of each building element and summed.	DL
Rossi et al. [44]	Belgium, Portugal and Sweden	192	EOL	50	Heating, cooling, DHW, ventilation, lighting, building automation and control	The on-site processes e.g., the finishing of steel structures (cutting, shot blasting, welding) are excluded; The embodied energy associated with replacement, refurbishment and repair of materials and products are assumed 5% every 10 years.	Process-based approach is used; BEES, CRTI, ICE and databases are used to obtain embodied energy of building materials	LCA analysis has been done using Equer software, linked to two other software namely Pleiades + Comfie	SA, DL
Stephan et al. [6]	Belgium	297	EOL	100	Heating, ventilation, DHW, lighting, cooking and appliances	Australian input–output-based hybrid embodied energy intensities are used for this case study that is located in Belgium; The life cycle transport energy demands of the building's occupants are considered; The recurrent embodied energy of nearby infrastructures (e.g., roads, power lines, water and gas distribution systems and sewage) is considered.	Input–output–based hybrid approach is used; Input–output data is taken from the Australian National Accounts; A database containing embodied energy coefficients for materials in Australia developed by [63] is used.	The LCA analysis is performed using equations	UA
Cellura et al. [45]	Italy	481.76	None	70	Heating and cooling, ventilation, lighting and plug loads	Not discussed.	Process-based approach is used ; Literature and SimaPro database are us; Data acquired from the local manufacturer of building materials.	The annual electricity requirement of the building is monitored, and then normalized for estimating the building's operational energy; SimaPro is used to perform the LCA analysis.	None

Authors	Country	Size (M^2)	System boundary				LCI	LCIA	Interpretation
			Stage(s) excluded	Life span (Yrs)	Operational energy	Assumptions			
Stephan et al. [5]	Belgium and Australia	297 and 330	EOL	50	Heating, cooling, ventilation, lighting, DHW, cooking and appliances	The embodied energy of nearby infrastructures (e.g., roads, power lines, water and gas distribution, and sewage) used to deliver energy to the building and life cycle transport energy demand of the building's occupants are considered.	Input–output–based hybrid approach is used; Input–output data is taken from the Australian National Accounts; A database containing embodied energy coefficients for materials in Australia developed by [63] is used.	Static equations are used to calculate the operational energy; The initial embodied energy is calculated multiplying the relevant coefficients by the final quantities of the respective materials, and summed; The recurrent embodied energy is calculated via summing the embodied energy of replaced materials across the building's life span.	UA
Crawford [36]	Australia	291.3	None	50	Heating, cooling, ventilation, lighting, DHW, cooking and appliances	To account for the contribution of EOL stage, 1% of the total life cycle energy demand is summed to the final achieved figure.	Input–output–based hybrid approach is used; Input–output data is taken from the Australian National Accounts; Australian process data obtained from the SimaPro Australian database.	The energy bills is used to determine the operational energy of the house; The embodied energy is calculated via multiplying the quantities of the materials by their respective energy coefficients, and summed.	DL
Pinky Devi and Palaniappan [31]	India	32.5	Maintenance, repair, and EOL	50	Lighting, ventilation, appliances and equipment	Assumptions are made where technical details of building envelope were unavailable.	Process-based approach is used; The relative embodied energy coefficients are taken from literature and ICE database.	Data related to the operational energy are collected from national statistics; The embodied energy is calculated via multiplying the quantities of the materials by their respective energy coefficients, and summed.	SA, DL
Paulsen and Sposto [46]	Brazil	48	Transport	50	Appliances and equipment and cooking	No analysis of thermal performance (heating and cooling for operational energy) has been performed.	The approach to quantifying the embodied energy is not specified; Data related to the operational energy are collected from national statistics; National Brazilian process data are used for seven groups of material. Data from Portugal are also used for three material groups; Literature is also used to extract relative embodied energy coefficients.	Static equations are used to calculate the operational energy; The embodied energy is calculated via multiplying the quantities of the materials by their respective energy coefficients, and summed.	None
Devi and Palaniappan [37]	India	10,800	Maintenance, repair, and renovation	50	Lighting, ventilation, and partial or no air-conditioning	The building operational energy is assumed to be same during the entire building life span; The embodied energy associated with EOL is assumed 3% of the total building life cycle energy demand.	Process-based approach is used; The buildings' energy consumptions are monitored for 21 months and used for estimating the operational energy; The relative embodied energy coefficients are taken from literature and ICE.	Data taken from survey, normalized and used for calculation of building operational energy use; The embodied energy is calculated via multiplying the quantities of the materials by their respective energy coefficients, and summed.	SA

Authors	Country	Size (M^2)	System boundary				LCI	LCIA	Interpretation
			Stage(s) excluded	Life span (Yrs)	Operational energy	Assumptions			
Bastos et al. [33]	Portugal	Type 2 (367), Type 3 (472) and type 8 (1,041)	EOL	75	Heating, cooling, ventilation, lighting, DHW, cooking and appliances	The energy consumption is assumed the same during the entire building's life span.	Process-based approach is used; The Lisbon Energy Matrix data are used for estimating the operational energy; ICE is used for embodied energy calculation.	The Lisbon Energy Matrix data are used to calculate the total energy use per year based on the ratio between residential electricity use and natural gas or LPG; The embodied energy is calculated via multiplying the quantities of the materials by their respective embodied energy coefficients, and summed.	DL
Ramesh et al. [29]	India	CS1 (104), CS2 (185), CS3 (62), CS4 (183), CS5 (135), CS6(175), CS7(1280), CS8 (1286), CS9(450), CS10(235)	Construction and EOL	75	Heating, cooling, ventilation, lighting, DHW, cooking and appliances	The annual operating energy is assumed to be constant throughout the entire building life span; The effects of climate change and occupants' behaviors in the future are not taken into consideration.	The approach to quantifying the embodied energy is not specified; The relative embodied energy coefficients are taken from literature.	The building operational energy is estimated using DesignBuilder software; The embodied energy is calculated via multiplying the quantities of the materials by their respective embodied energy coefficients, and summed.	None
Zhan et al. [47]	China	4235.21	None	70	Heating, ventilation, air conditioning, lighting, appliances and equipment	The operational energy usage associated with household appliances is excluded; Recycling is considered at EOL stage.	Input–output–based hybrid approach is used; National data sources are used for estimation of embodied energy such as Guangzhou IO table, Guangzhou Statistical Yearbook of 2013, China Construction Statistical Yearbook of 2013, and China Electric Power Yearbook of 2013.	Static equations are used to estimate the operational energy consumption; Embodied energy is calculated using hybrid LCA	None

Authors	Country	Size (M^2)	System boundary				LCI	LCIA	Interpretation
			Stage(s) excluded	Life span (Yrs)	Operational energy	Assumptions			
Iyer- Raniga and Wong [48]	Australia	Not specified [a]	None	100	Heating and cooling	All of the materials are assumed to be landfilled at the EOL stage; The technology utilized for material and productions are assumed to remain unchanged; due to the lack of available data regarding to the replacement lifetimes, the relevant data in US is used; the resource mix supplying electricity to the buildings is assumed static; the occupancy pattern of buildings is assumed static.	Process-based approach is used; The electricity and water bills are collected and compared against the achieved simulated results for the purpose of validation; SimaPro and Australian Unit Process LCI databases are used for estimation of buildings' embodied energy.	The buildings operational energies are estimated using AccuRate software; Embodied energy is calculated using hybrid LCA	SA, DL
Dodoo et al. [39]	Sweden	CLT (928), BC (928) and MS (935)	Replacement and maintenance	50	Heating, ventilation, tap water heating and appliances and facility management	The contribution of construction phase to the total building life cycle energy is assumed to be 4% of the material production primary energy; It is assumed that demolition energy would not exceed 10 kWh/m^2 [usable area]. In addition, 90% of the demolished concrete, steel and wood materials are assumed to be recovered or recycled during EOL stage.	Process-based approach is used; Literature, Ecoinvent v.2.2 database and SP Technical Research Institute of Sweden are used to obtain required data on embodied energy.	VIP-Energy simulation software is used to estimate the final operational energy of the building; then, the achieved results are converted to primary energy using ENSYST software; The embodied energy is calculated via multiplying the quantities of the materials by their respective energy coefficients, and summed.	SA
Tettey et al. [40]	Sweden	1,686	Replacement and maintenance	80	Heating, tap water heating and electricity for ventilation	Electricity usages for household appliances and lighting are excluded for estimating the building operational energy; 80 and 160 kWh/m2 are assumed for the on-site energy consumption of wood and concrete building systems respectively; The primary energy use for demolition of wood and concrete are assumed to be 10 and 20 kWh/m^2 respectively.	Process-based approach is used; The relative embodied energy coefficients are obtained from literature.	VIP-Energy simulation software is used to estimate the final operational energy of the building; then, the achieved results are converted to primary energy using ENSYST software; The embodied energy is calculated via multiplying the quantities of the materials by their respective energy coefficients, and summed.	UA
Mehta et al. [35]	India	2,588.40	On-site construction, replacement and maintenance, and EOL	50	Heating, cooling, ventilation, lighting, DHW, cooking and appliances	Energy bills of another building with similar specifications are used, namely type of the home, usable floor area per home and the number of rooms.	Process-based approach is used; Operational energy is calculated using energy bills; ICE is used to calculate embodied energy.	Operational energy is calculated using energy bills.	SA

Authors	Country	Size (M^2)	System boundary				LCI	LCIA	Interpretation
			Stage(s) excluded	Life span (Yrs)	Operational energy	Assumptions			
Zhu et al. [41]	China	6,890 and 216,200	EOL, Replacement and maintenance	50	Heating and cooling, lighting and appliances	The effects of on-site construction management skill is ignored.	Input–output–based hybrid approach is used; The input-output table developed by Chinese National Bureau of Statistics is used; The process-based energy intensity data are acquired from the China Building Material Academy and the Chinese Life Cycle Database developed by Sichuan University.	DesignBuilder software is used to estimate the building's operational energy; The embodied energy is calculated via multiplying the quantities of the materials by their respective energy coefficients, and summed.	None
Bastos et al. [32]	Portugal	CA (102) and SH (104)	EOL	50	Heating, cooling, ventilation, lighting, DHW, cooking and appliances	This study accounts for user transportation.	Process-based approach is used; The Ecoinvent database is used for quantification of the building's embodied energy.	The ratio between residential electricity use and natural gas or LPG from the Lisbon Energy Matrix is used to calculate the total operational energy use per year.	SA
Goggins et al. [49]	Ireland	106	Replacement and maintenance	60	Lighting, ventilation, and DHW	90% of the building materials are assumed to be recycled at the EOL of building and used for secondary purposes; No change in fuel mix would occur over building life span.	Process-based approach is used; ICE is used to calculate embodied energy.	DEAP software is used to estimate the operational energy; The embodied energy is calculated via multiplying the quantities of the materials by their respective energy coefficients, and summed.	None
Kristjansdottir et al. [50]	Norway	120	Construction and EOL	60	Lighting, heating, appliances, ventilation, DHW.	Replacement of PV panels are assumed to have 50% of the initial embodied energy load.	Process-based approach is used; Ecoinvent v3.2 database is used to calculate embodied energy.	IDA-ICE software is used to calculate the operating energy; Brightway2 is used to perform impact assessment.	DL, SA
Mistretta et al. [51]	Italy	481.76	None	70	Heating and cooling, ventilation, DHW, lighting, and appliances.	Not discussed.	Process-based approach is used; Process data are obtained from local manufacturers; Ecoinvent database is used to retrieve data about recycling of aluminum, steel, glass, and copper.	TRNSYS software is used to estimate operating energy in the refurbished building. For the baseline building, energy use is monitored; SimpaPro is used to assess the environmental impacts.	None

Abbreviations: **LCI:** Life cycle inventory; **LCIA**: Life cycle impact assessment; **Interpretation stage**: Sensitivity Analysis (SA); Uncertainty Analysis (UA); Discussion of Limitations (DL); Case study (CS).
Note: a) the sizes of buildings are not specified, and results are reported in MJ/m^2

Appendix B. Normalized operational energy and embodied energy of analyzed studies

Authors	Building character	Case study ID	Embodied energy (kWh/m^2.year)	Operational energy (kWh/m^2.year)
Aye et al. [27]	Steel structure	CS1	Steel (80)	Steel (119.88)
	Concrete structure	CS2	Concrete (53.55)	Concrete (112.54)
	Timber structure	CS3	Timber (58.29)	Timber (117.57)
Gustavsson et al. [38]	Wood-framed apartment	CS4	Assumed 50 years of life span (-15.38)	Assumed 50 years of life span (176.86)
Dodoo and Gustavsson [42]	Conventional building with EH system	CS5	Conventional building with EH (-1.56)	Conventional building with EH (278.64)
	Conventional building with HPH system	CS6	Conventional building with HPH (-1.56)	Conventional building with HPH (201.7)
	Conventional building with DH system	CS7	Conventional building with DH (-1.56)	Conventional building with DH (187.26)
	Passive building with EH system	CS8	Passive building with EH (-1.66)	Passive building with EH (250.8)
	Passive building with HPH system	CS9	Passive building with HPH (-1.66)	Passive building with HPH (192.12)
	Passive building with DH system	CS10	Passive building with DH (-1.66)	Passive building with DH (181.08)
Ramesh et al. [28]	Building with fired clay exterior walls	CS11	Building with fired clay exterior walls (29)	Building with fired clay exterior walls (174)
	Building with hollow concrete exterior walls	CS12	Building with hollow concrete exterior walls (27)	Building with hollow concrete exterior walls (172)
	Building with soil cement exterior walls	CS13	Building with soil cement exterior walls (27)	Building with soil cement exterior walls (171)
	Building with fly ash exterior walls	CS14	Building with fly ash exterior walls (28)	Building with fly ash exterior walls (169)
	Building with aerated concrete exterior walls	CS15	Building with aerated concrete exterior walls (27)	Building with aerated concrete exterior walls (167)
Stephan and Stephan [30]	Apartment buildings	CS16	150	266.66
Atmaca and Atmaca [43]	Building located in urban area	CS17	Urban area (43.33)	Urban area (167.22)
	Building located in urban rural	CS18	Rural area (26.11)	Rural area (135.55)
Rossi et al. [44]	Residential building located in Belgium	CS19	Belgium (24.39)	Belgium (274.41)
	Residential building located in Portugal	CS20	Portugal (24.39)	Portugal (174.72)
	Residential building located in Sweden	CS21	Sweden (26.18)	Sweden (327.79)
Stephan et al. [6]	Passive house	CS22	131	39.5
Cellura et al. [45]	Net zero energy building	CS23	137.82	48.42
Stephan et al. [5]	Passive house - Brussels, Belgium	CS24	Belgium (143.48)	Belgium (99.41)
	7-Star building (highenergy efficiency standards) - Melbourne, Australia	CS25	Australia (130)	Australia (160.62)
Crawford [36]	Insulated timber-framed brick veneer walls	CS26	120.88	81.66
Pinky Devi and Palaniappan [31]	Low-cost house	CS27	37.25	92.65
Paulsen and Sposto [46]	Low-cost house	CS28	43.97	97.57
Devi and Palaniappan [37]	Multi-story residential building apartment	CS29	72.77	116.66
Bastos et al. [33]	Conventional residential buildings with the area of 367 m2	CS30	Type 2 (15.47)	Type 2 (74.64) a
	Conventional residential buildings with the area of 472 m2	CS31	Type 3 (15.11)	Type 3 (59.33) a
	Conventional residential buildings with the area of 1,041 m2	CS32	Type 8 (13.87)	Type 8 (37.77) a
Ramesh et al. [29]	Conventional building located in Keerthi	CS 33	CS1-Conventional system (28.12)	CS1-Conventional system (348)
	Conventional building located in Eashwer	CS 34	CS2-Conventional system (21.17)	CS2-Conventional system (271)
	Conventional building located in Adil	CS 35	CS3-Conventional system (27.4)	CS3-Conventional system (303)
	Conventional building located in Anand	CS 36	CS4-Conventional system (21.49)	CS4-Conventional system (264)
	Conventional building located in Alwal	CS 37	CS5-Conventional system (18.56)	CS5-Conventional system (279)
	Conventional building located in RG	CS 38	CS6-Conventional system (22.12)	CS6-Conventional system (296)
	Conventional building located in Rock town	CS 39	CS7-Conventional system (23.27)	CS7-Conventional system (325)

Authors	Building character	Case study ID	Embodied energy (kWh/m^2.year)	Operational energy (kWh/m^2.year)
Ramesh et al. [29]	Conventional building located in Kiran Arcade	CS 40	CS8-Conventional system (21.8)	CS8-Conventional system (250)
	Conventional building located in Mahendra	CS 41	CS9-Conventional system (24.54)	CS9-Conventional system (309)
	Conventional building located in Nirmal	CS 42	CS10-Conventional system (23.50)	CS10-Conventional system (280)
	Insulated building located in Keerthi	CS 43	CS1-Insulated envelope (30.63)	CS1-Insulated envelope (234)
	Conventional building located in Eashwer	CS 44	CS2-Insulated envelope (22.69)	CS2-Insulated envelope (237)
	Insulated building located in Adil	CS 45	CS3-Insulated envelope (29.45)	CS3-Insulated envelope (245)
	Conventional building located in Anand	CS 46	CS4-Insulated envelope (27.08)	CS4-Insulated envelope (230)
	Insulated building located in Alwal	CS 47	CS5-Insulated envelope (20.87)	CS5-Insulated envelope (219)
	Insulated building located in RG	CS 48	CS6-Insulated envelope (23.90)	CS6-Insulated envelope (261)
	Insulated building located in Rock town	CS 49	CS7-Insulated envelope (24.65)	CS7-Insulated envelope (310)
	Insulated building located in Kiran Arcade	CS 50	CS8-Insulated envelope (22.87)	CS8-Insulated envelope (238)
	Insulated building located in Mahendra	CS 51	CS9-Insulated envelope (27.07)	CS9-Insulated envelope (285)
	Insulated building located in Nirmal	CS 52	CS10-Insulated envelope (25.19)	CS10-Insulated envelope (248)
Zhan et al. [47]	Typical residential building located in urban area	CS 53	22.77	45.19
Iyer- Raniga and Wong [48]	Heritage building with brick veneer envelope	CS 54	CS1 (63.61)	CS1 (45.00)
	Heritage building with weatherboard envelope	CS 55	CS2 (314.4)	CS2 (193.90)
	Heritage building with weatherboard envelope	CS 56	CS3 (118.33)	CS3 (170.50)
	Heritage building with weatherboard envelope	CS 57	CS4 (161.38)	CS4 (116.38)
	Heritage building with brick veneer envelope	CS 58	CS5 (180)	CS5 (108.80)
	Heritage building with solid brick	CS 59	CS6 (134.16)	CS6 (88.00)
	Heritage building with solid brick	CS 60	CS7 (137.22)	CS7 (82.22)
	Heritage building with brick veneer envelope	CS 61	CS8 (143.8)	CS8 (83.88)
Dodoo et al. [39]	Cross laminated timber structure with heat pump heated system	CS 62	CLT (-18.36)	CLT with HPH system (187)
	Beam-and-Column system structure with heat pump heated system	CS 63	BC (-14.2)	BC with HPH (192)
	Modular timber structure with heat pump heated system	CS 64	MT (-3.5)	MT with HPH (192)
	Cross laminated timber structure with district heated system	CS 65	CLT (-18.36)	CLT with DH system (176)
	Beam-and-Column system structure with district heated system	CS 66	BC (-14.2)	BC with DH (180)
	Modular timber structure with district heated system	CS 67	MT (-3.5)	MT with DH (180)
Tettey et al. [40]	Standard building with concrete system	CS 68	Standard building with concrete system (8.775)	Standard building with concrete system (137.47)
	Standard building with cross laminated timber structure	CS 69	Standard building with CLT (-20.18)	Standard building with CLT (137.47)
	Standard building with modular timber structure	CS 70	Standard building with MT (-4.43)	Standard building with MT (137.47)
	Passive building with concrete system	CS 71	Passive building with concrete system (9.52)	Passive building with concrete system (71.16)
	Passive building with modular timber structure	CS 72	Passive building with MT (-4.03)	Passive building with MT (71.16)
Mehta et al. [35]	Multi-story residential building	CS 73	34.75	179.70
Zhu et al. [41]	Prefabricated buildings located in Chengdu, China	CS 74	CS A (33.94)	CS A (86.11)
	Prefabricated buildings located in Shenzhen, China	CS 75	CS B (28.00)	CS B (113.88)
Bastos et al. [32]	City apartment	CS 76	CA (15.02)	CA (70.77)
	Suburban house	CS 77	SH (17.75)	SH (75.19)

Authors	Building character	Case study ID	Embodied energy (kWh/m².year)	Operational energy (kWh/m².year)
Goggins et al. [49]	Baseline building constructed according to 2005 Irish regulations. Airtightness 9.1 ac/hr@ 50 Pa.	CS 78	16.725	131.26
	Building constructed according to 2008 Irish regulations. Airtightness 5.44 ac/hr@ 50 Pa.	CS 79	17.06	100.96
	Building constructed according to 2011 Irish regulations. Airtightness 5.44 ac/hr@ 50 Pa.	CS 80	20.07	85.23
	Building constructed according to 2011 Irish regulations. Airtightness 0.45 ac/hr@ 50 Pa.	CS 81	18.73	83.07
	NZEB Airtightness 5.44 ac/hr@ 50 Pa.	CS 82	21.24	78.59
	NZEB. Airtightness 0.45 ac/hr@ 50 Pa.	CS 83	19.56	79.07
Kristjansdottir et al. [50]	NZEB	CS 84	80.30	55.50
Mistretta et al. [51]	Baseline building	CS 85	137.86	12.80
	NZEB (retrofitted)	CS 86	49.20	-90.0

Abbreviations: Cross laminated timber (CLT) system, Beam -and-Column system (BC), Modular timber system (MT); City apartment (CA); Suburban house (SH); Electric heated (EH); Heat pump heated (HPH); District heated (DH); Case study (CS).
Notes: a) this paper reports the operational energy with conversion factor of 2.5; b) the sizes of buildings are not specified, and results are reported in MJ/m²

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Chapter 4. The Need of Developing a Standardised Framework for the Incorporation of Embodied Energy

4.1 Introduction

The findings of the previous chapter indicate the existence of a significant inconsistency accruing from incomplete definitions of the system boundary, highlighting the need for devising a standardized framework to harmonise life cycle energy assessment (LCEA). This chapter aims to conduct a more comprehensive literature review to capture studies published between 1996 and 2020. The identified studies are analysed with respect to their methodological approaches in defining system boundary conditions in LCEA analysis. Therefore, the outcome of this chapter is to furnish a holistic understanding of the main sources of variations in LCEA. Further, this chapter lays out recommendations for streamlining the process of incorporating the embodied energy impacts into building energy efficiency regulations.

4.2 List of manuscripts

This part of the research has been produced as a journal article, published in the journal of *Energy and Built Environment*:

Omrany, H., Soebarto, V., Zuo, J., Sharifi, E., & Chang, R. (2021). What leads to variations in the results of life-cycle energy assessment? An evidence-based framework for residential buildings. *Energy and Built Environment,* 2(4), 392-405. DOI: https://doi.org/10.1016/j.enbenv.2020.09.005.

The paper is presented here in a reformatted version for consistency of the thesis presentation. The accepted manuscript can be found in Appendix II.

Statement of Authorship

Title of Paper	What leads to variations in the results of life-cycle energy assessment? An evidence-based framework for residential buildings
Publication Status	☑ Published ☐ Accepted for Publication ☐ Submitted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details	Omrany, Hossein, Veronica Soebarto, Jian Zuo, Ehsan Sharifi, and Ruidong Chang. (2021). What leads to variations in the results of life-cycle energy assessment? An evidence-based framework for residential buildings. Energy and Built Environment, 2(4), 392-405. DOI: https://doi.org/10.1016/j.enbenv.2020.09.005.

Principal Author

Name of Principal Author (Candidate)	Hossein Omrany		
Contribution to the Paper	Conceptualization, methodology, collecting the data (literature materials), data analysis, and writing—original draft preparation.		
Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	15/08/2021

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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ii. permission is granted for the candidate in include the publication in the thesis; and

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4.3 What leads to variations in the results of life-cycle energy assessment? An evidence-based framework for residential buildings

Residential buildings are one of the major contributors to climate change due to their significant impacts on global energy consumption. Hence, most countries have introduced regulations to minimize energy use in residential buildings. To date, the focus of these regulations has mainly been on operational energy while excluding embodied energy. In recent years, extensive studies have highlighted the necessity of minimizing both embodied energy and operational energy by applying the life-cycle energy assessment (LCEA) approach. However, the absence of a standardized framework and calculation methodology for the analysis of embodied energy has reportedly led to variations in the LCEA results. Retrospective research endeavoured to explore the causes of variations, with a limited focus on calculating embodied impacts. Despite the undertaken attempts, there is still a need to investigate the key parameters causing variations in LCEA results by examining methodological approaches of the current studies toward quantifications of embodied and operational energies. This paper aims to address three primary questions: 'what is the current trend of methodological approach for applying LCEA in residential buildings?'; 'what are the key parameters causing variations in LCEA results?'; and 'how can the continued variations in the application of LCEA in residential buildings be overcome?'. To this end, 40 LCEA studies representing 157 cases of residential buildings across 16 countries have been critically reviewed. The findings reveal four principal categories of parameters that potentially contribute to the varying results of LCEAs: system boundary definition, calculation methods, geographical context, and interpretation of results. This paper also proposes a conceptual framework to minimize variations in LCEA studies by standardizing the process of conducting LCEAs.

Keywords: Life cycle energy assessment; life cycle assessment; residential buildings; energy efficiency; embodied energy; operational energy.

1. Introduction

Residential buildings have a higher share in global energy consumption compared to non-residential buildings due to the larger portion both in terms of number of buildings and floor areas [1]. In 2017, the International Energy Agency held residential buildings responsible for nearly 22% of total energy use worldwide [2]. The projections made by the recent study also warn about further increasing global energy consumption in residential buildings within the next few decades owing to rapid urbanization, population growth, and economic development [3, 95]. Correspondingly, most countries have strengthened their measures to decrease energy use in residential buildings by legislating various building-related regulations. As an example, the requirements introduced by the Danish government for operational energy use in new buildings have been reduced to less than one third over the last 25 years [4]. In general, the primary objective of such regulations is to improve buildings' thermal performance by imposing minimum requirements on their physical characteristics [5]. Despite the potential of these regulatory standards to minimize operational energy, their implementations can paradoxically result in increasing the total life-cycle energy use of buildings due to ignoring the embodied impacts [6, 7]. This is echoed in the findings of Stephan et al. [6] who assessed the life-cycle energy performance of a Belgian passive house. Their results indicated that current certifications developed to promote energy efficiency in buildings cannot assure the reduction of the total energy consumption since embodied impacts are excluded. They also showed that the embodied energy of passive houses may constitute up to 77% of the total building life-cycle energy use over 100 years.

In recent years, academic studies have given more attention to the necessity of minimizing energy use throughout the entire building life cycle by including both embodied and operational energies. To demonstrate the significance of embodied impacts, numerous detailed cases of buildings have been developed by academics using the life-cycle energy assessment (LCEA) approach. Nevertheless, this surge of research has failed to alter the attitude of policymakers toward considering the importance of buildings' embodied energy when planning for the betterment of built environment [8]. Retrospective research has primarily placed the blame on the analysis of embodied energy where the absence of a standardized framework and calculation methodology often leads to displaying a significant spread of results in LCEA analyses [9]. Over the last decades, significant efforts have been made to standardize the application of life-cycle assessment in buildings through setting several international standards such as ISO 21929-1 [10], ISO 21931-1 [11], and the European standards developed by

Technical Committee TC350, including EN 15643-2 [12] and EN 15978 [13]. However, there is considerable evidence indicating variations in the results of LCEA analyses [4, 8, 14, 15]. Previous research has endeavoured to explore sources of variations, with a focus given only to the calculation of buildings' embodied impacts [16, 17]. Despite the undertaken attempts, there is still a need to investigate the key parameters causing variations in LCEA results by examining methodological approaches of the current studies toward quantifications of embodied and operational energies. Therefore, this paper aims to address three primary questions: 'what is the current trend of methodological approach for applying LCEA in residential buildings?'; 'what are the key parameters causing variations in LCEA results?'; and 'how can the continued variations in the application of LCEA in residential buildings be overcome?'. To this end, we first analysed 40 LCEA papers in order to address the two first questions. This paper then puts forward proposals for standardization of LCEA application in residential buildings by developing a conceptual framework in order to address the third question.

2. An overview of LCEA

Life-cycle assessment (LCA) is an approach toward identification and quantification of environmental loads attributed to services, products, or processes throughout their entire life cycles [18]. The International Organization for Standardization (ISO) introduced the first series of standards (14040, 14041, 14042, and 14043) relating to LCA between 1997 and 2000 [19]. In 2006, these standards were updated by amalgamating prior versions, which led to the current ISO standards 14040 and 14044 [20, 21]. These standards set up a framework to perform LCA, consisting of four major steps: (1) defining the goals and scope, (2) life-cycle inventory (LCI), (3) life-cycle impact assessment, and (4) interpretation. The first step involves establishing the goals and scope of the assessment, defining the system boundary, and specifying the quality criteria for inventory data. This is followed by an LCI, where the procedure for collecting and synthesizing data related to energy flows should be determined at each individual stage of a product's life cycle. The next step, life-cycle impact assessment, involves quantifying the environmental impacts of materials and energy flows and assigning them to their corresponding environmental impact categories. In the last step, the results of the LCA are interpreted in relation to the study's goals and scope, and recommendations are made for decision-making purposes.

LCEA is a version of the LCA that considers only the energy inputs at all stages of a building's life cycle [22, 23]. Adopting this approach to assess a building's energy performance means quantifying its total energy consumption, by considering both operational and embodied energy (Figure 1). Embodied energy refers to the amount of energy used for material production (i.e. extraction of raw materials and material manufacturing), assembly (i.e. construction/installation), replacement and maintenance, end-of-life (EOL) processes and transportation required between any of these steps [18, 23, 24]. The amount of energy consumed in the form of thermal (i.e. heating and cooling) and non-thermal loads (i.e. domestic hot water (DHW), electrical appliances and equipment, ventilation, lighting, and cooking) over a building's lifespan is known as operational energy [18, 23, 24].

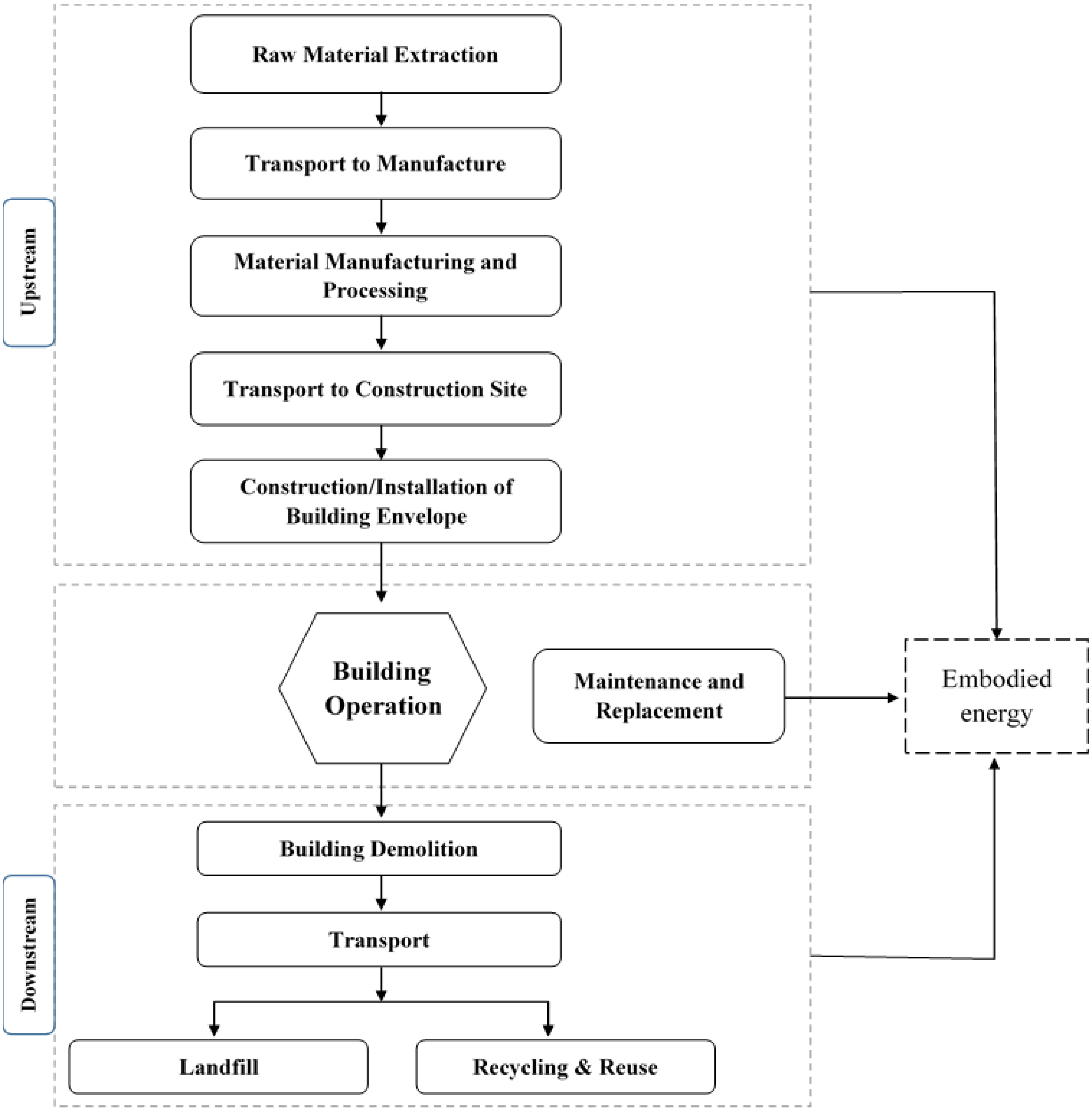

Figure 1. Building life cycle energy

3. Research methodology

This paper adopts a systematic literature review approach to identify published materials relating to the LCEA application in residential buildings. The review commenced with carrying out a comprehensive searching exercise through multiple databases, namely Web of Science, ProQuest, and Scopus. Using these platforms enables researchers to gain access to numerous international journals, based on which a systematic literature review can be conducted [25, 26]. The initial search was conducted using certain keywords, as tabulated in Table 1. The types of searched materials were 'articles' and 'reviews'; and the timespan set for the search was between 1996 and 2020, in which the starting year coincided with the publication of the first series of ISO standards. As a result, more than 750 publications were identified to meet the initial criteria.

Table 1. Keywords applied during the initial search

Keywords used to search for life-cycle energy assessment studies
Building life-cycle assessment; building life-cycle energy assessment; building energy performance; building life-cycle impact assessment; building life-cycle environmental assessment; building life-cycle; energy efficient buildings; residential buildings; building primary energy consumption; and building embodied energy analysis.

An initial screening check was performed based on the titles, abstracts, and conclusions of the identified materials in order to make a preliminary decision about the suitability of identified articles for inclusion. At this stage, certain criteria were considered to weed out irrelevant materials. First, publications written in any language other than English were filtered out, as well as non-peer reviewed articles. In addition, only studies with the application of LCEA approach in 'residential' buildings were considered for further analyses. Considering these criteria led to downsizing the collected materials to about 260.

After the initial screening, the contents of all remaining articles were checked qualitatively to ensure that only those falling within the scope of this paper were selected. Herein, studies that focused solely on embodied energy analysis were filtered out due to their limited approaches for the assessment of buildings' life-cycle energy use. In addition, this review only retained LCEA studies that measured buildings' energy performance based on primary energy because the primary energy is a better measure of the environmental impacts of buildings [27, 28]. As a result, 40 papers that analysed 157 cases of residential buildings across 16 countries were selected for detailed examinations. Summaries of these papers were exported to *Excel*

Spreadsheets for further analysis (See the Appendix). In this paper, we considered all types of residential buildings for the analysis, i.e. energy-efficient buildings, conventional buildings, high- and low-rise buildings, and urban and suburban buildings. This review considers different versions of a building analysed in one source as one case study.

Following the examination of the reviewed studies, a conceptual framework was developed. This framework primarily aims to simplify the intertwined processes involved in an LCEA by providing a clear description of the system boundary.

4. Analysis and results

The selected studies are analysed based on four main criteria: i) system boundary definitions, ii) methods applied for quantification of embodied energy, iii) methods applied for calculation of operational energy, and iv) approaches taken toward interpreting LCEA results. The Appendix includes a detailed list of analyses carried out in this paper.

4.1 Definition of system boundary

System boundary definition denotes the act of determining a set of variables that distinguish the system under study from other systems in an environment [16, 23]. In this paper, the approaches of analysed studies toward delineating system boundaries are analysed to identify: i) the building life-cycle stages excluded by the system boundary, ii) the building components and their systems included within the system boundary to calculate embodied impacts, iii) the parameters included within the system boundary to calculate operational energy, iv) the building lifespan, and v) the key assumptions made by the reviewed studies.

4.1.1 Exclusion of life cycle stages

The building life cycle stages consist of raw material extraction, material manufacturing and processing, construction/installation, operation, maintenance and replacement, transportations between any of these steps, and EOL (Figure 1). A whole LCEA then refers to the one that accounts for energy consumption throughout the entire buildings' life cycles. Table 2 shows the number of reviewed studies that excluded building life-cycle stages from the system boundary.

Table 2. Exclusion of building life cycle stages

Stages of building life cycle		Number of studies
Production	Raw material extraction	0
	Transport to manufacture	1
	Manufacturing and processing	0
Assembly	Transport to construction site	9
	Construction/installation	11
Maintenance	Maintenance and replacement	14
End of life	De-construction/demolition	23
	Transport	23
	Disposal	24
Reuse, recovery, recycling		26

The review reveals that 32% of the studies carried out a whole LCEA, while others omitted certain life cycle stages. The processes involved in the EOL stage (i.e. de-construction, transport, and disposal of construction wastage) were excluded by 58% of the studies. This exclusion was commonly justified due to i) the minor contribution of this stage to the total life-cycle energy use of buildings, and ii) uncertainties about deconstruction practices at the EOL [6, 29-38]. Amongst those that accounted for energy consumption at EOL, the common trend was to base the calculation on assumptions. For instance, Crawford [39] assumed that the energy needed for building deconstruction and disposal of its materials equated to 1% of the house's total life-cycle energy demand.

In addition, maintenance and replacement (also known as recurrent embodied energy) was excluded by 35% of the studies. Understanding the impacts of recurrent embodied energy is important for many reasons, such as making informed choices about building design and materials, and understanding the impact of the maintenance and management of buildings [9]. Studies have also shown that recurrent embodied energy may have a substantial effect on the total life-cycle energy use; thus, ignoring its impact can underestimate the environmental burdens of buildings. For instance, Stephan and Stephan [33] showed the recurrent embodied energy of a residential building in Lebanon may constitute up to 31% of the total building embodied energy. Crawford [39] also estimated that recurrent embodied energy of an Australian building can be up to 22% of the total building life-cycle energy demands. Furthermore, this paper found that the construction/installation stage was excluded by 27% of the studies. This was mainly due to its perceived minor impact on total building life-cycle energy use [30, 31, 40, 41] and the difficulty in gathering data on the energy consumption of on-site construction operations [37]. Some studies did not discuss the reasons for its exclusion [42-46]. Transportation of materials to the construction site was also excluded by 22% of the reviewed studies, which was mainly justified by its minor impact on total life-cycle energy use.

The reuse, recovery, and recycling of building materials was excluded by 65% of the reviewed studies. This term refers to the processes in which the environmental benefits of building materials beyond the defined system boundary are captured [47]. The use of this strategy has been widely seen as an effective measure to mitigate buildings' environmental impacts [48, 49]. This paper found that the amount of energy saved by using this strategy averaged between 5 to 38% of a building's total life-cycle energy use (Table 3).

Table 3. Energy saved at different stages through reusing, recovering and recycling building materials (kWh/m^2.year)

Reference	Building characteristics	Energy saved at production stage	Energy saved at construction stage	Energy saved at EOL stage	Total energy saving	Total energy saving (%)
Gustavsson et al. [50]	Wood-framed apartment	23.64	NA	11.42	35.06	17.84
Dodoo and Gustavsson [51]	Conventional building with electric heated system	7.78	NA	7.92	15.70	5.36
	Conventional building with heat pump heated system	7.78	NA	7.92	15.70	7.27
	Conventional building with district heated system	7.78	NA	7.92	15.70	7.79
	Passive building with electric heated system	8.0	NA	8.06	16.06	6.05
	Passive building with heat pump heated system	8.0	NA	8.06	16.06	7.77
	Passive building with district heated system	8.0	NA	8.06	16.06	8.22
Cellura et al. [52]	Net zero energy building	NA	NA	22.62	22.62	10.83
Dodoo et al. [53]	Cross laminated timber structure with heat pump heated system	20.92	1.44	11.80	34.16	16.85
	Beam-and-Column system structure with heat pump heated system	20.22	1.26	10.90	32.38	15.35
	Modular timber structure with heat pump heated system	10.18	1.10	9.04	20.32	9.73
	Cross laminated timber structure with district heated system	20.92	1.44	11.80	34.16	17.81
	Beam-and-Column system structure with district heated system	20.22	1.26	10.90	32.38	16.34
	Modular timber structure with district heated system	10.18	1.10	9.04	20.32	10.32
Tettey et al. [54]	Standard building with concrete system	1.92	NA	5.63	7.55	4.90
	Standard building with cross laminated timber structure	20.98	NA	10.67	31.65	21.24
	Standard building with modular timber structure	8.075	NA	6.30	14.38	9.75
	Passive building with concrete system	1.92	NA	5.63	7.55	8.55
	Passive building with modular timber structure	8.53	NA	6.57	15.10	18.37
Zhan et al [55]	Prefabricated building	NA	NA	4.99	4.99	6.84
Thormark [43]	Low energy building	NA	NA	31.12	31.12	36.75
Blengini and Di Carlo [56]	Low energy house	NA	NA	11.11	11.11	13.74
Takano et al. [46]	Detached house with light weight timber structure	NA	NA	21.96	21.96	17.95
	Row house with light weight timber structure	NA	NA	15.17	15.17	15.56
	Townhouse with light weight timber structure	NA	NA	15.42	15.42	17.77
	Apartment block with light weight timber structure	NA	NA	12.96	12.96	18.96

Detached house with cross laminated timber structure	NA	NA	35.06	35.06	26.03
Row house with cross laminated timber structure	NA	NA	29.04	29.04	26.93
Townhouse with cross laminated timber structure	NA	NA	31.9	31.9	32.60
Apartment block with cross laminated timber structure	NA	NA	28.77	28.77	37.48
Detached house with reinforced concrete panel structure	NA	NA	14.04	14.04	10.89
House with reinforced concrete panel structure	NA	NA	10.62	10.62	10.63
Townhouse with reinforced concrete panel structure	NA	NA	9.31	9.31	10.48
Apartment block with reinforced concrete panel structure	NA	NA	6.95	6.95	10.64
Detached house with steel structure	NA	NA	14.66	14.66	11.68
Row house with steel structure	NA	NA	10.67	10.67	10.70
Townhouse with steel structure	NA	NA	9.81	9.81	11.04
Apartment block with steel structure	NA	NA	7.72	7.72	11.08

Note: The detailed numerical values for recycling/reusing potentials were given by nine studies out of fourteen.

4.1.2 The extent of system boundary definition: calculating embodied energy

Calculating embodied energy largely depends on the extent to which the embodied impacts of building components and their systems are included within the system boundary. Table 4 presents the building components considered by the analysed studies when accounting for buildings' embodied energy. The review showed that the inclusion of embodied energy impacts of building components and their systems within the system boundary was inconsistent. The majority considered the embodied impacts of superstructure, substructure and finishings, whereas only half of the reviewed studies considered the embodied energy of building services. This can be related to the higher weights of the former components in buildings' bill of quantity, and the energy intensiveness of their production processes due to using high amounts of cement or steel [29, 33, 39, 50, 57]. On the other hand, 83% of the studies excluded the embodied energy of built-in furniture, fixtures, appliances or elements beyond building components (such as urban infrastructure or occupants' transportation) from their system boundaries. Further, the system boundaries defined by studies that investigated life-cycle energy performances of net-zero-energy buildings (NZEBs) were found to be wider than those considering conventional buildings since they also included the embodied impacts of renewable energy systems (RESs), such as photovoltaic panels, solar collectors, or wind turbines, within system boundaries.

Table 4. The embodied energy of building components considered by the reviewed studies

Elements	**Descriptions**	**Number of studies considered**
Superstructure	Structural frame; interior and exterior walls; stairs; floor; roof; windows; interior partitions; interior and exterior doors.	40
Substructure	Foundation; basements.	37
Finishing	Wall, floor and ceiling finishings.	30
Services	Sanitary installation, installations (water, lighting, electrical, ventilation); space heating and air conditioning; firefighting elements.	20
RES	Photovoltaic panels, solar collector, wind turbines.	12
Furniture, fixtures, appliances	Built-in furniture, interior fixtures, or appliances.	7

Elements beyond building	Urban infrastructure (e.g. roads, water, sewage systems); residents' mobility.	5

The possibility of expanding the system boundary to include parameters beyond the scale of a building has also been pointed out by a number of studies [6, 32-34, 44]. Stephan et al. [32] proposed a framework to consider the embodied impacts of nearby infrastructure (roads, water, sewage systems, etc.), and the energy used for occupants' transportation. This framework was then employed to analyse the life-cycle energy performances of two residential buildings in Australia and Belgium. The authors concluded that the occupants' transportation made up 25.4% and 33.8% of the entire building life-cycle energy consumption in the Belgian passive house and the Australian building, respectively. Bastos et al. [34] also performed an LCEA to compare energy consumption and greenhouse gas emissions of two buildings, one apartment building located in the city centre and a semidetached house in a suburban area. In addition to the embodied impacts of buildings, they also considered energy consumed for occupants' transportation. The results indicated the significance of energy consumption for occupants' transportation, especially for the suburban building.

4.1.3 The extent of system boundary definition: calculating operational energy

Energy is consumed in the forms of thermal and non-thermal loads over a building's lifespan in order to maintain a habitable indoor environment [18, 23, 24]. Parameters influencing thermal loads include heating and cooling, whereas DHW, electrical appliances, ventilation, lighting, and cooking are the factors that determine non-thermal loads. Hence, whether the system boundary is set to account for the impacts of these parameters directly affects the calculation of operational energy.

The review showed that the studies had different levels of inclusion to account for the impacts of parameters that affect operational energy use (Figure 2). It is found out that only 20% of the studies included all parameters [31-35, 37, 39, 52], while the impacts of cooking were excluded by 68% of the studies, followed by cooling (53%), lighting (38%), ventilation (28%), electrical appliances (28%), DHW (28%), and heating (10%). Moreover, one study did not discuss its level of inclusion for the assessment of operational energy usage [58]. Eliminating each parameter from the system boundary affects LCEA results by changing the proportion of operational energy [59, 60]. For example, Gustavsson and Joelsson [59] found that the share of embodied impacts in a building's total life-cycle energy usage decreased from 33% to 25%

once the scope had been extended from space heating only to include ventilation, DHW, and household electricity.

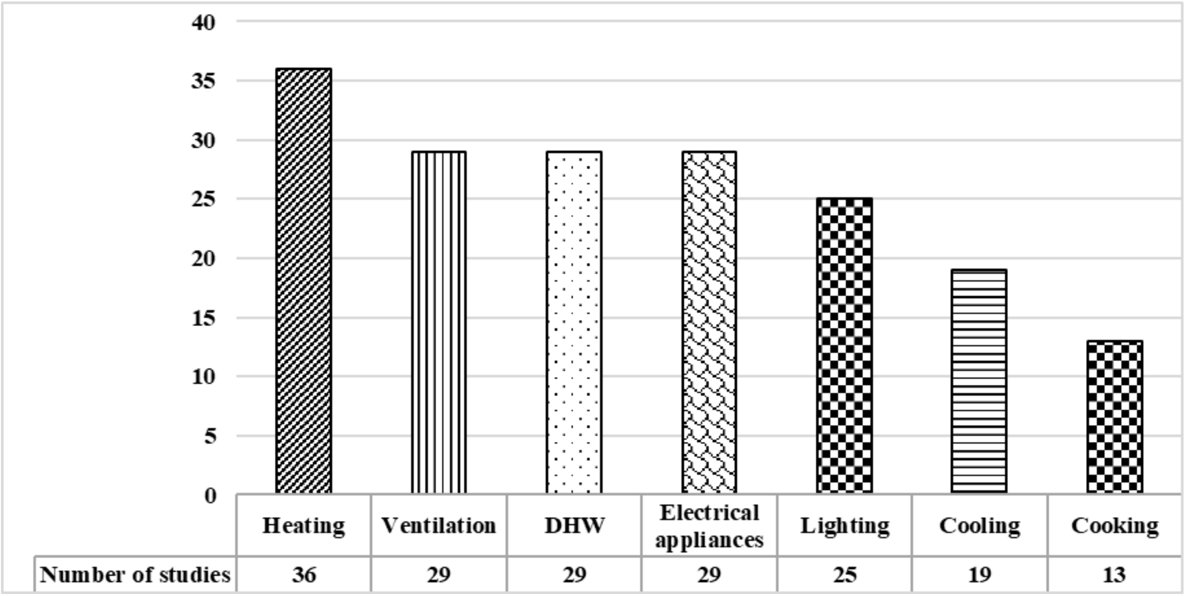

Figure 2. Number of studies that considered the inclusion of parameters influencing operational energy

It is also noted that the system boundary was commonly defined subjectively, without providing any contextual justification. Only four of the reviewed studies [7, 38, 42, 61] gave reasons for excluding certain parameters. For instance, Crawford et al. [7] only considered heating and cooling loads as these are the only demands considered by the Building Codes of Australia. Pinky Devi and Palaniappan [38] also justified the exclusion of cooking since it was usually done using firewood in low-cost houses in India. The subjectivity in the definition of the system boundary underlines the lack of a framework or a standardized approach for calculating buildings' operational energy usage.

4.1.4 Building lifespan

The range of building lifespans assumed by the analysed studies falls between 30 and 100 years, with the most frequently used lifespan of 50 years (Table 5). This assumption is of utmost importance due to its direct effect on the proportion of embodied and operational energy in an LCEA. The share of embodied energy in a building's total life-cycle energy use can be affected by calculations of recurrent embodied energy, as assuming a long lifespan leads to frequent replacement of building materials, while assuming a short lifespan will induce the need to change the entire building [62, 63]. Rauf and Crawford [63] studied the correlation between a building's lifespan and its embodied energy. They found that a building's embodied energy demands can be decreased by 29% by increasing the lifespan from 50 to 150 years. In addition, assumptions about a building's lifespan can affect operational energy, as prolonging the lifetime of a building results in an increase in energy consumption over its service life [64].

Table 5. Frequency of use of building lifespans

Country of case study	Building lifespan	Frequency of use	Reference
Australia	30 years	1	[44]
Canada	40 years	1	[65]
Australia, Sweden, Lebanon, Turkey, Belgium, Portugal, Norway, Finland, India, Thailand, China, Israel, Brazil	50 years	23	[7, 29, 32-34, 37-39, 43, 46, 50, 53, 57, 59, 61, 66-72]
Ireland, Norway, Belgium	60 years	3	[40-42]
China, Italy	70 years	4	[52, 55, 56, 73]
India, Portugal	75 years	3	[30, 31, 35]
Sweden	80 years	1	[54]
Belgium, Australia	100 years	4	[6, 45, 58, 74]

Determining a building's lifespan in an LCEA is challenging due to numerous variables involved in terminating a building's life such as urban redevelopment, deterioration of the building's physical condition, and damage from natural causes such as fire and flood. In an LCEA, the main concern in choosing a building's lifespan is that it is an arbitrary decision, as a number is simply assumed by referring to other research. In addition, there is an inconsistency in the choice of lifespan regarding the geographical region. This can be seen in Table 5, as the assumptions differ within one country, or region (e.g. the EU).

The ideal conditions for an accurate prediction of building lifespan are those in which the microclimate is well known, while the characteristics of all individual components and elements of the building can be determined using laboratory or real-life data [75]. However, this approach is impractical from an LCEA practitioner's point of view. It is therefore recommended to utilize a simpler "factor method" for such estimations, where the aim is to apply a "rough-and-ready" means of estimating rather than predicting buildings' service life [75]. The future direction in this particular area of LCEA may lie with developing performance-based estimation approaches in each region, combined with creating open-access databases containing information about the service lives of construction materials that can be accessible by all practitioners.

4.1.5 Assumptions

In an LCEA analysis, making assumptions is inevitable due to various uncertainties involved [23]. This paper identified various assumptions made by the reviewed studies and grouped them with respect to their corresponding stage of the building life cycle (Table 6).

Table 6. A summary of assumptions made by the reviewed studies

Targeted stage	Assumption	Reference
Production	• Use of databases containing embodied energy coefficients of building materials not originating in the country of the case studies; • Using input-output (I–O) data developed over a decade ago to represent energy intensities of construction materials; • Data for a similar material were used when more specific data were unavailable.	[6, 33, 39, 43, 57, 74]
Assembly	• Assuming one location to carry out all the production processes; • Assuming certain values of energy consumption as the effect of this stage on the entire life-cycle energy use (e.g. 80 kWh/m^2, 160 kWh/m^2 or 4% of the material production primary energy).	[50, 53, 54]
Operation	• Unchanged occupancy profile (occupants' behaviors, family size, etc.); • Unchanged patterns of use for heating and cooling systems; unchanged coefficient of performance rates for all mechanical systems; • Unchanged resource mix supplying electricity to the buildings; • Using energy bills of another building with similar specifications to estimate the building's operational energy.	[29-31, 35, 37, 51]
Maintenance and replacement	• The service life of the building's structural elements were assumed to be the same as the building itself; • Building materials were expected to be replaced with the same materials when they reached their end of service lives; • Assuming certain values of energy consumption as the effect of this stage on the entire life-cycle energy use; • Using the replacement lifetimes of U.S. construction materials for a case study in Australia; • Unchanged construction methods and materials during the entire building lifespan; • Replaced materials were assumed to have the same amount of embodied energy as the originals.	[41, 44, 46, 57, 66, 74]

EOL	• Assuming certain values of energy consumption as the effect of this stage on the entire life-cycle energy use (e.g. 1% or 3% of the total life-cycle energy demand); • Assuming 10 and 20 kWh/m^2 of energy consumption for demolishing wood and concrete respectively; • Using only one type of fuel to transport construction wastage; • Assuming the recovery of 90% of the wood-based demolition materials, while decaying 10% into the atmosphere.	[39, 50, 51, 53, 54, 57, 67]

The first group refers to the assumptions that pertain to the calculation of embodied energy at the production stage. These assumptions are commonly made in response to the absence of a locally-driven database. For instance, Devi and Palaniappan [67] applied a European database to compute the embodied impacts of a building in India. Similarly, Stephan and Stephan [33], and Stephan et al. [6] employed 'Australian input–output-based hybrid embodied energy intensities' to calculate the embodied energy of buildings located in Lebanon and Belgium, respectively. However, geographic representativeness of the data is an important parameter that needs to be considered when measuring embodied energy since countries differ in their manufacturing processes, construction technologies, economic sectors, energy tariffs, and fuel supply structure [28]. As such, adopting data that is non-native to the location of the building under study may compromise the accuracy of calculations of embodied energy.

The second group of assumptions relates to the operation stage. A common trend in calculating the operational energy of buildings is to compute energy use for one year of the building's operation, then the calculated value is multiplied by the number of years assumed for the building's lifespan. As a result, the studies commonly assumed that operational energy consumption would stay constant throughout the entire life of the building. This assumes the occupancy profile of a building would remain unchanged (in terms of family size or the occupancy schedule), or there would be no depreciation of heating and cooling systems (a constant coefficient of performance). In addition, none of the reviewed studies considered the effects of climate change on buildings' energy consumption. The calculation of operational energy usage has been commonly carried out by considering present climatic conditions, while ignoring the possible future effects of climate change. This assumption was only declared by three studies [30, 31, 65]. Previous studies have shown that heating and cooling demands can be affected by climate change. For instance, Karimpour et al. [76] performed a parametric analysis using the Typical Meteorological Year for 2070 to design the building envelope of a residential building in Adelaide, Australia. They concluded that heating will become significantly less important as buildings would be better insulated while the climate would be warmer, and therefore more focus should be allocated toward mitigation of cooling loads in buildings. As such, considering the impacts of climate change on operational energy demands is recommended for future LCEA studies.

The maintenance and replacement stage has also been subject to several assumptions, as shown in Table 6. Although not discussed by most of the studies, it is commonly assumed that building materials are to be replaced with similar materials when they reach the end of their service lives; thus, they incur the same amounts of embodied energy as the original materials.

The final group attributes to the assumptions made in order to facilitate calculating embodied impacts of construction/installation and EOL stages. As previously mentioned, these stages were excluded by the majority of the reviewed studies. Amongst those accounting for their contributions, some assumed certain values as the impacts of these stages on the total building life-cycle energy consumption. For instance, Gustavsson et al. [50] assumed that the primary energy used for the on-site construction of an eight-story apartment equalled 80 kWh/m^2. Analogously, studies assumed different values in order to account for the impacts of the EOL stage [39, 53, 67]. For example, Devi and Palaniappan [67] assumed that this stage consumed 3% of the total initial embodied energy.

Overall, the assumptions made for different stages of a building's life cycle can have a significant effect on the final results of an LCEA. Thus, all the assumptions in an LCEA study need to be clearly stated for the sake of transparency while justifying their contextual applicability. The sensitivity of each assumption toward total building life-cycle energy use should be tested at the interpretation stage. Three methods are identified here that can potentially be used in order to assure the robustness of the LCEA results (See section Interpretation).

4.2 Methods applied to calculate embodied energy

The results of an LCEA can be influenced by the method applied to calculate embodied impacts. The review shows that three major methods have been utilized to compute the embodied impacts of buildings, namely the process-based, economic input-output (I-O), and input-output-based hybrid methods. The process-based method is most effective when the physical flow of the system under study is identifiable and can be easily traced. However, this approach becomes difficult to apply when the inputs and outputs of the system are numerous [57]. Also, errors can be induced by the subjective truncation of the upstream production system [68]. On the other hand, the economic I-O method takes a top-down approach and utilizes the entire economy as the theoretical boundary to arrive at clear definitions of the system boundary. This method aims to determine the quantity of energy consumed to produce a specific service or product by decoding the flow of materials in an economy's structure. Although using this method improves the incomplete system boundary definition in the process-based method, it still suffers from a lack of product-specific data. To address this issue, the I-O-based hybrid approach was proposed to incorporate the inputs from the entire upstream supply chain by amalgamating the two previous approaches [23, 77]. The review revealed that 60% of the studies utilized the process-based approach; 23% used the I-O-based hybrid approach; only one study applied the economic I-O approach [44]. Furthermore, 15% of the studies did not discuss the methods they used to calculate embodied impacts [30, 31, 61, 70, 51, 54].

To compute embodied impacts, it is necessary to select a background database that contains datasets representing the technical and economic contexts of the case study [23]. It is found out that the background data required for embodied energy calculations were retrieved from two primary sources: 'literature' (i.e. data published by other research) and databases that are available publicly or commercially (Table 7). Overall, 13% of the studies solely relied on the literature to calculate embodied impacts. Using this approach may potentially undermine the reliability of the achieved results for decision-making purposes since the adopted background databases might not represent the regional contexts of the buildings under study. In addition, 33% of the studies used generic international databases, namely Inventory of Carbon and Energy, Athena Institute Impact Estimator, Ecoinvent, and Building for Environmental and Economic Sustainability, while 15% of the studies combined process-specific data acquired from different sources such as local manufacturers [50, 73], or databases developed nationally or regionally with generic international databases [53, 54, 71, 74] in order to increase the geographical representativeness of the data.

Table 7. Databases applied by the reviewed studies

Database	Developer	Data coverage	Boundary	LCI method	Ref.
SimaPro[1]	PRe´ Consultants, Netherlands	Industry data, U.S. LCI, Danish input-output database, Dutch input-output database, LCA food database, Ecoinvent	Cradle-to-grave	Process-based and I-O method	[29, 52, 74]

Ecoinvent	Ecoinvent centre, Swiss	Generic data on various products and processes including chemicals, waste management, agriculture, energy, washing agents, transport, paper & board, and building materials	Cradle-to-gate	I-O method	[34, 40, 41, 46, 53, 56, 71]
Inventory of Carbon and Energy	Bath University, UK	Specific-process data on over 200 construction materials, European, mainly UK data	Cradle-to-gate	Process-based method	[35, 37, 38, 42, 57, 66, 67]
AusLCI	Building Product Innovation Council, Australia	Process data on construction products and materials, Australian data	Cradle-to-grave	I-O method	[74]
Building for Environmental and Economic Sustainability	National Institute of Standards and Technology (U.S.)	Construction materials, mainly U.S. data	Cradle-to-grave	Process-based method	[66]
Database of Embodied Energy and Water Values for Materials	University of Melbourne	Construction materials, Australian data	Cradle-to-grave	I-O based hybrid method	[6, 7, 32, 39]
Chinese Life Cycle Database	Sichuan University, China; IKE Environmental Technology Co., China	Waste management, energy carriers, transport, materials and chemicals; data coverage for China	Cradle-to-gate	Process-based method	[68]
Athena Institute Impact Estimator database	Athena Sustainable Materials Institute	Construction materials, North American	Cradle-to-grave	Process-based method	[65]

Note: (1) the exact database has not been reported.

The findings show that the studies have taken different approaches toward calculating the embodied energy demands of the analysed buildings. These differences of approach, coupled with the differing definitions of the system boundary, make the LCEA results highly variable across the reviewed studies.

4.3 Methods applied to calculate operational energy

This paper found that the studies applied five main methods to calculate operational energy usage:

- Building energy performance simulation (BEPS) tools. The review showed that 65% of the studies utilized BEPS tools to calculate operational energy. In recent years, this method has been widely applied to support the processes involved in building design, construction, operation, and retrofitting [78]. However, the main challenge of the BEPS approach attributes to incorporating assumptions about occupant behaviours into the simulated model and whether or how much they reflect real-world occupant behaviours. Previous studies indicated that relying solely on simulation software may induce significant deviations between predicted and actual building performances [79, 80].

- Energy bills. Around 8% of the studies used the actual records of energy bills to calculate operational energy usage [37, 39, 57]. Employing this method enables researchers to comprehensively capture the effects of occupants' behaviours on energy usage. Nevertheless, using this method only provides an aggregate value for operational energy consumption, and does not provide a detailed breakdown of energy usage. This makes it difficult for decision-makers to identify the 'hot spots' of energy use in buildings and to provide solutions for energy reduction [23].
- Monitoring. 8% of the studies monitored buildings' energy consumption using sensors and actuators in order to calculate operational energy [52, 67, 73]. Using this method enables researchers to acquire detailed data on the actual energy use of buildings by continuously sensing instantaneous values of current and voltage, or gas usage to provide a measurement of energy used [81]. However, there are several challenges involved in using this method, in particular the issue of interoperability. This term refers to exchanging the data between components of building energy monitoring and metering systems in a standardized way so that they can properly communicate with each other irrespective of the manufacturing brands and physical medium [81]; thus, all the data corresponding to different types of energy use in buildings can be metered and recorded uninterruptedly. Furthermore, the high initial cost and the difficulty in managing and storing the high amounts of metering data can also be listed as potential challenges in using this method [81]
- National statistics. The review shows that 8% of studies utilized data representing national or regional statistics on energy consumption in the building sector in order to calculate operational energy use [34, 35, 38]. Using this method can potentially lead to a divergence between estimated and actual operational energy use since these data are developed based on the average energy consumption in the building sector. Moreover, the age of the data in this method can be a matter of concern. For instance, Bastos et al. [35] used data from 2002 related to the residential use of electricity and natural gas

from the Lisbon Energy Matrix in order to calculate a building's operational energy usage.

- Others. Other methods were applied in 10% of the reviewed studies [6, 32, 33, 55]. Stephan et al. [32] and Stephan et al. [6] used static equations in order to calculate heating and cooling loads, then non-thermal energy demands were estimated using regional per capita average energy consumption. In another study, Stephan and Stephan [33] utilized dynamic simulation software to calculate heating and cooling loads, while non-thermal energy demands were computed using regional averages for energy consumption in Lebanon. Zhan et al. [55] also used static equations to calculate the amount of energy consumed for heating, ventilation, air conditioning, and lighting during a building's operation. Using static equations can assist researchers to produce an accurate estimation of a building's energy performance at the early stage of building design; however, it can be time-consuming when the aim is to optimize a building design through parametric analysis [23].

The review showed that the studies applied different methods to measure operational energy use. The majority employed BEPS tools, mainly without validating their results. Only two studies validated their simulated results against actual data [72, 74]. The seldom reliance on this approach may lead to inaccurate results due to ignoring the impacts of occupants' behaviours on energy usage. For instance, Van Dronkelaar et al. [79] reported a discrepancy of 34% in total energy between design and actual building performance, with a 10–80% estimated effect of occupants' behaviours. Contrarily, the use of the energy bills [37, 39, 57] and monitoring [52, 67, 73] methods can address the aforementioned issue by taking into consideration the effects of occupants' behaviours on energy use over a building's lifespan. Using national or regional statistics on average energy consumption in the building sector was another method applied by the reviewed studies to calculate operational energy [34, 35, 38]; however, this approach can also lead to an inaccurate estimation of operational energy since it fails to account for the particular buildings' characteristics, occupants' behaviours, and the effects of microclimate on buildings' energy consumption.

In sum, LCEA results can also be affected by the method chosen to calculate operational energy. Quantifying the impacts of each method on the LCEA results is beyond the scope of this paper, though it is an important topic for future research.

4.4 Interpretation

Interpretation is the final stage of an LCEA in which the obtained results are discussed with regard to the scope and aim of the research and recommendations are made accordingly. In principle, the LCA standards recommend performing certain types of evaluation in order to assure the accuracy of the achieved results. For instance, ISO 14044 recommends three analyses: completeness check, sensitivity check, and consistency check [20]. Detailed explanations of these analyses can be found in [23]. EN 15978 also suggests undertaking result verification to formally confirm the achieved results [13]. In addition, EeBGuide recommends conducting an uncertainty analysis and states that, where possible, an alternative scenario should be modelled for each stage of the life cycle [47].

The findings showed that three methods have been applied by the analysed studies as a means of evaluation, namely sensitivity analysis, uncertainty analysis, and discussion of limitations. Uncertainty analysis measures the uncertainty in model outputs, which is derived from input uncertainty, while sensitivity analysis assesses the inputs' contributions to the total uncertainty in the analytical results [82]. Discussion of limitations refers to acknowledging the limitations of the LCEA and discussing their implications for the final results without undertaking any quantitative analysis. Regarding sensitivity analysis, 15% of the studies utilized only this method to examine the effect of inventory data parameters [34, 37, 53, 59, 67, 69]. In these studies, the impacts of several variables on total building life-cycle energy use were analysed, namely climate and energy mix, the choice of insulation materials, the method of assessing embodied energy at the production stage, building lifespan, air infiltration rate, ventilation heat recovery efficiency, and the effects of building location. Also, 13% of the reviewed studies applied uncertainty analysis [6, 32, 50, 54, 56]. For instance, interval analysis was used by a number of studies to evaluate uncertainties concerned with embodied energy data [6, 32]. Finally, 13% of the studies discussed limitations linked to their research [35, 39, 46, 57, 58]. Different limitations were discussed such as assuming a constant energy mix over 50 years, assuming the same service life for the building's structural components as for the building, and assumptions pertaining to building occupancy [57], using old I-O data [39], ignoring the EOL stage, using a database to calculate embodied energy that is derived from UK production processes [35], excluding the impacts of interior zoning of spaces (e.g. living room, bathroom, bedroom) on operational energy usage, and excluding the impacts of partition walls on embodied energy [46].

Furthermore, no study adopted all the three methods to evaluate the LCEA results, and only 18% of the studies included two of them, i.e. sensitivity analysis and discussion of limitations [7, 38, 40, 66, 74], uncertainty analysis and discussion of limitations [33], and sensitivity analysis and uncertainty analysis [41]. 42% of the studies also did not perform any evaluation.

5. Discussion

This section aims to offer responses to the first two research questions; 'what is the current trend of methodological approach for applying LCEA in residential buildings?'; and 'what are the key parameters causing variations in LCEA results?'. Table 8 shows the overall methodological trends of the reviewed studies. In this table, 12 major parameters are identified that can lead to varying LCEA results. These parameters are further categorized into four main groups: i) system boundary definition, ii) calculation methods, iii) geographical context, and iv) interpretation of results.

Table 8. Overall trends in the methodologies of the reviewed studies

Category	Methodological aspects	Overall trends in the LCEA studies
System boundary definition	Exclusion of building life-cycle stage.	58% excluded EOL; 35% replacement and maintenance; 27% excluded construction/installation; 22% excluded transport to construction site.
	Exclusion of reuse, recovery, and recycling.	65% of the reviewed studies.
	Building components considered for embodied energy assessment.	100% superstructure; 93% substructure; 75% finishings; 50% services; 30% RES; 18% built-in furniture/fixtures/appliances.
	Elements at the neighborhood scale considered for embodied energy calculation.	Occupants' transportation; urban infrastructure considered by 13%.
	Parameters considered for operational energy usage.	90% heating; 73% ventilation; 73% DHW; 73% electrical appliances; 63% lighting; 48% cooling; 33% cooking.
	Building lifespan.	58% assumed 50 years.
	Assumptions.	All stages are subject to assumptions.
Calculation methods	Methods used for calculating embodied energy.	60% process-based; 23% I-O-based hybrid; 3% economic I-O; 15% of the studies did not discuss their applied methods.
	Database employed for embodied energy calculation.	33% generic international databases; 13% literature; 15% combined generic international databases with national or regional databases.
	Methods used for calculating operational energy.	65% BEPS tools; 8% energy bills; 8% monitoring; 8% national statics; 10% other.
Geographical context	Distribution of countries.	58% Europe; 21% Asia; 16% Australia; 2.5% Brazil; 2.5% Canada.

Interpretation of results	Interpretation.	42% none; 15% sensitivity analysis; 13% uncertainty analysis; 13% discussion of limitations; 18% used two methods.

The incomplete definition of the system boundary is a primary issue relating to the LCEAs carried out by the analysed studies. It is interesting to mention that, with one exception [39], no study had a complete definition of the system boundary, that is, a definition that included all stages of a building's life cycle, all parameters influencing operational energy usage, and the embodied energy of all building components. Even studies with a broad definition of the system boundary for assessing embodied energy [6, 32-34, 44] excluded the impacts of certain stages of a building's life cycle or some influential parameters in calculating operational and embodied energy. Another issue associated with the LCEAs conducted by the reviewed studies is the subjectivity in defining the system boundary since they barely gave justifications for truncating system boundaries. As a result, the incomplete definitions of the system boundaries compromise the accuracy of LCEAs in representing the total life-cycle energy performance of buildings. This can further reduce decision-makers' ability to rely on these results for purposes such as implementing environmental practices (e.g. eco-labelling).

The review also revealed different approaches employed by the studies to measure embodied energy and operating energy. Regarding embodied energy, studies with a wider approach, namely the I-O-based hybrid, were more likely to yield a higher value as it captures energy usage embedded in both the downstream and upstream stages of the supply chain [7, 33, 77]. Likewise, the analysed studies adopted different methods to calculate operational energy. A limited number of studies applied methods that capture occupants' behaviour regarding energy consumption, namely energy bills [37, 39, 57] and monitoring [52, 67, 73], whereas the majority employed simulation software. Moreover, regional or national averages for energy consumption in residential buildings were used by some studies [34, 35, 38] to calculate the operational energy of buildings. Another major difference amongst the studies is the geographical context, which leads to certain inherent differences such as climatic conditions, building regulations, quality of raw materials, production processes, economy structure, different processes involved in producing secondary energy, energy tariffs, fuel supply structure, and labour [28]. This emphasizes the necessity of considering the geographical representativeness of data when computing embodied impacts. Pullen [83] estimated a possible error of 2.6 percent in the results for embodied energy due to differing tariffs paid by different material suppliers at different locations when using the I-O method. The last major difference was the interpretation of the LCEA results. This paper showed that a large percentage of studies (42%) eschewed any type of evaluation of their final results, despite the recommendations in the LCA standards.

Overall, it can be stated that the applicability of current LCEA results for decision-making purposes is limited due to incomplete definitions of the system boundary, with no possibility of conducting cross-comparison between LCEA studies. Cross-comparison is important when aiming to advance knowledge about LCEAs of residential buildings within a global context [23]. Previous studies endeavoured to plot the significance of operational energy against embodied energy (or vice versa) by juxtaposing various case studies [18, 24, 84-86]. For instance, Ramesh et al. [24] cross-compared 73 cases of residential and office buildings. It was concluded that operational energies constituted 80–90% of the total buildings' life cycle energy usage, while embodied energies made up 10–20%. It was further shown the total life cycle energy requirements of conventional residential buildings fell in the range of 150–400 kWh/m^2 per year and that of office buildings in the range of 250–550 kWh/m^2 per year. These comparisons are infeasible considering the significant variations existing among the studies. In one study, Yung et al. [87] attempted to compare residential and office buildings. They noted that some studies excluded the transportation and construction stages from their system boundaries. To account for the impacts of these excluded stages, 4% (for transportation) and 10% (for construction) of the initial embodied energy were added to the original values calculated by the researchers in order to make the cases comparable. To standardize operational energy, they considered energy usage for heating and cooling only, and then compared the embodied energy and operational energy of the cases. Despite the authors' great efforts, comparing LCEA studies with such unclear system boundary definitions and the variety of methodological choices can inherently increase the risk of misinterpretations if LCEA cases are utilized for inspiring particular design practices, or promoting indications for building regulations.

6. An evidence-based framework for LCEA research

This section aims to elaborate on the methodological bases of a conceptual framework that brings forward proposals for the standardization of LCEA use. The framework is developed based on the theoretical examination of the reviewed studies and the resultant reflections on the LCA methodology (Figure 3). Thus, it addresses the third research question; '*how can the continued variations in the application of LCEA in residential buildings be overcome?*'. This framework primarily targets to simplify the interlocking processes involved in an LCEA by providing a clear description of the system boundary. It encourages incorporating embodied impacts of building components within a stepwise approach consisting of four levels in that each one represents a different degree of inclusion for assessing embodied and operational impacts.

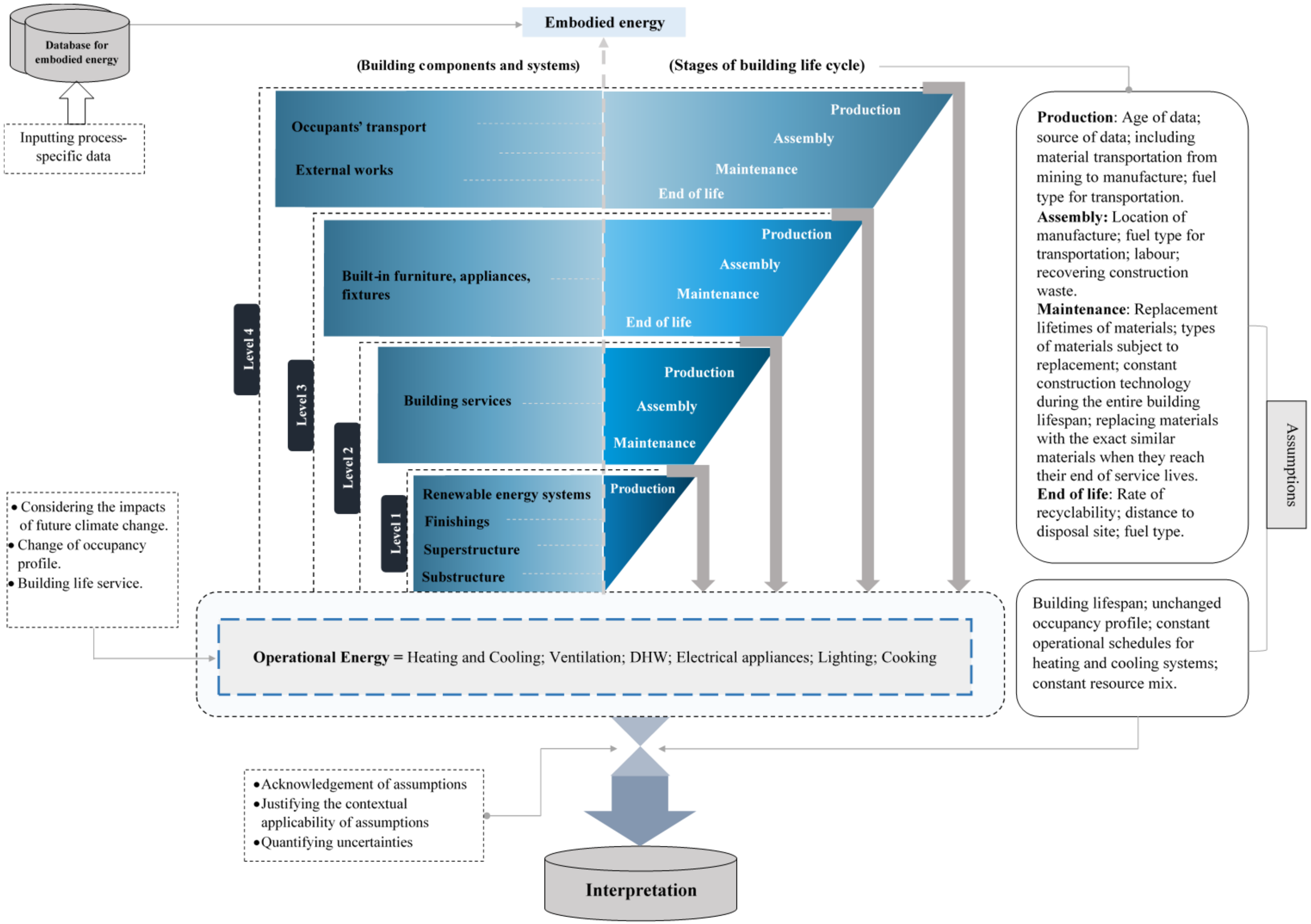

Figure 3. An evidence-based conceptual framework for LCEA research

6.1 Embodied energy

The importance of describing physical and temporal system boundaries has been widely emphasised by LCA standards to assure maintaining transparency and comparability. Description of physical system boundary refers to clearly stating which parts of the physical building components need to be included for assessment. Examples of these standards are ISO 21931-1 1 [11], and EN 15978:2011 [13], whereby building elements that should be considered for the analysis are recommended. These standards serve well in providing general guidance for practice, as well as providing a basis through which buildings' environmental impacts can be investigated. However, a more detailed framework is required when LCEA cases are to be horizontally compared e.g. for obtaining certification. The proposed framework recommends a stepwise approach by which buildings' embodied and operational impacts can be taken into consideration. Stepwise approach offers flexibility in assessing buildings' environmental impacts when dealing with data unavailability. Using this framework facilitates the possibility of comparing different versions of a similar building or cross comparing cases that are analysed by the LCEA approach.

The current study complements the description of physical system boundaries of current standards (i.e. EN 15978:2011 [13]) by recommending the inclusion of embodied impacts associated with renewable energy systems, and occupants' transport (Table 9). Considering the significant investment being made worldwide to support the concept of zero energy buildings, it is necessary to account for the embodied impacts of these components when the building is zero energy. The framework recommends including embodied impacts of renewable energy systems at level 1, where the inclusion of these components combined with superstructure, substructure, and finishings establishes the minimum level of LCEA assessment at building scale. Levels 2 and 3 promote adding embodied impacts of building services and fittings, built-in-furniture, and appliances to the system boundary in order to capture a holistic understating of buildings' environmental performance.

Table 9. Components suggested by international standards for inclusion within system boundary [13]

Main components	Sub-components
Substructure	Foundation; and basement.
Superstructure	Frame; upper floors; roof; stairs and ramps; external walls; windows and external doors; internal walls; and internal doors.
Internal finishes	Wall, floor and ceiling.

Fitting, furnishes and equipment	Fitting, furnishes and equipment
Services	Sanitary; water, and disposal installations; service equipment; heat source; ventilation and air conditioners; electrical and fuel installations; lift; and control system.
Prefabricated buildings	Complete buildings; building units; and pods.
Work to existing buildings	Minor demolition and alteration work; repairs to existing services; damp-proof course; façade retention; cleaning existing surfaces; and renovation work.
External works	Site preparation; roads, path, paving and surfaces; soft landscaping, planting and irritation systems; fencing, railing and walls; external fixtures, drainage, and services.
Renewable energy system	Photovoltaics panels and its supporting systems; solar collectors; and wind turbines.
Occupants' transport	Vehicles; access to public transport.

The assessment of embodied impacts relating to external works has been recommended by EN 15978:2011 (see table 9) [13]. This study suggests adding embodied impacts of occupants' transport to the physical system boundary (i.e. level 4) along with external works in order to account for the impacts of elements that are beyond the building scale. The review also showed that a number of studies endeavoured to include embodied impacts of nearby infrastructure, and occupants' transportation within their system boundaries [6, 32-34, 44]. Level 4 represents the ambitious level for assessing the life cycle energy performance of buildings.

Regarding the temporal system boundary, this study recommends that the embodied impacts of production (initial embodied energy) stage should be a minimum assessment requirement at the building level. The initial embodied energy plays a significant role in emitting GHGs into the atmosphere since they are mainly produced by combusting fossil fuels [7]. It is also widely accepted that initial embodied energy constitutes a higher percentage of total embodied energy use compared to other stages of building life cycle [6, 7, 23, 88, 89]. Additionally, the majority of current databases contain initial embodied impacts of building materials that are calculated based on energy inputs from the entire structure of an economy; thus, the impacts of this stage can be taken into consideration regardless of buildings' locations. Level 2 recommends including the impacts of recurrent embodied energy and assembly (construction/installation), while levels 3 and 4 encourage including embodied impacts of all the building life cycle stages.

6.2 Operational energy

From the review, it became evident that only 20% of the studies accounted for all parameters with potential impacts on operational energy [31-35, 37, 39, 52]. The proposed framework recommends that all parameters influencing operational energy use should be considered for assessment at all levels. Many jurisdictions across the world now aim to increase energy efficiency in the building sector by supporting the construction of energy-efficient buildings (e.g. NZEBs, and passive buildings). These dwellings are principally built to minimize operational energy consumption. The European Union's revised Energy Performance in Buildings Directive of 2010 is an exemplar of policy to support constructing buildings with high energy efficiency. It sets the nearly-zero energy building as the target for all new buildings from 2021 [90]. Similar examples can be found in other countries such as the U.S. [91], UK [92], Japan [93], and Australia [94]. Therefore, heating and cooling loads that are commonly considered by the vast majority of the studies for assessment, are likely to be minimized in the future while the shares of other parameters such as electrical appliances in consuming energy would be maximized.

The accuracy of measuring operational energy can be improved by future research. This review found out that the analysed studies commonly assumed an unchanged occupancy profile (e.g. family size, occupational settings and etc.) for the entire assessment period. To address this issue, the deterministic and stochastic statistical approaches can be employed in order to take the impacts of occupants' behaviours into consideration [23]. In the deterministic approach, different scenarios for users' behaviours on an hourly basis throughout a year should be defined, ranging from energy-saving to wasteful. Thereafter, the impacts of each scenario on building energy consumption can be measured and compared. Alternatively, a stochastic statistical model can be developed to predict occupants' presence throughout the year based on scholarly literature and national sociological investigations [47]. Despite the easier application of the first approach, using a stochastic statistical model may generate more accurate results. Moreover, considering the effects of future climate change on the heating and cooling demands can also be considered by future LCEA research when estimating operational energy usage. This consideration can potentially increase the accuracy of estimating operational energy consumption.

7. Conclusions

This paper approached the literature with the aim of addressing three key questions; 'what is the current trend of methodological approach for applying LCEA in residential buildings?'; 'what are the key parameters causing variations in LCEA results?'; and 'how can the continued variations in the application of LCEA in residential buildings be overcome?'. To this end, 40 LCEA studies representing 157 cases of residential buildings across 16 countries have been critically reviewed. The findings indicate that the current LCEA application in residential buildings suffers from an incomplete definition of the system boundary. This compromises the accuracy of LCEA results to be used for decision-making purposes. The key parameters leading to variations in LCEA results are the system boundary definitions, calculation methods, the geographical context, and interpretation of the results. The system boundary determines which building life-cycle stages are excluded from the assessment, including reuse, recovery, and recycling; which building components and systems are included in embodied energy calculations; whether elements beyond the building scale (e.g. urban infrastructure) are included in calculating embodied energy; the parameters of operational energy calculations; building lifespan; and assumptions. The calculation methods refer to the methods and background databases applied to calculate embodied energy, as well as the methods used to calculate operational energy. The geographical context refers to the different countries and/or regions in which LCEAs have been conducted. Finally, the interpretation of results refers to the studies' different methods of evaluating the accuracy of the LCEA results. Identifying the principal parameters with potential contributions to varying results in LCEAs can minimize the uncertainties accruing from LCEAs of residential buildings.

The findings also suggest that although the current LCA standards serve well in providing general guidance for practice as well as providing a basis for investigation of buildings' environmental impacts, they are still ineffective in harmonising the LCEA application. Thus, further research is needed for developing a more detailed framework when the aim is to horizontally compare cases (e.g. certification). This paper contributes to developing a conceptual framework for the standardization of LCEA use. The framework primarily targets to simplify various interlocking processes involved in an LCEA by providing a clear description of the system boundary. It encourages incorporating embodied impacts of building components within a stepwise approach consisting of four levels in that each one represents a different degree of inclusion for assessing embodied and operational energies. The framework offers the possibility of comparing different design strategies of a similar building or cross comparing cases that are analysed by the LCEA approach.

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Chapter 5. Exploring the significance of embodied energy in the Australian energy efficiency regulations

5.1 Introduction

Most countries have pledged commitment to minimise energy-related CO_2 emissions across industries by 2050. Australia's commitment includes the aim to transition its building sector to zero energy (and carbon) by increasing minimum requirements for the thermal performance of new and retrofitted buildings – mandated by building energy efficiency regulations (BEERs). Chapter 2 highlighted the importance of BEERs coverage (i.e., the scope of regulations for including the parameters that affect energy use in buildings) in decreasing energy use in the building sector. The current Australian BEERs excludes the impacts of embodied energy associated with building designs and only accounts for thermal loads of buildings, namely heating and cooling. Chapters 3 and 4 critically analysed the approaches of existing scholarly documents and underscored the need for devising a comprehensive framework to assist the incorporation of embodied energy impacts into BEERs. This chapter aims to explore the significance of embodied energy relating to Australian BEERs and investigate the repercussions of increasing energy efficiency requirements without considering the impacts of embodied energy. The findings will highlight the significance of embodied energy as it relates to the Australian BEERs.

5.2 List of manuscripts

This part of the research has been produced as a journal article, published in *Architectural Science Review*:

Omrany, H., Soebarto, V., & Ghaffarianhoseini, A. (2021). Rethinking the concept of building energy rating system in Australia: a pathway to life-cycle net-zero energy building design. *Architectural Science Review*, 1-15. DOI: https://doi.org/10.1080/00038628.2021.1911783.

The paper is presented here in a reformatted version for consistency of the thesis presentation. The accepted manuscript can be found in Appendix III.

Statement of Authorship

Title of Paper	
Publication Status	☑ Published ☐ Accepted for Publication ☐ Submitted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details	Omrany, H., Soebarto, V., & Ghaffarianhoseini, A. (2021). Rethinking the concept of building energy rating system in Australia: a pathway to life-cycle net-zero energy building design. Architectural Science Review, 1-15.

Principal Author

Name of Principal Author (Candidate)	Hossein Omrany		
Contribution to the Paper	Conceptualization, methodology, software, data analysis, and writing—original draft preparation.		
Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	13/07/2021

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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Contribution to the Paper	writing—review and editing		
Signature		Date	14/07/2021

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5.3 Rethinking the concept of building energy rating system in Australia: a pathway to life-cycle net-zero energy building design

Abstract

Over the last decades, Australia has taken several measures to tackle the increasing trend of energy use in residential buildings. Recently, the Trajectory for Low Energy Buildings has been endorsed aiming to reduce energy usage in residential buildings. However, the primary focus of this trajectory is on decreasing operational energy without considering the embodied energy of the building and systems. This paper aims to address one primary question; 'can the continued exclusion of embodied energy from the energy efficiency regulations effectively lead to reducing energy consumption in Australian residential buildings?'. The findings indicate that embodied energy becomes a dominating factor as buildings' thermal performances increase according to the Australian energy efficiency regulations. In transitioning from a standard 6.0-star building to a highly energy-efficient 8.7-star building, the proportion of embodied energy significantly increases from 20-40% to 50-75%. This study recommends establishing minimum mandatory requirements for buildings' embodied performance.

Keywords: Zero energy building; embodied energy; thermal performance; building regulations; building design; optimization design; Australia.

Background

Australia is currently experiencing a major housing boom with about 200,000 new dwellings being built each year (Schmidt, Crawford, and Warren-Myers 2020); and considerably more are needed annually in order to accommodate the projected population growth of nearly 40 million by 2050 (Australian Bureau of Statistics, population projections). In response to the impending intensification of energy demands, Australia has taken several measures to curb energy use in residential buildings over the last decades. In 1998, the importance of energy efficiency standards for housing and commercial buildings was recognised as a part of the National Greenhouse Strategy (NGS) (National Constructions Code 2019). An option outlined in the NGS was to introduce measures in the building codes of Australia (now called national construction codes) to decrease greenhouse gas (GHG) emissions by efficiently using energy. In 2003, the energy efficiency regulations (EERs) were introduced into the building codes of Australia for the first time, with a scope limited to only housing. These regulations were further expanded to include other building classifications in 2006, along with increasing the stringency for dwellings to a target of 5.0 stars (National Constructions Code 2019). In 2010, the minimum mandatory thermal requirements were increased to the equivalent of 6.0 stars for houses and apartments (National Constructions Code 2019). Currently, all new buildings need to meet certain thermal requirements equivalent to 6.0 stars in order to substantiate their compliance with the EERs (Daniel, Williamson, and Soebarto 2017; Daniel, Soebarto, and Williamson 2015).

Australia now aims to further strengthen its measures towards minimizing energy consumption in residential buildings. In February 2019, the '*Trajectory for Low Energy Buildings*' (TLEB) has been endorsed by the Council of Australian Governments as a national plan to realise zero energy and carbon-ready buildings by 2030 (Trajectory for Low Energy Buildings 2019). This trajectory targets to identify opportunities for energy efficiency improvements throughout the building system, from thermal performance to appliance energy usage and renewable energy generation (Trajectory for Low Energy Buildings 2019). It also promises to increase the minimum mandatory thermal requirements for new buildings to 6.5 stars equivalent in tropical and temperate climates, and up to 7.0 stars equivalent in colder climates. This increase sets to be periodically implemented in 2022 and 2025. The underlying aim of the TLEB is to promote the concept of zero energy buildings (ZEBs). It characterizes ZEBs as "*zero energy (and carbon) ready buildings have an energy efficient thermal shell and appliances, have sufficiently low energy use and have the relevant set-up so they are 'ready' to achieve net zero energy (and carbon) usage, if they are combined with renewable or decarbonised energy systems on-site or off-site*" (COAG 2018).

As stated in the definition above, the primary emphasis is on the reduction of operational energy by improving the energy efficiency of buildings' envelopes and using energy-efficient appliances. However, the limited focus given only to the improvement of buildings' operational energy can paradoxically result in increasing the total life-cycle energy use of buildings due to ignoring their embodied impacts (Stephan, Crawford, and De Myttenaere 2013a; Crawford et al. 2016). This is reflected in the findings of Stephan, Crawford, and De Myttenaere (2013a) who assessed the life-cycle energy performance of a passive house. Their results indicated that current standards developed to support the enhancement of energy efficiency in buildings cannot assure reducing the total energy consumption because the embodied impacts are excluded. In recent years, academic studies have given more attention to the necessity of minimizing energy use throughout the entire building life cycle considering both embodied and operational energies. Nevertheless, the surge of research has failed to alter the attitude of policymakers toward considering the importance of buildings' embodied energy when planning for the betterment of built environment (Säynäjoki 2017). Previous studies voiced concern about the exclusion of embodied impacts, stating that without immediate action, embodied energy would become the 'second wave' of environmental concern relating to buildings' performance (Pomponi and Moncaster 2018). The argument here is that reduction of operational energy can be somewhat addressed later on once the building is constructed by using energy-efficient appliances and equipment; however, any attempt to reduce embodied energy after construction shall provoke an additional increase of embodied energy. Hence, it is imperative for the EERs to not only consider the importance of reducing operational energy but also reflect upon decreasing embodied impacts concerned with building designs.

With the motivation outlined above, this study aims to highlight the significance of embodied energy attributed to the Australian EERs by addressing one primary question; 'can the continued exclusion of embodied energy from the energy efficiency regulations effectively lead to reducing energy consumption in Australian residential buildings?'. This study also puts forward proposals for the integration of embodied energy into the Australian building regulations. The remainder of this paper unfolds as follows: first, a literature review is provided to discuss the increasing demands for integrating embodied energy (and GHG emissions) into building regulations. The section on the energy rating system in Australia provides an overview of how buildings are appraised for compliance with EERs in Australia. The Research methodology section elaborates on the research approach and methods of the paper, followed by the Results and discussion section. The limitations and future research section discusses the limitations concerned with the study; prior to the Conclusion.

Literature review

In recent years, there has been a growing attention toward the importance of energy efficiency in the building sector by mandating the use of EERs and advocating voluntary schemes (Omrany and Marsono 2016). This approach, in turn, leads to the increase of embodied energy since adopting energy-efficiency measures usually requires installing additional materials (Crawford et al. 2016). Hence, previous research highlighted the necessity of incorporating embodied energy requirements into building EERs (Dodoo, Gustavsson, and Sathre 2011; Stephan, Crawford, and De Myttenaere 2012; Stephan and Stephan 2014; Crawford et al. 2016;

Koezjakov et al. 2018; Stephan and Stephan 2020). Stephan and Stephan (2014) performed a comprehensive life cycle energy analysis of an apartment in Beirut, considering embodied, operational and user transport energy demands. The study concluded by recommending the development and implementation of mandatory life cycle energy efficiency policies for the building sector. In another study, Koezjakov et al. (2018) investigated the correlation between heat energy demands and embodied energy in different types of Dutch residential buildings. The findings revealed that the values for operational and embodied energies in Dutch dwelling archetypes were amounted to 124 to 682 MJ/m^2.year and 52 to 106 MJ/m^2.year, respectively. Koezjakov et al. (2018) also recommended the inclusion of embodied energy use in the future building energy efficiency regulations as a measure to achieve the maximum global temperature increase of well below 2 °C by 2100.

Stephan and Stephan (2020) evaluated the life cycle energy and GHG emissions of an apartment in Lebanon. It was discovered that the attainment of life cycle zero energy and GHG emissions is feasible when due improvements in the building envelope are considered, along with using energy-efficient appliances and integrating solar panels. However, the adoption of these measures would add 159 kgCO_2e/(m^2 of gross floor area) and 252 kgCO_2-e/ (m^2 of gross floor area) of additional initial and recurrent embodied GHG emissions, respectively. Stephan and Stephan (2020) suggested the integration of life cycle embodied environmental flows into the future regulations and certifications that aim to enhance buildings' environmental performance. Stephan, Crawford, and De Myttenaere (2013a) analysed the total life cycle energy requirements of a typical Belgian passive building, considering embodied and operational energy as well as energy use for occupants' transport. The results indicated a significant share of embodied energy in total life cycle energy use by up to 77%, hence they conclusively stated that the current implementation of building energy efficiency certifications can reversely lead to increased energy use over building life cycle due to their limited scope.

In Australia, studies also endeavoured to highlight the necessity of including embodied energy into the current building energy efficiency regulations (Stephan, Crawford, and De Myttenaere 2012; Stephan, Crawford, and De Myttenaere 2013a; Stephan and Crawford 2016; Crawford et al. 2016; Schmidt, Crawford, and Warren-Myers 2020). In recent research, Schmidt, Crawford, and Warren-Myers (2020) modelled life cycle GHG emissions of all the detached dwellings that are constructed in Australia in 2019. The findings show that the life cycle GHG emissions for the reference year (i.e., 2019) are 39 MtCO_2-e, which would be further increased to 883 $MtCO_{2}$-e by 2030. This figure is much higher than the projected values for total emissions by 2030 of 563 $MtCO_{2}$-e under the business-as-usual scenario (Climate Action Tracker). Schmidt, Crawford, and Warren-Myers (2020) also found that the GHG emissions related to residential buildings in Australia are being underestimated by 60% owing to the exclusion of embodied energy or GHG emissions. In another study, Crawford et al. (2016) evaluated the effects of increasing energy efficiency of two residential buildings on the life cycle energy demands over a period of 50 years. The results showed that the current Australian regulations promoting building energy efficiency fail to achieve net life cycle energy savings due to excluding embodied impacts.

Despite the growing body of literature, there is still a need to investigate whether promoting the concept of highly energy-efficient buildings such as ZEB by using the current energy efficiency standards can reduce the overall energy usage in Australian residential buildings. To the best of authors' knowledge, this study is the first of its kind that specifically researches the life cycle energy repercussions associated with enhancing building energy efficiency according to the Australian national construction codes (NCC). The outcomes of this research may instigate the need for rethinking the concept of building energy rating systems in Australia by accounting for the embodied impacts of building designs.

Energy rating system in Australia

The thermal performance of all new residential buildings must meet minimum standards of energy efficiency set out by the NCC, Volume II (National Constructions Code 2019). To demonstrate the compliance, two overarching methods are implemented: i) proposal of an alternative solution (i.e. verification-using-a-reference-building), and ii) a deemed-to-satisfy approach (Daniel, Williamson, and Soebarto 2017). The first method is labour and knowledge-intensive, and it is mainly applied for the assessment of housing stock (Daniel, Williamson, and Soebarto 2017). The deemed-to-satisfy approach, which is more widely used offers two primary options to show compliance: i) elemental regulations, and ii) energy star rating. The first option specifies R-values for different building components and determines glazing and ventilation requirements. The energy star rating requires a building design to obtain 6.0 stars out of a maximum rating of 10 stars by using certain simulation software accredited by the NatHERS (Nationwide House Energy Rating Scheme). The NatHERS is a performance-based rating system established to rate dwellings based on their annual thermal performances (i.e. only heating and cooling loads) (NatHERS). A 10-star rating indicates that the dwelling would need nearly no additional heating and cooling in order to retain the indoor comfort level. The performance requirements specified by the EERs vary with respect to eight different climate zones that broadly encapsulate climate variations across Australia (Figure 1).

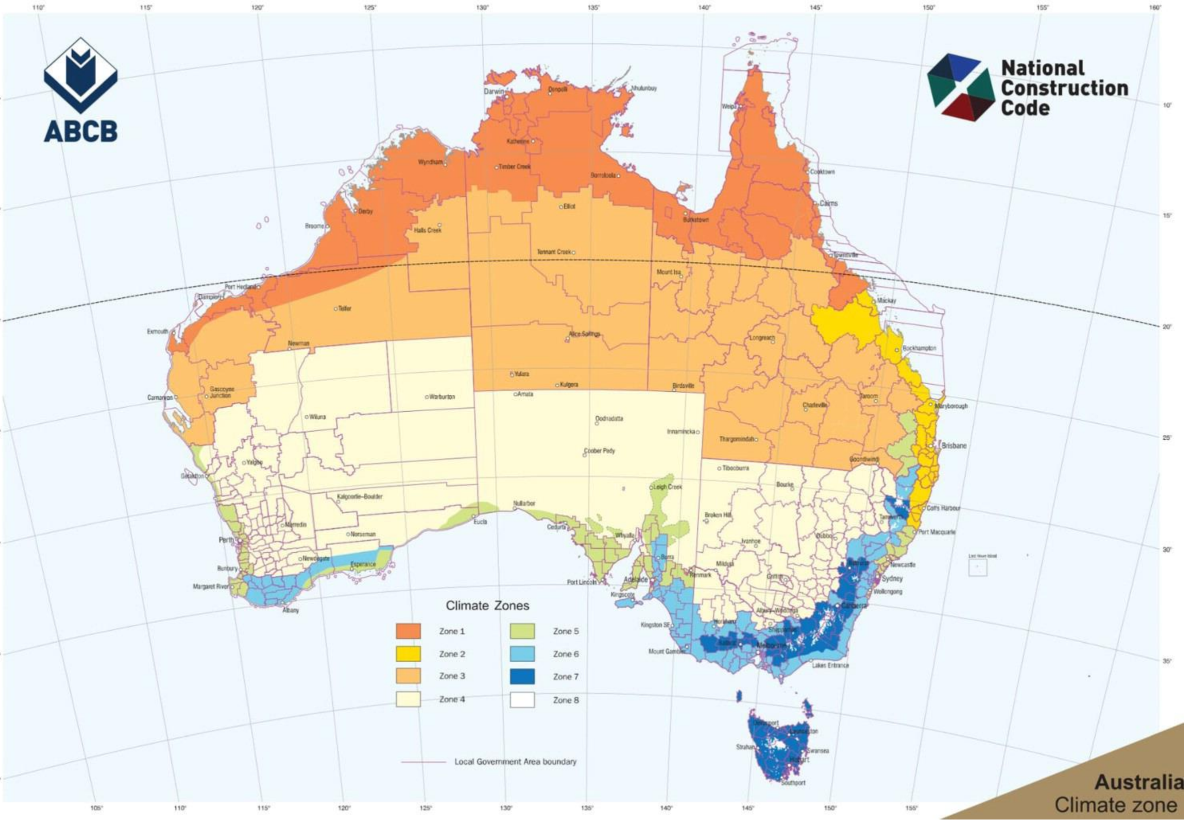

Figure 1. Australian climate zones [Sourced from (Australian Building Codes Board)]

The NatHERS further disaggregates Australia into 69 climate zones, allowing the software to account for the diverse climatic conditions across the country when simulating the thermal performance of a building. In this regard, Australia has one of the most climate-specific EERs in the world. Comparatively, the US, Spain, France, and Germany rely on eight, five, two, and one climatic zones, respectively (Rodríguez-Soria et al. 2014). This degree of precision, combined with the detailed scale of the thermal requirement specified for each climate zone, facilitates the possibility to utilize EERs as a basis for evaluating the life cycle energy implications associated with their implementations in the Australian residential buildings.

Research methodology

The overall methodological approach of the study consists of three main stages (Figure 2). The first stage involves selecting a case study that can meet three basic requirements: i) the building needs to be the most common type of residential building in Australia so that the results would have broader implications; ii) its architectural design represents the bulk of new dwellings in South Australia, Adelaide; and iii) it needs to meet the minimum mandatory thermal requirement according to the NatHERS rating scheme specified for the relevant climatic zone. Since this study used Adelaide (climate Zone 6) as the location for the case study building, a minimum star rating of 6.0 (total heating and cooling loads of no more than 96.0 MJ/m^2) must be achieved.

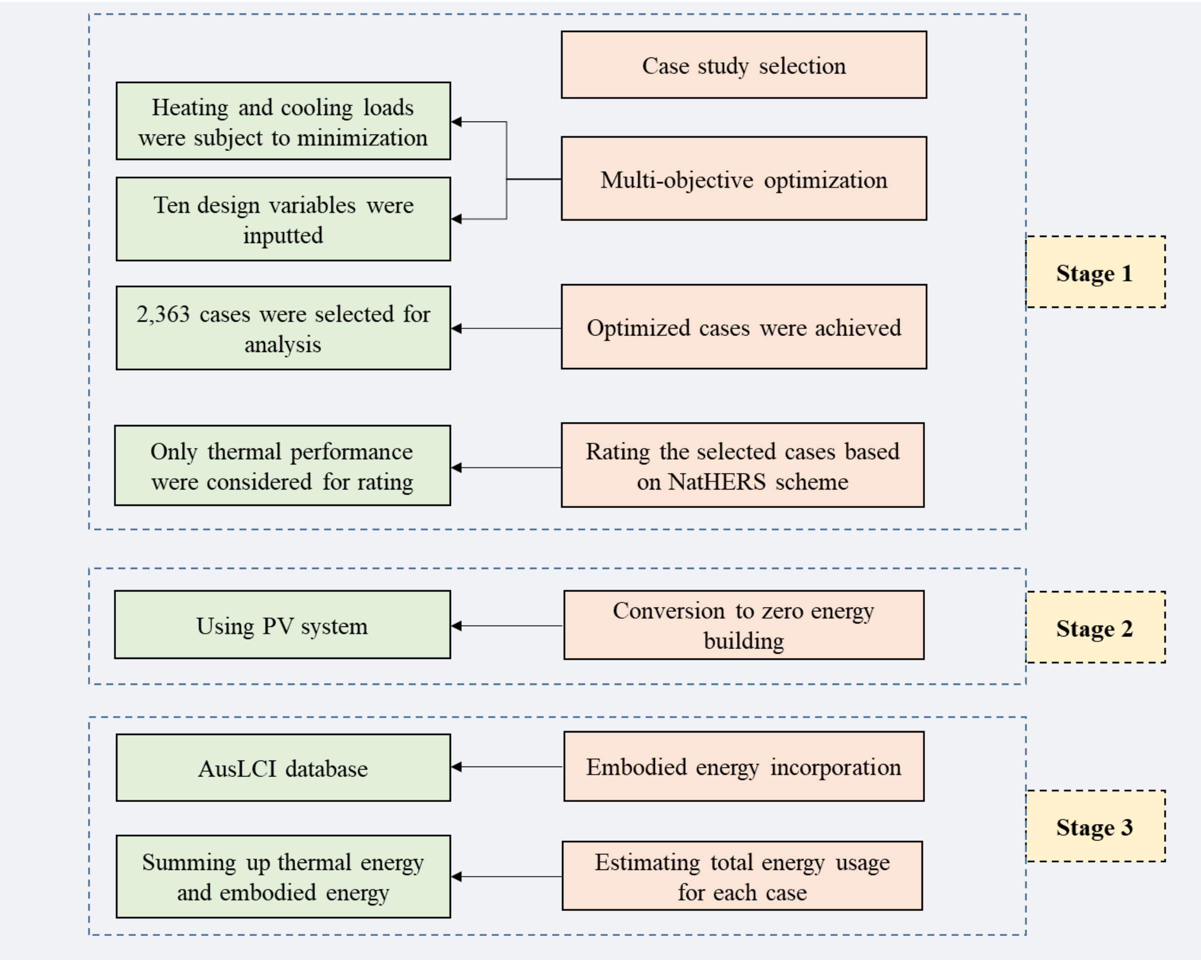

Figure 2. Research approach

After selecting the case study, a multi-objective optimization approach was employed in order to minimize the building's heating and cooling loads. For the purpose of the study, the optimization excluded embodied impacts of building materials in order to reflect the approach taken by TLEB in achieving ZEBs by only considering thermal performance. The results achieved from the optimization were then exported into *Excel spreadsheets* and sorted based on the obtained NatHERS Star rating. This led to developing a database containing nearly 2,400 cases of building designs with the highest rated design obtaining 8.7 stars.

In the second stage, Photovoltaic (PV) systems were added and sized for each individual design case in order to balance out the heating and cooling energy to achieve a zero operating energy building design.

In the third stage, embodied energies for all the cases were calculated using the AusLCI database and summed up with their heating and cooling energy over a period of 50 years in order to estimate total life cycle energy usage. The following sections elaborate further on the different stages of research methodology.

Description of the case study

Figure 3 shows the case study. This building represents the bulk of newly built single-storey detached dwellings in South Australia, Adelaide (Whole of House Verification – Stage 1 2018). It is also noteworthy to mention that detached dwellings comprise 69% of the total housing stock in Australia (Schmidt, Crawford, and Warren-Myers 2020). The net conditioned floor area of the building is 146.0 m^2. It also a garage with an area of 43.0 m^2, four bedrooms, three bathrooms, one living area, one rumpus, kitchen and dining room, and one room used as a study room. Table 1 shows the main characteristics of the building.

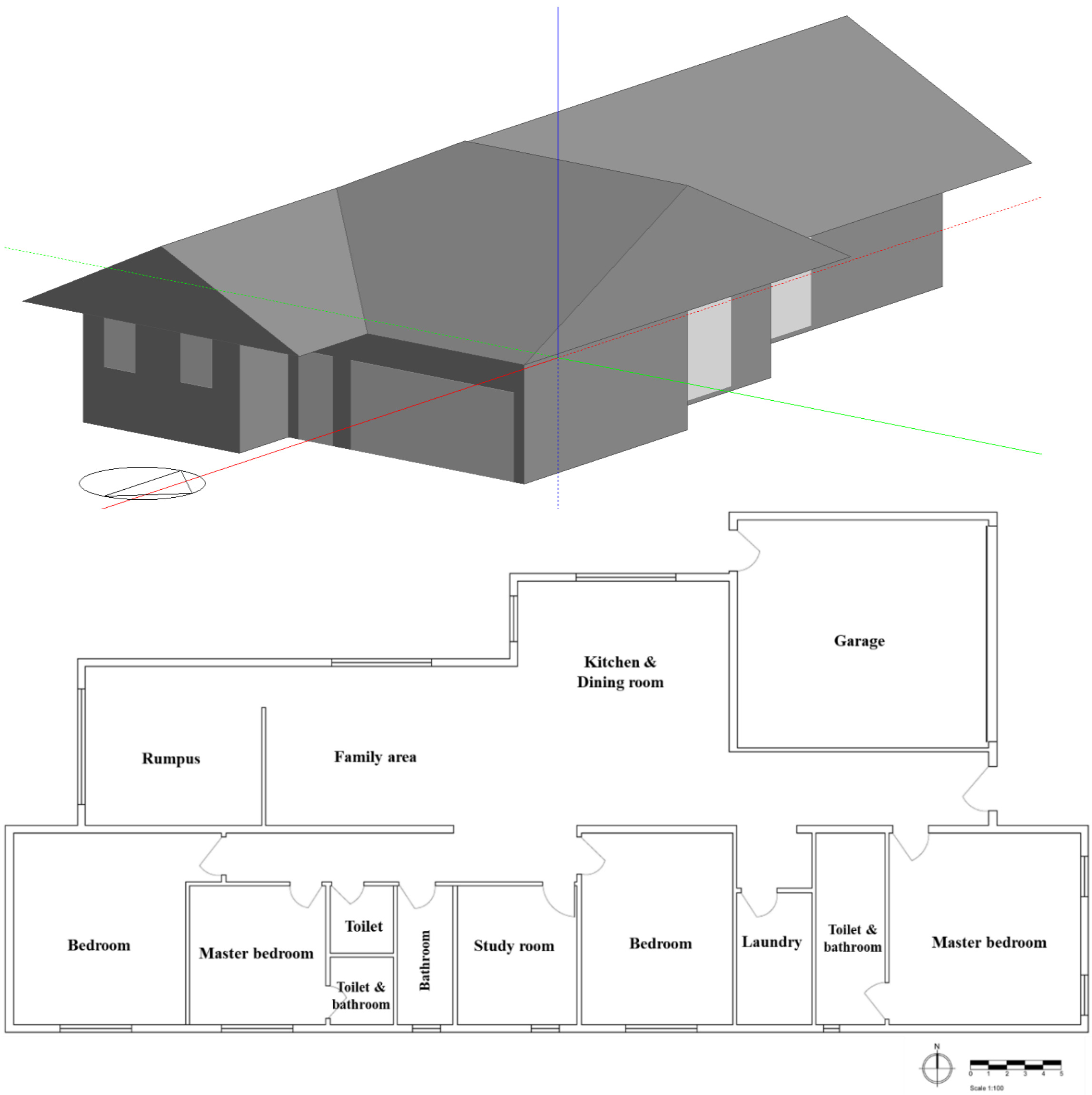

Figure 3. Base case model used for optimization

Table 1. Characteristics of the base model

Parameters	Quantity (m^2)	Value	Descriptions
Gross floor area (m^2)		189.85	
Net conditioned floor area (m^2)		146.78	
Wall height (m)		3.0	
External walls	173.0	U-value 0.659 W/m^2 K	Clay brick; Glass fibre batt insulation; Gypsum plasterboard
Ground floor	206.0	U-value 1.22 W/m^2 K	Waffle pods; Concrete
Pitched roof	383.0	U-value 5.227 W/m^2 K	Clay tile; Roofing felt
Slope of pitched roof (°)		23.0	
Ceiling	147.0	U-value 0.600 W/m^2 K	Glass fibre batt; Gypsum plasterboard
Internal walls	120.0	U-value 0.440 W/m^2 K	Insulated gypsum plasterboard
Windows	32.0	U-value 6.70 W/m^2 K, SHGC[1]= 0.570	Single glazed, aluminium frames
Overhang (m)		0.30	
Infiltration (ac/h at 50 Pa)		15.0	

Lighting	2.50 W/m^2-100lux (Normalised power density)	LED
Occupancy	Four people (i.e., a couple with two kids).	
Heating set point	21.0	
Cooling set point	25.0	
Ventilation system		Split

[1] Solar heat gain coefficient.

Heating and cooling are provided via a split air conditioner system - reverse cycle using electricity supplied from the grid. The coefficient of performance (COP) of the heating system was 2.25, with the maximum capacity of supplying 35.0^{O}C air temperature. The COP of cooling system is 3.0 with a maximum supply air temperature of 12.0^{O}C.

Climate of Adelaide

According to Köppen climate classification, Adelaide has a Mediterranean climate with cool to mild winters and warm to hot summers that requires using energy for both heating and cooling. Figure 4 illustrates the monthly average ambient air temperature for Adelaide airport between 1991 and 2020. According to this figure, February and July are the peak energy demands for cooling and heating, respectively.

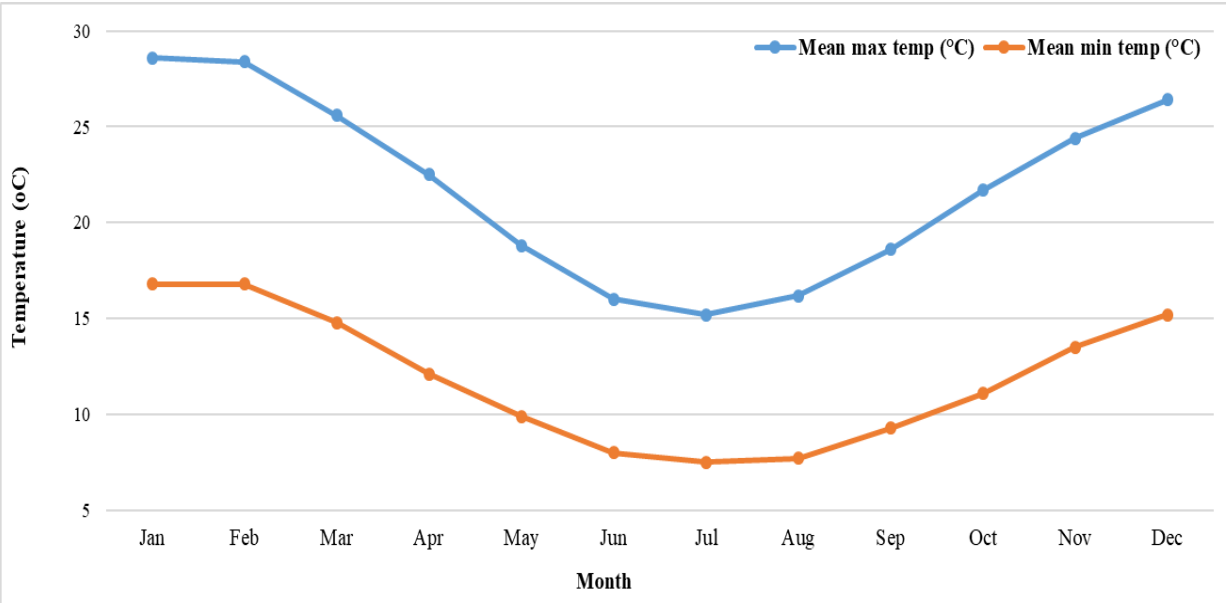

Figure 4. Monthly average ambient air temperature (Australian bureau of Meteorology)

Table 2 tabulates the maximum energy usage of thermal loads in Megajoules per meter square (MJ/m^2) for each star band in Adelaide. As shown, the annual thermal performance of a new residential building needs to be 96.0 MJ/m^2 (26.67 kWh/m^2) in order to obtain a 6.0 star rating.

In this paper, the thermal performance of the base case model was initially assessed by *AccuRate* to ensure that the building satisfies the obligatory thermal requirements. *AccuRate* is one of the software programs accredited by the NatHERS framework that can be used for energy rating in Australia. The results showed the thermal performance of the base model was 90.70 MJ/m^2.annum (6.1 Stars), which met the minimum mandatory requirements of EERs.

Table 2. Thermal requirements for NatHERS Star Band for Adelaide city (MJ/m^2.annum) (NatHERS Star Band Criteria)

Climate Zone	**Location**	**Energy Rating (Stars)**									
		0.50	**2.0**	**3.0**	**4.0**	**5.0**	**6.0**	**7.0**	**8.0**	**9.0**	**10.0**
16	Adelaide	584.0	325.0	227.0	165.0	125.0	96.0	70.0	46.0	22.0	3.0

Multi-objective optimisation

Multi-objective optimization differs from single-objective optimization due to the higher complexity driven by the complicated nature of concurrently satisfying several goals, often with conflicting outcomes (Pilechiha et al. 2020). To optimise a function with multiple objectives, a set of circumstances that define the optimal solutions needs to be established, and a *Pareto* frontier is drawn accordingly (Pilechiha et al. 2020). Figure 5 demonstrates a *Pareto* frontier for optimizing a function with two objectives. The *Pareto* front or *Pareto-optimal* refers to a set of best alternatives representing non-dominated solutions, meaning that these solutions are not dominated by other solutions (Kheiri 2018). In this regard, the upper and lower bounds of each objective are represented by the '*ideal objective vector*' and '*nadir objective vector*' respectively (Kheiri 2018). In many multi-objective optimization problems, realising the ideal objective vector may not be generally possible, and it can only be used as a reference to the trade-off between different alternatives (Deb 2001). Upon identifying non-dominated solutions, decision-makers can select a set of final solutions by which the function can be optimized.

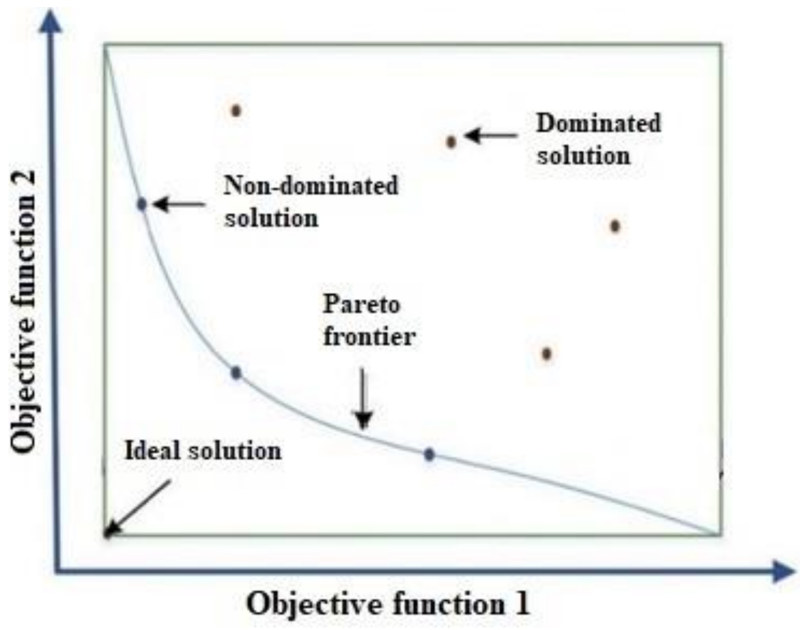

Figure 5. Demonstration of *Pareto* frontier of a multi-objective optimisation (Pilechiha et al. 2020)

The criteria to select an optimal solution, i.e., a final point amidst the non-dominated points, depending on the application. A standard minimization problem can be converted into a maximization problem or vice versa with the same solution. The minimization problem and its corresponding maximization problem are called duals of each other. This can be expressed as (Eq. 1):

$$max\,\{f_{(x)}\} \leftrightarrow min\,\{-f_{(x)}\}$$

In addition, a multi-objective optimization problem can be mathematically expressed as (Eq. 2):

$$\min_{S.t\ (g(\vec{x})\leq 0,\ \ h(\vec{x})=0)} f(\vec{x}) = [f_1(\vec{x}), f_2(\vec{x}), \dots, f_m(\vec{x})]^T$$

Where

$$x_i^{min} \leq x_i \leq x_i^{min}\ (i = 1, 2, \dots, n)$$

$$x = [x_1, x_2, \dots, x_n]\ ^T \in \Phi$$

$$y = [y_1, y_2, \dots, y_m]\ ^T \in \psi$$

Where *m* represents the number of objective functions set to be solved. Φ is the search space with *n* dimensions and identified by upper and lower bounds of the decision variables $x_i = (i = 1, 2, \dots, n)$.

$$x^{max} = [x_1^{max}, x_2^{max}, \dots, x_n^{max}]^T$$
$$x^{min} = [x_1^{min}, x_2^{min}, \dots, x_n^{min}]^T$$

$\boldsymbol{\psi}$ is the m-dimensional vector space of objective functions and is defined by θ, and the objective function $f(x)$. $g_i(\vec{x}) \leq 0 (j = 1,2, \dots, p)$ and $h_{(\vec{x})} = 0$ $(j = 1, 2, \dots, q)$ denotes p and q which are respectively the number of inequality and equality constraints (Pilechiha et al. 2020). If both p and q are equal to zero, then the problem is simplified as an unconstrained optimisation problem, which is the case of current study.

In this paper, DesignBuilderV6 was employed as the platform to carry out the optimization. The reason for selecting DesignBuilder resides with the capability of this software for carrying out optimization, whereas the NatHERS accredited tools (i.e., AccuRate, BERS, and FirstRate) only allow users to perform 'one-factor-at-a-time' (OFAT) experiments. The OFAT is a design method that involves testing the effects of factors one at a time in lieu of multiple factors at the same time (Tian 2013). DesignBuilderV6 adopts Non-Dominated Sorting Genetic Algorithm II (NSGA-II) for performing optimization (Description of the key features of DesignBuilder Optimization). The NSGA-II is an evolutionary multi-objective algorithm and offers a non-dominated sorting with a fast searching method towards finding the optimal solutions (Deb et al. 2000). NSGA-II resolves the issues concerned with the former genetic algorithms such as the lack of elitism, the convergence to local optimum, or the lack of genetic diversity (Gagnon et al. 2019). This algorithm is extensively applied in energy and building science as indicated in the literature review conducted by Attia et al. (2013), and it is among the most efficient genetic algorithms (Gagnon et al. 2019).

The key features of a generic algorithm, namely crossover probability (CRP) and mutation probability (MP) are not straightforward to set since they depend on the nonlinearity of the optimization problem, the typology of the input variable (continuous or discrete), the dimension of the problem space, and a trade-off with the available computational capacity of the operating system (Carlucci et al. 2015). There are two main approaches to set the values of these parameters; i) parameter tuning and ii) parameter control (Hassanat et al. 2019). The most common approach is the 'parameter tuning', which refers to the process of experimenting with different values for CRP and MP and then selecting the ones with the best results. In the second approach, the initial values of CRP and MP are altered during the run process (Hassanat et al. 2019). This paper adopted the first approach and ran multiple simulations varying CRP and

MP in order to find the best values. As a result, the most optimal solutions for reducing heating and cooling loads were achieved when CRP and MP were set 0.75 and 0.10 respectively; thus, these values were selected for the final run of the algorithm. Regarding the population size; 100 was set for this feature that was ten times the number of dimensions (design variables) in the optimization, as recommended by previous studies (Chen et al. 2012; Chen, Montgomery, and Bolufé-Röhler 2015). The 'number of generations' is another important feature of the generic algorithm that is the number of cycles to be run prior to termination (Hassanat et al. 2019). For initial experiments, this feature was set to 180 generations in order to limit the computational time, and it was set to 200 for the final run of algorithms to create enough search space for the algorithm to find the optimal designs.

Optimisation objectives and design variables

The objectives set for minimization are heating and cooling loads since the NatHERS energy rating scheme only accounts for these parameters (NatHERS, Software Accreditation Protocol 2019). The simulation model has also been established via *EnergyPlus8.9,* a simulation engine integrated into DesignBuilder (DesignBuilder, EnergyPlus Simulation), which considers detailed interactions of all building components and systems such as building envelope, windows, HVAC, and internal heat gains from different systems in order to calculate energy consumption (DesignBuilder, EnergyPlus Simulation). *EnergyPlus* is among the few simulation engines with the capability of running whole-building simulations. It builds on the most popular features of BLAST and DOE-2, but also includes many innovative simulation capabilities such as time steps of less than an hour, modular systems and plant integrated with heat balance-based zone simulation, multi-zone airflow, thermal comfort, and PV systems (DesignBuilder, EnergyPlus Background Information).

The design variables inputted for optimization are tabulated in table 3 along with their respective values. These variables can be categorised into two groups; i) those that are attributed to the building's physical enclosure i.e., external and internal walls, roof, floor, ceiling, walls, external doors, glazing, and window frames. These variables affect both the thermal performance and embodied energy of the building. The values for these variables are given in U-values (W/m^2-K) that correspond to a particular construction detail defined for each variable. The second group contains variables with an impact limited to the thermal performance of the building, namely air infiltration and orientation. Regarding air infiltration, previous studies showed the average air change rate for Australian new buildings is around 15 ac/h@50Pa, while 10 and 25 ac/h@50Pa correspond to very well-sealed and poorly sealed envelopes respectively (Ambrose, and Syme 2017). Hence, the value range set for air infiltration was defined between 10 and 25 ac/h@50Pa with an increment of 1.0.

Table 3. Design variables considered for optimization

Design variables	Description	Unit	Range	Increment
X_1	Orientation	(º)	0-180	10.0
X_2	Infiltration	ac/h@50Pa	10 – 25	1.0
X_3	U-value of external walls	W/m^2-K	0.090 – 2.770	NA
X_4	U-value of floor	W/m^2-K	0.170 – 1.220	NA
X_5	U-value pitched roof	W/m^2-K	0.156 – 5.227	NA
X_6	U-value ceiling	W/m^2-K	0.036 – 1.499	NA
X_7	U-value of windows	W/m^2-K	2.169 – 6.700	NA
X_8	U-value of external doors	W/m^2-K	0.323 – 3.124	NA
X_9	U-value of window frame	W/m^2-K	3.476 – 5.881	NA
X_{10}	U-value of internal walls	W/m^2-K	0.332 – 2.632	NA

The optimization converged at 184th generation, where no further improvements on the heating and cooling loads were identified. This led to achieving over 4500 iterations (Figure 6). The results were then exported into *Excel spreadsheets* for further analysis. The next step was to eliminate iterations with thermal loads higher than 96.0 MJ/m^2 (26.67 kWh/m^2), so that a 6-Star rating, which is the minimum mandatory thermal requirement for Adelaide, would be achieved. This process resulted in 2,363 design configurations, in that each one represents a unique building design of a single-storey detached building. Afterward, the remaining iterations were star-rated based on their respective heating and cooling loads. As a result, each star band contained several cases with different building designs. The highest-rated building designs, based on the NatHERS rating scheme, obtained 8.7 stars whereas the lowest building designs yielded 6.0 stars.

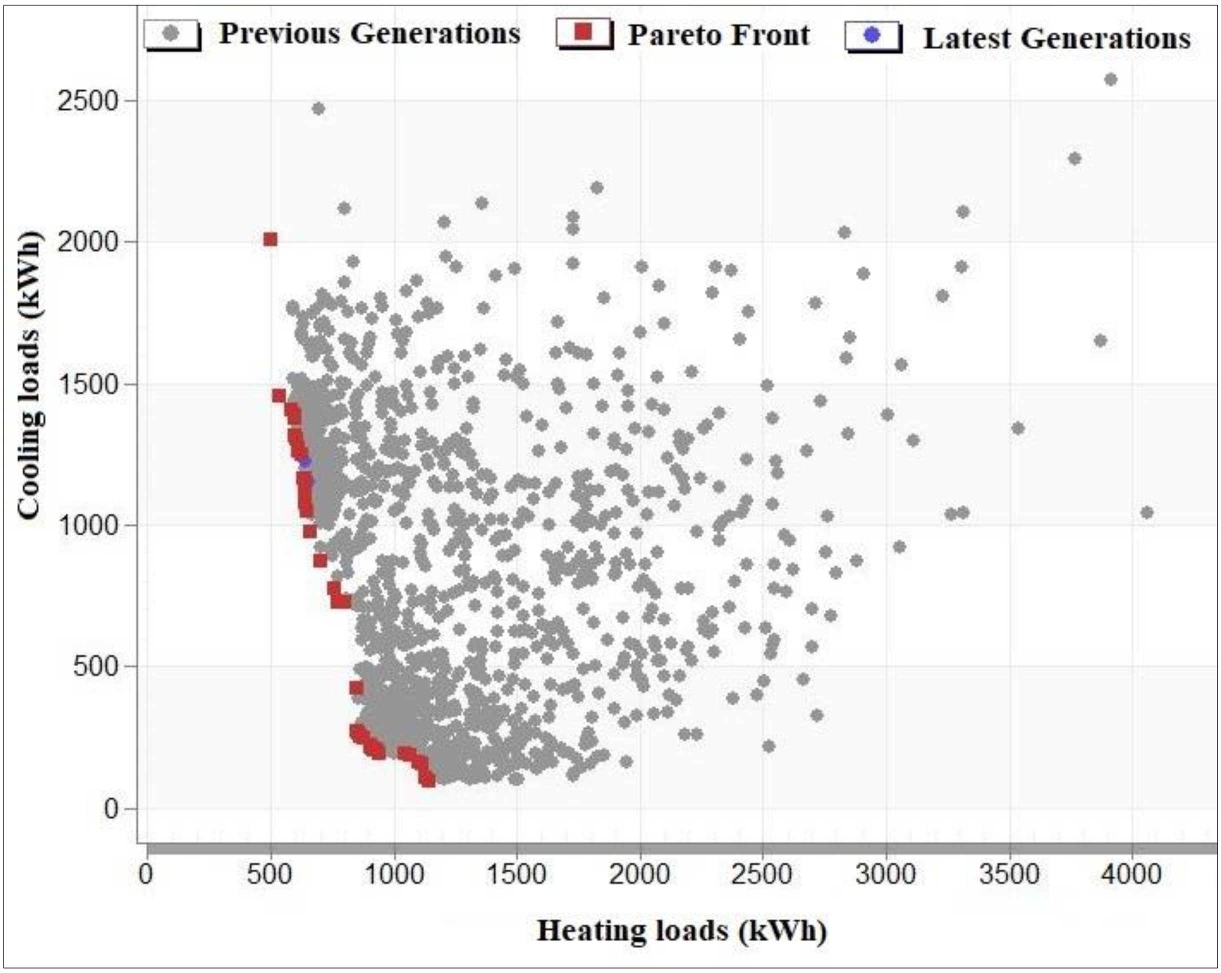

Figure 6. *Pareto* frontier achieved for optimization of heating and cooling loads

The next stage involved calculating the number of PV panels required for each building design to balance out heating and cooling energy. Since the fundamental objective of TLEB is to transition Australian residential buildings to zero energy buildings, this study assumed that all the cases have PV panels to negate their thermal energy demands. To this end, a common type of 220W PV system, with a size of 1.639m*0.982m and an efficiency rate of 80% was assumed to be employed by all the cases. The PV system was assumed to be oriented towards true North, with 30^o tilted. The average annual solar exposure in Adelaide was also considered to be 20.39 MJ/m^2 (Australian Government Bureau of Meteorology). In addition, the inverter efficiency was assumed at 8%. The aforementioned settings were applied for all the cases.

Analysis of embodied and operational energies

Quantification of materials was carried out using technical drawings of the building. Components considered for embodied energy analysis included external and internal walls, ceiling, roof, exterior doors, glazing and window frames, flooring construction (foundation and finishing materials), and PV panels. The embodied energy analysis of this study only accounted for the production and manufacturing of construction materials (i.e., initial embodied energy) (Figure 7).

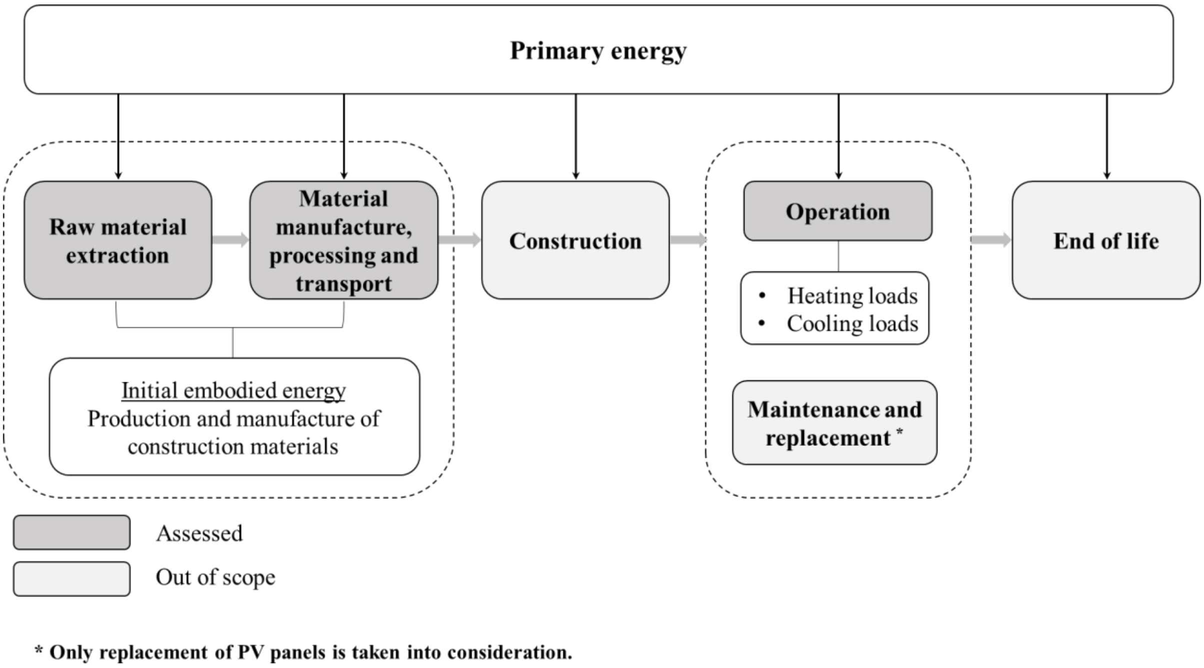

Figure 7. System boundary of the current study.

The end of life and construction stages were excluded due to their minor contributions to the total energy demands, as discovered by previous studies (Cabeza et al. 2014; Dahlstrøm et al. 2012; Crawford et al. 2016). In addition, this study only considered recurring embodied energy (replacement) relating to the PV panels. It is assumed that PV systems have a lifespan of 25 years, thus they are to be replaced once over a life service of 50 years. To quantify embodied energy, SimaPro software was applied using the AusLCI database Version 1.32-2020 as the background life cycle inventory database. The functional unit was also one square meter of gross floor area over a service lifetime of 50 years.

The assessment of operational energy has been carried out considering only heating and cooling loads of the cases. The thermal loads are converted into energy use for heating and cooling by applying the assumed COPs of the heating and cooling equipment (2.25 and 3.0 respectively). After this conversion, the primary energy is calculated using an electricity conversion factor of 3.40 (Stephan, Crawford, and De Myttenaere 2012) in order to capture a more holistic understating of overall energy consumption.

Results and discussion

The analysed cases are first star-rated based on their thermal performances using the NatHERS energy rating scheme. Then, the embodied impacts attributed to each case are superimposed in order to observe the significance of embodied energy. Table 4 presents total life cycle energy use (i.e., sums of thermal loads and embodied energy) of all the cases that are represented in Gigajoules (GJ) over a 50-year period.

Table 4. Total life cycle energy use of the analysed cases (GJ)

Star-rating	Total life cycle energy use*		Embodied energy% (Min.)	Embodied energy% (Max.)
	Min.	Max.	Min.	Max.
6.0	**1,267.96**	**1,843.69**	**19.99**	**39.90**
6.1	1,227.22	1,800.60	20.57	46.52
6.2	1,177.34	1,788.91	21.98	47.92
6.3	1,165.44	1,720.14	22.90	48.36
6.4	1,158.06	1,709.63	23.04	49.06
6.5	**1,137.07**	**1,766.26**	**22.98**	**51.72**
6.6	1,090.71	1,720.69	23.15	51.78
6.7	1,070.62	1,696.27	23.92	52.33
6.8	1,052.10	1,643.68	24.10	53.11
6.9	1,049.01	1,359.18	25.35	53.92
7.0	**993.22**	**1,563.50**	**26.09**	**54.89**
7.1	980.13	1,554.24	27.95	55.27
7.2	940.95	1,538.65	28.47	56.98
7.3	899.28	1,524.15	29.21	57.39
7.4	881.23	1,512.43	29.47	58.44
7.5	**857.85**	**1,497.27**	**30.06**	**60.04**
7.6	844.53	1,460.31	30.63	61.01
7.7	804.61	1,433.95	32.34	61.61
7.8	783.65	1,360.49	34.30	64.35
7.9	753.61	1,346.37	34.46	64.54
8.0	**737.88**	**1,370.38**	**36.83**	**69.11**
8.1	703.13	1,311.35	37.34	69.93
8.2	671.27	1,279.99	40.53	70.51
8.3	659.05	1,267.81	41.78	72.29
8.4	644.22	1,239.82	43.15	73.92
8.5	**623.21**	**1,185.37**	**47.73**	**74.33**
8.6	600.86	1,171.68	48.75	74.68
8.7	**592.73**	**1,172.66**	**50.47**	**74.75**

Total life cycle energy use presents the sums of total energy use (i.e., heating and cooling) and embodied energy over a 50-year period.

As shown in Table 4, the improvement of buildings' thermal performance in accordance with the NatHERS energy rating scheme can lead to an overall reduction in total life cycle energy use. However, the embodied energy becomes dominating as the buildings' energy efficiency increases. For instance, the transition from 6.0 stars to 6.5 and 7.0 stars, which is in line with the agenda of TLEB can decrease the total life cycle energy demands by 4-10% and 15-22%, respectively. Nevertheless, this transition results in increasing the share of embodied energy by 23-52% for 6.5 stars and 26-55% for 7.0 stars. Likewise, the comparison of 6.0 stars with 8.7 stars attests to the significance of embodied energy in buildings with higher energy efficiency. It can be seen that improving buildings' thermal performance from 6.0 stars to 8.7 stars leads to reducing buildings' total energy use by 36-53%, whereas embodied energies associated with these bands increase from 20-40% to 50-75%. These findings reaffirm the results of retrospective studies in regards to the significance of embodied energy in the Australian residential buildings (Crawford et al. 2016; Crawford and Stephan 2013; Stephan and Crawford 2014; Stephan, Crawford, and De Myttenaere 2013b; Crawford 2014; Stephan, Crawford, and De Myttenaere 2012). For instance, Crawford (2014) analysed the life cycle energy consumption of a typical detached residential building in Melbourne, Australia. The results indicated that embodied energy including initial and recurring embodied energy made up 59% of the total life cycle energy use of the building. In another research, Crawford and Stephan (2013) assessed the overall life cycle energy use of a residential building by accounting for operational energy, embodied energy (i.e., initial and recurring embodied energy), and transport energy. The results showed that the embodied, operational, and transport requirements represent comparable shares of the total at 32%, 37%, and 31%, respectively.

Table 5 also compares the thermal requirements specified by the NatHERS scheme for Adelaide with the total energy consumption calculated by this paper. It can be seen that the exclusion of embodied energy associated with each star band has resulted in underestimating the actual buildings' environmental impacts. For instance, a 6-star building can potentially use up to 51% more energy than the amount determined by the NatHERS scheme once the potential embodied impacts are considered. Similarly, an 8.7-star house, which is expected to consume less energy, may actually have the same as or even more environmental impacts than a 6.0-star house due to its high embodied energy.

Table 5. Comparison of NatHERS scheme with total energy loads (MJ/m^2.year)

Star-rating	Thermal requirements given by NatHERS	Total life cycle energy use*	
		Min.	Max.
6.0	96.0	133.57	194.23
6.5	83.0	119.79	186.07
7.0	70.0	104.63	164.71
7.5	58.0	90.37	157.73
8.0	46.0	77.73	144.36
8.5	33.0	65.65	124.87
8.7	28.60	62.44	123.54

Total life cycle energy use presents the sums of total energy use (i.e., heating and cooling) and embodied energy.

The findings of this study show that the reduction of operational energy should be addressed in parallel with abating embodied impacts; otherwise, energy consumption or GHG emissions shall be simply moved from one stage of the building life cycle to another without yielding an overall reduction. In this regard, policy can play a vital role in integrating the life cycle embodied environmental impacts into building energy efficiency regulations.

To date, only a limited number of countries have commenced incorporating embodied impacts into their building regulations. The Netherlands is the first country to introduce requirements for the measurement of embodied impacts, though not the reduction, into its building regulations (Building Decree 2012). According to section 5.2 of building decree 2012 (Building Decree 2012), the Dutch jurisdiction requires that the environmental impacts (i.e., GHG emissions and resource depletion) associated with the structural elements of a residential function or an office building with a total usable area exceeding 100 m^2 must be quantified. The enforcement of such a regulatory approach aims to stimulate the builders to utilise sustainable construction materials. However, no restriction has been applied by the Dutch building codes to the amounts of embodied energy associated with the used construction materials. Other countries have also taken their initial steps towards this end such as France (French Ministry of Environment Energy and the Sea), Finland (Kuittinen, and le Roux 2018), Norway (Norwegian Standard NS 3720: 2018), Denmark (Frivillig Baeredygtighetsklasse 2018; The Danish Government Strategy for the Circular Economy 2018), and Sweden (Boverket Klimatdeklaration Av Byggnader 2018). Switzerland also opts to implement the target of the ‘2000-Watt Society’, based on which primary energy use per person including embodied energy would be 2000 watts while limiting CO_2 emissions to no more than 1.0 ton of CO_2 equivalent per person per year by 2050 (Frischknecht et al. 2019).

Nevertheless, there are still many countries, including Australia that have been reluctant to recognise embodied energy as a part of their mandatory requirements for EERs. This is mainly attributed to the issues relating to the quantification of embodied energy, in which the varied approaches lead to displaying variations in the results of embodied energy analysis (Moncaster et al. 2019; Omrany et al. 2020a; Omrany et al. 2020b); despite existing several international standards such as ISO 21929-1 (ISO 21929-1 2011), ISO 21931-1 (ISO 21931-10 2010), and the European standards developed by Technical Committee TC350, including EN 15643-2 (EN 15978 2011) and EN 15978 (EN 15978 2011). This was first noted by Sartori and Hestnes (2007) through analysing 60 cases from 9 countries. More recent studies also highlighted the same issue and identified multiple reasons for such variations e.g. varied definitions of system boundary (i.e. physical and temporal), the use of different methods, buildings' geographic locations, data quality, or manufacturing technology (Omrany et al. 2020a; Omrany et al. 2020b; Pomponi, and Moncaster 2016; Dixit 2017; Anand, and Amor 2017; Hossain, and Ng 2018; Rasmussen et al. 2018). In a study, Moncaster et al. (2018) identified three major categories that contribute to varying results in embodied energy analysis, namely 'temporal differences in the stages considered'; 'spatial differences in the material boundaries'; and 'physical disparities in the data coefficients'.

Apart from the technical issues, there has been a misconception about the significance of embodied energy as to which factors other than operational energy constitute a negligible portion of the total environmental performance of buildings (Ramesh, Prakash, and Shukla 2010; Karimpour et al. 2014); thus, they can be neglected. These challenges have collectively discouraged policymakers from considering embodied impacts as a requirement for energy efficiency.

Proposals for incorporation of embodied energy

This section aims to bring forward proposals for the integration of embodied impacts with the Australian EERs. This study suggests establishing minimum mandatory requirements (energy budget) for 'embodied performance' of new and retrofitted buildings, similar to the current NatHERS scheme. This approach promotes considerations for maximum reduction of embodied impacts at the earliest design stage. In this regard, the main challenge is to establish standardized boundary conditions in terms of physical and temporal boundaries that can be applied by one Australian climate zone.

The temporal system boundary refers to determining which building life cycle stage is included for the assessment. While it is recommended to account for impacts of all life cycle stages, this study suggests that "cradle to gate" (i.e., initial embodied energy) should be considered as the minimum mandatory requirement for assessment of embodied impacts at the building level (Figure 8). The initial embodied energy plays a significant role in emitting GHGs into the atmosphere since they are mainly produced by burning fossil fuels (Crawford et al. 2016). It is also widely accepted that initial embodied energy constitutes a high percentage of total embodied energy use (Crawford et al. 2016; Stephan, Crawford, and De Myttenaere 2013a; Omrany et al. 2020a; Omrany et al. 2020b; Zhan et al. 2018; Stephan, and Stephan 2014); therefore, taking the impacts of this stage into consideration can capture a significant portion of the total embodied energy use of buildings. For instance, Zhan et al. (2018) endeavoured to calculate the energy consumption of a residential building in Guangzhou, China. The results showed that initial embodied energy made up 85% of the total building's embodied energy use. Similarly, Stephan and Stephan (2014) performed a comprehensive analysis to quantify the life cycle energy performance of a residential building in Lebanon. The results revealed that initial embodied energy represents 69% of the total life cycle embodied energy of the case study.

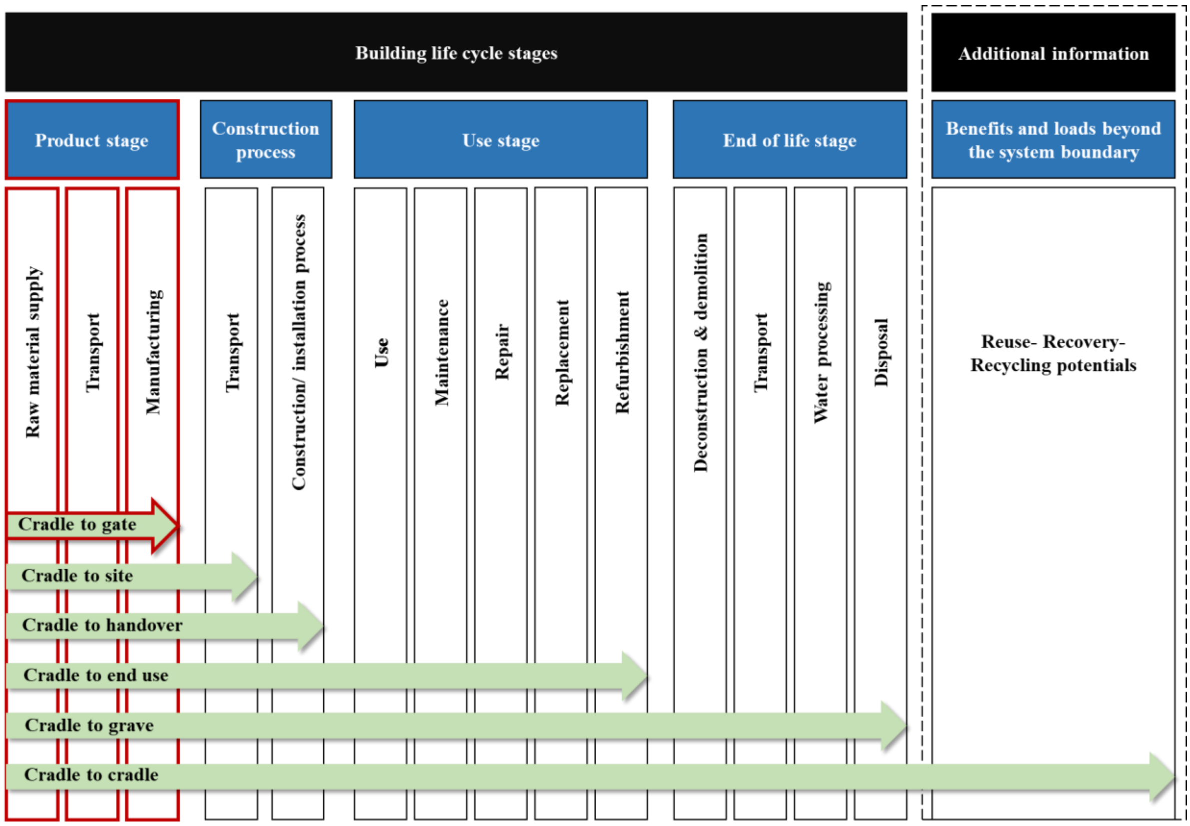

Figure 8. Proposed model for description of system boundary (modular structure adapted from EN 15978:2011 (EN 15978 2011).

Additionally, the majority of current LCA databases contain initial embodied impacts of building materials that are calculated based on energy inputs from the entire structure of an economy; thus, the impacts of this stage can be taken into consideration regardless of buildings' locations.

Physical system boundary refers to determining which building components need to be included in the assessment. This study suggests a checklist that can be considered as the minimum requirements for delineating physical system boundaries (Table 6). The recommended components are mainly attributed to physical enclosure of buildings. The inclusion of embodied impacts associated with renewable energy systems is also suggested, in the case of zero energy buildings. While recommending to include embodied impacts of other components (e.g. furniture, heating and cooling systems and etc.), considering their impacts by EERs may lead to incomparability since the choice of using these elements depends on a wide variety of factors, e.g. occupants' taste that cannot be predicted at the design stage.

Table 6. Recommended approach for delineation of physical system boundary

Building components	**Building sub-components**	**Recommended for inclusion**
Substructure	Foundation	▲
	Basement retaining walls	▲
	Ground floor	▲
Superstructure	Structural building frame	▲
	Exterior walls	▲
	Exterior doors	▲
	Window glazing	▲
	Interior walls	▲
	Floor construction	▲
	Ceiling construction	▲
	Roof construction	▲
	Stairs and ramps	▲
Renewable energy system	Photovoltaic panels; solar collectors; wind turbines; and etc.	▲
Building services	Water system	
	Sewage system	
	Heating system	
	Cooling system	
	Ventilation system	
	Electrical system	
	Conveying systems	
	Fire protection system	
Finishes	External finishes	
	Internal finishes	
	Fixed furniture	
	Furniture	
External	Balcony	▲
	Vegetation	
	Pavement	

The recommended approaches for standardization of system boundaries should be accompanied by developing embodied energy databases for materials so that designers can readily link their designs with material quantities to carry out embodied energy estimations. It is also important that the environmental product declarations (International Standard 14025/TR: Environmental labels and declarations 2006) for building materials would be enforced in Australia to provide up-to-date quantified environmental data relating to construction materials. A similar approach is being practiced by Dutch jurisdictions in which a national database (Nationale Milieudatabase) is developed containing different categories of products' environmental data (National Environmental Database). The database subjects to a periodic update every 5 years. Several accredited software are also developed to calculate the environmental performance of buildings based on the data of national database (National Environmental Database).

Limitations and future research

The current study suffers from a number of limitations that need to be highlighted. First, it only considers thermal loads (heating and cooling) for the assessment of building's operational energy and excludes non-thermal loads such as hot water, lighting, and electrical appliances. This is done to reflect on the limited assessment scope of the current regulatory scheme in Australia. However, non-thermal loads can be significant in consuming energy, especially in low energy and zero energy buildings. The statistics show that an average Australian dwelling consumes energy for the following purposes: heating and cooling (40%), water heating (23%), electrical appliances (e.g., laundry appliances or entertainment appliances) (14%), fridges and freezers (8%), lighting (7%), cooking (5%), and standby power (3%) (Home energy use in Australian house 2019). The findings of previous studies also affirm the significance of non-thermal parameters in consuming energy (Stephan, Crawford, and Myttenaere 2013b; Stephan, Crawford, and Myttenaere 2012). For instance, Stephan, Crawford, and Myttenaere (2013b) analysed life cycle energy and GHG emissions of detached houses in suburban Melbourne, Australia. The analysis showed that heating and cooling constituted 33.3% of total operational energy, while appliances used 47.7% followed by lighting (10.5%), hot water (4.7%), and cooking (3.9%). This limitation can be addressed by future research through considering both thermal and non-thermal loads. Furthermore, the assessment of thermal loads was carried out assuming that the occupational settings (e.g., scheduling and occupancy profile) would remain unchanged over the period of 50 years. The results can be widely affected due to varying occupational settings (e.g., scheduling and occupancy profile).

This study has proposed developing energy budgets for embodied energy performance of new and retrofitted buildings in Australia. The implementation of such an approach requires a thorough consideration of climate impacts on both embodied and operational energies. Studies showed that buildings' life cycle energy demands can be influenced by climatic conditions (Omrany et al. 2020a; Omrany et al. 2020b; Lawania and Biswas 2018). In a study, Lawania and Biswas (2018) endeavoured to design low-carbon houses with the consideration of climate impacts on embodied and operational energies across 18 regional locations in Western Australia. They selected a typical clay brick detached house, and employed Accurate and SimaPro software to calculate operational and embodied energies associated with the building respectively. The results showed that the total life cycle GHG emissions and embodied energy of the houses varied across the 18 selected locations depending on the climate zone of each region. In the end, Lawania and Biswas (2018) recommended a number of strategies that can effectively lead to reducing embodied GHG emissions and embodied energy consumption in Western Australia. The scope of current study is limited to only one climate, i.e., Adelaide, climate zone 16. Future research can expand the current scope to further investigate the effects of climate on embodied energy budgets for each Australian climate zone.

In addition, previous studies pointed out the difference between high-rise and low-rise buildings in terms of their attributed initial embodied energy use (Wang, Yu, and Pan 2018; Luo, Yang, and Liu 2016; Du et al. 2015). Wang, Yu, and Pan (2018) investigated the life cycle energy use of ten real-life buildings in Hong Kong, and reported that initial embodied energy usage of high-rise buildings was twice of low-rise ones. Du et al. (2015) also reviewed 42 case buildings, and conclusively stated that high-rise buildings had almost 50% more embodied energy compared to low-rise buildings. Treloar et al. (2001) highlighted even a larger difference, stating that high-rise buildings may have approximately 60% more initial embodied energy per unit gross floor area than low-rise buildings. The higher embodied energy of high-rise buildings can be related to i) using more materials, and ii) using materials with higher energy intensity, e.g., concrete and steel (Wang, Yu, and Pan 2018). The scope of this paper is limited to low-rise buildings (i.e., single-storey detached residential building); therefore, it is expected that variations in building classification will lead to different results. Information regarding building classifications in Australia can be found in (Building Codes of Australia). Thus, the full development of embodied energy budgets requires further analyses of embodied energy associated with different building types.

This study employed the AusLCI database to quantify the embodied impacts of building materials. This database is developed based on the economic input-output method. Although this method improves the incomplete system boundary definition in the process-based method, it still suffers from a lack of product-specific data. Previous studies showed that using a hybrid analysis method for analysing embodied energy can result in much higher values compared to other methods (Stephan, and Stephan 2014; Crawford 2011). Moreover, this research has not studied the relation between building size and embodied energy. The size of a building can directly influence its associated embodied energy use by affecting the quantity of materials needed for its construction. Large buildings inherently consume more embodied energy compared to smaller buildings; however, using the current metrics (e.g., gross, or usable floor area per square meter) to report life cycle energy use of buildings can misrepresent the fact that larger dwellings have more embodied energy. This is echoed in the findings of Stephan and Crawford (2016) that investigated the life cycle energy demands of 90 house sizes and four household sizes for a typical detached house in Melbourne, Australia. The results showed that the life cycle energy demand increased at a slower rate compared to house size; thus, using 'per m^2' to express energy efficiency can favour large houses even though they require more energy.

Conclusions

Over the last decades, Australia has taken several measures to tackle the increasing trend of energy use in residential buildings. In one of the latest attempts, the *Trajectory for Low Energy Buildings* has been endorsed aiming to reduce energy usage in residential buildings by supporting the concept of zero energy building in Australia. This trajectory targets to increase minimum mandatory thermal requirements for new residential buildings in 2022 and 2025. However, the primary focus is given to the reduction of operational energy while excluding the impacts of embodied energy. Therefore, this study aimed to address one primary question; 'can the continued exclusion of embodied energy from the energy efficiency regulations effectively lead to reducing energy consumption in Australian residential buildings?'. The findings indicate that the increase of buildings' thermal performance following the increase of star bands can bring an overall reduction of buildings' energy usage. However, the embodied energy becomes dominating as the star rating increases. It is shown that the transition from 6.0 stars to 6.5 and 7.0 stars can result in reducing the total life cycle energy demands by 4-10% and 15-22%, respectively. Nevertheless, this transition increases embodied energy proportions by 23-

52% for 6.5 stars and 26-55% for 7.0 stars. Moreover, the results showed that moving from a standard 6.0 stars building to a highly energy-efficient building of 8.7 stars can result in increasing embodied energy from 20-40% to 50-75%. The findings also point out the necessity of considering the reduction of embodied energy in parallel to operational energy as the limited focus given only to decreasing operational energy may lead to misrepresenting the actual buildings' environmental impacts.

This study suggests that the Australian energy efficiency regulations should introduce minimum mandatory requirements for the 'embodied performance' of new and retrofitted buildings. This approach can potentially promote considerations for maximum reduction of embodied impacts at the earliest design stages. However, the main challenge resides with establishing standardised boundary conditions (i.e., physical and temporal) that can be applied by one Australian climate zone. Recommendations are given in order to standardise boundary conditions for integrating embodied energy with energy efficiency regulations. It is suggested that initial embodied energy should be determined as the minimum mandatory requirements for assessment of embodied impacts at the building level. In terms of the physical system boundaries, this study suggests a detailed checklist that can be considered as the minimum compulsory requirement for assessment of buildings' embodied impacts.

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Chapter 6. Towards incorporation of embodied energy into building codes: proposals for standardisation of system boundary definition

6.1 Introduction

The significance of embodied energy impacts correlated to the current building energy efficiency regulations (BEERs) has been shown in previous chapter. It has become evident that the increase of energy efficiency in the building sector with the sole focus given to minimizing operational energy fails to yield a reduction in total energy consumption. This highlights an agenda for future development of policies in the building sector to account for the total building environmental impacts by considering measures to reduce both embodied and operational energies. Chapters 3 and 4 of this study have identified the main sources of variations in life cycle energy assessment (LCEA) that need to be regulated when planning to extend the coverage of current BEERs to incorporate the embodied energy impacts. This chapter aims to utilise the findings of previous chapters, namely chapters 3 and 4 to formulate a standard framework for defining system boundary conditions in LCEA. The findings of this chapter will provide such a framework while demonstrating its applicability by analysing case studies.

6.2 List of manuscripts

This part of the research has been produced as a journal article, published in the journal of *Buildings.*

Omrany, H., Soebarto, V., Zuo, J., & Chang, R. (2021). A Comprehensive Framework for Standardising System Boundary Definition in Life Cycle Energy Assessments. Buildings, 11(6), 230. DOI: https://doi.org/10.3390/buildings11060230.

The paper is presented here in a reformatted version for consistency of the thesis presentation. The accepted manuscript can be found in Appendix IV.

Statement of Authorship

Title of Paper	A Comprehensive Framework for Standardising System Boundary Definition in Life Cycle Energy Assessments
Publication Status	☑ Published ☐ Accepted for Publication ☐ Submitted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details	Omrany, Hossein, Veronica Soebarto, Jian Zuo, and Ruidong Chang. "A Comprehensive Framework for Standardising System Boundary Definition in Life Cycle Energy Assessments." Buildings 11, no. 6 (2021): 230. DOI: https://doi.org/10.3390/buildings11060230.

Principal Author

Name of Principal Author (Candidate)	Hossein Omrany		
Contribution to the Paper	Conceptualization, methodology, software, data analysis, and writing—original draft preparation.		
Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	15/08/2021

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Veronica Soebarto		
Contribution to the Paper	Methodology, review & editting, supervision.		
Signature	Professor Veronica Soebarto Digitally signed by Professor Veronica Soebarto DN: cn=Professor Veronica Soebarto, o=The University of Adelaide, ou=School of Architecture and Built Environment, email=veronica.soebarto@adelaide.edu.au, c=US Date: 2021.09.21 16:14:06 +09'30'	Date	21/09/2021

Name of Co-Author	Jian Zuo		
Contribution to the Paper	Review and supervision.		
Signature		Date	12/9/2021

Please cut and paste additional co-author panels here as required.

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Ruidong Chang		
Contribution to the Paper	Review and supervision.		
Signature		Date	14/09/2021

Name of Co-Author			
Contribution to the Paper			
Signature		Date	

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6.3 A Comprehensive Framework for Standardising System Boundary Definition in Life Cycle Energy Assessments

Abstract: This paper aims to propose a comprehensive framework for a clear description of system boundary conditions in life cycle energy assessment (LCEA) analysis in order to promote the incorporation of embodied energy impacts into building energy-efficiency regulations (BEERs). The proposed framework was developed based on an extensive review of 66 studies representing 243 case studies in over 15 countries. The framework consists of six distinctive dimensions, i.e., temporal, physical, methodological, hypothetical, spatial, and functional. These dimensions encapsulate 15 components collectively. The proposed framework possesses two key characteristics; first, its application facilitates defining the conditions of a system boundary within a transparent context. This consequently leads to increasing reliability of obtained LCEA results for decision-making purposes since any particular conditions (e.g., truncation or assumption) considered in establishing the boundaries of a system under study can be revealed. Second, the use of a framework can also provide a meaningful basis for cross comparing cases within a global context. This characteristic can further result in identifying best practices for the design of buildings with low life cycle energy use performance. Furthermore, this paper applies the proposed framework to analyse the LCEA performance of a case study in Adelaide, Australia. Thereafter, the framework is utilised to cross compare the achieved LCEA results with a case study retrieved from literature in order to demonstrate the framework's capacity for cross comparison. The results indicate the capability of the framework for maintaining transparency in establishing a system boundary in an LCEA analysis, as well as a standardised basis for cross comparing cases. This study also offers recommendations for policy makers in the building sector to incorporate embodied energy into BEERs.

Keywords: embodied energy; operational energy; net-zero energy building; energy efficiency; conceptual framework.

1. Introduction

High-performance buildings have gained momentum over the recent decades owing to their capacity to curb dependency on fossil fuels [1–4]. These buildings are principally constructed to minimise annual operational energy use so that they can achieve net-zero energy (and carbon) usage by integrating on-site renewable or decarbonised energy systems with the buildings [5]. Thus far, this concept has been introduced into the built environment through two general approaches [1]. The first approach is mainly voluntary, aiming to realise highly energy-efficient buildings by embracing green certification programs. Examples of this approach include Passivhaus in Germany [6], green buildings in Australia [7], and Minergie standard in Switzerland [8]. The second approach is a gradual process by which the performance thresholds to achieve energy-efficient buildings (e.g., nearly-zero energy buildings (NZEBs) or net-zero energy buildings) are progressively increased over time through mandatory building codes. In this approach, building energy-efficiency regulations (BEERs) play a vital role in fulfilling the attainment of high-performance buildings. An example of this approach is the Australian energy-efficiency regulations that aim to achieve zero energy (and carbon)-ready buildings by 2030 through increasing the mandatory thermal performance requirements for new buildings [9].

Nevertheless, previous studies have shown that the implementation of BEERs may lead to increasing the total environmental impacts of buildings due to their limited scopes to account for the impacts of embodied energy [10–12]. For instance, Omrany et al. [12] analysed the effects of enhancing a building's thermal efficiency on embodied energy. To carry out the study, the thermal performance of a residential building constructed in accordance with minimum mandatory requirements of Australia (i.e., 6-star building) was gradually increased to achieve high-performing buildings. The results showed that the share of embodied energy in total life cycle energy consumption increased from 20–40% to 50–75% in transitioning from a standard 6-star building to a highly energy-efficient building. In another study, Stephan et al. [10] analysed the total life cycle energy performance of a passive house located in Belgium and realised that the building's embodied energy constituted up to 77% of the total life cycle energy consumption. It was conclusively stated that the adoption of current energy-efficiency regulatory schemes may not necessarily result in minimising the overall life cycle energy use of buildings owing to the exclusion of embodied energy.

In recent years, literature has witnessed a growing body of research developed to demonstrate the significance of embodied energy attributed to buildings with high energy-efficiency performance. However, this surge of research has been unable to alter the mindset of policy makers about the necessity of abating buildings' embodied impacts when planning for enhancement of sustainability in the built environment [13]. Many studies have attempted to encourage the incorporation of embodied energy into BEERs by increasing the accuracy of embodied energy calculation methods [14–17]; investigating challenges for inclusion of embodied energy into BEERs from the perspectives of building professionals [18,19]; or integrating building information modelling techniques with the life cycle assessment (LCA) approach and building codes [20,21]. Despite increasing attention, the pathway for including the impacts of embodied energy into BEERs is still ambiguous. The chief reason for such an ambiguity resides with the complexity that BEERs encounter in accounting for the impacts of both operational and embodied energies due to various processes and parameters involved.

To address this challenge, the development of a comprehensive framework for a clear description of system boundaries can pave the way towards integrating the life cycle embodied environmental impacts into BEERs. Currently, the literature is lacking such a comprehensive framework. This lack is reflected in the findings of recent studies that reported variations in the results of life cycle energy assessment (LCEA) analyses [22–26]. In a recent study, Pan and Teng [26] conducted a holistic literature review analysis of 244 case studies, aiming to quantify potential variations in embodied energy calculations. The results showed that significant variations may stem from the choice of method for embodied energy assessment, i.e., a 200% increase from process-based to hybrid method. In addition, the varied approaches of studies to account for the effects of parameters influencing the assessments of embodied and operational energy can be critical in varying LCEA results [23, 24]. For instance, Pan and Teng [26] found that unclear descriptions of system boundaries for including cradle-to-gate and cradle-to-end of construction embodied energy may cause a 9.2% variation in the achieved results. Retrospective research showed that the primary cause of these variations relates to the subjective delineation of system boundaries in LCEA or LCA analyses [27–29], despite several international standards and frameworks that have been developed towards this end, such as ISO14040:2006 [30] or the European frameworks developed by Technical Committee TC350, e.g., EN 15978:2011 [31]. The subjectivity in defining system boundaries can potentially compromise the quality and reliability of obtained results for decision-making purposes while limiting the possibility for cross comparing LCEA cases.

With the motivation outlined above, this study aims to propose a structured framework through which the system boundaries in LCEA research can be explicitly defined. The framework proposed by this paper defines system boundaries within six distinctive dimensions, facilitating the possibility for policy makers to set requirements for incorporation of embodied impacts into BEERs at national or regional levels. This framework is also expected to assist with exploring the relative body of research that can lead to broadening our understanding of building energy performance within a global context by comparing LCEA cases. The remainder of this paper unfolds as: first, the research theoretical background is explained in Section 2 in order to provide an overview of the life cycle energy assessment approach, embodied energy, and operational energy. Section 2 also provides a review of previous studies aimed at developing a framework for standardisation of system boundary definition. Section 3 elaborates on the methodological approach of the research. Different dimensions of the proposed framework are then explained in Section 4. The implementation of the proposed framework is described in Section 5, before the discussion and conclusion in Sections 6 and 7, respectively.

2. Theoretical Background

2.1. An Overview of LCEA

The LCA is a quantitative approach to measure environmental burdens associated with processes, products, or services over their life cycles [32]. The International Organization for Standardization (ISO) introduced a framework to perform LCA analysis [33]. This framework consists of four primary steps, including (1) setting the goals and scope, (2) life cycle inventory (LCI), (3) life cycle impact assessment (LCIA), and (4) interpretation. The first step requires setting the overall goals and scope of the project along with establishing system boundaries and determining the inventory data quality requirements. The LCI is the next step whereby the process for obtaining and collating data of energy flows at each stage of a product's life cycle should be determined. This is followed by LCIA, where the environmental impacts correlated with materials and energy flows are quantified and assigned to their respective environmental impact categories. At the interpretation step, the obtained LCA results are interpreted with respect to the defined goals and scope of the research, and recommendations are issued accordingly.

LCEA is a version of the LCA that only accounts for energy usage at all stages of a building's life cycle [6, 24]. In this approach, the total energy performance of a building is quantitatively assessed considering both operational and embodied energies. Embodied energy is the amount of energy consumed at the upstream and downstream stages of the building's life cycle, including production of building materials (known as initial embodied energy), building construction, maintenance, and replacement (also known as recurrent embodied energy), end-of-life (EOL) processes, and transportation between any of these steps [23,24,32]. The operational energy refers to the amounts of energy used in the forms of thermal (i.e., heating and cooling) and non-thermal (i.e., domestic hot water (DHW), electrical appliances and equipment, ventilation, lighting, and cooking) energy over the life cycle of a building [23,24,32]. The scope of this study is limited to LCEA analysis; however, the final outcome can also be applicable to LCA research.

2.2. Previous Research on Developing Frameworks for System Boundaries

In the wider literature, a system boundary is defined in different ways. In the general system theory, Bertalanffy [8] defined a system boundary as an interaction interface whereby material, energy, or information is transferred in or out of the system. In societal system theory, this concept is described as barriers that differentiate a system from others in the environment through its spatial and temporal boundaries, any surrounding environmental affects characterised by its structure and purpose and expressed in its functionality [34]. In a narrower scope, a system boundary is defined by the ISO as a number of criteria that determine the inclusion of unit processes into a product system [33].

The absence of a standardised framework for defining system boundaries is commonly considered as a principal contributor to varying LCEA results [24, 25, 28, 35–39]. This was first noted by Sartori and Hestnes [40] through analysing 60 cases from nine countries. Recent studies have also attested to the key role of system boundary definition in deriving variations and identified multiple reasons for such phenomena, e.g., varied definitions of physical and temporal boundaries; the use of different methods for measuring embodied and operational energies; buildings' geographic locations, data source, and data quality; or manufacturing technology [23, 24, 27, 29, 40]. For instance, Moncaster et al. [29] identified three major categories that contribute to varying results in embodied energy analysis, namely "temporal differences in the stages considered"; "spatial differences in the material boundaries"; and "physical disparities in the data coefficients".

Despite the significance of a system boundary in determining the quality of LCEA results, a limited number of studies have been undertaken to standardise system boundary definition. Hammond and Jones [41] introduced a four-level regression model for the description of a system boundary. The first level accounts for all of the energy inputs used directly during processes such as construction, prefabrication, maintenance, replacement, demolition, and disposal in order to produce a product. The second level of the regression model promotes the inclusion of energy consumption sequestered into main and all upstream and downstream processes of materials and product manufacturing. The third level captures the amounts of energy use embedded in the production, delivery, and installation of machines that are utilised to manufacture materials, as well as on- and off-site construction processes. The final level represents the amount of energy expelled during the main, upstream, and downstream production processes of manufacturing machinery that in turn produces the machine (of third level regression). Although the proposed model endeavours to disentangle the energy inputs used at each stage of a building's life cycle, it still fails to capture other flows of data requirements for the environmental assessment of a building. Likewise, Fay [42] presented the same ideas about defining system boundary conditions that are composed of multiple levels. A similar boundary condition was also demonstrated by Herendeen [43] through analysing the life cycle energy use of car production. The results showed that 90% of the energy is consumed during processes of producing constituents of car materials such as steel, plastic, glass, etc., whereas only 10% of energy consumption relates to car manufacturing plants.

Dixit et al. [28] also proposed a conceptual framework based on performing a comprehensive literature review and synthesising relevant literature opinions on system boundary definition. The proposed framework primarily aimed to elaborate on the temporal and physical boundaries of a system under research. The study was concluded by recommending several measures that enable conducting the LCEA of a building. Stephan et al. [39] presented a comprehensive framework of a system boundary to capture the energy requirements at both building and urban scales. The framework accounts for operational and embodied energy usage of buildings, as well as embodied impacts related to nearby infrastructures and the occupants' transport energy. Although the framework promotes the integration of energy flows between embodied, operational, and transport requirements, it does not provide tailored data requirements for different dimensions of system boundaries. In another study, Pan [44] proposed a theoretical framework to assist multi-criteria decision making in selecting off-site construction technologies. The framework captures four aspects of system boundaries, namely, ontology, epistemology, methodology, and axiology. Pan's framework enables the theoretical investigation of system boundaries defined in previous studies of LCA and carbon emissions. Later on, Pan [37] developed a conceptual model that consists of eight boundaries including "the policy timeframe, building lifecycle, geographic, climatic, stakeholder, sector, density, and institutional boundaries". This framework provides the possibility of cross comparing different cases within a harmonised context. Despite the great details provided, the life cycle boundary of the framework only elaborates on the temporal dimension of the system boundary without providing detailed information on other facets.

The frameworks developed by the reviewed studies fall short of capturing all the dimensions involved in defining system boundaries. The majority aimed at simplifying the temporal and physical dimensions, and only the study by Pan [37] elaborated on aspects such as building geography, stakeholders, or the relative sector. This highlights the need for a much more comprehensive framework when aiming for the incorporation of embodied impacts into BEERs. The comprehensiveness of such a framework can assist policy makers to set certain requirements and standards for each dimension of the framework at national or regional scales.

3. Methodology

The overall methodological approach of this paper consists of three stages. The first stage involves the identification of variables that contribute to variations in LCEA results. Previous studies have examined a number of parameters with potential influence on the LCEA results, such as data quality, functional units, or calculation methods [27, 45]. However, the identified parameters reported in the existing literature were limited and sporadically sorted without any systematic understanding. Hence, comprehensive searching exercises were conducted throughout various scholarly databases, namely, Web of Science, ProQuest, and Scopus, in order to retrieve studies related to the LCEA approach. The literature review approach was a systematic approach; thus, certain limitations were considered. First, the scope of these literature analyses was limited to only residential buildings. Second, only studies that assessed the life cycle energy performance of residential buildings using primary energy were considered for detailed examinations. Despite the limitations considered, the literature review surveys managed to identify 66 LCEA research projects representing 243 case studies in over 15 countries. The findings of the literature review analysis were reported in [23, 24]. Thereafter, the approaches of the identified studies to defining system boundary conditions in LCEA research were analysed in depth. The findings identified 12 major parameters attributed to different aspects of LCEA methodology that potentially result in varying outcomes. These parameters were further grouped into the following four categories: "system boundary definition", "calculation methods", "geographical context", and "interpretation of results". Detailed discussion of the findings of the literature review analyses is beyond the scope of this paper; thus, readers are encouraged to refer to [23, 24] for further details.

The second stage involves developing a comprehensive framework to standardise system boundary conditions in LCEA research using the parameters identified by analysing the literature. Figure 1 illustrates the development process of the proposed framework that began with (i) reviewing the literature where parameters causing the variations in LCEA results were singled out [23, 24], (ii) consolidating the identified variables into six distinguished dimensions, and (iii) allocating each variable to its respective dimension. Since the scope of the literature review was limited to residential buildings, this paper also proposes consideration of "building types" and "building density" (i.e., number of storeys) as distinctive dimensions of a system boundary in LCEA analysis. Section 4 will further elaborate on each dimension of the framework.

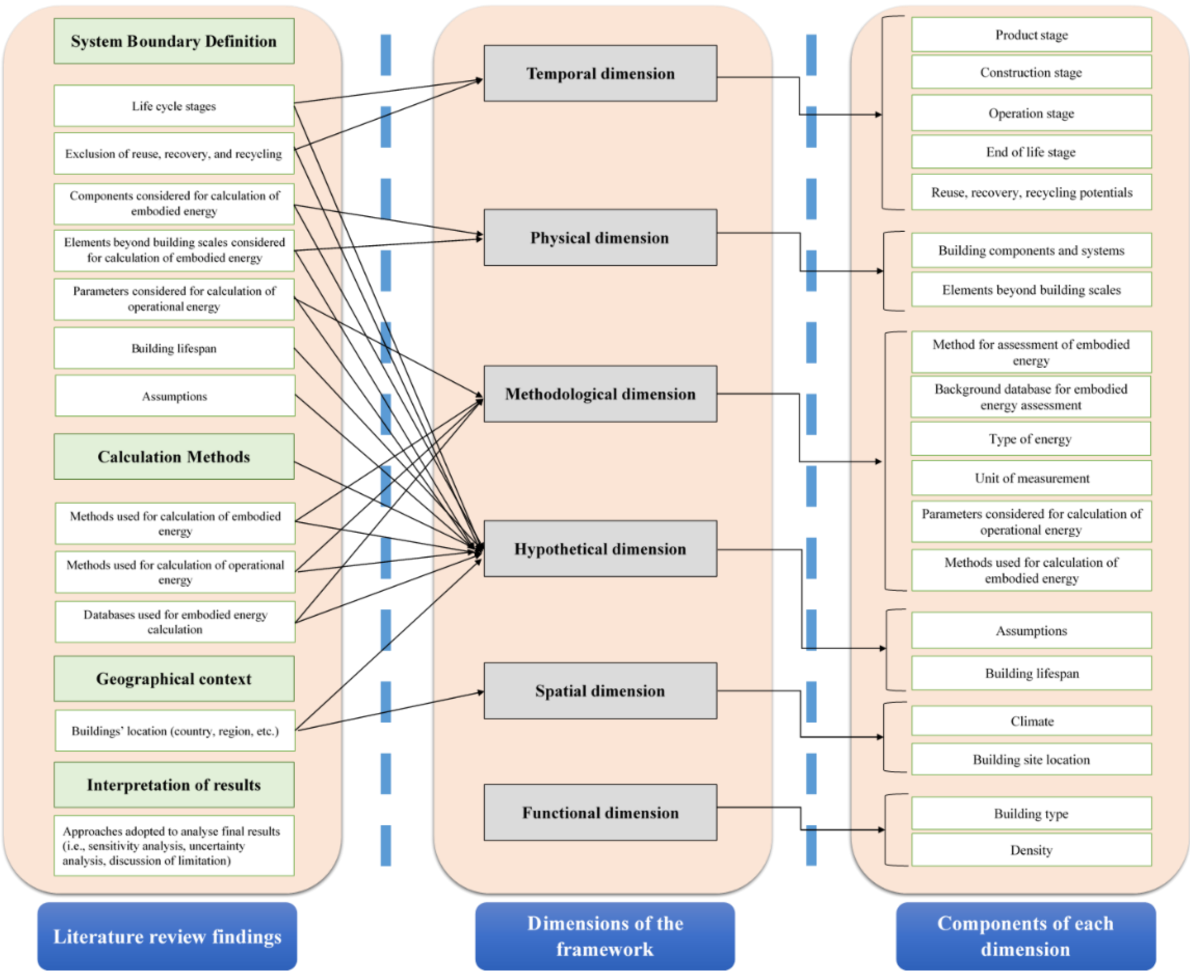


Figure 1. Different aspects of system boundaries in LCEA research.

The third stage involves demonstrating the implementation of the proposed framework. The applicability of a framework can generally be tested through different methods such as using focused community expert groups, surveys, case studies, experiments, or simulations [46, 47]. The current paper employs a simulation approach in order to evaluate the applicability of the proposed framework. To this end, the system boundary conditions of a residential building in

Adelaide, Australia, were first defined using the proposed framework. The annual operational energy of the case study was assessed using the EnergyPlus 8.9 simulation engine [79]. Regarding embodied energy, the quantity of materials was assessed through the building's drawings. To assess the embodied impacts of building materials, a database developed by Pullen [48] was utilised in order to calculate the building's embodied energy. The results calculated in this paper were then cross compared with the results of a case study analysed by Crawford [49], aiming to demonstrate the capacity of the proposed framework for cross comparing cases within a standardised context. Afterward, the results are discussed and implications for further research are highlighted.

4. The Proposed Framework

This paper defines a system boundary as a process of characterising attributes that are related to calculations of both embodied and operational energies. These attributes entail a wide array of data regarding the description of temporal, physical, methodological, hypothetical, spatial, and functional aspects of LCEA analysis (Table 1). The proposed framework aims to encourage the incorporation of embodied energy into BEERs by outlining a comprehensive description of system boundaries in LCEA analysis. The objectives of the proposed framework include (i) maintaining transparency in conducting the LCEA, and (ii) establishing a basis for performing cross comparison between cases within a lucid context.

Table 1. Different dimensions of a conceptual framework for system boundaries.

Boundary Dimensions	No.	Components of Boundary	Sub-Components
1. Temporal	(1.1)	Stages of building life cycle	Product; construction; operation; end-of-life; reuse, recovery, recycling potentials.
2. Physical	(2.1)	Building components and systems	Substructure; superstructure; renewable energy system; building services; finishes.
-	(2.2)	Elements beyond building scales	Occupants' transport; external works.
3. Methodological	(3.1)	Method for assessment of embodied energy	Process-based, economic input-output (I-O), and input-output-based hybrid.
	(3.2)	Background database for embodied energy assessment	Literature; publicly or commercially available databases.
			Age of data.
-	(3.3)	Type of energy	Primary energy; delivered energy.

-	(3.4)	Unit of measurement	Per m^2 of net conditioned floor area; whole building; building component/construction material.
-	(3.5)	Parameters contributing to operational energy assessment	Heating; cooling; DHW; electrical appliances; ventilation; lighting; and cooking.
-	(3.6)	Method for assessment of operational energy	Simulation approach; energy bills; monitoring; national statistics.
4. Hypothetical	(4.1)	Assumptions	Temporal dimension; physical dimension; calculation methods.
	(4.2)	Building lifespan	30–100 years.
5. Spatial	(5.1)	Climate	Tropical; dry; temperate; continental; polar.
-	(5.2)	Building site location	City; suburb; regional; remote.
6. Functional	(6.1)	Building type	Residential; non-residential (e.g., commercial; educational; institutional; industrial etc.).
-	(6.2)	Density	Low-rise, medium-rise, and high-rise.

The first objective promotes enhancing the reliability of LCEA results for decision-making purposes. A detailed definition of system boundary conditions enables the uptake of achieved results with due considerations once the system boundary is subjected to truncation. Previous research [50] asserted that the majority of studies fail to clearly reveal their adopted system boundaries, hence it can be difficult to fully understand the extent to which the data are input to the system boundary.

Cross comparison is important regarding the second objective, as it is widely used as an approach to validate the obtained results. Cross comparing LCEA cases can also lead to advancing our knowledge about the total life cycle energy performance of buildings, i.e., the proportion of either embodied or operational energy used in the total building life cycle. This characteristic can also result in identifying best practices for the design and construction of buildings with low life cycle energy use performance. However, this needs to be done within a standardised context and with respect to the conditions of system boundaries. To date, a wide range of studies have showcased the significance of operational energy versus embodied energy (or vice versa) by cross comparing multiple case studies [32, 40, 51–54]. For example, Ramesh et al. [51] performed a literature review analysis aiming to cross compare 73 cases of office and residential buildings. They conclusively stated that the operational energy made up 80–90% of the overall life cycle energy usage of buildings, whereas embodied energy constituted 10–20%. Furthermore, they attempted to convey a consolidated understanding of the total life cycle energy requirements of conventional residential buildings and office buildings. It was shown that the overall life cycle energy use of residential buildings can be in the range of 150–400 kWh/m2 per year and that of office buildings in the range of 250–550 kWh/m2 per year. These conclusions, driven by cross comparing LCEA cases without delving into their respective system boundaries, can be incomplete due to the varied approaches of studies for establishing system boundaries.

4.1. Temporal Dimension

The temporal dimension refers to determining which stage of the building life cycle is included in the system boundary. In this regard, EN 15978:2011 [31] provides a comprehensive guideline that segregates the building life cycle into five stages (Figure 2).

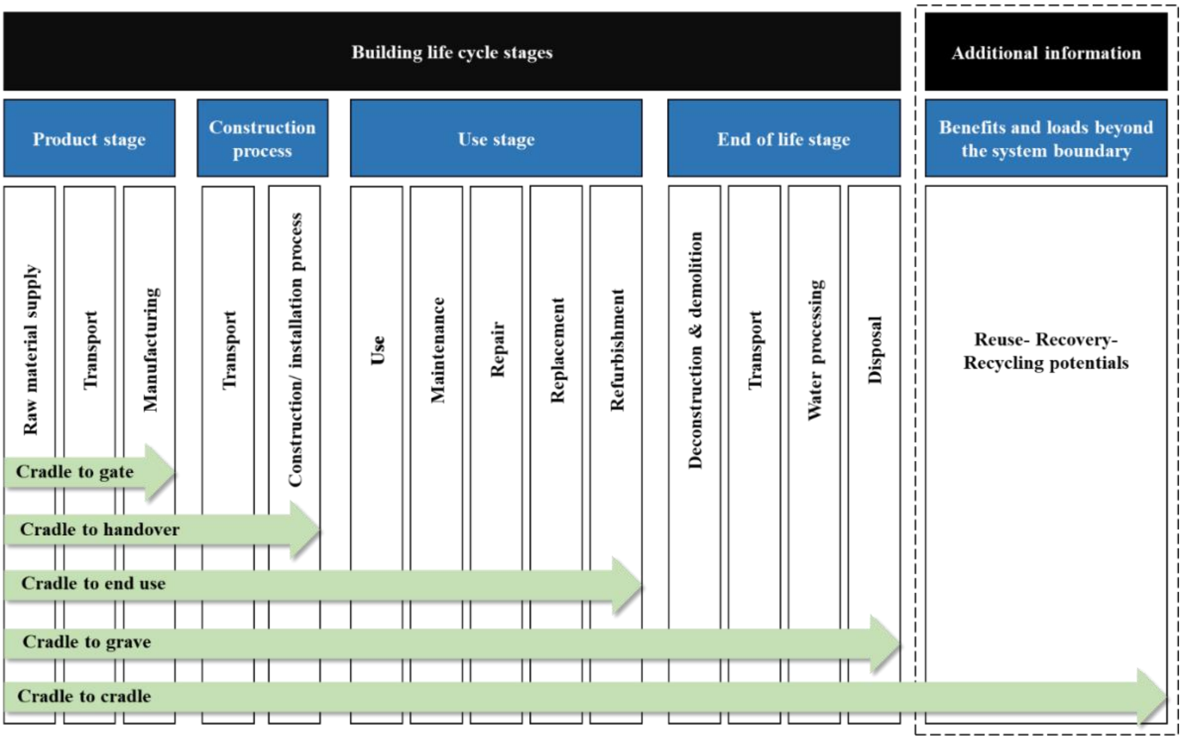


Figure 2. Proposed model for description of a system boundary (modular structure adapted from EN 15978:2011 [31]).

The cradle-to-gate includes energy inputs used for manufacturing construction materials, i.e., mining the materials, transporting the extracted materials to factories, and processing them. The cradle-to-handover includes all the processes from cradle-to-gate along with accounting for energy inputs related to transportation of materials to construction sites as well as on-site construction activities such as assembly, construction, disposal of construction wastages, etc. The cradle-to-end use refers to including energy inputs of product, construction, and use stages into the system boundary. The cradle-to-grave accounts for the amounts of energy used throughout all stages of a building's life cycle, including all the processes of upstream, downstream, and use phase. Finally, the cradle-to-cradle refers to capturing the environmental benefits of construction materials beyond the defined system boundary [23].

4.2. Physical Dimension

The physical dimension refers to determining which building component/systems are included in the system boundary. The current LCA standards, e.g., EN 15978:2011 [31], recommend a number of building elements that can be considered for inclusion into the system boundaries. This paper complements the description of physical system boundaries of the current standards by recommending the inclusion of embodied impacts attributed to renewable energy systems and occupants' transport (Table 2). Studies have shown that embodied impacts of renewable systems, e.g., the photovoltaic system (PV) or wind turbines, can be significant [55, 56]. In a study, Wong et al. [55] performed a comprehensive literature review analysis and concluded that the embodied energy required for the production of single-crystalline and multi-crystalline silicon PV systems amounted to 3532 MJ/m2 and 2876 MJ/m2 per year, respectively.

Table 2. Recommended components for inclusion in a physical system boundary at building scale.

Building Components	Building Sub-Components
Substructure	Foundation
-	Basement retaining walls
	Ground floor
Superstructure	Structural building frame
	Exterior walls
	Exterior doors
	Window glazing
	Interior walls
	Floor construction
	Ceiling construction
	Roof construction
	Stairs and ramps
Fitments	External finishes
	Internal finishes
	Fixed furniture
Renewable energy system	PV systems; solar collectors; wind turbines; etc.
Building services	Plumbing
	Heating system
	Cooling system
	Ventilation system
	Electrical system

	Lift
	Fire protection system
Furniture and appliances	Furniture
	Appliances
External works	Roads, path, paving and surfaces
	Fencing, railing and walls
	Shed
	Pergola
	External fixtures, drainage, and services
Transportation	Occupants' transport

This study also suggests including energy use relating to occupants' transports within the physical system boundary. Previous research endeavoured to incorporate embodied energies of such elements in the system boundary [10, 39, 57–59]. For instance, Stephan et al. [39] put forward a framework to measure embodied impacts of nearby infrastructure (roads, water, sewage systems, etc.), combined with the energy usage of occupants' transportation. The framework was then employed to assess the total energy use of two residential buildings in Australia and Belgium. The results revealed that the occupants' transports constituted 25.40 and 33.80% of the entire building life cycle energy use in the Belgian passive house and the Australian building, respectively. Bastos et al. [58] also compared the total life cycle energy demands and greenhouse gas (GHG) emissions of two residential buildings in Lisbon, an urban apartment, and a semi-detached suburban house. The analysis accounted for energy use at stages of production and operation, as well as the energy consumed due to occupants' transportation. The results indicated that the occupants' transport made up 51–57% of the entire energy use and GHG emissions for the semi-detached house, whereas operational energy was the largest contributor to energy use and GHG emissions (63–64%) for the apartment.

4.3. Methodological Dimension

As shown in Table 1, the methodological dimension contains six components that represent the key characteristics of a methodological approach for measuring embodied and operational energies. For the first component, embodied energy, there are three principal methods to compute buildings' embodied impacts, namely, the process-based, economic I–O and hybrid analysis methods [23, 24]. The process-based method collects and synthesises data relating to various services, products, as well as location-specific data to calculate embodied energy of construction materials [23]. These data can be retrieved from sources such as suppliers, contractors, and manufacturers. The economic I–O method utilises data representing an entire economy to quantify the amounts of energy used to generate a particular service or product.

The hybrid method fuses the two methods together in order to capture energy flows from the complete upstream supply chain. Whether the application of hybrid method yields a much higher value for embodied energy, as indicated by [15,57], is still a heated discussion since recent research [60] showed that the use of this method may not necessarily lead to achieving higher values due to restrictive assumptions concerned with it.

The selection of a background database is essential to calculate embodied energy. This database should contain data sets that represent the economic and technical contexts of the case study. In a comprehensive review, Omrany et al. [23] found that the databases needed for the calculation of embodied energy were collected from two main sources: literature (i.e., data published by other researchers) and databases that are available commercially or publicly. It is important to declare the database utilised for calculating embodied energy since the approach of each database towards quantification of embodied energy or embodied carbon emissions of materials can be different. For instance, the Inventory of Carbon and Energy, which contains over 200 construction materials, was developed based on the data collected via surveys and the data reported in the literature [61]. This approach differs from the Ecoinvent database, which was developed based on the economic I–O approach and quantifies inputs and outputs to and from the biosphere [61]. In addition, the age of data can affect the quality of the LCEA results and subsequently influence the comparability of cases. The databases with old data represent obsolete manufacturing technologies, hence their energy values can differ from updated ones [62].

The total energy consumption of a building can be measured using either primary energy or delivered (or site line) energy. Primary energy refers to the energy that is directly extracted from nature (e.g., crude oil, or coal) and is unprocessed [24, 27]. Delivered energy refers to the energy that is used on-site and produced by processing primary fuels such as electricity [24, 27]. The use of primary energy for conducting LCEA research is favoured over the delivered energy since it contains higher amounts of energy; thus, the environmental impacts of buildings can be captured more accurately.

The unit of measurement (also known as functional unit) represents the life cycle energy performance of the main entity (i.e., building) that has been subjected to LCEA analysis. The unit can be expressed in different forms, namely, per m2 of net conditioned floor area, as a whole building, or it can be a particular building component or a construction material. The proper selection of unit of measurement is of the greatest importance due to its influence on the accurate presentation of the LCEA results. In a study, Stephan and Crawford [63] studied the effect of dwelling size on life cycle energy demands using a parametric approach. It was revealed that the life cycle energy demands increased at a slower rate compared to house size. Hence, the expression of the total energy-efficiency performance of buildings per m2 would favour large houses, as these require more energy. They recommended that BEERs should utilise multiple functional units to measure the energy-efficiency performance of buildings. de Simone Souza et al. [64] also employed different functional units in order to evaluate their effects on the final LCA results. The selected units included "a building with defined lifetime and occupancy parameters", LCA performance of the building per m2 over one year, and "the accommodation of an occupant person of the dwelling over a day". This indicated the effects of functional unit selection on the final results.

Energy is consumed in non-thermal and thermal forms in order to retain the comfortability of indoor environments. Thermal energy refers to the amounts of energy used for the purposes of heating and cooling, while the non-thermal includes energies used for domestic hot water (DHW), electrical appliances, ventilation, lighting, and cooking. The estimation of a building's operational energy usage depends on the extent to which system boundaries are set to account for the impacts of these parameters over a building's lifespan [23, 24]. Exclusion of each parameter can directly affect the LCEA results by influencing the calculation of operational energy. In a study, Gustavsson and Joelsson [65] showed that the proportion of embodied energy to the total life cycle energy use of a building was reduced from 33 to 25% when the scope of assessment for operational energy was extended from only space heating to include ventilation, DHW, and household electricity.

The method applied to calculate operating energy in an LCEA analysis is another component of the methodological dimension. Recent studies [23, 24] revealed that four main methods, namely, "simulation", "energy bills", "monitoring", and "national statistics", have been commonly applied by LCEA studies for computing the operational energy use of buildings. It was found that most reviewed studies applied the simulation approach to calculate the energy usage of buildings. In this approach, the energy consumption of a building is calculated using a simulation engine, then the achieved figure is multiplied by the number of years assumed for building lifespan to estimate the operational energy of buildings. The energy bill is another method in which operational energy consumption is estimated using the actual energy bills of a building. In monitoring, sensors and actuators are employed to record and store the energy consumption of a building on a daily, monthly, or yearly basis. This method is similar to energy bills as both capture actual energy usage, except that monitoring can also provide a detailed breakdown of energy by use whereas the energy bills method only supplies an aggregate value for operational energy consumption [23, 24]. However, several challenges are also involved in employing the monitoring method, such as interoperability, high initial cost, and the difficulty in managing and storing the monitored data [66]. National statistics also denotes a method where national or regional statistics on energy consumption in the building sector are used for estimating operational energy. The employment of this method can illustrate the divergence between actual and estimated energy consumption as these data are developed based on the average energy usage in the building sector [23, 24].

4.4. Hypothetical Dimension

Making assumptions is inevitable in performing LCEA research. Assumptions are generally made due to the lack of reliable data, or to reduce the complexities involved in calculations of embodied or operational energies [24]. The importance of assumptions is also highlighted by international LCA standards [33], and it is recommended that they should be clearly acknowledged for the sake of transparency. The assumptions are made regarding different aspects of LCEA analysis, namely, temporal, physical dimensions, and building lifespan [23, 24]. Regarding the temporal dimension, the assumptions can be grouped as:

- Product stage: assumptions in this category are usually made due to the absence of a locally developed database. Hence, the LCEA researchers adopt the background database of another region/country in order to calculate embodied energy [10, 57, 67]. This subsequently compromises the accuracy and reliability of embodied energy calculations for decision-making purposes since manufacturing processes, economic sectors, construction technologies, fuel supply structure, and energy tariffs vary from one country to another.
- Operation: the most common assumption in this category relates to assuming that buildings' operational energy use will be constant throughout the entire period of assessment (e.g., for 50 years). This assumption implies that buildings' occupancy profiles will be unchanged in terms of family size or the settings of occupancy schedule, or there will be no depreciation of heating and cooling systems. Another assumption pertains to ignoring the possible effects of future climate change on the heating and cooling demands of buildings. The review conducted by Omrany et al. [23] showed that the majority of the analysed studies calculated operational energy use of buildings considering only the current climatic conditions. However, the

findings reported by recent studies have indicated that the heating and cooling demands of buildings can be affected by climate change [68].

- Recurrent embodied energy: there are also several assumptions made about this stage. The most common assumption is that building materials will be replaced with the same materials as they reach their end of service lives. Thus, they will incur the same amounts of embodied energy as original materials.
- Construction and EOL: due to numerous uncertainties involved, the common approach to account for the embodied impacts of these stages is to assume certain values as their respective contributions to the buildings' total embodied energies [23, 24]. For instance, Gustavsson et al. [69] assumed that the primary energy used for the on-site construction of an eight-story apartment equalled 80 kWh/m^2. Devi and Palaniappan [67] also assumed that the EOL stage consumed 3% of the total initial embodied energy.

The assumption of building lifespan is of utmost importance in an LCEA analysis owing to its direct influence on both operational and embodied energies. The embodied energy (i.e., recurrent embodied energy) can be affected by the assumption of building lifespan when assuming a long lifespan leads to frequent substitutions of building materials, while assuming a short lifespan triggers the need for changing the entire building. This assumption can also influence operational energy because extending the lifetime of a building results in an increase in energy consumption over its service life. Recent studies indicated that the range of building lifespans assumed by relevant literature falls within a range of 30 to 100 years [23, 24]. The physical dimension can also contain assumptions. This may relate to the process of obtaining and compiling bills of quantity for the calculation of a building's embodied impacts where reliable data are unavailable.

In sum, all the assumptions need to be clearly stated in LCEA research while justifying their contextual applicability.

4.5. Spatial Dimension

The climate directly influences the operational energy use of buildings by affecting heating and cooling demands. In this framework, the spatial dimension is used as a proxy for a building's geographical location to describe the climate zone. This study uses the Köppen climate classification scheme [70] to elaborate on the spatial dimension of system boundaries.

This scheme introduces five main climatic conditions, including tropical, dry, temperate, continental, and polar and each has its own subtypes.

The building site location is another component of the spatial dimension that refers to the travelling distance between a building's site location and urban facilities. Disclosure of this component can help with maintaining transparency for calculation of transport embodied energy as well as being a sub-component of the occupants' transport in the physical dimension.

4.6. Functional Dimension

The functional dimension refers to determining the type of building and density. The building types are commonly categorised as residential and non-residential buildings. Non-residential buildings include commercial, educational, institutional, industrial, etc. The number of storeys can also be used to describe the density of buildings, as suggested by Jan et al. [71]. Building density can directly impact LCEA results by affecting initial embodied energy use. Wang et al. [72] investigated the life cycle energy use of ten real-life buildings in Hong Kong and reported that the initial embodied energy usage of high-rise buildings was twice that of low-rise ones. Du et al. [73] also reviewed 42 case buildings and conclusively stated that high-rise buildings used almost 50% more embodied energy compared to low-rise buildings. Treloar et al. [74] highlighted an even larger difference, stating that high-rise buildings may use approximately 60% more initial embodied energy per unit of gross floor area than low-rise buildings. The higher embodied energy of high-rise buildings can be related to (i) using more materials, and (ii) using materials with higher energy intensity, e.g., concrete and steel [72]. Therefore, building density needs to be captured in defining the system boundary.

5. Implementation of the Framework

This section aims to demonstrate the applicability of the proposed framework. To this end, the total life cycle energy performance of an NZEB building that is a single-storey detached residential building located in Adelaide, South Australia, was analysed. The proposed framework was used to define the system boundary conditions of the LCEA analysis. Afterward, the proposed framework was employed in order to compare the achieved LCEA results with the results of a case study reported in the literature [49]. The case study retrieved from the literature was selected based on two principal considerations:

- The total life cycle energy performance of the case study must be analysed, with its results explicitly reported.

- The case study should provide enough data to reflect the six main dimensions of the framework.

The main purpose of this comparison was to illustrate the capacity of the proposed framework for revealing the conditions of system boundaries when cases are horizontally compared. This further helps to make decisions on normalising the identified differences.

5.1. Description of the Case Studies

Figure 3 demonstrates the schematic design of the NZEB-Adelaide case study. Both buildings represent the bulk of the new dwellings that are currently being constructed across Australia. Table 3 shows the main characteristics of the buildings. Further info regarding the Melbourne case study can be found in [49].

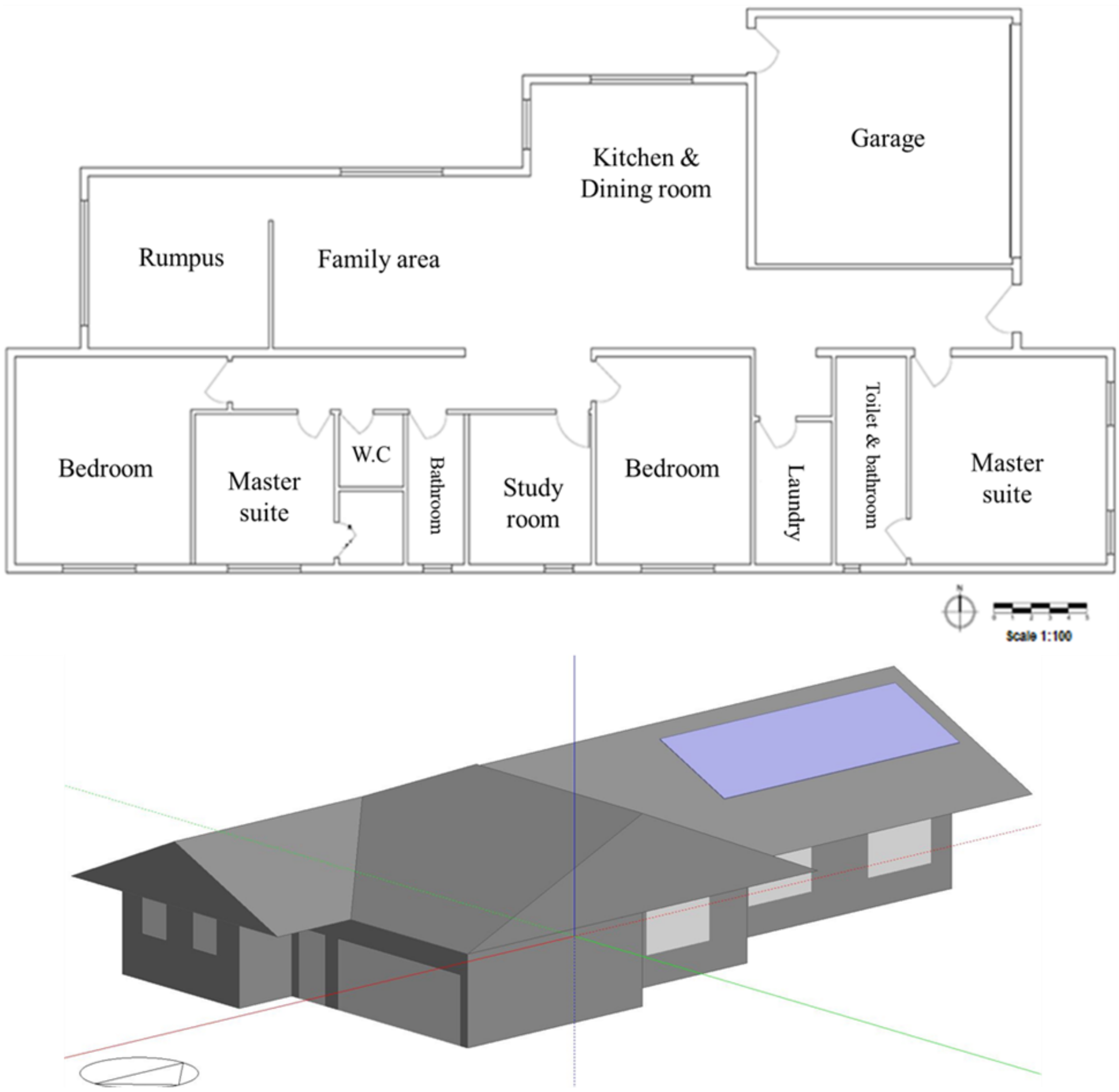


Figure 3. NZEB-Adelaide Case Study analysed by this paper. Details regarding the Melbourne Case Study can be found in [49].

Table 3. Characteristics of the case studies.

Characteristics	NZEB-Adelaide Case Study	Melbourne Case Study
Gross floor area (m^2)	189.85	291.30
Net conditioned floor area (m^2)	146.78	254.40
External walls	Brick veneer; glass fibre batt insulation; average U-value 0.659 W/m^2 K	Insulated timber-framed brick veneer walls
Footings/ground floor	Concrete slab on ground consisting of steel, concrete, blinding and membrane	Concrete waffle pod slab
Pitched roof	Clay tile; roofing felt	Concrete-tiled roof
Ceiling	Glass fibre batt; gypsum plasterboard	Not reported
Internal walls	Insulated gypsum plasterboard	Painted plasterboard internal linings
Windows	Single glazed 4 mm window panes with wooden frames. U-value 6.70 W/m^2 K; SHGC[1]= 0.570	Clear float glass 4 mm panes
Infiltration (ac/h at 50 Pa)	15.0	Not reported
Lighting	LED; 2.50 W/m^2–100 lux (normalised power density)	Not reported
Occupancy	Four people (i.e., a couple with two kids)	Not reported
Ventilation systems	Split air conditioner system–reverse cycle	Gas ducted heating system, and an evaporative cooling system

NB: [1] Solar heat gain coefficient.

Heating and cooling of the Adelaide case study were provided via a split air conditioner system–reverse cycle using electricity supplied from the grid. The coefficient of performance (COP) of the heating system was assumed to be 2.25, with the maximum capacity of supplying 35.0 °C air temperature. The COP of the cooling system was assumed to be 1.80 with the maximum supply air temperature of 12.0 °C. The Melbourne case study used a gas ducted heating system and an evaporative cooling system. An instantaneous gas-boosted solar hot water system was also used to provide hot water [49].

5.2. Definition of the System Boundary

The main dimensions of the system boundaries defined by both case studies are shown in Table 4. The use of the proposed framework enabled delineating system boundaries within a lucid context so that any truncation with potential effects on the LCEA results could be identified.

Table 4. Demonstrating the implementation of the proposed framework.

Boundary Dimension		Components of Boundary	Sub-Components	NZEB-Adelaide Case Study	Melbourne Case Study
Temporal	(1.1)	Stages of building life cycle	Product	▲	▲
			Construction	-	▲
			Operation	▲	▲
			Recurrent	▲	▲
			End-of-life		▲
			Reuse, recovery, recycling potentials		
Physical	(2.1)	Building components and systems	Substructure	▲	▲
			Superstructure	▲	▲
			Fitments	▲	▲
			Renewable energy system	▲	
			Building services	▲	
			Furniture and appliances		
	(2.2)	Elements beyond building scales	External works		
			Occupants' transport		
Methodological	(3.1)	Method for assessment of embodied energy	Process-based		
			Economic I-O	▲	
			Hybrid analysis		▲
	(3.2)	Background database for embodied energy assessment	Literature		
			Publicly or commercially available databases	Economic I–O data taken from the Australian National Accounts based on work by Pullen [48].	Economic I–O data taken from the Australian National Accounts, and process-based energy data for manufacture of specific materials, obtained from the SimaPro Australian database.
			Age of data	Economic I–O tables 1996–97.	Economic I–O tables 1996–97; process data 2010.
	(3.3)	Type of energy	Primary energy	▲	▲
			Delivered energy		
	(3.4)	Unit of analysis	Per m^2 of net conditioned floor area		
			Whole building	▲	▲
			Particular building component/construction material		
	(3.5)	Parameters contributing to	Heating	▲	▲
			Cooling	▲	▲
			DHW	▲	▲

		operational energy assessment	Electrical appliances	▲	▲
			Ventilation	▲	▲
			Lighting	▲	▲
			Cooking	▲	▲
	(3.6)	Method for assessment of operational energy	Simulation approach	▲	
			Energy bills		▲
			Monitoring		
			National statistics	▲	
Hypothetical	(4.1)	Assumptions	Product		
			Construction		
			Operation	▲	▲
			Recurrent	▲	▲
			End-of-life		▲
			Reuse, recovery, recycling potentials		
			Physical dimension		
	(4.2)	Building lifespan	30–100 years	50	50
Spatial	(5.1)	Climate	Tropical		
			Dry		
			Temperate	▲	▲
			Continental		
			Polar		
	(5.2)	Building site location	City	▲	
			Suburb		▲
			Regional		
			Remote		
Functional	(6.1)	Building type	Residential	▲	▲
			Non-residential		
	(6.2)	Density	Low-rise	▲	▲
			Medium-rise		
			High-rise		

NB: ▲ included in the system boundary.

Temporal Dimension

The total life cycle energy use of the NZEB-Adelaide case study was assessed considering the product, operation, and recurrent stages of the building life cycle. The embodied impacts associated with the EOL, and construction stages were excluded from the system boundary due to several uncertainties concerning the calculation of these stages, e.g., difficulty in gathering and documenting reliable data during on-site construction operations or the uncertain fate of materials after deconstructing the building [23]. Moreover, previous studies showed that these stages make minor contributions to the building's overall life cycle consumptions [75, 76]. Regarding the recurrent embodied energy, Table 5 tabulates the service lives of construction materials that are assumed by both studies to be replaced over the 50 years of building operations.

Table 5. Service lives of materials subjected to replacement over the buildings' life spans.

Building Materials	NZEB-Adelaide Case Study*	Melbourne Case Study
	Service Life (Years)	Service Life (Years)
Roof tiles	25	25
Paint for external surfaces	15	10
Plasterboard (10 mm)	25	30
Ceramic tiles	25	25
Carpet	10	25
PV panels	25	NA

NB: Source: a Dixit [77].

For the Melbourne case study, the LCEA assessment was undertaken considering all the stages of building life cycle, including product, construction, operation, recurrent, and EOL. Crawford [49] considered the construction stage as a component of initial embodied energy, and to account for its impacts, the material quantities (Q_m) were multiplied by their respective embodied energy coefficient (EC_m) in order to compute the total process-based hybrid embodied energy of the building. Afterward, the total I–O-based energy requirements of the processes for which material quantities were obtained (TER_m) in gigajoule (GJ) per Australian Dollar (AUD) from the I–O model were deducted from the total energy requirement of the residential building sector (TER_{rb}) (0.0106 GJ/AUD) in order to obtain the remainder, thus correcting sideways and downstream truncation errors. To calculate the overall initial embodied energy of the house (IEE), the remainder needed to be converted from GJ/AUD to

GJ/house using the estimated costs of the building construction and then added to the process-based hybrid embodied energy value. The approach for calculation of initial embodied energy can be expressed as Equation (1).

$$\text{IEE} = \sum_{m=1}^{M} (Q_m \times EC_m) + \left(TER_{rb} - \sum_{m=1}^{M} \text{TER}_m \right) \times C_h \qquad (1)$$

where IEE is the initial embodied energy of the building; Q_m represents quantities of delivered materials; EC_m is the embodied energy coefficients of the materials; TER_{rb} is the total energy requirements of the residential building sector in GJ per AUD; TER_m is the total energy requirement of the I–O-based processes representing the materials for which process data were collected, in GJ per AUD; C_h is the cost of the house, in AUD. Regarding the EOL stage, an amount equal to 1% of the total life cycle energy demand of the dwelling was assumed to be added to the final calculated value in order to account for the embodied impacts of the stage.

Physical Dimension

The elements included in the physical system boundaries of both case studies are shown in Table 6. As indicated, the NZEB-Adelaide building has PV panels installed on the sloped roof to neutralise the household electrical energy use. The system was sized considering the average annual solar exposure in Adelaide, which is 20.39 MJ/m^2 [77]. To harvest the maximum solar radiation, the PV panels were oriented towards the true north and tilted 23.0°. The size of PV panels was 1.639 m × 0.982 m, with an efficiency rate of 80%. The embodied energy calculation excludes the balance of system, and only accounts for PV panels.

Table 6. Building elements included in the physical dimension.

Building Components	Building Sub-Components	NZEB-Adelaide Case Study	Melbourne Case Study
Substructure	Foundation	▲	▲
	Basement retaining walls	NA	NA
	Ground floor	▲	▲
Superstructure	Structural building frame	▲	▲
	Exterior walls	▲	▲
	Exterior doors	▲	▲
	Window glazing	▲	▲
	Interior walls	▲	▲
	Floor construction	▲	▲

	Ceiling construction	▲	▲
	Roof construction	▲	▲
	Stairs and ramps	NA	NA
Fitments	External finishes	Paint on external walls	Paint on external walls
	Internal finishes	Ceramic tiles and carpet	Ceramic tiles and carpet
	Fixed furniture	Kitchen cabinet	NA
Renewable energy system	Photovoltaic panels; solar collectors; wind turbines, etc.	PV panels	NA
Building services	Plumbing	Piping; steel sinks; taps/fittings; water services; baths	NA
	Heating system	NA	NA
	Cooling system	NA	NA
	Ventilation system	NA	NA
	Electrical system	NA	NA
	Lift	NA	NA
	Fire protection system	NA	NA
			NA
Furniture and appliances	Furniture	NA	NA
	Appliances/equipment	Oven/hob; air conditioner	Heating, hot water and cooking appliances
External works	Roads, path, paving and surfaces	NA	NA
	Fencing, railing and walls	NA	NA
	Shed	NA	NA
	Pergola	NA	NA
	External fixtures, drainage, and services	NA	NA
Transportation	Occupants' transport	NA	NA

NB: ▲ included in the system boundary.

Methodological Dimension

The background database employed for the calculation of embodied energy in the NZEB-Adelaide case study is based on an economic I–O approach, developed by Pullen [48]. The economic I–O approach utilises the entire structure of an economy as the theoretical boundary of a system in order to compute the amounts of energy used to produce a particular material. This method has a wider approach towards calculating embodied energy compared to the process-based method due to its accounting for both the direct and indirect effects of the upstream supply chain. Cabeza et al. [78] found that studies with an economic I–O approach reported larger embodied impacts owing to the inclusion of indirect effects. On the other hand, Crawford [49] adopted an I–O-based hybrid analysis for calculating the embodied energy impacts of the building. The I–O model of Australian energy use was developed using economic I–O data retrieved from the Australian National Accounts in 1996–97, and the process-based energy data for manufacturing specific materials were acquired from the SimaPro Australian database. To streamline the assessment process, he derived a number of embodied energy coefficients for building materials [15] through which the overall embodied impacts of materials were calculated via multiplying the relevant coefficients by their quantities.

The LCEA analyses for both case studies were carried out based on primary energy consumption while accounting for all parameters contributing to thermal and non-thermal energy use. Regarding the NZEB-Adelaide case study, this study adopted a "simulation approach" to estimate the operational energy usage. To this end, the case study model was first developed in DesignBuilderV6 software, and then the thermal and non-thermal loads (including electrical appliances and lighting) were calculated using the EnergyPlus 8.9 simulation engine. EnergyPlus considers detailed interactions of all building components and systems such as building envelope, windows, HVAC, and internal heat gains from different systems in order to calculate heating and cooling loads [79]. The estimated loads were then converted into energy use by applying the assumed coefficient of performance (COP) of the equipment. After this conversion, the primary energy consumption was calculated using an electricity conversion factor of 3.40 for Australia [39]. Due to the software's limitation in simulating gas consumption, the amount of natural gas used for cooking and hot water was estimated based on national statistics for South Australia, which is 15 GJ per household per year [80]. Thereafter, a primary energy factor of 1.40 [39] was used to convert natural gas use into primary energy consumption.

The "energy bill" approach was utilised by Crawford [49] in order to calculate the building's operational energy use. To do this, the total annual delivered operational energy requirement was estimated by averaging energy bills (including both thermal and non-thermal energy use) of the house for three consecutive years. The delivered energy use was then converted into primary energy consumptions using relevant converting factors for electricity and natural gas.

Spatial Dimension

According to the Köppen climate classification, Adelaide has a hot Mediterranean climate (Csa) with cool to mild winters and warm to hot summers that require consuming energy for both heating and cooling. Melbourne has a temperate oceanic climate (Cfb) with ample precipitation and rainfall during the entire year. Similar to Adelaide, energy is needed for addressing heating and cooling demands throughout the year in Melbourne. Figure 4 illustrates the monthly average ambient air temperature for Adelaide airport and Melbourne airport between 1991 and 2020. According to this figure, February and July are the peak energy demands for cooling and heating in both cities, respectively [80].

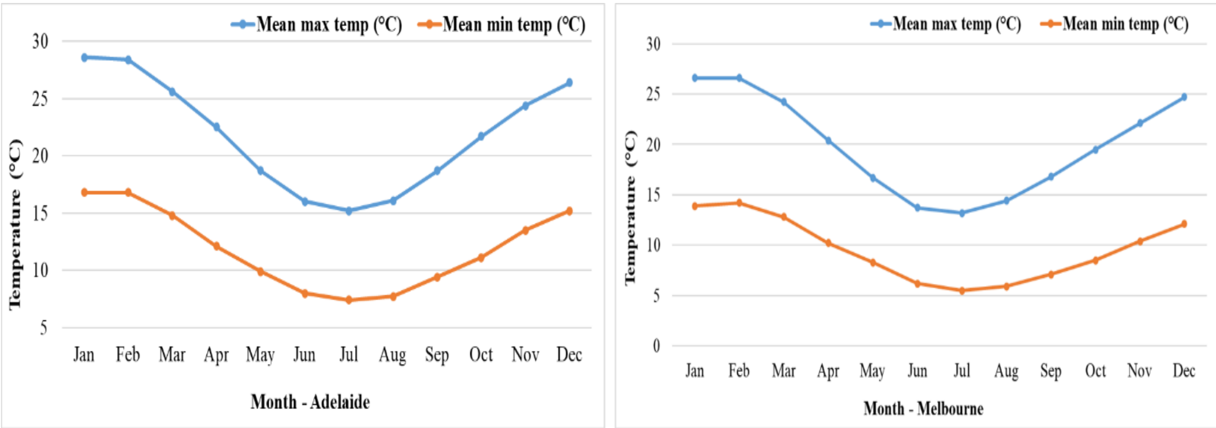


Figure 4. Monthly average ambient air temperature for Adelaide [79], and Melbourne [76].

Hypothetical Dimension

The operational energy for both case studies was assessed assuming that the occupational settings (e.g., scheduling and occupancy profile) would remain unchanged over the period of 50 years. It is also assumed that performance coefficients of electrical equipment and appliances, as well as the efficiency rate of PV panels used in the NZEB-Adelaide case study, would be constant during the entire assessment period. Furthermore, the resource mix supplying electricity to the buildings was assumed for both cases to be unchanged over the 50 years. It is also noteworthy to mention that neither of the cases accounted for the effects of future climate change on heating and cooling energy demands.

In addition, both studies assumed that certain building elements were subject to periodic maintenance and replacement (i.e., recurrent embodied energy) (See Table 5). To calculate the recurrent embodied energy, it was necessary to assume that these materials would be substituted with the same materials, thus incurring the same amounts of embodied energy as the originals. Regarding the EOL stage, Crawford [49] assumed that the energy needed for deconstruction and disposal of materials amounted to 1% of the overall life cycle energy consumption of the building.

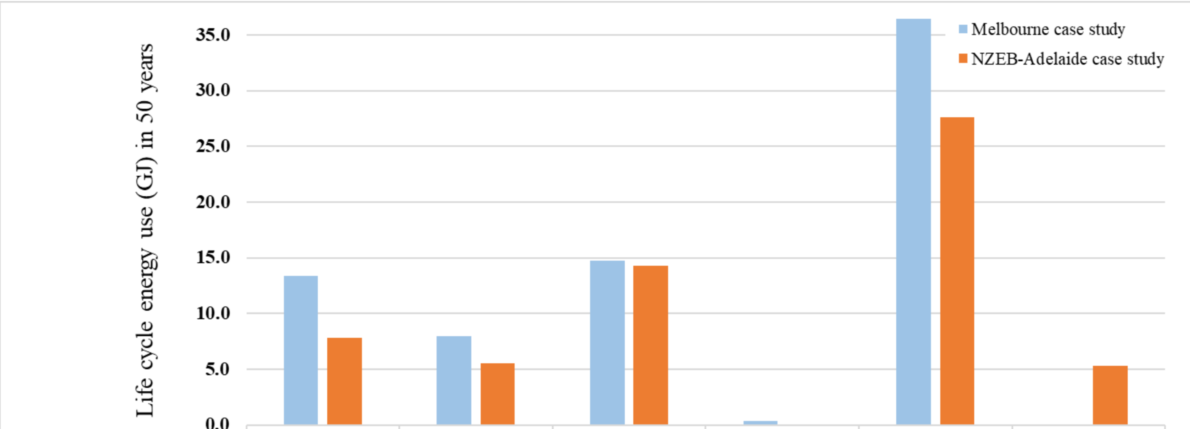
The life span of the NZEB-Adelaide case study was assumed to be 50 years, as recommended by ASHRAE and U.S. Green Building Council (USGBC) [81]. Recent studies have also shown that most of the research analysed considered a life service of 50 years [23, 24]. Similarly, Crawford [49] performed the LCEA analysis assuming 50 years of building life service. In addition, the unit of measurements utilised to report the LCEA analysis is “entire building” for both cases.

Functional Dimension

Both of the case studies are single-storey detached residential buildings that belong to the “residential” and “low-rise” sub-components of the functional dimension. The NZEB-Adelaide case study represents the bulk of new dwellings being presently constructed by volume builders in Australia (Figure 4) [82]. Currently, all new buildings need to meet certain thermal requirements the equivalent of 6.0 stars in order to substantiate their compliance with the energy-efficiency regulations in Australia [83]. According to the Commonwealth Scientific and Industrial Research Organisation (CSIRO), most of the accredited buildings fall in the range of 6.0 to 6.9 stars [83]. Being 6.6 stars, the NZEB-Adelaide case study met the minimum mandatory thermal requirements for residential buildings specified by national construction codes in Australia. Detailed information regarding the Australian building energy codes can be found in [84, 85].

5.3. Analysis of the Case Studies

Figure 5 illustrates the breakdowns of the total life cycle energy requirements of both cases. For the NZEB-Adelaide case study, it indicates that operational energy use constituted the largest portion of the total life cycle energy use of the building (51.80%), followed by the initial embodied energy (28.3%), and the recurrent embodied energy (19.9%). The amount of operational energy usage estimated for the NZEB case was relatively lower than the Melbourne case. This difference can be explained by the varied approaches of the two studies to the estimation of operational energy use. The use of the energy bills approach allowed to comprehensively capture the variety of occupant behaviours in using energy, thus the potential variability between the predicted (simulated) and actual energy performance of the building was zero. Contrarily, a discrepancy can potentially occur in the simulation approach since it relied on only one pre-defined occupational profile setting in order to quantify energy consumption for an entire year. The study by Van Dronkelaar et al. [86] showed that the magnitude of deviation between simulated and measured energy use in buildings can be +34% with a standard deviation of 55% based on 62 buildings investigated. Another reason may be due to the calculations of natural gas consumption in the two studies. For the Melbourne case, the primary energy consumption of natural gas was estimated to be 8.02 GJ (i.e., 2336.50 GJ) over 50 years of building operation that included cooking, hot water, and heating [49]. However, the natural gas consumption in the case of the NZEB building (i.e. 1050 GJ over 50 years) only accounted for hot water and cooking since heating demand was supplied via electricity [80].



	Initial embodied energy	Recurrent embodied energy	Total operational energy in 50 years	Demolition & disposal energy	Total life cycle energy use	Total energy generation via renewable energy
Melbourne case study	13.4	8.0	14.7	0.4	36.4	0.0
NZEB-Adelaide case study	7.8	5.5	14.3	0.0	27.6	5.3

Figure 5. Life cycle energy use of the case studies normalised per square meter of gross floor areas over 50 years.

The initial embodied energy calculated for the Melbourne case study was significantly higher than the value achieved for the NZEB-Adelaide case study (Figure 5). This difference can be related to the hybrid life cycle approach applied by Crawford [49] to carry out LCEA analysis. Studies by Crawford [15] and Stephan and Stephan [57] showed that the application of a hybrid life cycle approach can yield higher embodied energy values by 3.8 and 3.9 times compared to other methods, respectively. Moreover, Crawford [49] counted the energy usage of the construction stage towards initial embodied energy, as explained in the section on temporal dimension, whereas the NZEB-Adelaide case study excluded the construction stage. The higher recurrent embodied energy of the Melbourne case study can also be explained by the wider approach used by Crawford [49] for calculating the embodied impacts of the building. It is noteworthy to mention that both case studies assumed that materials would be replaced by the same ones when they reached their end of service lives, thus having the same amounts of embodied energy impacts as originals.

In addition, the two studies differed in terms of establishing their temporal and physical dimensions of the system boundaries. Crawford [49] accounted for the impacts of the EOL stage by adding 1% of the total life cycle energy demand to the final figure calculated for the LCEA performance of the building. On the other hand, the NZEB-Adelaide case study included the embodied impacts of PV panels in the physical dimension of the system boundary, which affects both initial embodied and recurrent energies. The PV panels were engaged to zero out the electrical energy demands of the building, which led to generating 1013.844 GJ of energy over the 50 years.

6. Discussion

The importance of reducing embodied energy has become a hostile debate in recent years due to its increasing contribution to energy consumption in the built environment. The World Green Building Council predicted that embodied carbon driven from the embodied energy of construction projects will be responsible for more than 50% of the entire carbon emissions by 2050 worldwide [26]. The results of this study also revealed that embodied energy constituted 60 and 48% of the total life cycle energy demands of the Melbourne and Adelaide case studies, respectively. In this regard, studies discerned that, without immediate action, embodied energy will be an impending environmental concern related to the performance of buildings [45]. Therefore, there has been an increasing demand for mitigation of embodied energy in the built environment over the last decade.

One approach to minimise the impacts of embodied energy is to incorporate such a requirement into current BEERs. Thus far, only a few countries have started incorporating embodied energy into their building regulations. The Netherlands was the first country to introduce requirements for the measurement, though not the reduction, of embodied impacts into its building regulations [87, 88]. Other countries have also taken their first steps towards this end such as France [78], Finland [89], Norway [89], Denmark [90, 91], and Sweden [92]. However, the abatement of embodied energy as a requirement mandated by BEERs is still being neglected by most countries [45]. One of the main reasons for such an exclusion lies with the complexities involved in assessing embodied energy in conjunction with operational energy. The assessment of embodied energy is less straightforward compared to operational energy owing to the various intertwined processes involved, as well as several variables that should be counted towards the assessment of embodied energy. This paper proposed a comprehensive framework to standardise system boundary conditions in LCEA research. The overarching aim of the framework is to encourage the incorporation of embodied energy into building regulations by (i) identifying the main parameters causing variation in LCEA results, and (ii) structuring the identified parameters into six dimensions. Although the case studies analysed by this paper are located in Australia, the framework can be adopted by other countries for the purpose of standardising LCEA analysis.

The proposed framework has two key characteristics. First, its application facilitates defining the conditions of a system boundary within a transparent context. This, in turn, will lead to increasing the reliability of obtained LCEA results for decision-making purposes, since any particular conditions (e.g., truncation, or assumption) considered in establishing the boundaries of the system under study can be revealed. In addition, the use of the proposed framework provides a meaningful basis for cross comparing cases within a global context. This can further result in identifying best practices for the design of buildings with low life cycle energy use performance. In regard to policy making, the framework introduces 15 variables that are categorised into six distinguished dimensions. The policy makers can set certain requirements and standards for each dimension to be practised within a national or a regional level. As an illustration, Birgisdóttir et al. [93] suggested that cradle-to-handover (See Figure 2) should be considered as the minimum requirements for assessing the energy of buildings. The Norwegian Research Centre on Zero Emission Buildings also presented different levels of data requirements for assessment of buildings' embodied emissions [94].

The incorporation of embodied energy impacts into BEERs also requires revising the current mindset of policy making in the building sector. In general, the implementation of energy policies has three components, i.e., "sticks", "tambourines", and "carrots" [95, 96]. In the building sector context, sticks represent regulations, codes, and standards through which a benchmarking basis is provided to identify non-compliant buildings with the given requirements. The tambourines are the tools employed to enhance public awareness about compliance requirements and energy-saving strategies such as building labelling. The carrots refer to the incentives considered for encouraging the best practices in the building sector such as subsidies and rebates or loans. The change in mindset should occur in all the three pillars of energy policy implementation in order to accommodate the inclusion of embodied energy into BEERs (Figure 6).

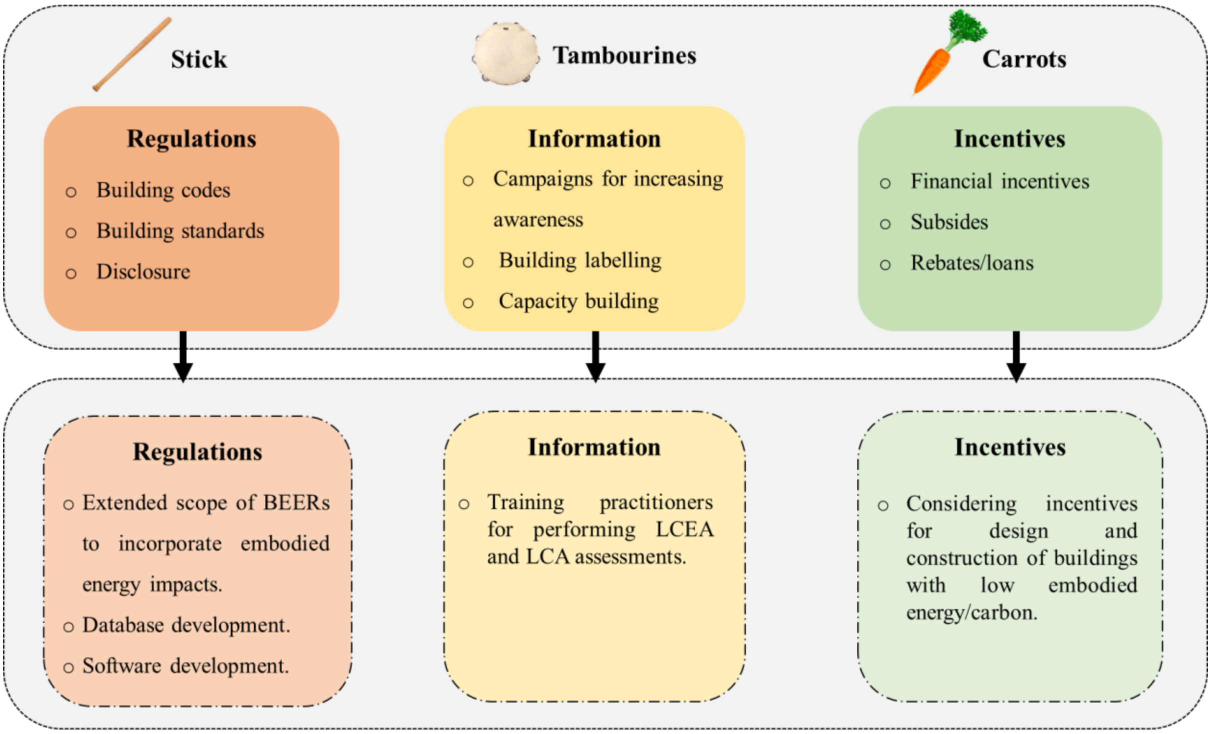


Figure 6. Proposal on further actions for incorporation of embodied energy into BEERs.

Regarding regulations, the scope of current BEERs needs to be extended to include embodied energy. The current scopes of building energy regulations are generally limited to only enhancing the operational energy performance of buildings [45, 87]. Hence, the importance of minimising the embodied energy of buildings should be first acknowledged by BEERs and reflected accordingly in the regulatory scheme of building codes. The recommended approach should be accompanied by, first, embodied energy databases to be developed nationally in order to represent the peculiarities of the country, such as economic sectors, construction technologies, manufacturing processes, energy tariffs, and fuel supply structure [23, 62]. The Environmental Performance in Construction (EPiC) is an example of such a database that contains the embodied energy coefficients of several building materials in Australia [97]. It is also important that the environmental product declarations (EPDs) [98] for building materials are enforced to provide up-to-date quantified environmental data relating to construction materials. In parallel, investment should be made in developing software with the capacity of pairing with embodied energy databases; thus, designers can readily link their designs with material quantities to carry out embodied energy estimations.

The inclusion of embodied energy into the BEERs will also require launching extensive LCEA or LCA training processes across all professions in the construction industry. This was affirmed by Schwarz et al. [99], who investigated the opinions of building professionals on potential challenges to including embodied energy into BEERs. The interviewees pointed out the necessity of initiating LCA learning programs due to the lack of knowledge in the current industry. Lastly, the design and construction of buildings with low embodied energy or embodied carbon performance should be promoted by BEERs through providing different types of incentives. The integrated policies combining the three pillars mentioned above can effectively instigate the promotion of best practice in constructing low life cycle energy buildings in the sector.

7. Conclusions

The main motivation for this study was inspired by the continued exclusion of embodied impacts from the frameworks of BEERs in most countries. Despite increasing attention, the pathway for including the impacts of embodied energy into BEERs is still ambiguous. The principal reason for such an ambiguity resides with the complexities that BEERs encounter when accounting for the impacts of both operational and embodied energies due to the various processes and parameters involved. To address this challenge, the development of a comprehensive framework for a clear description of system boundaries can pave the way towards integrating the life cycle embodied environmental impacts into BEERs. Currently, the literature is lacking such a comprehensive framework. Therefore, this paper proposed a comprehensive framework for a clear description of system boundary conditions in LCEA analysis with the aim of promoting the incorporation of embodied energy impacts into BEERs.

The proposed framework was developed based on an extensive literature review analysis of 66 studies representing 243 case studies in over 15 countries. The framework consists of six distinctive dimensions, including temporal, physical, methodological, hypothetical, spatial, and functional. These dimensions encapsulate 15 components collectively. The proposed framework has two key characteristics. First, its application facilitates defining the conditions of a system boundary within a transparent context. This can consequently lead to increasing the reliability of obtained LCEA results for decision-making purposes since any particular condition (e.g., truncation, or assumption) considered in establishing the boundaries of the system under study is revealed. In addition, the use of the proposed framework provides a meaningful basis for cross comparing cases within a global context. This can further result in identifying best practices for the design of buildings with low life cycle energy use performance. In regard to policy making, certain requirements and standards can be set for each dimension of the framework to be practised within a national or regional level. This will provide much better control over standardising the process of including embodied energy into BEERs.

The applicability of the proposed framework was tested by applying the framework to assess the life cycle energy performance of a residential building in Adelaide, Australia. To this end, the framework was first employed to define the system boundary conditions of the case study. It was then utilised to cross compare the obtained results with another case study retrieved from the literature. This cross comparison was carried out to illustrate the capacity of the developed framework for cross comparison. The results of these case studies reaffirm the significance of embodied energy consumption associated with buildings. Results showed that embodied energy constituted 48.2 and 60% of the total life cycle energy usage for the Adelaide and Melbourne case studies, respectively. These findings underline the urgent demand for incorporation of embodied energy impacts into energy-efficiency building codes. In this regard, the use of the proposed framework contributed to the clear definition of system boundary conditions as well as to providing a standardised basis for cross comparison of cases.

This study also recommends altering the current mindset of policy making in the building sector in order to embrace the addition of embodied energy to BEERs. First, it is recommended that the current scope of BEERs be extended to include the impacts of embodied energy. This inclusion should be accompanied by developing embodied energy databases. It is also recommended that the environmental product declarations for building materials should be enforced to provide up-to-date quantified environmental data relating to construction materials. Furthermore, software should be developed with the capacity to pair with embodied energy databases so that designers can readily link their designs with material quantities to perform embodied energy estimations. It is also necessity to launch extensive training processes across all professions in the construction industry in order to increase awareness of LCEA or LCA calculations. In addition, it is recommended that different types of incentives should be allocated in order to promote the design and construction of buildings with low embodied energy or embodied carbon performance. The integrated policies combining the three pillars mentioned above can effectively instigate the promotion of best practices in constructing low life cycle energy buildings in the sector.

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Chapter 7. Discussion

7.1 Introduction

This chapter aims to provide an overall discussion about the explorations carried out in chapters 3 to 6. As the preceding chapters have presented detailed discussions devoted to addressing each of the research questions, this chapter will focus on discussing the interconnections between all the aspects explored and provides recommendations for future studies.

7.2 Promotion of energy efficiency measures by BEERs

This thesis recommends that the future generation of BEERs should promote adoption of energy-efficiency measures throughout the entire process of building design and construction. In general, the energy-efficiency measures within the context of high-performing buildings such as NZEBs can be grouped into two clusters including i) measures contributing to minimisation of building loads, and ii) measures that help buildings to meet the required loads by using less energy. Examples of the first group are largely design-centric such as the energy-efficient design of building envelope, building orientation, interior layout, solar shading, energy-conscious behaviours of occupants, or window-to-wall ration and etc. (Wei and Skye 2021). The second group entails measures that support the use of energy-efficient equipment such as mechanical systems (e.g., HVAC and DHW) and appliances such as lighting, refrigerator, washing machines, dryers, etc in buildings (Wei and Skye 2021).

This is also echoed in the findings of Attia et al., (2013) that surveyed the experts' opinions about choosing energy-efficiency measures for optimising the design of NZEBs. The results showed that experts often optimised mechanical systems (53%) and control systems (53%), followed by building envelopes (50%). Other variables such as layout & geometry (25%), internal gains (18%), occupancy (11%), and location & climate (7%) were less often optimized, perhaps because these parameters are decided earlier in the design process prior to involving energy designers. As for optimization objectives for designing NZEBs, the study found that experts selected energy (100%) and cost (64%) as the objective functions with the highest importance, followed by comfort (36%), carbon emissions (18%), lighting (7%), and indoor air quality (4%). Studies have also reported achieving a significant reduction in building energy consumption by employing energy efficiency measures (Crawford et al., 2016; Shin et al., 2019). One possible path for future versions of BEERs is to advocate for adoption of energy efficiency measures that can mitigate total life cycle energy and carbon impacts of buildings. In this regard, the paper published by Pomponi and Moncaster (2016) is probably one of the most comprehensive studies that introduces seventeen strategies for mitigating buildings' life cycle environmental impacts. The use of materials with lower embodied carbon, better design, increased reuse of construction materials with high embodied energy and embodied carbon, and stronger policy drivers are a number of key measures recommended by (Pomponi and Moncaster, 2016). Further, it was conclusively stated that the reduction of total building life cycle environmental impacts of buildings can only be achieved via a pluralistic approach as no single mitigation strategy alone seems to be effective towards this end. The agenda of BEERs' future generation should also reflect on promoting energy efficiency strategies/measures that can support mitigation of total life cycle environmental impacts of buildings.

7.3 The need for extending the coverage of current building energy efficiency regulations

Chapter 5 investigated the significance of embodied energy impacts associated with building energy efficiency regulations (BEERs) of Australia. The findings indicate that an increase in operational energy efficiency can lead to an overall reduction in life cycle energy use of buildings. The results showed that the total life cycle energy usage was decreased from 1,268 –1,844 GJ for standard 6-star buildings to 593.0–1,173 GJ for highly energy-efficient buildings. However, it is revealed that embodied energy becomes dominant as operational energy reduces. The analysis showed that embodied energy can increase significantly from 253–736 GJ to 299–877 GJ when transitioning from 6.0-stars to buildings with energy efficiency rating equivalent to 8.7-stars. This shows that the exclusion of embodied energy from the current Australian BEERs leads to ignoring 50–75 percent of energy usage associating with buildings.

Implementation of BEERs while they have limited scope may impact the transition of Australian residential buildings toward achieving a comprehensive reduction of energy and carbon consumption in the built environment. Hence, it is incumbent upon future policies to extend the coverage of current BEERs in order to incorporate the impacts of embodied energy. Therefore, this study recommends that the trajectory developed to provide guidelines for shifting the Australian building sector should be revised to ensure the minimisation of total building life cycle energy impacts in order to reduce greenhouse gas emissions from the building sector. In this regard, certain measures should be taken into consideration to streamline the process of BEERs' coverage in Australia.

Chapter 6 discussed the necessity of considering changes in the three pillars of building policy implementation, namely "sticks", "tambourines", and "carrots" in order to accommodate the inclusion of embodied energy. Therefore, this chapter provides tailored recommendations for future building policies in Australia to account for the impacts of total building life cycle energy performance.

Sticks: adjustments for building energy efficiency regulations

As previously discussed, sticks symbolise regulations, codes, and standards that provide a benchmarking basis for identifying buildings that fail to meet the requirements. This study recommends two major changes in the coverage of current Australian BEERs.

First, the impacts of embodied energy relating to building designs should be included in the current regulations. To this end, an energy budget should be formulated for different climate zones of Australia introducing minimum requirements for the total life cycle energy performance of buildings. The energy budget that is currently implemented in Australia only accounts for thermal loads (i.e., cooling and heating) of buildings (NatHERS, 2016). Therefore, the scope of this scale should be extended to include embodied energy in combination with thermal loads of buildings. The framework developed by this study can be utilised to standardize the definition of system boundaries, determining which building components or parameters should be taken into consideration for calculating embodied and operational energies. The proposed framework comprehensively captures all the parameters contributing to the computation of buildings' total life cycle energy performance.

Second, this study recommends adopting a stepwise approach for incorporating embodied energy into the BEERs. Chapter 4 introduced a four-level framework representing different degrees of inclusion to account for the embodied and operational impacts. The use of a stepwise approach offers flexibility in assessing buildings' environmental impacts when dealing with data unavailability (Omrany et al., 2021). Regarding embodied energy, this study recommends that future BEERs should mandate the assessment of superstructures, substructures, finishes, and renewable energy systems as the minimum data requirements. This requirement can be gradually increased in the following mandating the assessment of other components and building life cycle stages as suggested in the framework developed in Chapter 4, so all buildings can achieve life-cycle net-zero energy by 2030.

The recommended approach should be accompanied by developing databases containing embodied energy impacts of construction materials that are calculated with the consideration for Australian contexts, for example, economy, construction industry, technologies, among others. The Environmental Performance in Construction (EPiC) is an example of a database that contains embodied energy coefficients of over 250 common construction materials in Australia (Crawford et al., 2020). These databases need to be periodically updated in order to represent the actual environmental impacts of buildings. It is also important that the environmental product declarations (EPDs) for building materials is enforced in Australia to provide up-to-date quantified environmental data relating to construction materials. In this regard, the international standards such as ISO 21930 (ISO 21930:2017) are beneficial by providing principles, specifications, and requirements to develop EPDs for construction products and services, construction elements and integrated technical systems used in any type of construction works.

In parallel, software should be developed enabling practitioners to carry out whole building life cycle analysis via linking building designs with the embodied energy databases. Currently, there are four software programmes, namely AccuRate Sustainability, FirstRate5, BERS Pro, and HERO being utilised for evaluating energy performance of buildings in Australia (NatHERS, 2021). All of these tools employ one calculation engine, the Chenath Engine that was developed and is maintained by CSIRO (NATHERS, 2019). The approach of these tools towards calculating the thermal loads of buildings is represented in equation 1. As shown, the total energy load (EL) is calculated by summing the total heating load (HL) (MJ/. annum) and total cooling load (i.e., the sum of the sensible and latent cooling loads) (CL) (MJ/. annum) and then dividing by the conditioned floor area (CFA) (m^2). The Chenath Engine uses the area adjustment factor (AAF) to adjust the total energy load in accordance with the conditioned area. The use of AAF increases energy loads for buildings with larger conditioned floor areas and decreases the energy loads for buildings with smaller conditioned floor areas in proportion to the total building surface area to floor area ratios of a range of dwellings in the particular climate zone (NATHERS, 2012).

$$EL = \left(\frac{HL+CL}{CFA}\right) \times AAF \qquad \text{Equation (1)}$$

The current calculation tools suffer from a number of limitations. First, these tools assume a standard occupancy profile and disallow users to modify it. As a result, the calculation engine sets assumptions on the internal heat loads and the resultant demands for active heating and cooling. These assumptions include latent heat which is related to the changes happening in the moisture content of the air and sensible heat that is generated by occupants, cooking, lighting, and electrical appliances (NATHERS, 2012). Previous studies showed that considering such assumptions may lead to significant variations between actual and simulated estimates of the energy performance of buildings (Daniel et al., 2015; Daniel et al., 2017; Williamson et al., 2010). In a study, Daniel et al. (2015) examined the effects of occupant behaviours in low energy houses on the energy rating systems in Australia. The results indicated the failure of the current regulatory rating scheme to adequately reflect actual heating and cooling practices in low-energy dwellings – thus, the energy usage within the studied cases is overestimated. Another issue of concern with the current tools is that the users cannot create their own materials within the library, and they are limited by the choices of generic materials, insulation (bulk) materials and air gaps provided for them (NATHERS, 2019). This limitation may deter the use of new construction materials into the building sector of Australia. Therefore, future generations of these tools should address these limitations.

This study would also like to draw attention to the need to extend the coverage of the current Australian BEERs to account for the impacts of all parameters contributing to the operational energy usage of buildings including thermal (i.e., heating and cooling) and non-thermal (i.e., domestic hot water, electrical appliances and equipment, ventilation, lighting, and cooking) loads. As previously discussed, the current Australian regulatory rating system only considers the impacts of thermal loads and excludes the energy consumption driven by other parameters such as electrical appliances, lighting, or cooking. This limitation is primarily caused by the unmodifiable occupancy profile of the software. The recent report issued by the International Energy Agency (IEA) showed that the total energy consumption led by electrical appliances, lighting, and cooking in Australia amounted to 23%, 6%, and 6%, respectively (IEA, 2018). This confirms that a limited approach can lead to underestimating the actual energy performance and environmental impacts of buildings. As a result, this could compromise taking effective actions toward minimising the energy usage of buildings at the early stage of building design. Therefore, this study recommends that future generations of building policies should consider extending the coverage of current BEERs to accommodate not only embodied energy but also all the parameters leading to the thermal and non-thermal energy usage of buildings.

The framework proposed in chapter 6 can be employed to account for the impacts of total building life cycle energy impacts.

Tambourines: engagement of public views

In the context of building sector, tambourines represent the measures implemented in order to raise public knowledge about compliance requirements and energy-saving strategies. In this regard, it is important to increase awareness about the importance of incorporating embodied energy impacts into the current BEERs of Australia by launching different campaigns and workshops. The benefits and co-benefits of such a pivotal change in the current mindset of Australian building policies should be elucidated for the targeted communities. Moreover, proactive training is needed to ensure that practitioners engaged in the building sector have expertise in assessing life cycle energy (or environmental) performance of buildings. Currently, the Australian government is administrating a wide range of training courses teaching energy efficiency practices in the construction industry including accredited training, on-the-job learning, government workshops, and programs offered by professional and industry associations (Energy Efficiency Training, 2021). The inclusion of embodied energy impacts into the current regulatory rating system requires launching training courses to educate individuals on the tools, procedures, and standards for carrying out the life cycle assessment. The training should also increase knowledge about the importance of standardising system boundary conditions as well as elaborating on the data requirements for each level of the multi-layered framework when assessing total impacts of buildings' life cycle energy performance.

In parallel, it is of great importance to conduct a comprehensive survey soliciting the opinions of all professions working across the building sector about the barriers facing the mandatory inclusion of buildings' embodied energy assessments into the current BEERs. Such a survey should also seek opinions on opportunities for overcoming the identified barriers. The early involvement of key stakeholders makes it easier to identify and resolve any potential concerns or barriers related to the inclusion of embodied energy in the BEERs prior to finalisation. This increases the likelihood that stakeholders will support the implementation of the new version of BEERs once enacted. Currently, there is no study that has explored the perspectives of Australian stakeholders about the potential barriers to potentially impede the incorporation of embodied energy into building energy policies.

Carrots: the need for launching incentives

The carrots represent incentives used in different forms such as subsidies, rebates, and loans to encourage better practises in the construction industry. The exercise of incentives coupled with penalties (i.e., sticks) assures the alignment of stakeholders' interests with the desired policy outcome, such as code implementation. Penalties used to be the most common tools for the execution of building policy codes by national and local governments. Examples of such an approach could be the refusal of construction and occupancy permits, fines for non-compliances construction, or suspending the licenses of third parties who fail to enforce the code appropriately (Evans et al., 2017). However, several countries have looked into employing "carrots" or incentives, to further enhance compliance, particularly where requiring comprehensive compliance through local governments is difficult due to capacity and/or willingness, or where they want to encourage construction that exceeds the code. For instance, several cities in India have opted to decrease zoning requirements for green or code-compliant buildings (Evans et al., 2017).

Currently, the Australian government offers a range of incentives to promote energy efficiency in the building sector. The electricity feed-in tariff for renewable energy is one example that pays for surplus electricity produced by small-scale solar photovoltaic (PV) or wind power systems (Overview of Electricity feed-in tariff, 2021). The Australian government also offers several programs that help residents with the costs associated with purchasing renewable technologies. For instance, the Small-scale Renewable Energy Scheme assists households and small businesses across Australia with the purchase costs of installing small-scale renewable energy systems such as PV, wind turbines, hydro systems, solar water heaters, and air source heat pumps (Overview of Small-scale Renewable Energy Scheme, 2021). The Retailer Energy Productivity Scheme is another scheme introduced by the South Australian government to save energy and support energy productivity for households, businesses, and the broader energy system, with a focus on low-income households (Overview of The Retailer Energy Productivity Scheme, 2021; Retailer energy productivity scheme, 2021). This scheme encourages the installation of "efficient lighting products", "low-flow showerheads", "standby power controllers", "ceiling insulation", "high-efficiency appliances", and "efficient water heaters".

Regarding the inclusion of embodied energy, incentives can be granted to buildings with low life cycle energy or environmental impacts, as determined by the regulatory rating system. The implementation of this approach can positively contribute to reducing the use of energy (or carbon)-intensive products in the building sector, limiting their impacts on national carbon emissions while encouraging cleaner production of construction products. To achieve a thorough understanding of the incentives encouraging the construction of buildings with low life cycle energy usage, comprehensive surveys can be conducted seeking the opinions of different stakeholders involved in the building sector of Australia. Indeed, the integrated policies combining the three pillars mentioned above (i.e., sticks, tambourines, and carrots) can effectively address the promotion of best practices in constructing low life cycle energy buildings in the sector.

7.4 Change of paradigm: from cost-effective operational energy to cost-effective life cycle energy

Chapter 1 illustrated the agenda of the current trajectory for low-energy buildings (TLEB) in Australia. TLEB aims to realise the state of energy or carbon zero in the sector by identifying cost-effective opportunities that can contribute to minimizing energy bills of households such as increasing the thermal performance of buildings' envelopes or using energy-efficient appliances (Trajectory for Low Energy Buildings, 2019a; Trajectory for low energy buildings, 2019c; Trajectory for low energy buildings, 2019b). It is axiomatic that a more energy-efficient building results in lower energy bills. However, there is a limitation regarding the willingness of the market to embrace the cost-effective measures introduced by policy. Hence, there is a plethora of research in recent years to understand the trade-offs between the optimization of buildings' operational energy and costs associated with incorporating these measures (Wang et al., 2020).

This study argues that the current scope of BEERs should be extended to accommodate the total life cycle energy impacts. As such, it recommends that the trajectory for low-energy buildings should promote the adoption of cost-effective measures with the capacity to reduce total life cycle energy consumption in the building sector. The cost-effectiveness of such measures should be quantified based on their life cycle cost implications. Those involved in construction projects often tend to focus on capital investment and construction expenditures without considering buildings' long-term operating costs (Laustsen, 2008). These parties are mainly concerned with the direct costs and may be reluctant or unable to assess future expenses including those for energy and other resources. The majority of actors in building projects also lack the skill of carrying out lifecycle cost analysis to steer construction practices toward improving future efficiency. In this regard, the Australian research community can be supportive of the change in the paradigm of building energy efficiency policies by identifying lifecycle cost-effective measures that can mitigate the life cycle energy (or environmental) performance of buildings. The current study has been able to quantify the impact of including or excluding embodied energy in life-cycle energy assessments of buildings, and this needs further studies that investigate the impact of embodied energy on the life-cycle costs of buildings.

7.5 Limitations and direction future research

This section aims to highlight a number of limitations concerned with this thesis. First, the framework proposed in chapter 6 has been developed based on the examination of life cycle energy performances of residential case studies retrieved from academic sources such as Web of Science, ProQuest, and Scopus. Nevertheless, there are case studies from industry and commercial practices that could also be examined in order to further develop the framework. The literature review was also limited to residential buildings, excluding non-residential cases such as commercial buildings. Future studies can improve this limitation by examining life cycle energy performance of different building types. This will help the framework to become more comprehensive. Future studies can also use guidelines and standards developed by international nongovernmental organizations such as ISO 21930 (ISO 21930:2017) and ISO 21678 (ISO 21678:2020) for further development of the framework. Second, this research tested the application of the proposed framework using case studies via a simulation approach. The framework's applicability can also be investigated qualitatively by conducting focus group research to gather the perspectives of LCA and construction practitioners in order to identify potential areas for the future development of the framework.

This thesis has proposed a framework consisting of six dimensions that encapsulate a wide array of attributes associated with the estimation of buildings' life cycle energy performance. However, the investigation of possibilities for improving components of each dimension was beyond the scope of this thesis. For instance, the methodological dimension of the framework has six components including i) method for assessment of embodied energy, ii) background database for embodied energy assessment, iii) type of energy, iv) unit of measurement, v) parameters contributing to operational energy assessment, and vi) method for assessment of operational energy. Since the scope has been limited to proposing a framework for standardising LCEA assessment, this study has not contributed to improving calculation methodologies for the assessment of operational embodied energies and emission impacts related to the operational and embodied performance of buildings. As such, future research can build on this limitation and improve components and sub-components of each dimension.

This thesis has selected ‘energy’ as the unit of assessment for measuring environmental performance of buildings since it is a universal metric for the quantitative evaluation of a process or a phenomenon. The ‘energy’ is also a fundamental unit needed to understand carbon emission impacts of buildings and the extent to which the building sector is contributing to global warming. Therefore, the calculations carried out in chapters 5 and 6 in order to evaluate operational and embodied energies have only considered the life cycle energy impacts of the case studies. This limitation can be improved in future research by investigating life cycle emission impacts of case studies using the framework proposed by this thesis. In addition, considerations regarding life cycle emission impacts can be coupled with the guideline provided by the Climate Active Carbon Neutral Standard for Buildings that has been recently launched as a voluntary building standard to manage GHG emissions and realise carbon neutrality in Australia (Carbon Neutral Buildings, 2019). These standards outline best-practice guidance on how to measure, reduce, offset, validate, and report emissions related to buildings’ operation.

Chapter 8. Conclusion

The Australian residential sector is one of the key contributors to the overall energy consumption and greenhouse gas (GHG) emissions. Currently, Australia is experiencing a major housing boom with about 200,000 new dwellings being built each year; and considerably more are needed annually in order to accommodate the projected population growth of over 40 million by 2050. Hence, it is expected that this sector would have even a higher impact on energy consumption and the emission of GHG in the future. In this regard, building energy efficiency regulations (BEERs) can play a significant role in mitigating the environmental impacts of the residential sector. BEERs often impose minimum requirements on the amount of energy that buildings are required to consume within a year to remain operational. Generally, energy is consumed in two main forms: thermal (i.e., heating and cooling) and non-thermal loads (i.e., domestic hot water, electrical appliances and equipment, ventilation, lighting, and cooking) over a building's lifespan. The coverage of BEERs differs from one country to another in terms of accounting for the impacts of parameters leading to energy consumption. In Australia, the first set of national mandatory energy efficiency standards was enforced in 2003. Ever since, energy efficiency requirements of building codes of Australia (BCA) only consider thermal loads of building designs, namely heating and cooling loads.

Australia now opts to strengthen its measures towards reducing energy consumption in residential buildings. Recently, the *Trajectory for Low Energy Buildings* (TLEB) has been endorsed to introduce a national plan for achieving zero energy and carbon-ready buildings by 2030 in the Australian building sector. The TLEB aims to gradually increase the minimum mandatory requirements set by Australian BEERs for new and retrofitted buildings. In this sense, the BEERs will be utilised as a vehicle to deliver zero energy and carbon-ready buildings. Nevertheless, the transition of residential buildings toward zero energy using the current BEERs may never be truly realised due to the limited coverage of current regulations. This study argues that the coverage of current BEERs should be extended to include the embodied energy impacts of buildings, besides addressing operational energy. Otherwise, energy consumption or carbon emissions simply move from one stage of building life cycle to another without yielding an overall net-zero energy use.

This thesis aims to encourage the incorporation of embodied energy into the BEERs of Australia. To this end, the significance of embodied energy associated with Australian BEERs was demonstrated. This was done by assessing the total life cycle energy performance of more than 2,300 cases of residential buildings ranging from standard 6-star buildings to highly energy-efficient buildings. The results revealed that the proportion of embodied energy significantly increases from 20–40% to 50–75% in transitioning from a standard 6.0-star building to a highly energy-efficient 8.7-star building, respectively. This underlines the importance of embodied energy when moving toward energy neutrality in the building sector.

Further, this study puts forward a comprehensive framework that enables the incorporation of embodied energy into BEERs by standardizing system boundary definitions in life cycle energy assessment (LCEA). To realise this objective, comprehensive reviews of the literature related to the application of LCEA in residential buildings were conducted. As a result, more than sixty studies were analysed with respect to the approach taken toward defining system boundary conditions. The findings indicated that the current trend of LCEA application in residential buildings suffers from significant inaccuracy because of incomplete definitions of the system boundary, in tandem with the lack of consensus on measurements of operational and embodied energies. Therefore, there is a need to develop a comprehensive framework through which system boundary definition for calculations of embodied and operational energies can be standardized.

This study further proposed a framework to standardise system boundary conditions in LCEA analysis using the findings of a literature review. The framework consists of six distinctive dimensions, that is, temporal, physical, methodological, hypothetical, spatial, and functional. These dimensions encapsulate 15 components collectively, including ‘stages of building life cycle’, ‘building components and systems’, ‘elements beyond building scales’, ‘method for assessment of embodied energy’, ‘background database for embodied energy assessment’, ‘type of energy’, ‘unit of measurement’, ‘parameters contributing to operational energy assessment’, ‘method for assessment of operational energy’, ‘assumptions’, ‘building lifespan’, ‘climate’, ‘building site location’, ‘building type’, and ‘density’.

The proposed framework has two main characteristics. First, its application facilitates defining the conditions of a system boundary within a transparent context. This consequently leads to increased reliability of LCEA results for decision-making purposes since any particular conditions (e.g., truncation or assumption) considered in establishing the boundaries of a system under study are apparent.

Second, the use of a framework can also provide a meaningful basis for cross comparison of cases within a global context. This characteristic can further result in identifying best practices for the design of buildings with low life cycle energy use performance. Furthermore, this study applied the proposed framework to analyse the LCEA performance of a case study in Adelaide, Australia. Thereafter, the framework was utilized to cross-compare the achieved LCEA results with a case study retrieved from literature in order to demonstrate the framework's capacity for cross-comparison. The results indicated the capability of the framework for maintaining transparency in establishing a system boundary in an LCEA analysis, as well as a standardized basis for cross comparison of cases.

This study also offers a number of recommendations in order to streamline the process of incorporating embodied energy into the Australian BEERs. Regarding the code implementation, this study recommends two major changes in the coverage of current BEERs of Australia. First, the impacts of embodied energy relating to building designs should be included in the current regulations. To this end, an energy budget should be developed for different climate zones of Australia introducing minimum requirements for the total life cycle energy performance of buildings. Further, this study recommends adopting a stepwise approach for incorporating embodied energy into the BEERs. This can be done by mandating the assessment of superstructure, substructure, finishings, and renewable energy systems as the minimum data requirements. This requirement can be gradually increased after mandating the assessment of other components and building life cycle stages as suggested in the framework developed in Chapter 4, with all buildings being life-cycle net-zero energy by 2030. The recommended approach should be accompanied by developing databases containing embodied energy impacts of construction materials that are calculated with the consideration of Australian contexts, for example, economy, construction industry, technologies, among others. In parallel, software should be developed enabling practitioners to carry out whole building life cycle analysis via linking building designs with the embodied energy databases.

This study also recommends extending the coverage of current BEERs of Australia to account for the impacts of all parameters contributing to the operational energy usage of buildings including thermal and non-thermal loads. The inclusion of embodied energy impacts in the current regulatory rating system also requires increasing the awareness of stakeholders about the importance of incorporating embodied energy impacts into the current BEERs of Australia by launching campaigns and workshops. The benefits of such a change should be elaborated for the targeted communities by launching proactive training.

As highlighted, it is important to conduct a comprehensive survey soliciting the opinions of all professions working across the building sector about the barriers facing the mandatory inclusion of buildings' embodied energy assessments into the current BEERs. Early involvement of key stakeholders makes it easier to identify and resolve any potential concerns or barriers related to the inclusion of embodied energy in the BEERs prior to finalisation. It is also recommended that incentives be granted to buildings with low life cycle energy or environmental impacts, as determined by the regulatory rating system.

This study also recommends that the trajectory for low-energy buildings should promote the adoption of cost-effective measures with the capacity to reduce total life cycle energy consumption in the building sector. The cost-effectiveness of such measures should be quantified based on their life cycle cost implications.

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Appendix I – Manuscript: Application of life cycle energy assessment in residential buildings: a critical review of recent trends

sustainability

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Review

Application of Life Cycle Energy Assessment in Residential Buildings: A Critical Review of Recent Trends

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Abstract: Residential buildings are responsible for a considerable portion of energy consumption and greenhouse gas emissions worldwide. Correspondingly, many attempts have been made across the world to minimize energy consumption in this sector via regulations and building codes. The focus of these regulations has mainly been on reducing operational energy use, whereas the impacts of buildings' embodied energy are frequently excluded. In recent years, there has been a growing interest in analyzing the energy performance of buildings via a life cycle energy assessment (LCEA) approach. The increasing amount of research has however caused the issue of a variation in results presented by LCEA studies, in which apparently similar case studies exhibited different results. This paper aims to identify the main sources of variation in LCEA studies by critically analyzing 26 studies representing 86 cases in 12 countries. The findings indicate that the current trend of LCEA application in residential buildings suffers from significant inaccuracy accruing from incomplete definitions of the system boundary, in tandem with the lack of consensus on measurements of operational and embodied energies. The findings call for a comprehensive framework through which system boundary definition for calculations of embodied and operational energies can be standardized.

Keywords: life cycle energy assessment; life cycle assessment; residential buildings; energy efficiency; sustainability

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1. Introduction

The residential sector is responsible for consuming 27% of energy and emitting 17% of the greenhouse gas (GHG) emissions worldwide [1,2]. This percentage differs between countries due to varying climatic conditions, energy requirements, social and economic situations, and the availability of main energy resources [3]. Due to the significance of this sector in mitigating global climate change, considerable efforts have been undertaken across many countries to reduce energy consumption in residential buildings by legislating various regulations and building codes. These regulations are mainly in place to minimize the environmental impacts associated with energy use from heating, cooling, and lighting [4]. However, recent studies have shown the reduction of building operational energy use can lead to an increase in total building life cycle energy use due to increasing the embodied energy from the building components [5–8]. Therefore, research into investigating embodied energy using the life cycle energy assessment (LCEA) approach has been increasing in recent years, with numerous detailed case studies of individual buildings developed by academics.

The LCEA is a simplified version of the life cycle assessment (LCA), which only accounts for energy inputs at different stages of the life cycle, including both embodied energy and operational energy [9]. The increasing amount of research has however caused an issue of variations in results presented by LCEA studies, in which apparently similar case studies exhibited different results. To date, a plethora of studies have been conducted exploring reasons for variations in the results of LCEA studies [4,10–13]. For instance, Dixit et al. [10] identified key parameters which can lead to varying results in embodied energy analysis, namely system boundary definitions, the methods used for measurement of embodied energy, geography, the type of energy (i.e., primary or secondary energy), age and source of data, data completeness, manufacturing technology, feedstock energy considerations, and temporal representativeness.

The majority of the conducted studies only looked at parameters with potential influence on calculating embodied energy, whereas variations can also be induced from the measurement of building operational energy. Therefore, there is currently a lack of studies adopting a comprehensive approach to seek possible sources of variations throughout the entire process of LCEA analysis while including both operational and embodied energy measurements. To address this gap, the literature relating to the LCEA application in residential buildings has been reviewed with the aim to identify causes of variations in performing LCEA analysis. To this end, we limited the scope of our paper to examining studies published from 2010 onwards. This facilitated the possibility to capture the most up-to-date trends of LCEA application in residential buildings. The identified studies were then analyzed based on their definitions of system boundaries, and methods were applied to estimate embodied energy and operational energy, as well as to interpret the results achieved.

2. An Overview of Life Cycle Energy Assessment (LCEA)

The LCA is an approach for identifying and assessing the environmental impacts of products, services, or processes throughout their entire life cycles, namely extracting raw materials, processing and manufacturing, operation, and end-of-life (EOL) [14–18]. The first sets of LCA standards were established during 1997–2000 by the International Organization for Standardization (ISO), leading to the ISO standards 14040, 14041, 14042, and 14043 [19]. In 2006, the updates to these standards were finalized in which the previous versions were amalgamated into ISO 14040 and 14044 [20,21]. The major feature of an ISO standard is a four-step iterative framework, including a goal and scope definition, inventory analysis, life-cycle impact assessment (LCIA), and interpretation (Figure 1).

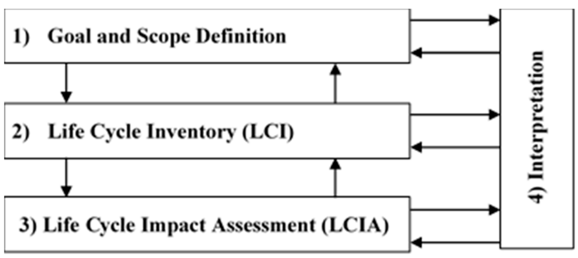

Figure 1. The Life Cycle Assessment (LCA) framework based on International Organization for Standardization (ISO) standard [22].

The first step to perform an LCA analysis is to establish the goals and scope of the study, which encompass defining system boundaries and functional units, as well as determining the quality criteria for inventory data. The life-cycle inventory (LCI) analysis refers to the procedure of collecting data and synthesizing information pertaining to the physical material and energy flows in different stages of the product life cycle. The LCIA is the stage where the environmental impacts of various material and energy flows are quantified and assigned to different environmental impact categories. At the end, the achieved results are finalized for conclusion, recommendation, and decision making purposes.

The LCEA focuses on the evaluation of energy inputs for different phases of the life cycle [9]. Figure 2 demonstrates the system boundary for performing a whole LCEA study, consisting of raw material extraction, material processing and manufacturing, transportation of materials to the construction site, the process of construction, installation, and erection, building operations and its maintenance, and demolition. The life cycle energy of buildings can be sub-divided into embodied and operational energy.

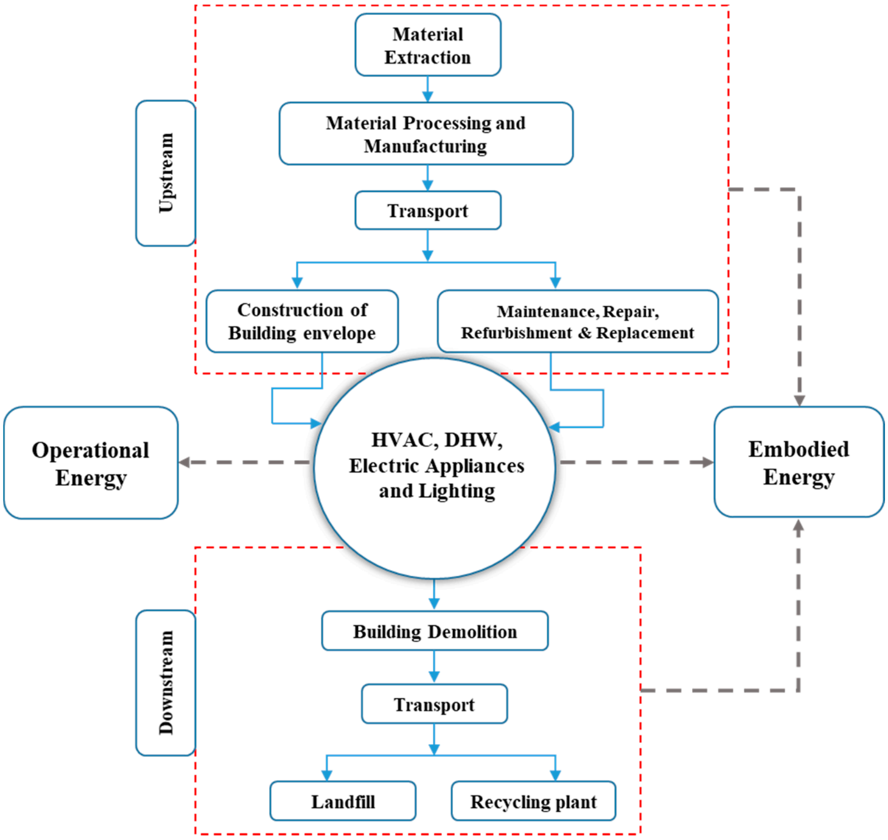

Figure 2. Building life cycle energy (adapted from reference [23]).

Operational energy refers to the amounts of energy consumed in the forms of heating and cooling, domestic hot water (DHW), electrical appliances and equipment, ventilation, lighting, and cooking in order to retain the indoor comfort conditions [24]. The share of operational energy to the total building life cycle energy use is usually higher than the embodied energy [14,23]. As a result, the minimization of this energy has been the focus of many policy-driven schemes developed in different countries to support the construction of energy-efficient buildings.

Embodied energy refers to energy used to extract and refine raw materials, manufacture materials, assemble components, conduct on-site construction, complete EOL processes, and carry out any transportation required between any of these steps [14,15]. Overall, embodied energy can be divided into:

- Initial embodied energy: refers to the quantity of energy incurred for the initial construction of the building including extracting raw materials, processing the extracted materials, and transporting building materials to construction sites and on-site construction and installation.
- Recurring embodied energy: refers to the total amounts of energy embodied in the materials used for maintaining and rehabilitating a building during its life span.
- EOL: refers to the amounts of energy required to demolish the building and to transport the resulted wastages to landfill sites and/or recycling plants.

The LCEA is, therefore, the sum of embodied energy and operational energy of a building. The reliability of results depends on the completeness and accuracy of the data and the robustness of the methodology applied to carry out an LCEA analysis. The following section elaborates on the research methodology used in this paper.

3. Materials and Methods

This paper analyzed instances of the LCEA application in residential buildings using a systematic literature review. The review considered publication materials from various academic databases, namely Scopus, Google Scholar, and Web of Science. The application of multiple search engines to investigate the body of literature covers the weaknesses of one source by using the strength of others [25,26]. The approach to conducting the review consists of three main steps.

During the first step, all LCA-related scholarly research publications (more than 300 papers) from 2010 onwards related to the LCA application in residential buildings were identified based on a comprehensive keyword searching exercise (Table 1).

Table 1. Keywords used in the research approach.

Keywords Applied at the First Stage
Life cycle assessment; sustainability assessment; life cycle energy assessment; operational and embodied energy; life cycle environmental assessment; building energy performance; life cycle assessment tools; building energy consumption; building environmental emissions; sustainable construction; life cycle inventory; sustainable building design; building embodied emissions.

During the second stage, the titles and abstracts of the identified documents were screened to make an initial judgment about the aptness of the publications for inclusion. Here, the key criteria considered for further analyzing the retrieved materials were (i) the studies must apply LCEA, and (ii) the focus of assessment must be on residential buildings. Also, the studies that were not peer-reviewed or written in English were excluded. In addition, we only accounted for the studies that considered primary energy to perform LCEA analysis. The evaluation of building energy performance can be implemented considering either primary or secondary (delivered) energy. In general, these two cannot be directly compared as they contain different quantities of energy. The energy delivered for end-use contains lower amounts of energy than the actual quantities of primary energy utilized to generate and distribute secondary energy. Thus, the impacts of buildings' life cycle energy use on the built environment can be better represented by using primary energy [11].

During the third stage, the selection process was controlled qualitatively by checking the content of all publication materials in order to ensure that only those corresponding to the scope of this paper were chosen for detailed examination. At this stage, studies with a sole focus on investigating embodied energy were not selected for examination, as they were not holistic in their approaches for appraisal of a building's life cycle energy performance. Analogously, studies with unavailable data on buildings' life cycle energy uses were also excluded from further analysis. It is noteworthy to mention that this survey accounted for all types of residential buildings including conventional and low-energy use buildings (e.g., passive buildings, net zero energy building, nearly zero energy buildings), high-rise buildings, as well as buildings located in rural and urban areas. As a result, 26 papers representing 86 case studies across 12 countries were selected. This paper considers different versions of a similar building investigated in one source, as case studies. The following sections provide a detailed analysis of the case studies.

4. Analysis and Results

This section aims to discuss the findings of the reviewed studies. The detailed list of analysis can be found in Appendices A and B (Tables A1 and A2).

4.1. System Boundary Definition

The system boundary refers to a set of variables that delineate the boundary of a particular system and distinguish it from other systems in an environment [12]. The approaches of the reviewed studies to defining system boundaries were analyzed with respect to excluding stage(s) from the building's life cycle, building components considered for embodied energy calculation, parameters considered for operational energy calculations, building life span, and the key assumptions.

4.1.1. Stages Excluded

As indicated in Figure 2, the stages of a building life cycle include raw material extraction, material processing and manufacturing, transport, on-site construction and installation, operational phase, and EOL. A whole LCEA study refers to an assessment which accounts for the analysis of energy usage while considering all stages of building life cycle.

The review shows that only 27% of the studies performed a whole LCEA analysis, while others neglected the impacts of certain stages on total building energy use. It was found that 50% of the studies excluded the EOL from the system boundaries, which is mainly justified due to its minor contribution to the total building life cycle energy use or the lack of clarity on the deconstruction practices after the end of building life service [5,6,27–35]. Amongst those which considered energy consumption at the EOL, studies usually avoided performing detailed analysis to unveil energy usage at this stage. For instance, Crawford [36] added 1% of the total building energy demands in order to account for the energy usage at the EOL stage. Similarly, Devi and Palaniappan [37] added an amount equal to 3% of the total building life cycle energy use to help consider energy usage at the EOL stage. In addition, 'replacement and maintenance' (recurrent embodied energy) has been a subject of exclusion for 27% of the reviewed studies [27,31,37–41] despite the significant effects that this phase may have on the total building life cycle energy use. Studies reported the recurrent embodied energy may represent up to 31% of a total building's embodied energy [30]. In another study, Crawford [36] demonstrated the impacts of recurrent embodied energy can constitute up to 22% of total building life cycle energy demands. Moreover, 'on-site construction', and 'transport' were excluded from system boundaries by 15% and 4% of the reviewed studies, respectively.

4.1.2. Building Components Considered for Measurement of Embodied Energy

The review shows the studies were inconsistent in accounting for the impacts of embodied energy pertaining to building components and systems (Table 2). From Table 2, it can be understood that there is a consensus on considering embodied energy impacts associated with main building components, namely the building envelope (i.e., external walls, roof, and floor). However, the definition of system boundary differs amongst the reviewed studies concerning inclusion of the impacts of embodied energy related to building systems and installations as well as furniture, appliances, and fixtures.

Table 2. Different approaches toward the assessment of building embodied energy.

Author(s)	Building Components	Furniture/Fixtures/Appliances	Elements Beyond Building Scale
Aye et al. [27]	Columns and beams, external and internal walls, external cladding, ceiling, roof, floor, doors and windows, floor tiling, staircase.	NA	NA
Gustavsson et al. [38]	Foundation, floor structure, roof, external and internal walls, doors and windows, balconies, stairs.	Interior fixtures	NA
Dodoo and Gustavsson [42]	Foundation, floor, roof, external and internal walls, insulation, doors and windows, balconies, stairs.	NA	NA
Ramesh et al. [28]	Exterior walls, roof and floor, insulation.	NA	NA
Stephan and Stephan [30]	Exterior walls, roof, floor, building structure, insulation, building systems.	NA	Urban infrastructure, occupants' transport
Atmaca and Atmaca [43]	External and internal walls, doors and windows, roof, floor, wall and roof tiles, insulation, building structure, foundation, façade (plastering, painting).	NA	NA
Rossi et al. [44]	Basement slab, external and internal walls, roof and floor.	NA	NA
Stephan et al. [6]	Building structure and sub-structure, external and internal walls, finishings, floor, roof, foundation, systems (piping and wiring), doors and windows, insulations.	Carpet, fixtures	Urban infrastructure, occupants' transport
Cellura et al. [45]	Electrical systems, solar thermal system, Photovoltaic (PV) systems, air handling unit, thermal plant, domestic hot water (DHW) plant, building sub-structure, external and internal walls, building structure, roof and floor, foundation.	NA	NA
Stephan et al. [5]	Building structure and sub-structure, external and internal walls, finishings, floor, roof, foundation, systems (piping and wiring), doors and windows, insulations.	NA	Urban infrastructure (i.e., roads, power lines, water and gas distribution, and sewage)
Crawford [36]	External walls, roof and floor, doors and windows, paint, building structure, insulation, foundation.	Finishes, appliances, carpet, fitout	NA
Pinky Devi and Palaniappan [31]	External walls, roof and floor, building structural frames, systems (plumbing, firefighting and wiring), painting and plastering, foundation.	NA	NA
Paulsen and Sposto [46]	External and internal walls, painting and plastering, roof and floor, ceiling, windows, indoor and external doors.	NA	NA
Devi and Palaniappan [37]	Building envelope, structural frames/concreting work, finishing (plastering, painting and tiling), doors and windows, sanitary installations, systems (plumbing and water pipes) and steel work (tubes for atrium glazing and stainless steel accessories).	NA	NA
Bastos et al. [33]	External and internal walls, floor, roof, staircases, building structures, windows, external and internal doors.	NA	NA
Ramesh et al. [29]	External walls, roof, widows, PV panels, wind turbine, wiring and installation.	NA	NA
Zhan et al. [47]	External walls, floor, roof, foundation, finishing (plastering, painting and tiling), building structure.	NA	NA
Iyer-Raniga and Wong [48]	Foundations, columns, upper floors, staircases, roof, external and internal walls, windows, external and internal doors, floor and ceiling finishes.	NA	NA
Dodoo et al. [39]	External and internal walls, intermediate floor and ceiling, roof, foundation, windows and doors, elevator and stair, services and installations, finishes.	NA	NA

Table 2. *Cont.*

Author(s)	Building Components	Furniture/Fixtures/Appliances	Elements Beyond Building Scale
Tettey et al. [40]	Building structure, external and internal walls, floor, insulation and finishes, foundation, windows.	NA	NA
Mehta et al. [35]	Building structure, external walls, foundation, roof, floor, and painting.	NA	NA
Zhu et al. [41]	External walls, precast façade, staircase, slab, balcony, painting, windows, finishes.	NA	NA
Bastos et al. [32]	External and internal walls, wooden and concrete floors, staircase, roof, windows, foundations, external and internal doors.	NA	Occupants' transport
Goggins et al. [49]	External walls, foundations and floors, roof, chimney, stairs, PV panels, ventilation systems.	NA	NA
Kristjansdottir et al. [50]	PV system, space-heating system, external and internal walls, foundation, windows and external doors, roof, insulation.	NA	NA
Mistretta et al. [51]	Blinds, electrical system, solar thermal system, PV system, air handling unit, thermal plant, DHW plant, building frame, external and internal walls, support structures, roof, foundations.	NA	NA

Studies also pointed out the possibility of extending their system boundaries to include parameters beyond building elements [5,6,30]. Stephan et al. [5] put forward a framework to account for the impacts of embodied and operational energy of a building while considering the embodied energy of nearby infrastructure (i.e., roads, power lines, water and gas distribution, and sewage) and the transport energy of its occupants. In this framework, they calculated the embodied energy of surrounding infrastructures using process-based hybrid analysis. To do this, the embodied energy of each form of infrastructure was calculated based on the infrastructure density in m/km^2 and attributed to the building based on the population density and the number of users as per Equation (1):

$$\mathrm{LCEE_{if}} = \sum_{i=1}^{I}\left(\mathrm{LCEE_i} \times \mathrm{D_i} \times \frac{\mathrm{NO}}{\mathrm{PD}}\right) \quad (1)$$

where $\mathrm{LCEE_{if}}$ is the life cycle embodied energy of infrastructure in GJ, LCEEi is the life cycle embodied energy of infrastructure i in GJ/m, $\mathrm{D_i}$ is the density of infrastructure i in m/km^2, NO is the number of occupants in the building, and PD is population density in inhabitants/km^2. Additionally, they accounted for the energy used as the result of occupants' mobility. They applied this framework to analyze the life cycle energy usage of two buildings located in Australia and Belgium. The results showed the users' transport constituted 25.4% and 33.8% of the total building life cycle energy demands in a Belgian passive house and an Australian building, respectively. In another study, Stephan and Stephan [30] estimated the life cycle energy use of a residential building in Lebanon considering the energy embodied in users' transport, including both direct and indirect energy requirements. The direct energy refers to mobility process itself i.e., using fuel in the engine of a car, whereas indirect energy refers to all the processes supporting mobility, such as car registration, insurance, manufacturing the car itself, etc. The life cycle transport energy demand of the building's occupants ($\mathrm{LCTE_b}$) was calculated by multiplying the energy intensity of transport modes used in Lebanon (i.e., gasoline cars) by the average traveling distance of occupants using Equation (2):

$$\mathrm{LCTE_b} = \mathrm{UL_b} \times \sum_{c=1}^{C}(\mathrm{DCI_c} + \mathrm{IEI_c}) \times \mathrm{ATD_c} \quad (2)$$

where: $\mathrm{LCTE_b}$ = Life cycle transport energy demand of the occupants of building b, in GJ; $\mathrm{UL_b}$ = Useful life of building b, in years; $\mathrm{DEI_c}$ = Direct energy intensity of car c, in GJ/km; $\mathrm{IEI_c}$ = Indirect energy intensity of car c, in GJ/km; and $\mathrm{ATD_c}$ = Average annual travel distance of car c, in km. The results showed the building life cycle energy demand of the building was dominated by transport energy with a share of 49%, followed by operational and embodied energy with the shares of 33 and 18%, respectively.

From the review, it can be realized that the studies differ according to their approaches for excluding certain stages of building life cycle and measuring embodied energy associated with building components. It was found that the exclusion of building life cycle stages occurs mainly due to the perceived minor impacts of these stages on the total building life cycle energy demand or the uncertainties relating to the fate of building materials at the end of building life. In addition, the reviewed studies were inconsistent in assessing the embodied energy of building components. Although most of the studies only accounted for embodied energy related to building components, the possibility of including embodied energies of parameters such as urban infrastructure or occupants' mobility was also suggested by a number of studies.

4.1.3. Parameters Considered for Operational Energy Measurement

The operational energy measurement depends on the extent to which parameters (i.e., heating and cooling, DHW, electrical appliances and equipment, ventilation, lighting, and cooking) are considered for assessment. From the review, it was found that 27% of the reviewed studies accounted for the impacts of all contributors [5,29,30,32,33,35,36]. It was also revealed that 62% of the studies excluded the impacts of cooking on operational energy use, followed by DHW (38%), electrical appliances (35%), lighting (27%), and ventilation (23%). The exclusion of each parameter can influence total building life cycle energy demands by affecting the proportions of operational energy and embodied energy [52,53]. For instance, Gustavsson and Joelsson [52] showed the share of embodied energy in the total building's life cycle energy use was reduced from 33% to 25% when the scope of the study was extended from only space heating to including the energy associated with household electricity, DHW, and ventilation.

Although none of the reviewed studies has given justifications, their exclusions can be related to the minor influence that each of these parameters could have on operational energy use.

4.1.4. Building Life Span

The life span assumed by the reviewed studies ranged from 50 to 100, with the most commonly used life span of 50 years (Table 3). The assumption of building life span can directly influence the share of both embodied and operational energy. This factor can impact the contribution of embodied energy to the total building life cycle energy consumption by affecting recurrent embodied energy [54,55]. The operational energy can also be influenced by the assumption of building life span as the increase of building life span leads to increasing operational energy, whereas assuming a short life span may result in increasing embodied energy over the building's life cycle owing to more frequent substitution of the whole building [56]. In a study, Rauf and Crawford [55] investigated the relation between a building's life span and its embodied energy by using a comprehensive hybrid embodied energy assessment technique. The results unveiled that extending the building's life span from 50 to 150 can result in reducing the life cycle embodied energy demands of the building by 29%.

Table 3. Frequency of building life span.

Building Life Span	Frequency of Use
50 years	15
60 years	2
70 years	3
75 years	3
80 years	1
100 years	3 *
Total	27

Note: * Gustavsson et al. [38] considered two life spans: 50 and 100.

4.1.5. Assumptions

The assumptions are of the utmost importance in conducting LCEA studies due to their effects on the completeness and accuracy of the achieved results [19]. It was found that the assumptions made by the reviewed studies were associated with different phases of the building life cycle, including the initial, on-site construction, operation, replacement and maintenance, and EOL stages (Table 4).

Table 4. Overview of the assumptions made by the reviewed studies.

Stage of Building Life Cycle Targeted	Assumption	Reference
Operation phase	The schedule for operating heating and cooling systems is assumed to remain unchanged during the entire course of life cycle assessment; The detailed occupational schedules and gains are not considered; The efficiency of heat pump system is assumed to be constant over time; The annual operating energy is assumed to remain consistent in throughout the entire building life span; The effects of climate change and occupants' behaviors in the future are not taken into consideration; The resource mix supplying electricity to the buildings is assumed to be static;	[27–29,33,42]
Initial embodied energy	Australian database of construction materials is used to calculate the embodied energy; Australian input–output-based hybrid embodied energy intensities are used for a case study located in Belgium; Using I–O data relating to production stage that occurred over a decade ago;	[6,30,36,43,48]
Embodied energy of on-site construction	All the manufacturing processes are assumed to be undertaken in one place; The primary energy used for on-site construction is assumed to be 80 kWh/m^2; The primary energy used for on-site construction is assumed to be 4% of the material production primary energy; 80 and 160 kWh/m^2 are assumed for the on-site energy consumption of wood and concrete building systems respectively;	[38–40]
Embodied energy of replacement and refurbishment	The structural elements of the building are assumed to have the same service life as the house; The embodied energy associated with replacement, refurbishment and repair of materials and products are assumed to be 5% every 10 years; The replacement lifetimes of construction materials in US are used for LCEA of buildings in Australia; The standard construction methods and materials are assumed to remain the same during the entire building life span;	[43,44,48]
Embodied energy of EOL	5% waste of material is assumed during construction; 90% of the wood-based demolition materials are assumed to be recovered while 10% decays into atmosphere; Only one type of fuel is assumed to be used for transporting the wastages; To account for the contribution of EOL stage, 1% of the total life cycle energy demand is summed to the final achieved figure; The embodied energy associated with EOL is assumed to be 3% of the total building life cycle energy demand; The primary energy use for demolition of wood and concrete are assumed to be 10 and 20 kWh/m^2 respectively; All of the materials are assumed to be landfilled at the EOL stage; It is assumed that demolition energy will not exceed 10 kWh/m^2	[36–40,42,43]

The first group of assumptions involved the operation stage. It was noted that the estimation of a building's operational energy is commonly carried out for one year, and then the achieved figure has been multiplied by the number of years in which the LCEA study is conducted. Studies assumed that operational energy use would remain unchanged during the entire course of assessment. Although making such an assumption was only declared by a number of authors (as citied in Table 4), it can be mentioned that all the reviewed studies have made a similar assumption. Assuming a constant operational energy consumption implies that the building would have a constant schedule for heating and cooling systems, there would be unchanged patterns of occupancy (e.g., family size or behaviors), or heating and cooling systems would not be subject to depreciation. In another study, Iyer-Raniga and Wong [48] assumed that the resource mix used to supply electricity of the building would be unaltered during 100 years of building operation, despite hefty investments being made globally to promote utilizing renewable energy sources.

The second group contains assumptions related to the estimation of initial embodied energy. Due to the lack of available and reliable data, studies applied databases from other countries in order to calculate embodied energy. For instance, Stephan and Stephan [30] used an Australian database containing embodied energy coefficients for building materials to calculate the embodied energy of a residential building in Lebanon. In another study, Stephan et al. [6] used Australian input–output-based hybrid embodied energy intensities to estimate the embodied energy of a passive building in Belgium. Likewise, Devi and Palaniappan [37] used the Inventory of Carbon and Energy (ICE), which is a database developed in the EU, to estimate the embodied energy of a residential building in India. This assumption may potentially compromise the quality of LCEA results due to inherent differences between the two countries, e.g., different economic sectors (in case of developing input–output matrix) or different construction practices and technologies. The justification given for making such assumptions is commonly related to the absence of a locally developed database.

Assumptions are also made to estimate embodied energy associated with on-site construction, replacement and refurbishment, and EOL stages. Gustavsson et al. [38] assumed primary energy used for on-site construction of an eight-story wood framed apartment is 80 kWh/m^2. Dodoo et al. [39] also assumed that on-site construction embodied energy is equivalent to 4% of the material production primary energy. As shown in Table 4, assumptions were made on replacement and refurbishment of the buildings. Atmaca and Atmaca [43] assumed that the standard construction methods and practices would be unchanged during the entire building life span. The substitution of building materials during the use phase of the building with the exact same material is another assumption, which is not commonly specified but has been utilized by the majority of the LCEA studies. For this assumption, construction materials would be replaced by similar materials with the same energy intensities. Regarding to the EOL stage, studies assumed different shares of energy consumptions [36,37,39]. For instance, Devi and Palaniappan [37] assumed that this stage consumes 3% of the total building life cycle energy demand. Dodoo et al. [39] also assumed the demolition at the EOL stage would not exceed 10 kWh/m^2.

The majority of these assumptions were made to mitigate the complexity involved in embodied energy calculation or due to the lack of reliable data. Considering the potential impacts of assumptions on results, it can be recommended for LCEA studies to clearly mention assumptions while justifying their contextual applicability and appropriateness. Moreover, assessing the impacts of each assumption on the LCEA results could be an interesting topic for future research.

4.2. The Assessment of Embodied Energy

The embodied energy assessment commences with obtaining qualitative and quantitative data for each unit process that will be included within the system boundaries. For buildings, these data are collected by investigating technical specifications or drawings of buildings, site surveys or using contractor records. A similar approach was undertaken by the reviewed studies to collect the required data. For instance, Gustavsson et al. [38] used construction drawings and personal communication with staff of the construction industries to obtain the total quantities of building materials.

Once the required data are collected, the method to quantify embodied energy needs to be determined. Three major approaches are commonly used for the calculation of embodied energy, including the process-based approach, economic input-output (I-O) approach, and input-output-based hybrid approach. The process-based is a traditional approach, which is preferred when the physical flow of goods and services can be easily identified and traced. However, this method may become overwhelmingly complicated when inputs and outputs are numerous [43]. Moreover, it is prone to errors induced by the subjective removal of the iterative effect from the upstream production system [41]. Alternatively, the economic I-O approach follows a top-down approach and treats the whole economy as the boundary of analysis in order to arrive at consistent boundary definitions between studies. The economic I-O is based on the flow of materials in an economic structure aiming to determine the amount of primary energy required to produce a specific product or service. Although the application of this approach rectifies the incompleteness of the system boundary for capturing the upstream effects, it still lacks product-specific data. Hence, an I-O based hybrid approach was proposed to combine both process-based and economic I-O approaches and therefore cover the inputs from the entire upstream supply chain [57].

From the review, it was found that 62% of the reviewed studies applied the process-based approach to assess embodied energy, while 27% utilized the I-O based hybrid approach. Furthermore, 11% of the reviewed studies did not discuss their approaches for measurement of embodied energy. The magnitude of estimates achieved by the reviewed studies for embodied energy largely depends on the approach used for the calculation of this energy. Studies with the I-O based hybrid approach were more likely to obtain a high value for embodied energy since this approach captures energy usage embedded in both upstream and downstream stages of the building life cycle [7,30,57].

To calculate embodied energy associated with building materials, a background database containing datasets that represent technical and economic context must be selected. From the review, it was found the required background data were retrieved from two primary sources: 'literature', and publicly or commercially available databases (Table 5). The 'literature' refers to the embodied energy coefficients of previously published LCEA studies. Overall, 19% of the reviewed studies solely relied on the literature for calculating embodied energy. The mere reliance on literature may potentially compromise the quality of the achieved results, since the background databases are not representative of the building's regional contexts (construction technology, climatic conditions, etc.).

Table 5. Databases applied by reviewed studies.

Database	Developer	Data Coverage	Access	Boundary	LCI Method
SimaPro	PRe' Consultants, Netherlands	Ecoinvent, US LCI, Danish input-output database, Dutch input-output database, LCA food database, Industry data	Licensed access	Cradle-to-grave	Process- based and I-O method
Ecoinvent	Ecoinvent centre, Swiss	General products and processes including energy, transport, building materials, chemicals, washing agents, paper and board, agriculture, waste management, International data	Licensed access	Cradle-to-gate	Process-based method
ICE	Bath University, UK	Construction and building materials, EU, mostly UK data	Publicly available	Cradle-to-gate	Process-based method
AusLCI	Building Product Innovation Council, Australia	Building and construction materials and products, Building product maintenance and replacement life data, Australian data	Publicly available	Cradle-to-grave	Process-based method
BEES	National Institute of Standards and Technology (U.S.)	Construction and building materials, mostly U.S. data	Publicly available	Cradle-to-grave	Process-based method
Database of Embodied Energy and Water Values for Materials	The University of Melbourne	Construction and building materials, Australian data	Publicly available	Cradle-to-grave	I-O based hybrid method
CLCD	Sichuan University, China; IKE Environmental Technology CO., Ltd., China	Materials and chemicals, energy carriers, transport, and waste management, China	Publicly available	Cradle-to-gate	Process-based method

In addition, several databases including both process-based and I-O based hybrid databases were employed for calculation of buildings' embodied energy (Table 5). The findings indicate that 50% of the studies used generic international databases, namely ICE, Building for Environmental and Economic Sustainability (BEES), SimaPro, and Ecoinvent. Other process-based databases such as the Chinese Life Cycle Database (CLCD) and Australian National Life Cycle Inventory Database (AusLCI) were also used by the reviewed studies to acquire process specific data in order to form I-O hybrid databases [27,30,36,41].

From the review, it became evident that the studies differ significantly with respect to their approaches for calculating buildings' embodied energy. These variations stem from different types of methods and databases applied by the reviewed studies to assess buildings' embodied energy, combined with excluding a stage(s) of building life span, considering embodied energies associated with different building components, assuming different building life spans, and various assumptions attributing values to embodied energy calculations.

4.3. The Assessment of Operational Energy

Operational energy is commonly known for having the highest share of energy consumption in a building's life cycle [14,23]. Although previous studies attempted to draw a solid conclusion of a building's operational energy by juxtaposing different case studies [9,14,23,58–60], cross-comparison cannot be implemented in reality due to the varying approaches of studies for measuring operational energy. As previously mentioned, system boundary definition is a critical factor in calculating operational energy, as it involves including parameters with a potential influence on how operational energy use is determined. In addition, methods applied to calculate buildings' operational energy is another important variable leading to variations in LCEA results. Based on the review, methods utilized by the studies to calculate buildings' operational energy usage are categorized into four groups:

- Using the actual records of building energy usage collected from utility bills, or energy audit exercises. The review found that 12% of the studies used this method to calculate the operational energy. Using this approach enables researchers to take into consideration all types of energy consumed in buildings including heating, cooling, lighting, DHW, cooking, and appliances. For instance, Atmaca and Atmaca [43] and Mehta et al. [35] used energy bills to estimate building operational energy use. Employing this method provides the ability to capture the dynamics of occupants' behaviors on energy consumption within a year. However, the application of this method can only supply an aggregated figure of building energy consumption, while failing to present a detailed breakdown of energy by use. This would potentially prevent decision makers from identifying the hot spots of energy consumption in building and providing solutions for energy reduction.
- Using energy simulation software. It was found that 44% of the reviewed studies applied simulation software packages to estimate optional energy use. These software packages are commonly capable of producing detailed data on the annual energy consumption of buildings. Although the application of simulation software may ease the process of estimating operational energy, the accuracy of results achieved via simulation software can still be improved. One way to approach this challenge is to calibrate the simulation model to fit the real energy performance of the existing building. In addition, the impacts of users' behaviors on energy usage can be better taken into consideration. The two possible approaches to better account for the impacts of users' behaviors on energy use in buildings are deterministic and stochastic statistical approaches [61]. The deterministic approach refers to defining different scenarios for users' behaviors ranging from 'energy saving' to 'wasteful' behavior scenarios in respect to using energy in building e.g., DHW, on an hourly basis throughout the year. In addition, sensitivity analysis can be applied for the same purpose where sufficient data on users' behaviors are unavailable. Alternatively, the stochastic statistical model can be used to predict the users' attendance and activity in the

building for inclusion into a simulation. In this model, relevant data should be collected through literature and national sociological investigations.

- Static equations. Another method used by the reviewed studies (22%) for estimating operational energy was static equations [5,6,30,46,47]. In a study, Stephan et al. [5] estimated the operational energy of a residential building using Equation (3):

$$LCOPE_b = UL_b \times \sum_{e=1}^{E} (1 - SF_e) \times \frac{OPE_e}{n_e} \quad (3)$$

where $LCOPE_b$ is the life cycle primary operational energy of the building b in GJ, UL_b is the useful life of the building b, SF_e is the solar fraction for the end-use e, OPE_e is the yearly operational final energy demand of the end-use e in GJ, and ηeis the average efficiency of the end-use e. The annual operational energy uses for heating and cooling were estimated by applying Equation (4):

$$OPE_h = HDH \times [U_b \times A_{ht} + (1 - \eta_{HR}) \times SV_{ht}) \quad (4)$$

where OPE_h is the operational final heating energy demand in kWh, HDH is the thousands of heating degree hours for the building site in Kh, U_b is the average heat transfer coefficient for the building in $W/(m^2K)$, A_{ht} is the area of heat transfer in m^2, ηHR is the efficiency of the heat recovery system if present, and V_{ht} is the ventilation heat transfer in W/K. The cooling energy demand was also calculated using Equation (4) by substituting the cooling degree hours for the heating degree hours. The ventilation energy demand was achieved by using Equation (5):

$$OPEv = V \times H \times P \quad (5)$$

where OPEv is the operational final ventilation energy in kWh, V is the ventilated volume in m3, H is the thousands of hours of mechanical ventilation per year, and P is the average fan power in W/m^3. The energy demands for DHW, appliances, and cooking were determined by multiplying regional per capita averages by the number of users in the house. Lighting was calculated by multiplying average annual energy usage per m^2 by the usable floor area of the building. The average regional energy consumption data were then gained by using records published by governmental bodies. The final energy demands achieved were converted into primary energy applying appropriate conversion factors. Equation (3) also accounted for situations where solar systems are installed. In this case, solar fractions should be deduced from the final energy consumption of related end-uses. However, using this method can be time-consuming once the aim is to optimize a building design through parametric analysis. In addition, this method fails to capture buildings' thermal history when calculating cooling and heating loads e.g., time delay between heat absorptance and heat release by enclosing components of a room.
- Miscellaneous. Other methods have been also used by the reviewed studies for calculating operational energy. For instance, Cellura et al. [45] monitored the annual energy consumption of a building in order to have an accurate estimate of the building operational energy use. Similarly, Devi and Palaniappan [37] monitored buildings' energy consumption for 21 months and then used the data for estimation of operational energy. In another study, Bastos et al. [32,33] estimated the operational energy consumptions while considering the ratio between residential electricity use and natural gas or LPG provided by the Lisbon Energy Matrix, which provides estimates of energy use in Lisbon building stock using 2002 data.

Similar to embodied energy, the approaches for calculation of operational energy also differed across the reviewed studies in two major aspects; (i) accounting for the impacts of parameters contributing to operational energy use and (ii) the approaches applied for calculation of operational energy use. The varied approaches for calculations of both embodied energy and operational energy may significantly influence the accuracy and completeness of the results reported by LCEA studies.

4.4. Interpretation

The final stage of an LCEA study is 'interpretation' in which the results of the analyses are discussed and recommendations are accordingly given. The interpretation of each LCEA study is unique, corresponding to the particular goal and defined system boundaries. The ISO 14044 recommends performing different types of 'evaluations' including a completeness check, sensitivity check, and consistency check in order to provide assurance of the robustness of the achieved results [20]. The completeness check refers to the process in which the completeness of all relevant information and data required for the interpretation is checked. The sensitivity analysis means that the reliability of the results and conclusions should be checked by determining how they are affected by uncertainties in the data, allocation methods, calculations of category indicator results, etc. The consistency check refers to the process in which the assumptions, methods, and data should be checked for whether they are consistent with the goal and scope of the study.

From the review, it was realized that three methods were commonly utilized by the reviewed studies as a means of 'evaluation': sensitivity analysis, uncertainty analysis, and discussion of limitations. In regards to sensitivity analysis, 31% of the studies applied this method to test the influence of inventory data parameters. For instance, Rossi et al. [44] assessed the impacts of climate and the energy mix on total building life cycle energy demands. Dodoo et al. [39] also tested the influence of insulation choices, building life span, air infiltration rates, and ventilation heat recovery (VHR) efficiency. The building life service is another parameter which has been subject to sensitivity analysis by studies [37,48]. Pinky Devi and Palaniappan [31] considered the influence of service life and efficiency in building operations on the total building life cycle energy use. Regarding the uncertainty analysis, 19% of the reviewed studies used this method. Gustavsson et al. [38] performed a qualitative uncertainty analysis, while Stephan and Stephan [30], Stephan et al. [5], and Stephan et al. [6] used the interval analysis method to quantitatively compute the uncertainty in embodied energy figures. Finally, 31% of the reviewed studies discussed the inherent limitations involving their research. Overall, no study performed all of the aforementioned evaluation methods, five studies included two of them [30,31,44,48,50], and ten studies did not consider performing any evaluation [27–29,41,42,45–47,49,51].

In addition to ISO 14044's recommendation of a number of evaluations in order to assure the quality of results, other standards and guidelines have suggested certain measures to be taken at the interpretation stage. The EN 15978 introduced some rules to maintain the quality of final research, namely involving data validation [61]. Furthermore, EeBGuide recommends carrying out an uncertainty analysis, and where it is relevant, modeling an alternative scenario for each life cycle stage of a building [61].

4.5. Reuse and Recycling Potentials

The reuse and recycling potential refers to the process in which the benefits and loads from materials and energy beyond the assessed building's system boundary are captured [61]. It was found that eight studies considered processes associated with recycling potentials of building materials [27,38–40,42,45,49,51]. They considered reusing materials such as biomass residues during the production stage [47–49,55] and on the construction site [39] as well as recycling building materials such as concrete, steel, and wood at the EOL stage [47–49,55]. Table 6 shows the amounts of energy saved at the production, construction, and EOL stages of a building life cycle, along with representing the percentage of energy saved throughout the entire building life cycle by recycling or reusing materials (detailed data on energy saving were available for five studies).

Table 6. The reuse, recovery, and recycling potential for reducing total building life cycle energy use across the building life cycle (kWh/m^2.annuam).

Reference	Case Study ID	Energy Recovered at Production Stage	Energy Recovered at Construction Stage	Energy Recovered at EOL Stage	Total Energy Recovered	Total Energy Saved (%)
Gustavsson et al. [38]	CS 4	23.64	NA	11.42	35.06	17.84
Dodoo and Gustavsson [42]	CS 5	7.78	NA	7.92	15.70	5.36
	CS 6	7.78	NA	7.92	15.70	7.27
	CS 7	7.78	NA	7.92	15.70	7.79
	CS 8	8.0	NA	8.06	16.06	6.05
	CS 9	8.0	NA	8.06	16.06	7.77
	CS10	8.0	NA	8.06	16.06	8.22
Cellura et al. [45]	CS23	NA	NA	19.01	19.01	9.14
Dodoo et al. [39]	CS 62	20.92	1.44	11.80	34.16	15.70
	CS 63	20.22	1.26	10.90	32.38	9.54
	CS 64	10.18	1.10	9.04	20.32	9.04
	CS 65	20.92	1.44	11.80	34.16	14.88
	CS 66	20.22	1.26	10.90	32.38	15.02
	CS 67	10.18	1.10	9.04	20.32	9.54
Tettey et al. [40]	CS 68	1.92	NA	5.63	7.55	4.90
	CS 69	20.98	NA	10.67	31.65	21.24
	CS 70	8.075	NA	6.30	14.38	9.75
	CS 71	1.92	NA	5.63	7.55	8.55
	CS 72	8.53	NA	6.57	15.10	18.37

Reusing and recycling building materials has already been suggested as an effective strategy to mitigate energy use in the building life cycle by decreasing embodied energy [8,62]. Based on Table 6, it can be observed that this strategy led to the reduction of total building life cycle energy use by the range of 5% to 22%.

5. Methodological Challenges

The overall methodological trends of the reviewed studies are shown in Table 7. As indicated, the present application of LCEA in residential buildings suffers from 'incompleteness' in defining system boundaries, and has 'ambiguity' in terms of measuring embodied energy and operational energy. Regarding 'incompleteness', it was realized the majority of the reviewed studies tended to exclude certain stages of the building life cycle from system boundaries. The impacts of energy consumed at the EOL were commonly discounted, with the reasoning that this stage may contribute negligibly to the total life cycle energy use of buildings. This approach not only leads to truncating system boundaries, but also deprives studies of the beneficial potential of reusing or recycling building materials at this stage.

Table 7. Overall trends of methodological aspects compiled from the reviewed studies.

Methodological Aspects	Overall Trends of Reviewed Studies for LCEA Application
Stages of building life cycle excluded	50% excluded EOL; 27% replacement and maintenance; 15% excluded on-site construction; 4% excluded transport.
Elements proposed for inclusion within system boundary	Three studies accounted for the inclusion of user's mobility over building life cycle; three studies accounted for the embodied energy of infrastructure on which buildings rely for receiving energy.
Building life span	58% of the reviewed studies considered 50 years as the life span.
Assumptions	All stages have been subject to assumptions.
Reuse, recovery and recycling potential	31% of the reviewed studies considered recycling and reusing building materials.
The approach used for quantification of embodied energy	62% used process-based approach and 27% applied I-O based hybrid approach.
Database applied for estimating embodied energy	50% used generic international databases; 19% relied on the literature to retrieve embodied energy coefficients.
Contributors considered when estimating operational energy	62% excluded cooking; 38% excluded DHW; 35% excluded electrical appliances; 27% excluded lighting; and 23% excluded ventilation.

Table 7. *Cont.*

Methodological Aspects	Overall Trends of Reviewed Studies for LCEA Application
Methods used for estimation of operational energy	44% used software; 22% used static equations; 12% used energy bills. Other methods were also used such as monitoring energy consumption and using the national average of energy use for building stock.
Interpretation	31% used sensitivity analysis; 19% used uncertainty analysis; 31% discussed the limitations of these approaches. 19% used two methods.
Geographical context	50% focused on Europe; 31% on Asia; 15% on Australia; 4% on South America.

Furthermore, the extent of the inclusion of embodied energy impacts associated with building components and systems was unclear. Some studies limited their scopes of assessment to analyzing building elements (e.g., the building envelope) while there were studies which endeavored to include the embodied energy of urban infrastructure and occupants' mobility within the system boundaries. Likewise, the extent of the inclusion of parameters contributing to buildings' operational energy use varied across the reviewed studies. Only seven studies accounted for all of the parameters [5,29,30,32,33,35,36], whereas others excluded the impacts of a number of parameters. The lack of consensus on measurements of operational and embodied energies was also noted among the reviewed studies. The diversity in methods applied for calculating embodied and operational energies can affect the completeness and accuracy of the LCEA results while limiting cross comparability of the analyzed case studies. Apart from technical characteristics of LCEA analysis, the difference in geographic contexts of the reviewed studies was another source of variation in aspects of climatic conditions, quality of raw materials, production processes, economic data, processes of delivered energy generation, transport distances, energy use (fuel) in transport, and labor [10].

Despite the promising outlook of LCEA applications, the current state of this research area is plagued by inaccuracies accruing from incomplete definitions of system boundaries, coupled with ambiguous approaches for calculating embodied and operational energies. Hence, the process of decision-making can be affected due to inaccurate and incomplete results reported by LCEA studies. The inaccurate results can also influence the successful implementation of environmental practices, namely eco-labeling, through which users are informed about the environmental characteristics of buildings. Furthermore, the inconsistencies shown in Table 7 that exist throughout the entire process of LCEA analysis makes cross-comparison of the case studies impossible. Cross-comparison is important in developing an advanced knowledge about LCEA applications in residential buildings within a global context.

The diversity in applying LCEA signifies the necessity of developing a framework to standardize system boundaries, while providing guidelines on the measurements of operational and embodied energies. Previous studies endorsed a similar need to develop a standardized framework for the measurement of buildings' embodied energy [13]. However, the findings of this study showed that variations could also be induced from the measurement of operational energy. Therefore, there is a need to develop a much comprehensive framework to account for the buildings' environmental impacts, which would consider both embodied and operational energies.

6. Conclusions

This paper reviewed the current trend of LCEA application in residential buildings using a systematic literature review. Notwithstanding the extensiveness of the collected data and synthetic process of analyzing their embedded information relevant to the study's objectives, a number of limitations can be highlighted. First, the process of data collection and content analysis has been limited to the search engines, databases, and applied research terms. Moreover, the scope of the paper was limited to analyzing materials published from 2010 onwards, aiming to obtain an up-to-date understanding the use of LCEA for residential buildings. Despite the highlighted limitations, this paper managed to identify 26 papers representing 86 case studies across 12 countries. The analysis of the case studies enabled this paper to capture the most recent trends of utilizing LCEA for residential buildings.

The review shows the LCEA application for residential buildings is yet to be fully-fledged in providing accurate and complete results for decision-making purposes. This review shows the current trend of utilizing LCEA is suffering from an incomplete definition of system boundaries, combined with the ambiguous approaches for calculating embodied and operational energies. These limitations can further lead to affecting the process of decision-making while limiting the cross-comparability of the case studies. The necessity of developing a framework for standardization of system boundary definition in embodied energy measurement has been already highlighted by previous studies [13]. The findings of this study call for a comprehensive framework in which system boundary definitions for assessments of both embodied energy and operational energy can be standardized, while providing guidelines on methods for measuring these energies.

7. Future Study

This paper is a part of an ongoing project that aims to develop a conceptual framework to which the energy consumption of residential buildings throughout their entire building life cycles can be taken into consideration in a systematic and comparable approach. The next step for this research is to develop the framework based on the findings of this paper, and then validate its feasibility by assessing case studies.

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Appendix A

Table A1. Studies utilized LCEA in residential buildings.

Authors	Country	Size (M^2)	System Boundary				LCI	LCIA	Interpretation
			Stage(s) Excluded	Life Span (Yrs)	Operational Energy	Assumptions			
Aye et al. [27]	Australia	3943	EOL and replacement & maintenance	50	Heating and cooling	The schedule for operating heating and cooling systems is assumed constant; The detailed occupational schedules and gains are not considered; The efficiency of heat pump system is assumed to consistent over time.	Input–output–based hybrid approach is used; Input–output data is taken from the Australian National Accounts, combined with energy intensity factors by fuel type; Process specific data are retrieved from SimaPro Australian database	TRNSYS simulation software is used to estimate the building operational energy; The materials' quantities are multiplied by their respective embodied energy intensities, and summed.	None
Gustavsson et al. [38]	Sweden	3374	Replacement & maintenance	50 and 100	Heating, DHW, household electricity, and electricity for facility management purposes.	The primary energy used for on-site construction is assumed 80 kWh/m^2; 5% waste of material is assumed during construction; 90% of the wood-based demolition materials are assumed to be recovered.	Process-based approach is used; Detailed info acquired from the manufacturers of building materials; Literature is used to obtain required embodied energy intensities of building materials	ENORM and ENSYST software are used to estimate the operational energy; The materials' quantities are multiplied by their respective embodied energy intensities, and summed	UA
Dodoo and Gustavsson [42]	Sweden	1190	None	50	Heating, DHW, electricity for ventilation fans and pump, and electricity for household.	The efficiency of heating systems is assumed to be 85% and consistent throughout the entire building life span; It is assumed that 90% of concrete, wood and steel materials would be recovered at EOL.	Process-based approach is used; Literature is used for obtaining primary data on embodied energy.	VIP + software is used to estimate the operational energy; ENSYST is used to calculate the final energy for the operation activities; The embodied energy calculation is carried out multiplying the unit values by the area of each building element.	None
Ramesh et al. [28]	India	85.5	Construction and EOL	75	Heating, cooling, DHW, ventilation, household appliances and lighting.	The annual operating energy is assumed to remain constant throughout the entire building life span; The effects of climate change and occupants' behaviors in the future are not taken into consideration.	The approach to quantifying the embodied energy is not specified; Literature is used for obtaining primary data on embodied energy	DesignBuilder software is used to estimate the operational energy; The embodied energy calculation is carried out multiplying the unit values by the area of each building element and summed.	None

Table A1. *Cont.*

Authors	Country	Size (M²)	System Boundary				LCI	LCIA	Interpretation
			Stage(s) Excluded	Life Span (Yrs)	Operational Energy	Assumptions			
Stephan and Stephan [30]	Lebanon	904	EOL	50	Heating, cooling, ventilation, lighting, DHW, cooking and appliances	Australian database of construction materials is used to calculate the embodied energy; The embodied energy of infrastructures used to deliver energy to the building and life cycle transport energy demand of the building's occupants are considered.	Input–output–based hybrid approach is used; Hybrid database of construction materials developed by [63]; Process specific data are obtained from manufacturers.	DEROB-LTH software is used to calculate the heating and cooling loads; Equation is applied to calculate operational energy of DHW, ventilation, cooking, appliances and lighting; The embodied energy is calculated by multiplying the quantity of materials by their relevant embodied energy coefficient.	UA, DL
Atmaca and Atmaca [43]	Turkey	Urban area (6760) and rural area (1320)	None	50	Heating, cooling, DHW, lighting, appliances, cooking	The standard construction methods and materials are assumed to remain the same during the entire building life span; The structural elements of the building are assumed to have the same service life as the house; All the manufacturing processes are assumed to be undertaken in one place; Only one type of fuel is assumed to be used for transporting the wastages.	Process-based approach is used; Literature and Inventory of Carbon and Energy (ICE) Version 2.0 are used to obtain embodied energy of building materials.	The actual energy consumption records obtained from utility bills and questionnaires are used for estimation of building operational energy; The embodied energy calculation is carried out multiplying the unit values by the area of each building element and summed.	DL
Rossi et al. [44]	Belgium, Portugal and Sweden	192	EOL	50	Heating, cooling, DHW, ventilation, lighting, building automation and control	The on-site processes e.g., the finishing of steel structures (cutting, shot blasting, welding) are excluded; The embodied energy associated with replacement, refurbishment and repair of materials and products are assumed 5% every 10 years.	Process-based approach is used; BEES, CRTI, ICE and databases are used to obtain embodied energy of building materials	LCA analysis has been done using Equer software, linked to two other software namely Pleiades + Comfie	SA, DL
Stephan et al. [6]	Belgium	297	EOL	100	Heating, ventilation, DHW, lighting, cooking and appliances	Australian input–output-based hybrid embodied energy intensities are used for this case study that is located in Belgium; The life cycle transport energy demands of the building's occupants are considered; The recurrent embodied energy of nearby infrastructures (e.g., roads, power lines, water and gas distribution systems and sewage) is considered.	Input–output-based hybrid approach is used; Input–output data is taken from the Australian National Accounts; A database containing embodied energy coefficients for materials in Australia developed by [63] is used.	The LCA analysis is performed using equations	UA

Table A1. *Cont.*

Authors	Country	Size (M^2)	System Boundary				LCI	LCIA	Interpretation
			Stage(s) Excluded	Life Span (Yrs)	Operational Energy	Assumptions			
Cellura et al. [45]	Italy	481.76	None	70	Heating and cooling, ventilation, lighting and plug loads	Not discussed.	Process-based approach is used; Literature and SimaPro database are us; Data acquired from the local manufacturer of building materials.	The annual electricity requirement of the building is monitored, and then normalized for estimating the building's operational energy; SimaPro is used to perform the LCA analysis.	None
Stephan et al. [5]	Belgium and Australia	297 and 330	EOL	50	Heating, cooling, ventilation, lighting, DHW, cooking and appliances	The embodied energy of nearby infrastructures (e.g., roads, power lines, water and gas distribution, and sewage) used to deliver energy to the building and life cycle transport energy demand of the building's occupants are considered.	Input–output–based hybrid approach is used; Input–output data is taken from the Australian National Accounts; A database containing embodied energy coefficients for materials in Australia developed by [63] is used.	Static equations are used to calculate the operational energy; The initial embodied energy is calculated multiplying the relevant coefficients by the final quantities of the respective materials, and summed; The recurrent embodied energy is calculated via summing the embodied energy of replaced materials across the building's life span.	UA
Crawford [36]	Australia	291.3	None	50	Heating, cooling, ventilation, lighting, DHW, cooking and appliances	To account for the contribution of EOL stage, 1% of the total life cycle energy demand is summed to the final achieved figure.	Input–output–based hybrid approach is used; Input–output data is taken from the Australian National Accounts; Australian process data obtained from the SimaPro Australian database.	The energy bills is used to determine the operational energy of the house; The embodied energy is calculated via multiplying the quantities of the materials by their respective energy coefficients, and summed.	DL
Pinky Devi and Palaniappan [31]	India	32.5	Maintenance, repair, and EOL	50	Lighting, ventilation, appliances and equipment	Assumptions are made where technical details of building envelope were unavailable.	Process-based approach is used; The relative embodied energy coefficients are taken from literature and ICE database.	Data related to the operational energy are collected from national statistics; The embodied energy is calculated via multiplying the quantities of the materials by their respective energy coefficients, and summed.	SA, DL
Paulsen and Sposto [46]	Brazil	48	Transport	50	Appliances and equipment and cooking	No analysis of thermal performance (heating and cooling for operational energy) has been performed.	The approach to quantifying the embodied energy is not specified; Data related to the operational energy are collected from national statistics; National Brazilian process data are used for seven groups of material. Data from Portugal are also used for three material groups; Literature is also used to extract relative embodied energy coefficients.	Static equations are used to calculate the operational energy; The embodied energy is calculated via multiplying the quantities of the materials by their respective energy coefficients, and summed.	None

Table A1. *Cont.*

Authors	Country	Size (M^2)	System Boundary				LCI	LCIA	Interpretation
			Stage(s) Excluded	Life Span (Yrs)	Operational Energy	Assumptions			
Devi and Palaniappan [37]	India	10,800	Maintenance, repair, and renovation	50	Lighting, ventilation, and partial or no air-conditioning	The building operational energy is assumed to be same during the entire building life span; The embodied energy associated with EOL is assumed 3% of the total building life cycle energy demand.	Process-based approach is used; The buildings' energy consumptions are monitored for 21 months and used for estimating the operational energy; The relative embodied energy coefficients are taken from literature and ICE.	Data taken from survey, normalized and used for calculation of building operational energy use; The embodied energy is calculated via multiplying the quantities of the materials by their respective energy coefficients, and summed.	SA
Bastos et al. [33]	Portugal	Type 2 (367), Type 3 (472) and type 8 (1041)	EOL	75	Heating, cooling, ventilation, lighting, DHW, cooking and appliances	The energy consumption is assumed the same during the entire building's life span.	Process-based approach is used; The Lisbon Energy Matrix data are used for estimating the operational energy; ICE is used for embodied energy calculation.	The Lisbon Energy Matrix data are used to calculate the total energy use per year based on the ratio between residential electricity use and natural gas or LPG; The embodied energy is calculated via multiplying the quantities of the materials by their respective embodied energy coefficients, and summed.	DL
Ramesh et al. [29]	India	CS1 (104), CS2 (185), CS3 (62), CS4 (183), CS5 (135), CS6(175), CS7(1280), CS8 (1286), CS9(450), CS10(235)	Construction and EOL	75	Heating, cooling, ventilation, lighting, DHW, cooking and appliances	The annual operating energy is assumed to be constant throughout the entire building life span; The effects of climate change and occupants' behaviors in the future are not taken into consideration.	The approach to quantifying the embodied energy is not specified; The relative embodied energy coefficients are taken from literature.	The building operational energy is estimated using DesignBuilder software; The embodied energy is calculated via multiplying the quantities of the materials by their respective embodied energy coefficients, and summed.	None
Zhan et al. [47]	China	4235.21	None	70	Heating, ventilation, air conditioning, lighting, appliances and equipment	The operational energy usage associated with household appliances is excluded; Recycling is considered at EOL stage.	Input–output–based hybrid approach is used; National data sources are used for estimation of embodied energy such as Guangzhou IO table, Guangzhou Statistical Yearbook of 2013, China Construction Statistical Yearbook of 2013, and China Electric Power Yearbook of 2013.	Static equations are used to estimate the operational energy consumption; Embodied energy is calculated using hybrid LCA	None

Table A1. *Cont.*

Authors	Country	Size (M^2)	System Boundary				LCI	LCIA	Interpretation
			Stage(s) Excluded	Life Span (Yrs)	Operational Energy	Assumptions			
Iyer- Raniga and Wong [48]	Australia	Not specified [a]	None	100	Heating and cooling	All of the materials are assumed to be landfilled at the EOL stage; The technology utilized for material and productions are assumed to remain unchanged; due to the lack of available data regarding to the replacement lifetimes, the relevant data in US is used; the resource mix supplying electricity to the buildings is assumed static; the occupancy pattern of buildings is assumed static.	Process-based approach is used; The electricity and water bills are collected and compared against the achieved simulated results for the purpose of validation; SimaPro and Australian Unit Process LCI databases are used for estimation of buildings' embodied energy.	The buildings operational energies are estimated using AccuRate software; Embodied energy is calculated using hybrid LCA	SA, DL
Dodoo et al. [39]	Sweden	CLT (928), BC (928) and MS (935)	Replacement and maintenance	50	Heating, ventilation, tap water heating and appliances and facility management	The contribution of construction phase to the total building life cycle energy is assumed to be 4% of the material production primary energy; It is assumed that demolition energy would not exceed 10 kWh/m^2 [usable area]. In addition, 90% of the demolished concrete, steel and wood materials are assumed to be recovered or recycled during EOL stage.	Process-based approach is used; Literature, Ecoinvent v.2.2 database and SP Technical Research Institute of Sweden are used to obtain required data on embodied energy.	VIP-Energy simulation software is used to estimate the final operational energy of the building; then, the achieved results are converted to primary energy using ENSYST software; The embodied energy is calculated via multiplying the quantities of the materials by their respective energy coefficients, and summed.	SA
Tettey et al. [40]	Sweden	1686	Replacement and maintenance	80	Heating, tap water heating and electricity for ventilation	Electricity usages for household appliances and lighting are excluded for estimating the building operational energy; 80 and 160 kWh/m^2 are assumed for the on-site energy consumption of wood and concrete building systems respectively; The primary energy use for demolition of wood and concrete are assumed to be 10 and 20 kWh/m^2 respectively.	Process-based approach is used; The relative embodied energy coefficients are obtained from literature.	VIP-Energy simulation software is used to estimate the final operational energy of the building; then, the achieved results are converted to primary energy using ENSYST software; The embodied energy is calculated via multiplying the quantities of the materials by their respective energy coefficients, and summed.	UA
Mehta et al. [35]	India	2588.40	On-site construction, replacement and maintenance, and EOL	50	Heating, cooling, ventilation, lighting, DHW, cooking and appliances	Energy bills of another building with similar specifications are used, namely type of the home, usable floor area per home and the number of rooms.	Process-based approach is used; Operational energy is calculated using energy bills; ICE is used to calculate embodied energy.	Operational energy is calculated using energy bills; The embodied energy is calculated via multiplying the quantities of the materials by their respective energy coefficients, and summed.	SA

Table A1. *Cont.*

Authors	Country	Size (M²)	System Boundary				LCI	LCIA	Interpretation
			Stage(s) Excluded	Life Span (Yrs)	Operational Energy	Assumptions			
Zhu et al. [41]	China	6890 and 216,200	EOL, Replacement and maintenance	50	Heating and cooling, lighting and appliances	The effects of on-site construction management skill is ignored.	Input–output–based hybrid approach is used; The input-output table developed by Chinese National Bureau of Statistics is used; The process-based energy intensity data are acquired from the China Building Material Academy and the Chinese Life Cycle Database developed by Sichuan University.	DesignBuilder software is used to estimate the building's operational energy; The embodied energy is calculated via multiplying the quantities of the materials by their respective energy coefficients, and summed.	None
Bastos et al. [32]	Portugal	CA (102) and SH (104)	EOL	50	Heating, cooling, ventilation, lighting, DHW, cooking and appliances	This study accounts for user transportation.	Process-based approach is used; The Ecoinvent database is used for quantification of the building's embodied energy.	The ratio between residential electricity use and natural gas or LPG from the Lisbon Energy Matrix is used to calculate the total operational energy use per year.	SA
Goggins et al. [49]	Ireland	106	Replacement and maintenance	60	Lighting, ventilation, and DHW	90% of the building materials are assumed to be recycled at the EOL of building and used for secondary purposes; No change in fuel mix would occur over building life span.	Process-based approach is used; ICE is used to calculate embodied energy.	DEAP software is used to estimate the operational energy; The embodied energy is calculated via multiplying the quantities of the materials by their respective energy coefficients, and summed.	None
Kristjansdottir et al. [50]	Norway	120	Construction and EOL	60	Lighting, heating, appliances, ventilation, DHW.	Replacement of PV panels are assumed to have 50% of the initial embodied energy load.	Process-based approach is used; Ecoinvent v3.2 database is used to calculate embodied energy.	IDA-ICE software is used to calculate the operating energy; Brightway2 is used to perform impact assessment.	DL, SA
Mistretta et al. [51]	Italy	481.76	None	70	Heating and cooling, ventilation, DHW, lighting, and appliances.	Not discussed.	Process-based approach is used; Process data are obtained from local manufacturers; Ecoinvent database is used to retrieve data about recycling of aluminum, steel, glass, and copper.	TRNSYS software is used to estimate operating energy in the refurbished building. For the baseline building, energy use is monitored; SimpaPro is used to assess the environmental impacts.	None

Abbreviations: LCI: Life cycle inventory; LCIA: Life cycle impact assessment; Interpretation stage: Sensitivity Analysis (SA); Uncertainty Analysis (UA); Discussion of Limitations (DL); Case study (CS). Note: (a) the sizes of buildings are not specified, and results are reported in MJ/m^2.

Appendix B

Table A2. Normalized operational energy and embodied energy of analyzed studies.

Authors	Building Character	Case Study ID	Embodied Energy (kWh/m^2.year)	Operational Energy (kWh/m^2.year)
Aye et al. [27]	Steel structure	CS1	Steel (80)	Steel (119.88)
	Concrete structure	CS2	Concrete (53.55)	Concrete (112.54)
	Timber structure	CS3	Timber (58.29)	Timber (117.57)
Gustavsson et al. [38]	Wood-framed apartment	CS4	Assumed 50 years of life span (-15.38)	Assumed 50 years of life span (176.86)
Dodoo and Gustavsson [42]	Conventional building with EH system	CS5	Conventional building with EH (−1.56)	Conventional building with EH (278.64)
	Conventional building with HPH system	CS6	Conventional building with HPH (−1.56)	Conventional building with HPH (201.7)
	Conventional building with DH system	CS7	Conventional building with DH (−1.56)	Conventional building with DH (187.26)
	Passive building with EH system	CS8	Passive building with EH(−1.66)	Passive building with EH(250.8)
	Passive building with HPH system	CS9	Passive building with HPH (−1.66)	Passive building with HPH (192.12)
	Passive building with DH system	CS10	Passive building with DH(−1.66)	Passive building with DH(181.08)
Ramesh et al. [28]	Building with fired clay exterior walls	CS11	Building with fired clay exterior walls (29)	Building with fired clay exterior walls (174)
	Building with hollow concrete exterior walls	CS12	Building with hollow concrete exterior walls (27)	Building with hollow concrete exterior walls (172)
	Building with soil cement exterior walls	CS13	Building with soil cement exterior walls (27)	Building with soil cement exterior walls (171)
	Building with fly ash exterior walls	CS14	Building with fly ash exterior walls (28)	Building with fly ash exterior walls (169)
	Building with aerated concrete exterior walls	CS15	Building with aerated concrete exterior walls (27)	Building with aerated concrete exterior walls (167)
Stephan and Stephan [30]	Apartment buildings	CS16	150	266.66
Atmaca and Atmaca [43]	Building located in urban area	CS17	Urban area (43.33)	Urban area (167.22)
	Building located in urban rural	CS18	Rural area (26.11)	Rural area (135.55)
Rossi et al. [44]	Residential building located in Belgium	CS19	Belgium (24.39)	Belgium (274.41)
	Residential building located in Portugal	CS20	Portugal (24.39)	Portugal (174.72)
	Residential building located in Sweden	CS21	Sweden (26.18)	Sweden (327.79)
Stephan et al. [6]	Passive house	CS22	131	39.5
Cellura et al. [45]	Net zero energy building	CS23	137.82	48.42
Stephan et al. [5]	Passive house - Brussels, Belgium	CS24	Belgium (143.48)	Belgium (99.41)
	7-Star building (highenergy efficiency standards) - Melbourne, Australia	CS25	Australia (130)	Australia (160.62)
Crawford [36]	Insulated timber-framed brick veneer walls	CS26	120.88	81.66
Pinky Devi and Palaniappan [31]	Low-cost house	CS27	37.25	92.65
Paulsen and Sposto [46]	Low-cost house	CS28	43.97	97.57
Devi and Palaniappan [37]	Multi-story residential building apartment	CS29	72.77	116.66

Table A2. *Cont.*

Authors	Building Character	Case Study ID	Embodied Energy (kWh/m^2.year)	Operational Energy (kWh/m^2.year)
Bastos et al. [33]	Conventional residential buildings with the area of 367 m^2	CS30	Type 2 (15.47)	Type 2 (74.64) a
	Conventional residential buildings with the area of 472 m^2	CS31	Type 3 (15.11)	Type 3 (59.33) a
	Conventional residential buildings with the area of 1041 m^2	CS32	Type 8 (13.87)	Type 8 (37.77) a
Ramesh et al. [29]	Conventional building located in Keerthi	CS 33	CS1-Conventional system (28.12)	CS1-Conventional system (348)
	Conventional building located in Eashwer	CS 34	CS2-Conventional system (21.17)	CS2-Conventional system (271)
	Conventional building located in Adil	CS 35	CS3-Conventional system (27.4)	CS3-Conventional system (303)
	Conventional building located in Anand	CS 36	CS4-Conventional system (21.49)	CS4-Conventional system (264)
	Conventional building located in Alwal	CS 37	CS5-Conventional system (18.56)	CS5-Conventional system (279)
	Conventional building located in RG	CS 38	CS6-Conventional system (22.12)	CS6-Conventional system (296)
	Conventional building located in Rock town	CS 39	CS7-Conventional system (23.27)	CS7-Conventional system (325)
	Conventional building located in Kiran Arcade	CS 40	CS8-Conventional system (21.8)	CS8-Conventional system (250)
	Conventional building located in Mahendra	CS 41	CS9-Conventional system (24.54)	CS9-Conventional system (309)
	Conventional building located in Nirmal	CS 42	CS10-Conventional system (23.50)	CS10-Conventional system (280)
	Insulated building located in Keerthi	CS 43	CS1-Insulated envelope (30.63)	CS1-Insulated envelope (234)
	Conventional building located in Eashwer	CS 44	CS2-Insulated envelope (22.69)	CS2-Insulated envelope (237)
	Insulated building located in Adil	CS 45	CS3-Insulated envelope (29.45)	CS3-Insulated envelope (245)
	Conventional building located in Anand	CS 46	CS4-Insulated envelope (27.08)	CS4-Insulated envelope (230)
	Insulated building located in Alwal	CS 47	CS5-Insulated envelope (20.87)	CS5-Insulated envelope (219)
	Insulated building located in RG	CS 48	CS6-Insulated envelope (23.90)	CS6-Insulated envelope (261)
	Insulated building located in Rock town	CS 49	CS7-Insulated envelope (24.65)	CS7-Insulated envelope (310)
	Insulated building located in Kiran Arcade	CS 50	CS8-Insulated envelope (22.87)	CS8-Insulated envelope (238)
	Insulated building located in Mahendra	CS 51	CS9-Insulated envelope (27.07)	CS9-Insulated envelope (285)
	Insulated building located in Nirmal	CS 52	CS10-Insulated envelope (25.19)	CS10-Insulated envelope (248)
Zhan et al. [47]	Typical residential building located in urban area	CS 53	22.77	45.19
Iyer- Raniga and Wong [48]	Heritage building with brick veneer envelope	CS 54	CS1 (63.61)	CS1 (45.00)
	Heritage building with weatherboard envelope	CS 55	CS2 (314.4)	CS2 (193.90)
	Heritage building with weatherboard envelope	CS 56	CS3 (118.33)	CS3 (170.50)
	Heritage building with weatherboard envelope	CS 57	CS4 (161.38)	CS4 (116.38)
	Heritage building with brick veneer envelope	CS 58	CS5 (180)	CS5 (108.80)
	Heritage building with solid brick	CS 59	CS6 (134.16)	CS6 (88.00)
	Heritage building with solid brick	CS 60	CS7 (137.22)	CS7 (82.22)
	Heritage building with brick veneer envelope	CS 61	CS8 (143.8)	CS8 (83.88)

Table A2. *Cont.*

Authors	Building Character	Case Study ID	Embodied Energy (kWh/m^2.year)	Operational Energy (kWh/m^2.year)
Dodoo et al. [39]	Cross laminated timber structure with heat pump heated system	CS 62	CLT (−18.36)	CLT with HPH system (187)
	Beam-and-Column system structure with heat pump heated system	CS 63	BC (−14.2)	BC with HPH (192)
	Modular timber structure with heat pump heated system	CS 64	MT (−3.5)	MT with HPH (192)
	Cross laminated timber structure with district heated system	CS 65	CLT (−18.36)	CLT with DH system (176)
	Beam-and-Column system structure with district heated system	CS 66	BC (−14.2)	BC with DH (180)
	Modular timber structure with district heated system	CS 67	MT (−3.5)	MT with DH (180)
Tettey et al. [40]	Standard building with concrete system	CS 68	Standard building with concrete system (8.775)	Standard building with concrete system (137.47)
	Standard building with cross laminated timber structure	CS 69	Standard building with CLT (−20.18)	Standard building with CLT (137.47)
	Standard building with modular timber structure	CS 70	Standard building with MT (−4.43)	Standard building with MT (137.47)
	Passive building with concrete system	CS 71	Passive building with concrete system (9.52)	Passive building with concrete system (71.16)
	Passive building with modular timber structure	CS 72	Passive building with MT (−4.03)	Passive building with MT (71.16)
Mehta et al. [35]	Multi-story residential building	CS 73	34.75	179.70
Zhu et al. [41]	Prefabricated buildings located in Chengdu, China	CS 74	CS A (33.94)	CS A (86.11)
	Prefabricated buildings located in Shenzhen, China	CS 75	CS B (28.00)	CS B (113.88)
Bastos et al. [32]	City apartment	CS 76	CA (15.02)	CA (70.77)
	Suburban house	CS 77	SH (17.75)	SH (75.19)
Goggins et al. [49]	Baseline building constructed according to 2005 Irish regulations. Airtightness 9.1 ac/hr@ 50 Pa.	CS 78	16.725	131.26
	Building constructed according to 2008 Irish regulations. Airtightness 5.44 ac/hr@ 50 Pa.	CS 79	17.06	100.96
	Building constructed according to 2011 Irish regulations. Airtightness 5.44 ac/hr@ 50 Pa.	CS 80	20.07	85.23
	Building constructed according to 2011 Irish regulations. Airtightness 0.45 ac/hr@ 50 Pa.	CS 81	18.73	83.07
	NZEB Airtightness 5.44 ac/hr@ 50 Pa.	CS 82	21.24	78.59
	NZEB. Airtightness 0.45 ac/hr@ 50 Pa.	CS 83	19.56	79.07
Kristjansdottir et al. [50]	NZEB	CS 84	80.30	55.50
Mistretta et al. [51]	Baseline building	CS 85	137.86	12.80
	NZEB (retrofitted)	CS 86	49.20	−90.0

Abbreviations: Cross laminated timber (CLT) system, Beam-and-Column system (BC), Modular timber system (MT); City apartment (CA); Suburban house (SH); Electric heated (EH); Heat pump heated (HPH); District heated (DH); Case study (CS). Notes: (a) this paper reports the operational energy with conversion factor of 2.5; (b) the sizes of buildings are not specified, and results are reported in MJ/m^2.

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Appendix II – Manuscript: What leads to variations in the results of life-cycle energy assessment? An evidence-based framework for residential buildings

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What leads to variations in the results of life-cycle energy assessment? An evidence-based framework for residential buildings

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A R T I C L E I N F O

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A B S T R A C T

Residential buildings are one of the major contributors to climate change due to their significant impacts on global energy consumption. Hence, most countries have introduced regulations to minimize energy use in residential buildings. To date, the focus of these regulations has mainly been on operational energy while excluding embodied energy. In recent years, extensive studies have highlighted the necessity of minimizing both embodied energy and operational energy by applying the life-cycle energy assessment (LCEA) approach. However, the absence of a standardized framework and calculation methodology for the analysis of embodied energy has reportedly led to variations in the LCEA results. Retrospective research endeavoured to explore the causes of variations, with a limited focus on calculating embodied impacts. Despite the undertaken attempts, there is still a need to investigate the key parameters causing variations in LCEA results by examining methodological approaches of the current studies toward quantifications of embodied and operational energies. This paper aims to address three primary questions: 'what is the current trend of methodological approach for applying LCEA in residential buildings?'; 'what are the key parameters causing variations in LCEA results?'; and 'how can the continued variations in the application of LCEA in residential buildings be overcome?'. To this end, 40 LCEA studies representing 157 cases of residential buildings across 16 countries have been critically reviewed. The findings reveal four principal categories of parameters that potentially contribute to the varying results of LCEAs: system boundary definition, calculation methods, geographical context, and interpretation of results. This paper also proposes a conceptual framework to minimize variations in LCEA studies by standardizing the process of conducting LCEAs.

1. Introduction

Residential buildings have a higher share in global energy consumption compared to non-residential buildings due to the larger portion both in terms of number of buildings and floor areas [1]. In 2017, the International Energy Agency held residential buildings responsible for nearly 22% of total energy use worldwide [2]. The projections made by the recent study also warn about further increasing global energy consumption in residential buildings within the next few decades owing to rapid urbanization, population growth, and economic development [3,95]. Correspondingly, most countries have strengthened their measures to decrease energy use in residential buildings by legislating various building-related regulations. As an example, the requirements introduced by the Danish government for operational energy use in new buildings have been reduced to less than one third over the last 25 years [4]. In general, the primary objective of such regulations is to improve buildings' thermal performance by imposing minimum requirements on their physical characteristics [5]. Despite the potential of these regulatory standards to minimize operational energy, their implementations can paradoxically result in increasing the total life-cycle energy use of buildings due to ignoring the embodied impacts [6,7]. This is echoed in the findings of Stephan et al. [6] who assessed the life-cycle energy performance of a Belgian passive house. Their results indicated that current certifications developed to promote energy efficiency in buildings cannot assure the reduction of the total energy consumption since embodied impacts are excluded. They also showed that the embodied energy of passive houses may constitute up to 77% of the total building life-cycle energy use over 100 years.

In recent years, academic studies have given more attention to the necessity of minimizing energy use throughout the entire building life cycle by including both embodied and operational energies. To demonstrate the significance of embodied impacts, numerous detailed cases of buildings have been developed by academics using the life-cycle energy assessment (LCEA) approach. Nevertheless, this surge of research has failed to alter the attitude of policymakers toward considering the importance of buildings' embodied energy when planning for the betterment of built environment [8]. Retrospective research has primarily placed the blame on the analysis of embodied energy where the absence of a standardized framework and calculation methodology often leads

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to displaying a significant spread of results in LCEA analyses [9]. Over the last decades, significant efforts have been made to standardize the application of life-cycle assessment in buildings through setting several international standards such as ISO 21929-1 [10], ISO 21931-1 [11], and the European standards developed by Technical Committee TC350, including EN 15643-2 [12] and EN 15978 [13]. However, there is considerable evidence indicating variations in the results of LCEA analyses [4,8,14,15]. Previous research has endeavoured to explore sources of variations, with a focus given only to the calculation of buildings' embodied impacts [16, 17]. Despite the undertaken attempts, there is still a need to investigate the key parameters causing variations in LCEA results by examining methodological approaches of the current studies toward quantifications of embodied and operational energies. Therefore, this paper aims to address three primary questions: 'what is the current trend of methodological approach for applying LCEA in residential buildings?'; 'what are the key parameters causing variations in LCEA results?'; and 'how can the continued variations in the application of LCEA in residential buildings be overcome?'. To this end, we first analysed 40 LCEA papers in order to address the two first questions. This paper then puts forward proposals for standardization of LCEA application in residential buildings by developing a conceptual framework in order to address the third question.

2. An overview of LCEA

Life-cycle assessment (LCA) is an approach toward identification and quantification of environmental loads attributed to services, products, or processes throughout their entire life cycles [18]. The International Organization for Standardization (ISO) introduced the first series of standards (14040, 14041, 14042, and 14043) relating to LCA between 1997 and 2000 [19]. In 2006, these standards were updated by amalgamating prior versions, which led to the current ISO standards 14040 and 14044 [20,21]. These standards set up a framework to perform LCA, consisting of four major steps: (1) defining the goals and scope, (2) life-cycle inventory (LCI), (3) life-cycle impact assessment, and (4) interpretation. The first step involves establishing the goals and scope of the assessment, defining the system boundary, and specifying the quality criteria for inventory data. This is followed by an LCI, where the procedure for collecting and synthesizing data related to energy flows should be determined at each individual stage of a product's life cycle. The next step, life-cycle impact assessment, involves quantifying the environmental impacts of materials and energy flows and assigning them to their corresponding environmental impact categories. In the last step, the results of the LCA are interpreted in relation to the study's goals and scope, and recommendations are made for decision-making purposes.

LCEA is a version of the LCA that considers only the energy inputs at all stages of a building's life cycle [22,23]. Adopting this approach to assess a building's energy performance means quantifying its total energy consumption, by considering both operational and embodied energy (Fig. 1). Embodied energy refers to the amount of energy used for material production (i.e. extraction of raw materials and material manufacturing), assembly (i.e. construction/installation), replacement and maintenance, end-of-life (EOL) processes and transportation required between any of these steps [18,23,24]. The amount of energy consumed in the form of thermal (i.e. heating and cooling) and non-thermal loads (i.e. domestic hot water (DHW), electrical appliances and equipment, ventilation, lighting, and cooking) over a building's lifespan is known as operational energy [18,23,24].

3. Research methodology

This paper adopts a systematic literature review approach to identify published materials relating to the LCEA application in residential buildings. The review commenced with carrying out a comprehensive searching exercise through multiple databases, namely Web of Science, ProQuest, and Scopus. Using these platforms enables researchers to gain access to numerous international journals, based on which a systematic literature review can be conducted [25,26]. The initial search was conducted using certain keywords, as tabulated in Table 1. The types of searched materials were 'articles' and 'reviews'; and the timespan set for the search was between 1996 and 2020, in which the starting year coincided with the publication of the first series of ISO standards. As a result, more than 750 publications were identified to meet the initial criteria.

An initial screening check was performed based on the titles, abstracts, and conclusions of the identified materials in order to make a preliminary decision about the suitability of identified articles for inclusion. At this stage, certain criteria were considered to weed out irrelevant materials. First, publications written in any language other than English were filtered out, as well as non-peer reviewed articles. In addition, only studies with the application of LCEA approach in 'residential' buildings were considered for further analyses. Considering these criteria led to downsizing the collected materials to about 260.

After the initial screening, the contents of all remaining articles were checked qualitatively to ensure that only those falling within the scope of this paper were selected. Herein, studies that focused solely on embodied energy analysis were filtered out due to their limited approaches for the assessment of buildings' life-cycle energy use. In addition, this review only retained LCEA studies that measured buildings' energy performance based on primary energy because the primary energy is a better measure of the environmental impacts of buildings [27,28]. As a result, 40 papers that analysed 157 cases of residential buildings across 16 countries were selected for detailed examinations. Summaries of these papers were exported to *Excel Spreadsheets* for further analysis (See the Appendix). In this paper, we considered all types of residential buildings for the analysis, i.e. energy-efficient buildings, conventional buildings, high- and low-rise buildings, and urban and suburban buildings. This review considers different versions of a building analysed in one source as one case study.

Following the examination of the reviewed studies, a conceptual framework was developed. This framework primarily aims to simplify the intertwined processes involved in an LCEA by providing a clear description of the system boundary.

4. Analysis and results

The selected studies are analysed based on four main criteria: i) system boundary definitions, ii) methods applied for quantification of embodied energy, iii) methods applied for calculation of operational energy, and iv) approaches taken toward interpreting LCEA results. The Appendix includes a detailed list of analyses carried out in this paper.

4.1 Definition of system boundary

System boundary definition denotes the act of determining a set of variables that distinguish the system under study from other systems in an environment [16,23]. In this paper, the approaches of analysed studies toward delineating system boundaries are analysed to identify: i) the building life-cycle stages excluded by the system boundary, ii) the building components and their systems included within the system boundary to calculate embodied impacts, iii) the parameters included within the system boundary to calculate operational energy, iv) the building lifespan, and v) the key assumptions made by the reviewed studies.

4.1.1. Exclusion of life cycle stages

The building life cycle stages consist of raw material extraction, material manufacturing and processing, construction/installation, operation, maintenance and replacement, transportations between any of these steps, and EOL (Fig. 1). A whole LCEA then refers to the one that accounts for energy consumption throughout the entire buildings' life

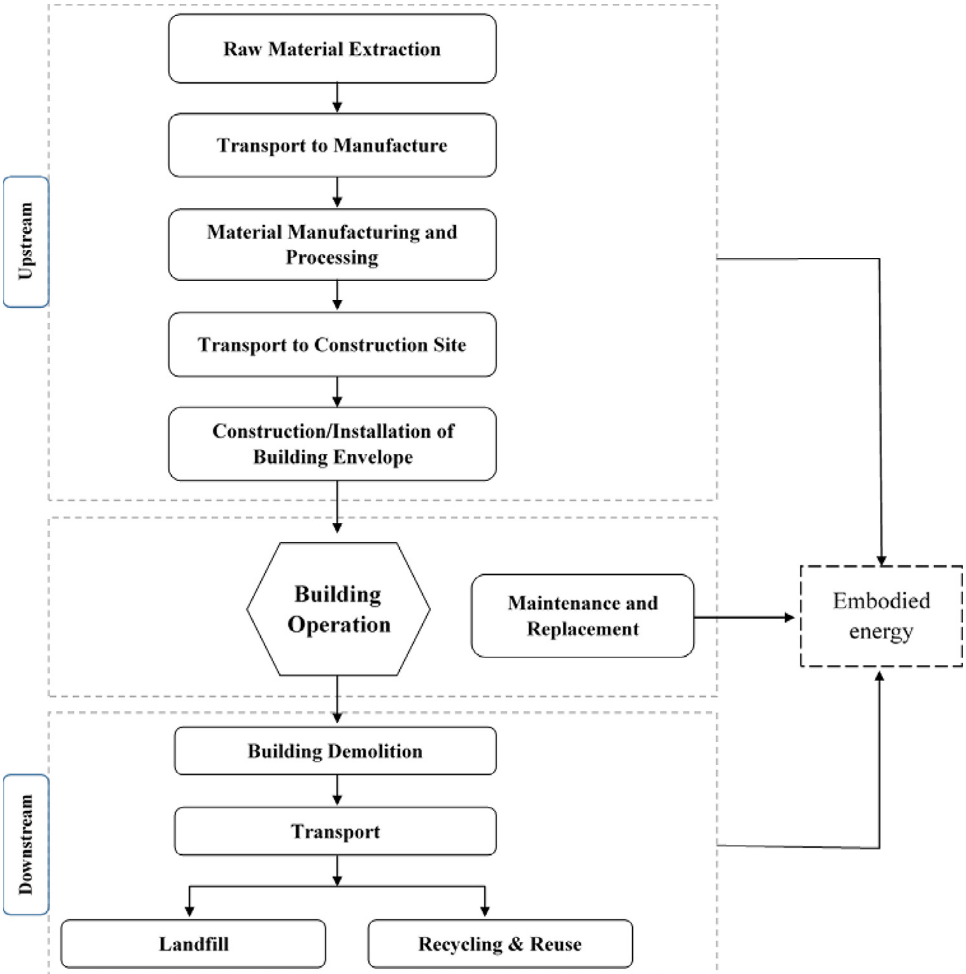

Fig. 1. Building life cycle energy

Table 1
Keywords applied during the initial search

Keywords used to search for life-cycle energy assessment studies
Building life-cycle assessment; building life-cycle energy assessment; building energy performance; building life-cycle impact assessment; building life-cycle environmental assessment; building life-cycle; energy efficient buildings; residential buildings; building primary energy consumption; and building embodied energy analysis.

Table 2
Exclusion of building life cycle stages

Stages of building life cycle	Number of studies	
Production	Raw material extraction	0
	Transport to manufacture	1
	Manufacturing and processing	0
Assembly	Transport to construction site	9
	Construction/installation	11
Maintenance	Maintenance and replacement	14
End of life	De-construction/demolition	23
	Transport	23
	Disposal	24
Reuse, recovery, recycling		26

cycles. Table 2 shows the number of reviewed studies that excluded building life-cycle stages from the system boundary.

The review reveals that 32% of the studies carried out a whole LCEA, while others omitted certain life cycle stages. The processes involved in the EOL stage (i.e. de-construction, transport, and disposal of construction wastage) were excluded by 58% of the studies. This exclusion was commonly justified due to i) the minor contribution of this stage to the total life-cycle energy use of buildings, and ii) uncertainties about deconstruction practices at the EOL [6,29–38]. Amongst those that accounted for energy consumption at EOL, the common trend was to base the calculation on assumptions. For instance, Crawford [39] assumed that the energy needed for building deconstruction and disposal of its materials equated to 1% of the house's total life-cycle energy demand.

In addition, maintenance and replacement (also known as recurrent embodied energy) was excluded by 35% of the studies. Understanding the impacts of recurrent embodied energy is important for many reasons, such as making informed choices about building design and materials, and understanding the impact of the maintenance and management of buildings [9]. Studies have also shown that recurrent embodied energy may have a substantial effect on the total life-cycle energy use; thus, ignoring its impact can underestimate the environmental burdens of buildings. For instance, Stephan and Stephan [33] showed the recurrent embodied energy of a residential building in Lebanon may constitute up to 31% of the total building embodied energy. Crawford [39] also estimated that recurrent embodied energy of an Australian building can be up to 22% of the total building life-cycle energy demands. Further-

Table 3
Energy saved at different stages through reusing, recovering and recycling building materials (kWh/m^2.year)

Reference	Building characteristics	Energy saved at production stage	Energy saved at construction stage	Energy saved at EOL stage	Total energy saving	Total energy saving (%)
Gustavsson et al. [50]	Wood-framed apartment	23.64	NA	11.42	35.06	17.84
Dodoo and Gustavsson [51]	Conventional building with electric heated system	7.78	NA	7.92	15.70	5.36
	Conventional building with heat pump heated system	7.78	NA	7.92	15.70	7.27
	Conventional building with district heated system	7.78	NA	7.92	15.70	7.79
	Passive building with electric heated system	8.0	NA	8.06	16.06	6.05
	Passive building with heat pump heated system	8.0	NA	8.06	16.06	7.77
	Passive building with district heated system	8.0	NA	8.06	16.06	8.22
Cellura et al. [52]	Net zero energy building	NA	NA	22.62	22.62	10.83
Dodoo et al. [53]	Cross laminated timber structure with heat pump heated system	20.92	1.44	11.80	34.16	16.85
	Beam-and-Column system structure with heat pump heated system	20.22	1.26	10.90	32.38	15.35
	Modular timber structure with heat pump heated system	10.18	1.10	9.04	20.32	9.73
	Cross laminated timber structure with district heated system	20.92	1.44	11.80	34.16	17.81
	Beam-and-Column system structure with district heated system	20.22	1.26	10.90	32.38	16.34
	Modular timber structure with district heated system	10.18	1.10	9.04	20.32	10.32
Tettey et al. [54]	Standard building with concrete system	1.92	NA	5.63	7.55	4.90
	Standard building with cross laminated timber structure	20.98	NA	10.67	31.65	21.24
	Standard building with modular timber structure	8.075	NA	6.30	14.38	9.75
	Passive building with concrete system	1.92	NA	5.63	7.55	8.55
	Passive building with modular timber structure	8.53	NA	6.57	15.10	18.37
Zhan et al [55]	Prefabricated building	NA	NA	4.99	4.99	6.84
Thormark [43]	Low energy building	NA	NA	31.12	31.12	36.75
Blengini and Di Carlo [56]	Low energy house	NA	NA	11.11	11.11	13.74
Takano et al. [46]	Detached house with light weight timber structure	NA	NA	21.96	21.96	17.95
	Row house with light weight timber structure	NA	NA	15.17	15.17	15.56
	Townhouse with light weight timber structure	NA	NA	15.42	15.42	17.77
	Apartment block with light weight timber structure	NA	NA	12.96	12.96	18.96
	Detached house with cross laminated timber structure	NA	NA	35.06	35.06	26.03
	Row house with cross laminated timber structure	NA	NA	29.04	29.04	26.93
	Townhouse with cross laminated timber structure	NA	NA	31.9	31.9	32.60
	Apartment block with cross laminated timber structure	NA	NA	28.77	28.77	37.48
	Detached house with reinforced concrete panel structure	NA	NA	14.04	14.04	10.89
	House with reinforced concrete panel structure	NA	NA	10.62	10.62	10.63
	Townhouse with reinforced concrete panel structure	NA	NA	9.31	9.31	10.48
	Apartment block with reinforced concrete panel structure	NA	NA	6.95	6.95	10.64
	Detached house with steel structure	NA	NA	14.66	14.66	11.68
	Row house with steel structure	NA	NA	10.67	10.67	10.70
	Townhouse with steel structure	NA	NA	9.81	9.81	11.04
	Apartment block with steel structure	NA	NA	7.72	7.72	11.08

Note: The detailed numerical values for recycling/reusing potentials were given by nine studies out of fourteen.

more, this paper found that the construction/installation stage was excluded by 27% of the studies. This was mainly due to its perceived minor impact on total building life-cycle energy use [30,31,40,41] and the difficulty in gathering data on the energy consumption of on-site construction operations [37]. Some studies did not discuss the reasons for its exclusion [42–46]. Transportation of materials to the construction site was also excluded by 22% of the reviewed studies, which was mainly justified by its minor impact on total life-cycle energy use.

The reuse, recovery, and recycling of building materials was excluded by 65% of the reviewed studies. This term refers to the processes in which the environmental benefits of building materials beyond the defined system boundary are captured [47]. The use of this strategy has been widely seen as an effective measure to mitigate buildings' environmental impacts [48,49]. This paper found that the amount of energy saved by using this strategy averaged between 5 to 38% of a building's total life-cycle energy use (Table 3).

4.1.2. The extent of system boundary definition: calculating embodied energy

Calculating embodied energy largely depends on the extent to which the embodied impacts of building components and their systems are included within the system boundary. Table 4 presents the building components considered by the analysed studies when accounting for buildings' embodied energy. The review showed that the inclusion of embodied energy impacts of building components and their systems within the system boundary was inconsistent. The majority considered the embodied impacts of superstructure, substructure and finishings, whereas only half of the reviewed studies considered the embodied energy of building services. This can be related to the higher weights of the former components in buildings' bill of quantity, and the energy intensiveness of their production processes due to using high amounts of cement or steel [29,33,39,50,57]. On the other hand, 83% of the studies excluded the embodied energy of built-in furniture, fixtures, appliances or elements beyond building components (such as urban infrastructure or

Table 4
The embodied energy of building components considered by the reviewed studies

Elements	Descriptions	Number of studies considered
Superstructure	Structural frame; interior and exterior walls; stairs; floor; roof; windows; interior partitions; interior and exterior doors.	40
Substructure	Foundation; basements.	37
Finishing	Wall, floor and ceiling finishings.	30
Services	Sanitary installation, installations (water, lighting, electrical, ventilation); space heating and air conditioning; firefighting elements.	20
RES	Photovoltaic panels, solar collector, wind turbines.	12
Furniture, fixtures, appliances	Built-in furniture, interior fixtures, or appliances.	7
Elements beyond building	Urban infrastructure (e.g. roads, water, sewage systems); residents' mobility.	5

occupants' transportation) from their system boundaries. Further, the system boundaries defined by studies that investigated life-cycle energy performances of net-zero-energy buildings (NZEBs) were found to be wider than those considering conventional buildings since they also included the embodied impacts of renewable energy systems (RESs), such as photovoltaic panels, solar collectors, or wind turbines, within system boundaries.

The possibility of expanding the system boundary to include parameters beyond the scale of a building has also been pointed out by a number of studies [6,32–34,44]. Stephan et al. [32] proposed a framework to consider the embodied impacts of nearby infrastructure (roads, water, sewage systems, etc.), and the energy used for occupants' transportation. This framework was then employed to analyse the life-cycle energy performances of two residential buildings in Australia and Belgium. The authors concluded that the occupants' transportation made up 25.4% and 33.8% of the entire building life-cycle energy consumption in the Belgian passive house and the Australian building, respectively. Bastos et al. [34] also performed an LCEA to compare energy consumption and greenhouse gas emissions of two buildings, one apartment building located in the city centre and a semidetached house in a suburban area. In addition to the embodied impacts of buildings, they also considered energy consumed for occupants' transportation. The results indicated the significance of energy consumption for occupants' transportation, especially for the suburban building.

4.1.3. The extent of system boundary definition: calculating operational energy

Energy is consumed in the forms of thermal and non-thermal loads over a building's lifespan in order to maintain a habitable indoor environment [18,23,24]. Parameters influencing thermal loads include heating and cooling, whereas DHW, electrical appliances, ventilation, lighting, and cooking are the factors that determine non-thermal loads. Hence, whether the system boundary is set to account for the impacts of these parameters directly affects the calculation of operational energy.

The review showed that the studies had different levels of inclusion to account for the impacts of parameters that affect operational energy use (Fig. 2). It is found out that only 20% of the studies included all parameters [31–35,37,39,52], while the impacts of cooking were excluded by 68% of the studies, followed by cooling (53%), lighting (38%), ventilation (28%), electrical appliances (28%), DHW (28%), and heating (10%). Moreover, one study did not discuss its level of inclusion for the assessment of operational energy usage [58]. Eliminating each parameter from the system boundary affects LCEA results by changing the proportion of operational energy [59,60]. For example, Gustavsson and Joelsson [59] found that the share of embodied impacts in a building's total life-cycle energy usage decreased from 33% to 25% once the scope had been extended from space heating only to include ventilation, DHW, and household electricity.

It is also noted that the system boundary was commonly defined subjectively, without providing any contextual justification. Only four of the reviewed studies [7,38,42,61] gave reasons for excluding certain parameters. For instance, Crawford et al. [7] only considered heating and cooling loads as these are the only demands considered by the Building Codes of Australia. Pinky Devi and Palaniappan [38] also justified the exclusion of cooking since it was usually done using firewood in low-cost houses in India. The subjectivity in the definition of the system boundary underlines the lack of a framework or a standardized approach for calculating buildings' operational energy usage.

4.1.4. Building lifespan

The range of building lifespans assumed by the analysed studies falls between 30 and 100 years, with the most frequently used lifespan of 50 years (Table 5). This assumption is of utmost importance due to its direct effect on the proportion of embodied and operational energy in an LCEA. The share of embodied energy in a building's total life-cycle energy use can be affected by calculations of recurrent embodied energy, as assuming a long lifespan leads to frequent replacement of building materials, while assuming a short lifespan will induce the need to change the entire building [62,63]. Rauf and Crawford [63] studied the correlation between a building's lifespan and its embodied energy. They found that a building's embodied energy demands can be decreased by 29% by increasing the lifespan from 50 to 150 years. In addition, assumptions about a building's lifespan can affect operational energy, as prolonging the lifetime of a building results in an increase in energy consumption over its service life [64].

Determining a building's lifespan in an LCEA is challenging due to numerous variables involved in terminating a building's life such as urban redevelopment, deterioration of the building's physical condition, and damage from natural causes such as fire and flood. In an LCEA, the main concern in choosing a building's lifespan is that it is an arbitrary decision, as a number is simply assumed by referring to other research. In addition, there is an inconsistency in the choice of lifespan regarding the geographical region. This can be seen in Table 5, as the assumptions differ within one country, or region (e.g. the EU).

The ideal conditions for an accurate prediction of building lifespan are those in which the microclimate is well known, while the characteristics of all individual components and elements of the building can be determined using laboratory or real-life data [75]. However, this approach is impractical from an LCEA practitioner's point of view. It is therefore recommended to utilize a simpler "factor method" for such estimations, where the aim is to apply a "rough-and-ready" means of estimating rather than predicting buildings' service life [75]. The future direction in this particular area of LCEA may lie with developing performance-based estimation approaches in each region, combined with creating open-access databases containing information about the service lives of construction materials that can be accessible by all practitioners.

4.1.5. Assumptions

In an LCEA analysis, making assumptions is inevitable due to various uncertainties involved [23]. This paper identified various assumptions

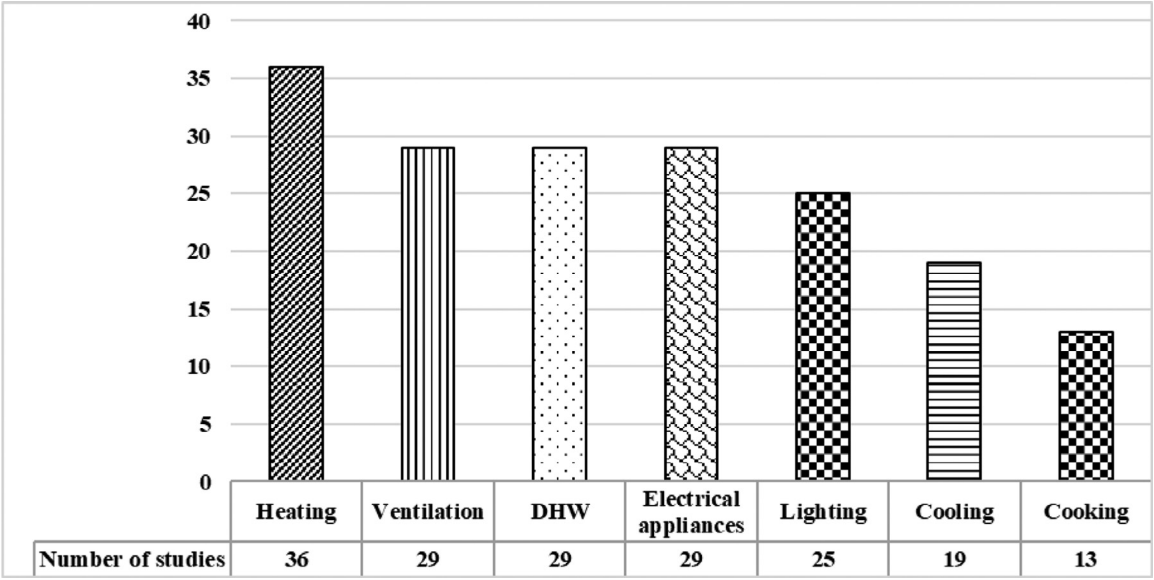

Fig. 2. Number of studies that considered the inclusion of parameters influencing operational energy

Table 5
Frequency of use of building lifespans

Country of case study	Building lifespan	Frequency of use	Reference
Australia	30 years	1	[44]
Canada	40 years	1	[65]
Australia, Sweden, Lebanon, Turkey, Belgium, Portugal, Norway, Finland, India, Thailand, China, Israel, Brazil	50 years	23	[7,29,32–34,37–39,43,46,50,53,57,59,61,66–72]
Ireland, Norway, Belgium	60 years	3	[40–42]
China, Italy	70 years	4	[52,55,56,73]
India, Portugal	75 years	3	[30,31,35]
Sweden	80 years	1	[54]
Belgium, Australia	100 years	4	[6,45,58,74]

made by the reviewed studies and grouped them with respect to their corresponding stage of the building life cycle (Table 6).

The first group refers to the assumptions that pertain to the calculation of embodied energy at the production stage. These assumptions are commonly made in response to the absence of a locally-driven database. For instance, Devi and Palaniappan [67] applied a European database to compute the embodied impacts of a building in India. Similarly, Stephan and Stephan [33], and Stephan et al. [6] employed 'Australian input–output-based hybrid embodied energy intensities' to calculate the embodied energy of buildings located in Lebanon and Belgium, respectively. However, geographic representativeness of the data is an important parameter that needs to be considered when measuring embodied energy since countries differ in their manufacturing processes, construction technologies, economic sectors, energy tariffs, and fuel supply structure [28]. As such, adopting data that is non-native to the location of the building under study may compromise the accuracy of calculations of embodied energy.

The second group of assumptions relates to the operation stage. A common trend in calculating the operational energy of buildings is to compute energy use for one year of the building's operation, then the calculated value is multiplied by the number of years assumed for the building's lifespan. As a result, the studies commonly assumed that operational energy consumption would stay constant throughout the entire life of the building. This assumes the occupancy profile of a building would remain unchanged (in terms of family size or the occupancy schedule), or there would be no depreciation of heating and cooling systems (a constant coefficient of performance). In addition, none of the reviewed studies considered the effects of climate change on buildings' energy consumption. The calculation of operational energy usage has been commonly carried out by considering present climatic conditions, while ignoring the possible future effects of climate change. This assumption was only declared by three studies [30,31,65]. Previous studies have shown that heating and cooling demands can be affected by climate change. For instance, Karimpour et al. [76] performed a parametric analysis using the Typical Meteorological Year for 2070 to design the building envelope of a residential building in Adelaide, Australia. They concluded that heating will become significantly less important as buildings would be better insulated while the climate would be warmer, and therefore more focus should be allocated toward mitigation of cooling loads in buildings. As such, considering the impacts of climate change on operational energy demands is recommended for future LCEA studies.

The maintenance and replacement stage has also been subject to several assumptions, as shown in Table 6. Although not discussed by most of the studies, it is commonly assumed that building materials are to be replaced with similar materials when they reach the end of their service lives; thus, they incur the same amounts of embodied energy as the original materials.

The final group attributes to the assumptions made in order to facilitate calculating embodied impacts of construction/installation and EOL stages. As previously mentioned, these stages were excluded by the majority of the reviewed studies. Amongst those accounting for their contributions, some assumed certain values as the impacts of these stages on the total building life-cycle energy consumption. For instance, Gustavsson et al. [50] assumed that the primary energy used for the on-site

Table 6
A summary of assumptions made by the reviewed studies

Targeted stage	Assumption	Reference
Production	• Use of databases containing embodied energy coefficients of building materials not originating in the country of the case studies; • Using input-output (I–O) data developed over a decade ago to represent energy intensities of construction materials; • Data for a similar material were used when more specific data were unavailable.	[6,33,39,43,57,74]
Assembly	• Assuming one location to carry out all the production processes; • Assuming certain values of energy consumption as the effect of this stage on the entire life-cycle energy use (e.g. 80 kWh/m², 160 kWh/m² or 4% of the material production primary energy).	[50,53,54]
Operation	• Unchanged occupancy profile (occupants' behaviors, family size, etc.); • Unchanged patterns of use for heating and cooling systems; unchanged coefficient of performance rates for all mechanical systems; • Unchanged resource mix supplying electricity to the buildings; • Using energy bills of another building with similar specifications to estimate the building's operational energy.	[29–31,35,37,51]
Maintenance and replacement	• The service life of the building's structural elements were assumed to be the same as the building itself; • Building materials were expected to be replaced with the same materials when they reached their end of service lives; • Assuming certain values of energy consumption as the effect of this stage on the entire life-cycle energy use; • Using the replacement lifetimes of U.S. construction materials for a case study in Australia; • Unchanged construction methods and materials during the entire building lifespan; • Replaced materials were assumed to have the same amount of embodied energy as the originals.	[41,44,46,57,66,74]
EOL	• Assuming certain values of energy consumption as the effect of this stage on the entire life-cycle energy use (e.g. 1% or 3% of the total life-cycle energy demand); • Assuming 10 and 20 kWh/m² of energy consumption for demolishing wood and concrete respectively; • Using only one type of fuel to transport construction wastage; • Assuming the recovery of 90% of the wood-based demolition materials, while decaying 10% into the atmosphere.	[39,50,51,53,54,57,67]

construction of an eight-story apartment equalled 80 kWh/m^2. Analogously, studies assumed different values in order to account for the impacts of the EOL stage [39,53,67]. For example, Devi and Palaniappan [67] assumed that this stage consumed 3% of the total initial embodied energy.

Overall, the assumptions made for different stages of a building's life cycle can have a significant effect on the final results of an LCEA. Thus, all the assumptions in an LCEA study need to be clearly stated for the sake of transparency while justifying their contextual applicability. The sensitivity of each assumption toward total building life-cycle energy use should be tested at the interpretation stage. Three methods are identified here that can potentially be used in order to assure the robustness of the LCEA results (See section Interpretation).

4.2. Methods applied to calculate embodied energy

The results of an LCEA can be influenced by the method applied to calculate embodied impacts. The review shows that three major methods have been utilized to compute the embodied impacts of buildings, namely the process-based, economic input-output (I-O), and input-output-based hybrid methods. The process-based method is most effective when the physical flow of the system under study is identifiable and can be easily traced. However, this approach becomes difficult to apply when the inputs and outputs of the system are numerous [57]. Also, errors can be induced by the subjective truncation of the upstream production system [68]. On the other hand, the economic I-O method takes a top-down approach and utilizes the entire economy as the theoretical boundary to arrive at clear definitions of the system boundary. This method aims to determine the quantity of energy consumed to produce a specific service or product by decoding the flow of materials in an economy's structure. Although using this method improves the incomplete system boundary definition in the process-based method, it still suffers from a lack of product-specific data. To address this issue, the I-O-based hybrid approach was proposed to incorporate the inputs from the entire upstream supply chain by amalgamating the two previous approaches [23,77]. The review revealed that 60% of the studies utilized the process-based approach; 23% used the I-O-based hybrid approach; only one study applied the economic I-O approach [44]. Furthermore, 15% of the studies did not discuss the methods they used to calculate embodied impacts [30,31,61,70,51,54].

To compute embodied impacts, it is necessary to select a background database that contains datasets representing the technical and economic contexts of the case study [23]. It is found out that the background data required for embodied energy calculations were retrieved from two primary sources: 'literature' (i.e. data published by other research) and databases that are available publicly or commercially (Table 7). Overall, 13% of the studies solely relied on the literature to calculate embodied impacts. Using this approach may potentially undermine the reliability of the achieved results for decision-making purposes since the adopted background databases might not represent the regional contexts of the

Table 7
Databases applied by the reviewed studies

Database	Developer	Data coverage	Boundary	LCI method	Ref.
SimaPro[1]	PRe´ Consultants, Netherlands	Industry data, U.S. LCI, Danish input-output database, Dutch input-output database, LCA food database, Ecoinvent	Cradle-to-grave	Process-based and I-O method	[29,52,74]
Ecoinvent	Ecoinvent centre, Swiss	Generic data on various products and processes including chemicals, waste management, agriculture, energy, washing agents, transport, paper & board, and building materials	Cradle-to-gate	I-O method	[34,40,41,46,53,56,71]
Inventory of Carbon and Energy	Bath University, UK	Specific-process data on over 200 construction materials, European, mainly UK data	Cradle-to-gate	Process-based method	[35,37, 38,42,57, 66,67]
AusLCI	Building Product Innovation Council, Australia	Process data on construction products and materials, Australian data	Cradle-to-grave	I-O method	[74]
Building for Environmental and Economic Sustainability	National Institute of Standards and Technology (U.S.)	Construction materials, mainly U.S. data	Cradle-to-grave	Process-based method	[66]
Database of Embodied Energy and Water Values for Materials	University of Melbourne	Construction materials, Australian data	Cradle-to-grave	I-O based hybrid method	[6,7,32,39]
Chinese Life Cycle Database	Sichuan University, China; IKE Environmental Technology Co., China	Waste management, energy carriers, transport, materials and chemicals; data coverage for China	Cradle-to-gate	Process-based method	[68]
Athena Institute Impact Estimator database	Athena Sustainable Materials Institute	Construction materials, North American	Cradle-to-grave	Process-based method	[65]

Note: (1) the exact database has not been reported.

buildings under study. In addition, 33% of the studies used generic international databases, namely Inventory of Carbon and Energy, Athena Institute Impact Estimator, Ecoinvent, and Building for Environmental and Economic Sustainability, while 15% of the studies combined process-specific data acquired from different sources such as local manufacturers [50,73], or databases developed nationally or regionally with generic international databases [53,54,71,74] in order to increase the geographical representativeness of the data.

The findings show that the studies have taken different approaches toward calculating the embodied energy demands of the analysed buildings. These differences of approach, coupled with the differing definitions of the system boundary, make the LCEA results highly variable across the reviewed studies.

4.3. Methods applied to calculate operational energy

This paper found that the studies applied five main methods to calculate operational energy usage:

- Building energy performance simulation (BEPS) tools. The review showed that 65% of the studies utilized BEPS tools to calculate operational energy. In recent years, this method has been widely applied to support the processes involved in building design, construction, operation, and retrofitting [78]. However, the main challenge of the BEPS approach attributes to incorporating assumptions about occupant behaviours into the simulated model and whether or how much they reflect real-world occupant behaviours. Previous studies indicated that relying solely on simulation software may induce significant deviations between predicted and actual building performances [79,80].
- Energy bills. Around 8% of the studies used the actual records of energy bills to calculate operational energy usage [37,39,57]. Employing this method enables researchers to comprehensively capture the effects of occupants' behaviours on energy usage. Nevertheless, using this method only provides an aggregate value for operational energy consumption, and does not provide a detailed breakdown of energy usage. This makes it difficult for decision-makers to identify the 'hot spots' of energy use in buildings and to provide solutions for energy reduction [23].
- Monitoring. 8% of the studies monitored buildings' energy consumption using sensors and actuators in order to calculate operational energy [52,67,73]. Using this method enables researchers to acquire detailed data on the actual energy use of buildings by continuously sensing instantaneous values of current and voltage, or gas usage to provide a measurement of energy used [81]. However, there are several challenges involved in using this method, in particular the issue of interoperability. This term refers to exchanging the data between components of building energy monitoring and metering systems in a standardized way so that they can properly communicate with each other irrespective of the manufacturing brands and physical medium [81]; thus, all the data corresponding to different types of energy use in buildings can be metered and recorded uninterruptedly. Furthermore, the high initial cost and the difficulty in managing and storing the high amounts of metering data can also be listed as potential challenges in using this method [81]
- National statistics. The review shows that 8% of studies utilized data representing national or regional statistics on energy consumption in the building sector in order to calculate operational energy use [34,35,38]. Using this method can potentially lead to a divergence between estimated and actual operational energy use since these data are developed based on the average energy consumption in the building sector. Moreover, the age of the data in this method can be a matter of concern. For instance, Bastos et al. [35] used data from 2002 related to the residential use of electricity and natural gas from the Lisbon Energy Matrix in order to calculate a building's operational energy usage.
- Others. Other methods were applied in 10% of the reviewed studies [6,32,33,55]. Stephan et al. [32] and Stephan et al. [6] used static equations in order to calculate heating and cooling loads, then non-thermal energy demands were estimated using regional per capita average energy consumption. In another study, Stephan and Stephan [33] utilized dynamic simulation software to calculate heating and cooling loads, while non-thermal energy demands were computed

using regional averages for energy consumption in Lebanon. Zhan et al. [55] also used static equations to calculate the amount of energy consumed for heating, ventilation, air conditioning, and lighting during a building's operation. Using static equations can assist researchers to produce an accurate estimation of a building's energy performance at the early stage of building design; however, it can be time-consuming when the aim is to optimize a building design through parametric analysis [23].

The review showed that the studies applied different methods to measure operational energy use. The majority employed BEPS tools, mainly without validating their results. Only two studies validated their simulated results against actual data [72,74]. The seldom reliance on this approach may lead to inaccurate results due to ignoring the impacts of occupants' behaviours on energy usage. For instance, Van Dronkelaar et al. [79] reported a discrepancy of 34% in total energy between design and actual building performance, with a 10–80% estimated effect of occupants' behaviours. Contrarily, the use of the energy bills [37,39,57] and monitoring [52,67,73] methods can address the aforementioned issue by taking into consideration the effects of occupants' behaviours on energy use over a building's lifespan. Using national or regional statistics on average energy consumption in the building sector was another method applied by the reviewed studies to calculate operational energy [34,35,38]; however, this approach can also lead to an inaccurate estimation of operational energy since it fails to account for the particular buildings' characteristics, occupants' behaviours, and the effects of microclimate on buildings' energy consumption.

In sum, LCEA results can also be affected by the method chosen to calculate operational energy. Quantifying the impacts of each method on the LCEA results is beyond the scope of this paper, though it is an important topic for future research.

4.4. Interpretation

Interpretation is the final stage of an LCEA in which the obtained results are discussed with regard to the scope and aim of the research and recommendations are made accordingly. In principle, the LCA standards recommend performing certain types of evaluation in order to assure the accuracy of the achieved results. For instance, ISO 14044 recommends three analyses: completeness check, sensitivity check, and consistency check [20]. Detailed explanations of these analyses can be found in [23]. EN 15978 also suggests undertaking result verification to formally confirm the achieved results [13]. In addition, EeBGuide recommends conducting an uncertainty analysis and states that, where possible, an alternative scenario should be modelled for each stage of the life cycle [47].

The findings showed that three methods have been applied by the analysed studies as a means of evaluation, namely sensitivity analysis, uncertainty analysis, and discussion of limitations. Uncertainty analysis measures the uncertainty in model outputs, which is derived from input uncertainty, while sensitivity analysis assesses the inputs' contributions to the total uncertainty in the analytical results [82]. Discussion of limitations refers to acknowledging the limitations of the LCEA and discussing their implications for the final results without undertaking any quantitative analysis. Regarding sensitivity analysis, 15% of the studies utilized only this method to examine the effect of inventory data parameters [34,37,53,59,67,69]. In these studies, the impacts of several variables on total building life-cycle energy use were analysed, namely climate and energy mix, the choice of insulation materials, the method of assessing embodied energy at the production stage, building lifespan, air infiltration rate, ventilation heat recovery efficiency, and the effects of building location. Also, 13% of the reviewed studies applied uncertainty analysis [6,32,50,54,56]. For instance, interval analysis was used by a number of studies to evaluate uncertainties concerned with embodied energy data [6,32]. Finally, 13% of the studies discussed limitations linked to their research [35,39,46,57,58]. Different limitations were discussed such as assuming a constant energy mix over 50 years, assuming the same service life for the building's structural components as for the building, and assumptions pertaining to building occupancy [57], using old I-O data [39], ignoring the EOL stage, using a database to calculate embodied energy that is derived from UK production processes [35], excluding the impacts of interior zoning of spaces (e.g. living room, bathroom, bedroom) on operational energy usage, and excluding the impacts of partition walls on embodied energy [46].

Furthermore, no study adopted all the three methods to evaluate the LCEA results, and only 18% of the studies included two of them, i.e. sensitivity analysis and discussion of limitations [7,38,40,66,74], uncertainty analysis and discussion of limitations [33], and sensitivity analysis and uncertainty analysis [41]. 42% of the studies also did not perform any evaluation.

5. Discussion

This section aims to offer responses to the first two research questions; 'what is the current trend of methodological approach for applying LCEA in residential buildings?'; and 'what are the key parameters causing variations in LCEA results?'. Table 8 shows the overall methodological trends of the reviewed studies. In this table, 12 major parameters are identified that can lead to varying LCEA results. These parameters are further categorized into four main groups: i) system boundary definition, ii) calculation methods, iii) geographical context, and iv) interpretation of results.

The incomplete definition of the system boundary is a primary issue relating to the LCEAs carried out by the analysed studies. It is interesting to mention that, with one exception [39], no study had a complete definition of the system boundary, that is, a definition that included all stages of a building's life cycle, all parameters influencing operational energy usage, and the embodied energy of all building components. Even studies with a broad definition of the system boundary for assessing embodied energy [6,32–34,44] excluded the impacts of certain stages of a building's life cycle or some influential parameters in calculating operational and embodied energy. Another issue associated with the LCEAs conducted by the reviewed studies is the subjectivity in defining the system boundary since they barely gave justifications for truncating system boundaries. As a result, the incomplete definitions of the system boundaries compromise the accuracy of LCEAs in representing the total life-cycle energy performance of buildings. This can further reduce decision-makers' ability to rely on these results for purposes such as implementing environmental practices (e.g. eco-labelling).

The review also revealed different approaches employed by the studies to measure embodied energy and operating energy. Regarding embodied energy, studies with a wider approach, namely the I-O-based hybrid, were more likely to yield a higher value as it captures energy usage embedded in both the downstream and upstream stages of the supply chain [7,33,77]. Likewise, the analysed studies adopted different methods to calculate operational energy. A limited number of studies applied methods that capture occupants' behaviour regarding energy consumption, namely energy bills [37,39,57] and monitoring [52,67,73], whereas the majority employed simulation software. Moreover, regional or national averages for energy consumption in residential buildings were used by some studies [34,35,38] to calculate the operational energy of buildings. Another major difference amongst the studies is the geographical context, which leads to certain inherent differences such as climatic conditions, building regulations, quality of raw materials, production processes, economy structure, different processes involved in producing secondary energy, energy tariffs, fuel supply structure, and labour [28]. This emphasizes the necessity of considering the geographical representativeness of data when computing embodied impacts. Pullen [83] estimated a possible error of 2.6 percent in the results for embodied energy due to differing tariffs paid by different material suppliers at different locations when using the I-O method. The last major difference was the interpretation of the LCEA results. This

Table 8
Overall trends in the methodologies of the reviewed studies

Category	Methodological aspects	Overall trends in the LCEA studies
System boundary definition	Exclusion of building life-cycle stage.	58% excluded EOL; 35% replacement and maintenance; 27% excluded construction/installation; 22% excluded transport to construction site.
	Exclusion of reuse, recovery, and recycling.	65% of the reviewed studies.
	Building components considered for embodied energy assessment.	100% superstructure; 93% substructure; 75% finishings; 50% services; 30% RES; 18% built-in furniture/fixtures/appliances.
	Elements at the neighborhood scale considered for embodied energy calculation.	Occupants' transportation; urban infrastructure considered by 13%.
	Parameters considered for operational energy usage.	90% heating; 73% ventilation; 73% DHW; 73% electrical appliances; 63% lighting; 48% cooling; 33% cooking.
	Building lifespan.	58% assumed 50 years.
	Assumptions.	All stages are subject to assumptions.
Calculation methods	Methods used for calculating embodied energy.	60% process-based; 23% I-O-based hybrid; 3% economic I-O; 15% of the studies did not discuss their applied methods.
	Database employed for embodied energy calculation.	33% generic international databases; 13% literature; 15% combined generic international databases with national or regional databases.
	Methods used for calculating operational energy.	65% BEPS tools; 8% energy bills; 8% monitoring; 8% national statics; 10% other.
Geographical context	Distribution of countries.	58% Europe; 21% Asia; 16% Australia; 2.5% Brazil; 2.5% Canada.
Interpretation of results	Interpretation.	42% none; 15% sensitivity analysis; 13% uncertainty analysis; 13% discussion of limitations; 18% used two methods.

paper showed that a large percentage of studies (42%) eschewed any type of evaluation of their final results, despite the recommendations in the LCA standards.

Overall, it can be stated that the applicability of current LCEA results for decision-making purposes is limited due to incomplete definitions of the system boundary, with no possibility of conducting cross-comparison between LCEA studies. Cross-comparison is important when aiming to advance knowledge about LCEAs of residential buildings within a global context [23]. Previous studies endeavoured to plot the significance of operational energy against embodied energy (or vice versa) by juxtaposing various case studies [18,24,84–86]. For instance, Ramesh et al. [24] cross-compared 73 cases of residential and office buildings. It was concluded that operational energies constituted 80–90% of the total buildings' life cycle energy usage, while embodied energies made up 10–20%. It was further shown the total life cycle energy requirements of conventional residential buildings fell in the range of 150–400 kWh/m^2 per year and that of office buildings in the range of 250–550 kWh/m^2 per year. These comparisons are infeasible considering the significant variations existing among the studies. In one study, Yung et al. [87] attempted to compare residential and office buildings. They noted that some studies excluded the transportation and construction stages from their system boundaries. To account for the impacts of these excluded stages, 4% (for transportation) and 10% (for construction) of the initial embodied energy were added to the original values calculated by the researchers in order to make the cases comparable. To standardize operational energy, they considered energy usage for heating and cooling only, and then compared the embodied energy and operational energy of the cases. Despite the authors' great efforts, comparing LCEA studies with such unclear system boundary definitions and the variety of methodological choices can inherently increase the risk of misinterpretations if LCEA cases are utilized for inspiring particular design practices, or promoting indications for building regulations.

6. An evidence-based framework for LCEA research

This section aims to elaborate on the methodological bases of a conceptual framework that brings forward proposals for the standardization of LCEA use. The framework is developed based on the theoretical examination of the reviewed studies and the resultant reflections on the LCA methodology (Fig. 3). Thus, it addresses the third research question; '*how can the continued variations in the application of LCEA in residential buildings be overcome?*'. This framework primarily targets to simplify the interlocking processes involved in an LCEA by providing a clear description of the system boundary. It encourages incorporating embodied impacts of building components within a stepwise approach consisting of four levels in that each one represents a different degree of inclusion for assessing embodied and operational impacts.

6.1. Embodied energy

The importance of describing physical and temporal system boundaries has been widely emphasised by LCA standards to assure maintaining transparency and comparability. Description of physical system boundary refers to clearly stating which parts of the physical building components need to be included for assessment. Examples of these standards are ISO 21931-1 1 [11], and EN 15978:2011 [13], whereby building elements that should be considered for the analysis are recommended. These standards serve well in providing general guidance for practice, as well as providing a basis through which buildings' environmental impacts can be investigated. However, a more detailed framework is required when LCEA cases are to be horizontally compared e.g. for obtaining certification. The proposed framework recommends a stepwise approach by which buildings' embodied and operational impacts can be taken into consideration. Stepwise approach offers flexibility in assessing buildings' environmental impacts when dealing with data unavailability. Using this framework facilitates the possibility of comparing different versions of a similar building or cross comparing cases that are analysed by the LCEA approach.

The current study complements the description of physical system boundaries of current standards (i.e. EN 15978:2011 [13]) by recommending the inclusion of embodied impacts associated with renewable energy systems, and occupants' transport (Table 9). Considering the significant investment being made worldwide to support the concept of zero energy buildings, it is necessary to account for the embodied impacts of these components when the building is zero energy. The framework recommends including embodied impacts of renewable energy systems at level 1, where the inclusion of these components combined with superstructure, substructure, and finishings establishes the mini-

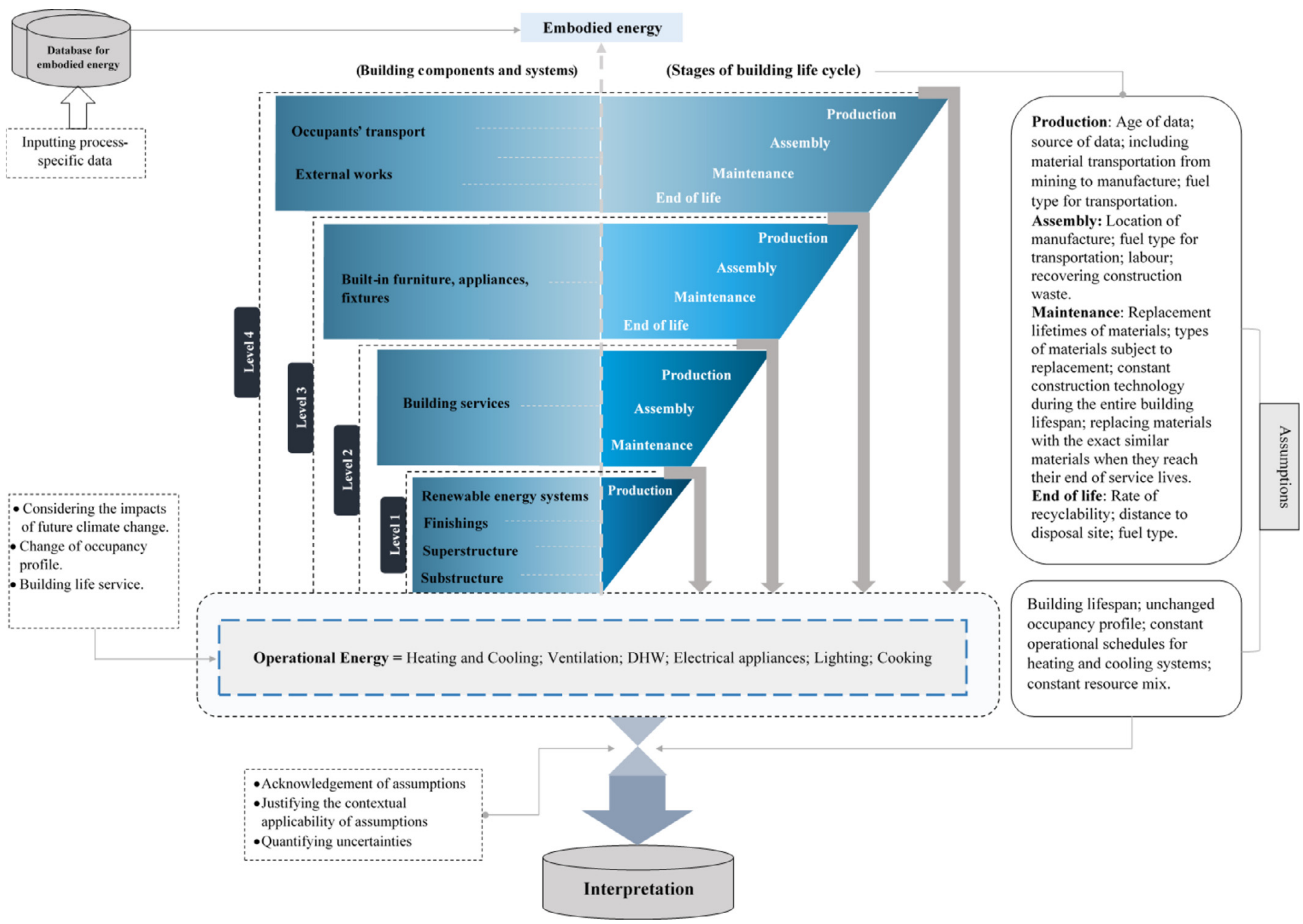

Fig. 3. An evidence-based conceptual framework for LCEA research

Table 9
Components suggested by international standards for inclusion within system boundary [13]

Main components	Sub-components
Substructure	Foundation; and basement.
Superstructure	Frame; upper floors; roof; stairs and ramps; external walls; windows and external doors; internal walls; and internal doors.
Internal finishes	Wall, floor and ceiling.
Fitting, furnishes and equipment	Fitting, furnishes and equipment
Services	Sanitary; water, and disposal installations; service equipment; heat source; ventilation and air conditioners; electrical and fuel installations; lift; and control system.
Prefabricated buildings	Complete buildings; building units; and pods.
Work to existing buildings	Minor demolition and alteration work; repairs to existing services; damp-proof course; façade retention; cleaning existing surfaces; and renovation work.
External works	Site preparation; roads, path, paving and surfaces; soft landscaping, planting and irritation systems; fencing, railing and walls; external fixtures, drainage, and services.
Renewable energy system	Photovoltaics panels and its supporting systems; solar collectors; and wind turbines.
Occupants' transport	Vehicles; access to public transport.

mum level of LCEA assessment at building scale. Levels 2 and 3 promote adding embodied impacts of building services and fittings, built-in-furniture, and appliances to the system boundary in order to capture a holistic understating of buildings' environmental performance.

The assessment of embodied impacts relating to external works has been recommended by EN 15978:2011 (see table 9) [13]. This study suggests adding embodied impacts of occupants' transport to the physical system boundary (i.e. level 4) along with external works in order to account for the impacts of elements that are beyond the building scale. The review also showed that a number of studies endeavoured to include embodied impacts of nearby infrastructure, and occupants' transportation within their system boundaries [6,32–34,44]. Level 4 represents the ambitious level for assessing the life cycle energy performance of buildings.

Regarding the temporal system boundary, this study recommends that the embodied impacts of production (initial embodied energy) stage should be a minimum assessment requirement at the building level. The initial embodied energy plays a significant role in emitting GHGs into the atmosphere since they are mainly produced by combusting fossil fuels [7]. It is also widely accepted that initial embodied energy constitutes a higher percentage of total embodied energy use compared to other stages of building life cycle [6,7,23,88,89]. Additionally, the majority of current databases contain initial embodied impacts of building materials that are calculated based on energy inputs from the entire structure of an economy; thus, the impacts of this stage can be taken into consideration regardless of buildings' locations. Level 2 recommends including the impacts of recurrent embodied energy and assembly (construction/installation), while levels 3 and 4 encourage including embodied impacts of all the building life cycle stages.

6.2. Operational energy

From the review, it became evident that only 20% of the studies accounted for all parameters with potential impacts on operational energy [31–35,37,39,52]. The proposed framework recommends that all parameters influencing operational energy use should be considered for assessment at all levels. Many jurisdictions across the world now aim to increase energy efficiency in the building sector by supporting the construction of energy-efficient buildings (e.g. NZEBs, and passive buildings). These dwellings are principally built to minimize operational energy consumption. The European Union's revised Energy Performance in Buildings Directive of 2010 is an exemplar of policy to support constructing buildings with high energy efficiency. It sets the nearly-zero energy building as the target for all new buildings from 2021 [90]. Similar examples can be found in other countries such as the U.S. [91], UK [92], Japan [93], and Australia [94]. Therefore, heating and cooling loads that are commonly considered by the vast majority of the studies for assessment, are likely to be minimized in the future while the shares of other parameters such as electrical appliances in consuming energy would be maximized.

The accuracy of measuring operational energy can be improved by future research. This review found out that the analysed studies commonly assumed an unchanged occupancy profile (e.g. family size, occupational settings and etc.) for the entire assessment period. To address this issue, the deterministic and stochastic statistical approaches can be employed in order to take the impacts of occupants' behaviours into consideration [23]. In the deterministic approach, different scenarios for users' behaviours on an hourly basis throughout a year should be defined, ranging from energy-saving to wasteful. Thereafter, the impacts of each scenario on building energy consumption can be measured and compared. Alternatively, a stochastic statistical model can be developed to predict occupants' presence throughout the year based on scholarly literature and national sociological investigations [47]. Despite the easier application of the first approach, using a stochastic statistical model may generate more accurate results. Moreover, considering the effects of future climate change on the heating and cooling demands can also be considered by future LCEA research when estimating operational energy usage. This consideration can potentially increase the accuracy of estimating operational energy consumption.

7. Conclusions

This paper approached the literature with the aim of addressing three key questions; 'what is the current trend of methodological approach for applying LCEA in residential buildings?'; 'what are the key parameters causing variations in LCEA results?'; and 'how can the continued variations in the application of LCEA in residential buildings be overcome?'. To this end, 40 LCEA studies representing 157 cases of residential buildings across 16 countries have been critically reviewed. The findings indicate that the current LCEA application in residential buildings suffers from an incomplete definition of the system boundary. This compromises the accuracy of LCEA results to be used for decision-making purposes. The key parameters leading to variations in LCEA results are the system boundary definitions, calculation methods, the geographical context, and interpretation of the results. The system boundary determines which building life-cycle stages are excluded from the assessment, including reuse, recovery, and recycling; which building components and systems are included in embodied energy calculations; whether elements beyond the building scale (e.g. urban infrastructure) are included in calculating embodied energy; the parameters of operational energy calculations; building lifespan; and assumptions. The calculation methods refer to the methods and background databases applied to calculate embodied energy, as well as the methods used to calculate operational energy. The geographical context refers to the different countries and/or regions in which LCEAs have been conducted. Finally, the interpretation of results refers to the studies' different methods of evaluating the accuracy of the LCEA results. Identifying the principal parameters with potential contributions to varying results in LCEAs can minimize the uncertainties accruing from LCEAs of residential buildings.

The findings also suggest that although the current LCA standards serve well in providing general guidance for practice as well as providing a basis for investigation of buildings' environmental impacts, they are still ineffective in harmonising the LCEA application. Thus, further research is needed for developing a more detailed framework when the aim is to horizontally compare cases (e.g. certification). This paper contributes to developing a conceptual framework for the standardization of LCEA use. The framework primarily targets to simplify various interlocking processes involved in an LCEA by providing a clear description of the system boundary. It encourages incorporating embodied impacts of building components within a stepwise approach consisting of four levels in that each one represents a different degree of inclusion for assessing embodied and operational energies. The framework offers the possibility of comparing different design strategies of a similar building or cross comparing cases that are analysed by the LCEA approach.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.enbenv.2020.09.005.

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Appendix III – Manuscript: Rethinking the concept of building energy rating system in Australia: a pathway to life-cycle net-zero energy building design

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Rethinking the concept of building energy rating system in Australia: a pathway to life-cycle net-zero energy building design

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ABSTRACT

Over the last decades, Australia has taken several measures to tackle the increasing trend of energy use in residential buildings. Recently, the Trajectory for Low Energy Buildings has been endorsed aiming to reduce energy usage in residential buildings. However, the primary focus of this trajectory is on decreasing operational energy without considering the embodied energy of the building and systems. This paper aims to address one primary question; '*can the continued exclusion of embodied energy from the energy efficiency regulations effectively lead to reducing energy consumption in Australian residential buildings*?'. The findings indicate that embodied energy becomes a dominating factor as buildings' thermal performances increase according to the Australian energy efficiency regulations. In transitioning from a standard 6.0-star building to a highly energy-efficient 8.7-star building, the proportion of embodied energy significantly increases from 20–40% to 50–75%. This study recommends establishing minimum mandatory requirements for buildings' embodied performance.

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Zero energy building; embodied energy; thermal performance; building regulations; building design; optimization design; Australia

Background

Australia is currently experiencing a major housing boom with about 200,000 new dwellings being built each year (Schmidt, Crawford, and Warren-Myers 2020); and considerably more are needed annually in order to accommodate the projected population growth of nearly 40 million by 2050 (Australian Bureau of Statistics 2017). In response to the impending intensification of energy demands, Australia has taken several measures to curb energy use in residential buildings over the last decades. In 1998, the importance of energy efficiency standards for housing and commercial buildings was recognized as a part of the National Greenhouse Strategy (NGS) (National Constructions Code 2019). An option outlined in the NGS was to introduce measures in the building codes of Australia (now called national construction codes) to decrease greenhouse gas (GHG) emissions by efficiently using energy. In 2003, the energy efficiency regulations (EERs) were introduced into the building codes of Australia for the first time, with a scope limited to only housing. These regulations were further expanded to include other building classifications in 2006, along with increasing the stringency for dwellings to a target of 5.0 stars (National Constructions Code 2019). In 2010, the minimum mandatory thermal requirements were increased to the equivalent of 6.0 stars for houses and apartments (National Constructions Code 2019). Currently, all new buildings need to meet certain thermal requirements equivalent to 6.0 stars in order to substantiate their compliance with the EERs (Daniel, Soebarto, and Williamson 2015; Daniel, Williamson, and Soebarto 2017).

Australia now aims to further strengthen its measures towards minimizing energy consumption in residential buildings. In February 2019, the '*Trajectory for Low Energy Buildings*' (TLEB) has been endorsed by the Council of Australian Governments as a national plan to realize zero energy and carbon-ready buildings by 2030 (Trajectory for Low Energy Buildings 2019). This trajectory targets to identify opportunities for energy efficiency improvements throughout the building system, from thermal performance to appliance energy usage and renewable energy generation (Trajectory for Low Energy Buildings 2019). It also promises to increase the minimum mandatory thermal requirements for new buildings to 6.5 stars equivalent in tropical and temperate climates, and up to 7.0 stars equivalent in colder climates. This increase sets to be periodically implemented in 2022 and 2025. The underlying aim of the TLEB is to promote the concept of zero energy buildings (ZEBs). It characterizes ZEBs as

> zero energy (and carbon) ready buildings have an energy efficient thermal shell and appliances, have sufficiently low energy use and have the relevant set-up so they are "ready" to achieve net zero energy (and carbon) usage, if they are combined with renewable or decarbonised energy systems on-site or off-site. (COAG 2018)

As stated in the definition above, the primary emphasis is on the reduction of operational energy by improving the energy efficiency of buildings' envelopes and using energy-efficient appliances. However, the limited focus given only to the improvement of buildings' operational energy can paradoxically result in increasing the total life-cycle energy use of buildings due to ignoring their embodied impacts (Stephan, Crawford, and

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De Myttenaere 2013a; Crawford et al. 2016). This is reflected in the findings of Stephan, Crawford, and De Myttenaere (2013a) who assessed the life-cycle energy performance of a passive house. Their results indicated that current standards developed to support the enhancement of energy efficiency in buildings cannot assure reducing the total energy consumption because the embodied impacts are excluded. In recent years, academic studies have given more attention to the necessity of minimizing energy use throughout the entire building life cycle considering both embodied and operational energies. Nevertheless, the surge of research has failed to alter the attitude of policymakers toward considering the importance of buildings' embodied energy when planning for the betterment of built environment (Säynäjoki et al. 2017). Previous studies voiced concern about the exclusion of embodied impacts, stating that without immediate action, embodied energy would become the 'second wave' of environmental concern relating to buildings' performance (Pomponi and Moncaster 2018). The argument here is that reduction of operational energy can be somewhat addressed later on once the building is constructed by using energy-efficient appliances and equipment; however, any attempt to reduce embodied energy after construction shall provoke an additional increase of embodied energy. Hence, it is imperative for the EERs to not only consider the importance of reducing operational energy but also reflect upon decreasing embodied impacts concerned with building designs.

With the motivation outlined above, this study aims to highlight the significance of embodied energy attributed to the Australian EERs by addressing one primary question; 'can the continued exclusion of embodied energy from the energy efficiency regulations effectively lead to reducing energy consumption in Australian residential buildings?'. This study also puts forward proposals for the integration of embodied energy into the Australian building regulations. The remainder of this paper unfolds as follows: first, a literature review is provided to discuss the increasing demands for integrating embodied energy (and GHG emissions) into building regulations. The section on the energy rating system in Australia provides an overview of how buildings are appraised for compliance with EERs in Australia. The Research methodology section elaborates on the research approach and methods of the paper, followed by the Results and discussion section. The limitations and future research section discusses the limitations concerned with the study; prior to the Conclusion.

Literature review

In recent years, there has been a growing attention toward the importance of energy efficiency in the building sector by mandating the use of EERs and advocating voluntary schemes (Omrany and Marsono 2016). This approach, in turn, leads to the increase of embodied energy since adopting energy-efficiency measures usually requires installing additional materials (Crawford et al. 2016). Hence, previous research highlighted the necessity of incorporating embodied energy requirements into building EERs (Dodoo, Gustavsson, and Sathre 2011; Stephan, Crawford, and De Myttenaere 2012; Stephan and Stephan 2014; Crawford et al. 2016; Koezjakov et al. 2018; Stephan and Stephan 2020). Stephan and Stephan (2014) performed a comprehensive life cycle energy analysis of an apartment in Beirut, considering embodied, operational and user transport energy demands. The study concluded by recommending the development and implementation of mandatory life cycle energy efficiency policies for the building sector. In another study, Koezjakov et al. (2018) investigated the correlation between heat energy demands and embodied energy in different types of Dutch residential buildings. The findings revealed that the values for operational and embodied energies in Dutch dwelling archetypes were amounted to 124 to 682 MJ/m^2.year and 52 to 106 MJ/m^2.year, respectively. Koezjakov et al. (2018) also recommended the inclusion of embodied energy use in the future building energy efficiency regulations as a measure to achieve the maximum global temperature increase of well below 2°C by 2100.

Stephan and Stephan (2020) evaluated the life cycle energy and GHG emissions of an apartment in Lebanon. It was discovered that the attainment of life cycle zero energy and GHG emissions is feasible when due improvements in the building envelope are considered, along with using energy-efficient appliances and integrating solar panels. However, the adoption of these measures would add 159 $kgCO_2e/(m^2$ of gross floor area) and 252 $kgCO_{2-}e/$ (m^2 of gross floor area) of additional initial and recurrent embodied GHG emissions, respectively. Stephan and Stephan (2020) suggested the integration of life cycle embodied environmental flows into the future regulations and certifications that aim to enhance buildings' environmental performance. Stephan, Crawford, and De Myttenaere (2013a) analyzed the total life cycle energy requirements of a typical Belgian passive building, considering embodied and operational energy as well as energy use for occupants' transport. The results indicated a significant share of embodied energy in total life cycle energy use by up to 77%, hence they conclusively stated that the current implementation of building energy efficiency certifications can reversely lead to increased energy use over building life cycle due to their limited scope.

In Australia, studies also endeavoured to highlight the necessity of including embodied energy into the current building energy efficiency regulations (Stephan, Crawford, and De Myttenaere 2012, 2013a; Crawford et al. 2016; Stephan and Crawford 2016; Schmidt, Crawford, and Warren-Myers 2020). In recent research, Schmidt, Crawford, and Warren-Myers (2020) modelled life cycle GHG emissions of all the detached dwellings that are constructed in Australia in 2019. The findings show that the life cycle GHG emissions for the reference year (i.e. 2019) are 39 $MtCO_{2-}e$, which would be further increased to 883 $MtCO_{2-}e$ by 2030. This figure is much higher than the projected values for total emissions by 2030 of 563 $MtCO_{2-}e$ under the business-as-usual scenario (Climate Action Tracker 2019). Schmidt, Crawford, and Warren-Myers (2020) also found that the GHG emissions related to residential buildings in Australia are being underestimated by 60% owing to the exclusion of embodied energy or GHG emissions. In another study, Crawford et al. (2016) evaluated the effects of increasing energy efficiency of two residential buildings on the life cycle energy demands over a period of 50 years. The results showed that the current Australian regulations promoting building energy efficiency fail to achieve net life cycle energy savings due to excluding embodied impacts.

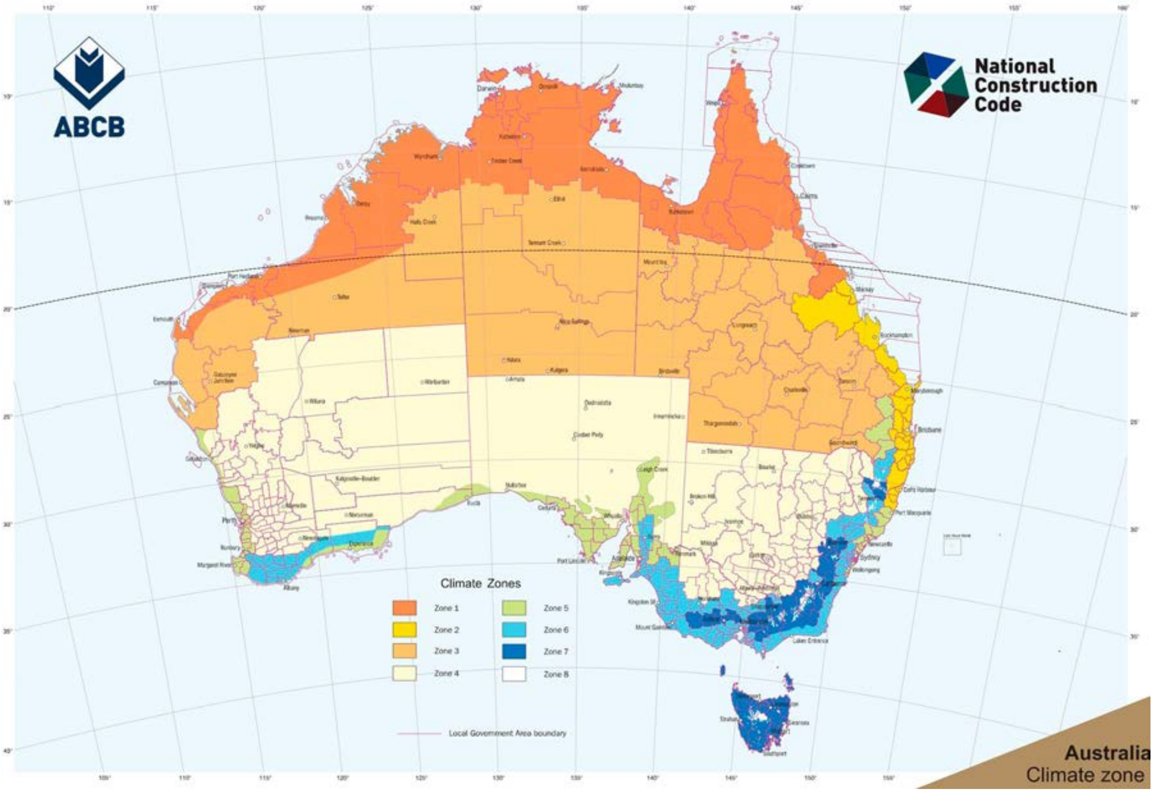

Figure 1. Australian climate zones [Sourced from (Australian Building Codes Board 2015)].

Despite the growing body of literature, there is still a need to investigate whether promoting the concept of highly energy-efficient buildings such as ZEB by using the current energy efficiency standards can reduce the overall energy usage in Australian residential buildings. To the best of authors' knowledge, this study is the first of its kind that specifically researches the life cycle energy repercussions associated with enhancing building energy efficiency according to the Australian national construction codes (NCC). The outcomes of this research may instigate the need for rethinking the concept of building energy rating systems in Australia by accounting for the embodied impacts of building designs.

Energy rating system in Australia

The thermal performance of all new residential buildings must meet minimum standards of energy efficiency set out by the NCC, Volume II (National Constructions Code 2019). To demonstrate the compliance, two overarching methods are implemented: (i) proposal of an alternative solution (i.e. verification-using-a-reference-building), and (ii) a deemed-to-satisfy approach (Daniel, Williamson, and Soebarto 2017). The first method is labour and knowledge-intensive, and it is mainly applied for the assessment of housing stock (Daniel, Williamson, and Soebarto 2017). The deemed-to-satisfy approach, which is more widely used offers two primary options to show compliance: (i) elemental regulations, and (ii) energy star rating. The first option specifies R-values for different building components and determines glazing and ventilation requirements. The energy star rating requires a building design to obtain 6.0 stars out of a maximum rating of 10 stars by using certain simulation software accredited by the NatHERS (Nationwide House Energy Rating Scheme 2019). The NatHERS is a performance-based rating system established to rate dwellings based on their annual thermal performances (i.e. only heating and cooling loads) (NatHERS). A 10-star rating indicates that the dwelling would need nearly no additional heating and cooling in order to retain the indoor comfort level. The performance requirements specified by the EERs vary with respect to eight different climate zones that broadly encapsulate climate variations across Australia (Figure 1).

The NatHERS further disaggregates Australia into 69 climate zones, allowing the software to account for the diverse climatic conditions across the country when simulating the thermal performance of a building. In this regard, Australia has one of the most climate-specific EERs in the world. Comparatively, the US, Spain, France, and Germany rely on eight, five, two, and one climatic zones, respectively (Rodríguez-Soria et al. 2014). This degree of precision, combined with the detailed scale of the thermal requirement specified for each climate zone, facilitates the possibility to utilize EERs as a basis for evaluating the life cycle energy implications associated with their implementations in the Australian residential buildings.

Research methodology

The overall methodological approach of the study consists of three main stages (Figure 2). The first stage involves selecting a case study that can meet three basic requirements: (i) the building needs to be the most common type of residential building

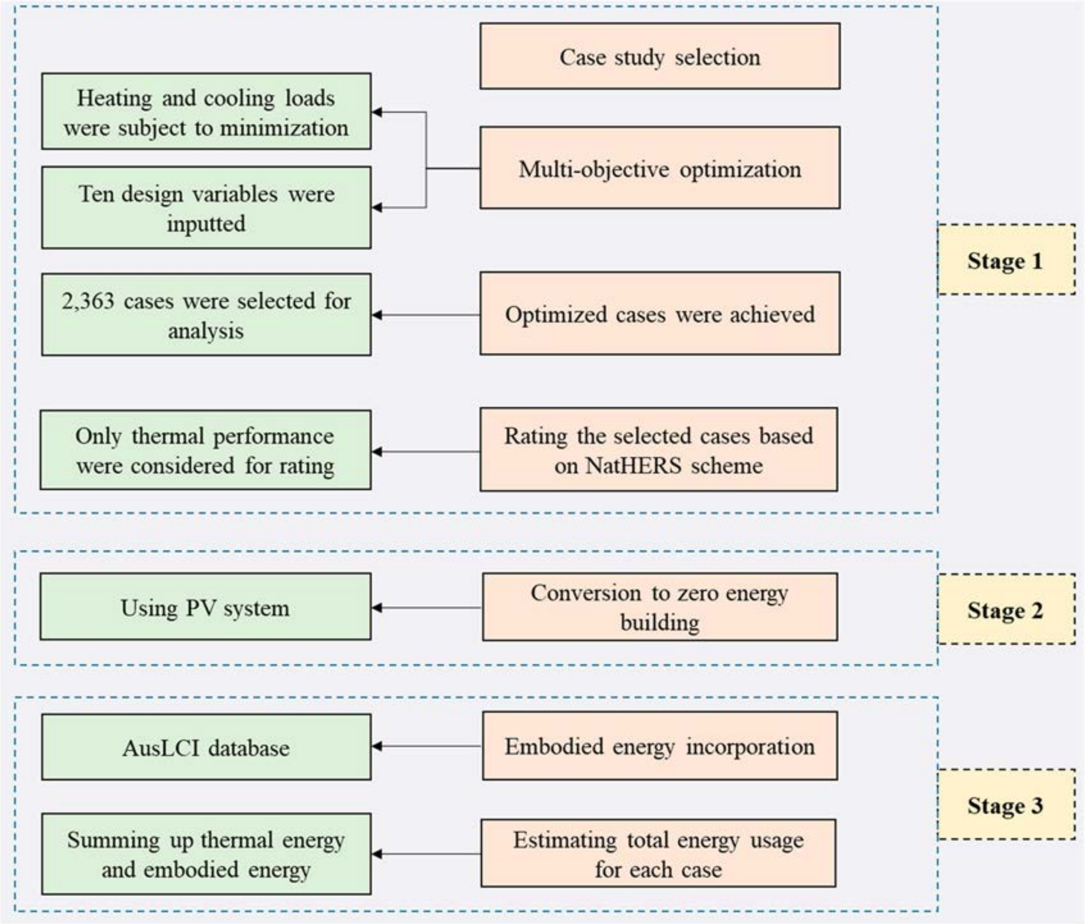

Figure 2. Research approach.

in Australia so that the results would have broader implications; (ii) its architectural design represents the bulk of new dwellings in South Australia, Adelaide; and (iii) it needs to meet the minimum mandatory thermal requirement according to the NatHERS rating scheme specified for the relevant climatic zone. Since this study used Adelaide (climate Zone 6) as the location for the case study building, a minimum star rating of 6.0 (total heating and cooling loads of no more than 96.0 MJ/m^2) must be achieved.

After selecting the case study, a multi-objective optimization approach was employed in order to minimize the building's heating and cooling loads. For the purpose of the study, the optimization excluded embodied impacts of building materials in order to reflect the approach taken by TLEB in achieving ZEBs by only considering thermal performance. The results achieved from the optimization were then exported into *Excel spreadsheets* and sorted based on the obtained NatHERS Star rating. This led to developing a database containing nearly 2,400 cases of building designs with the highest rated design obtaining 8.7 stars.

In the second stage, Photovoltaic (PV) systems were added and sized for each individual design case in order to balance out the heating and cooling energy to achieve a zero operating energy building design.

In the third stage, embodied energies for all the cases were calculated using the AusLCI database and summed up with their heating and cooling energy over a period of 50 years in order to estimate total life cycle energy usage. The following sections elaborate further on the different stages of research methodology.

Description of the case study

Figure 3 shows the case study. This building represents the bulk of newly built single-storey detached dwellings in South Australia, Adelaide (Whole of House Verification – Stage 1 2018). It is also noteworthy to mention that detached dwellings comprise 69% of the total housing stock in Australia (Schmidt, Crawford, and Warren-Myers 2020). The net conditioned floor area of the building is 146.0 m^2. It also a garage with an area of 43.0 m^2, four bedrooms, three bathrooms, one living area, one rumpus, kitchen and dining room, and one room used as a study room. Table 1 shows the main characteristics of the building.

Heating and cooling are provided via a split air conditioner system – reverse cycle using electricity supplied from the grid. The coefficient of performance (COP) of the heating system was 2.25, with the maximum capacity of supplying 35.0°C air temperature. The COP of cooling system is 3.0 with a maximum supply air temperature of 12.0°C.

Climate of Adelaide

According to Köppen climate classification, Adelaide has a Mediterranean climate with cool to mild winters and warm to hot summers that requires using energy for both heating

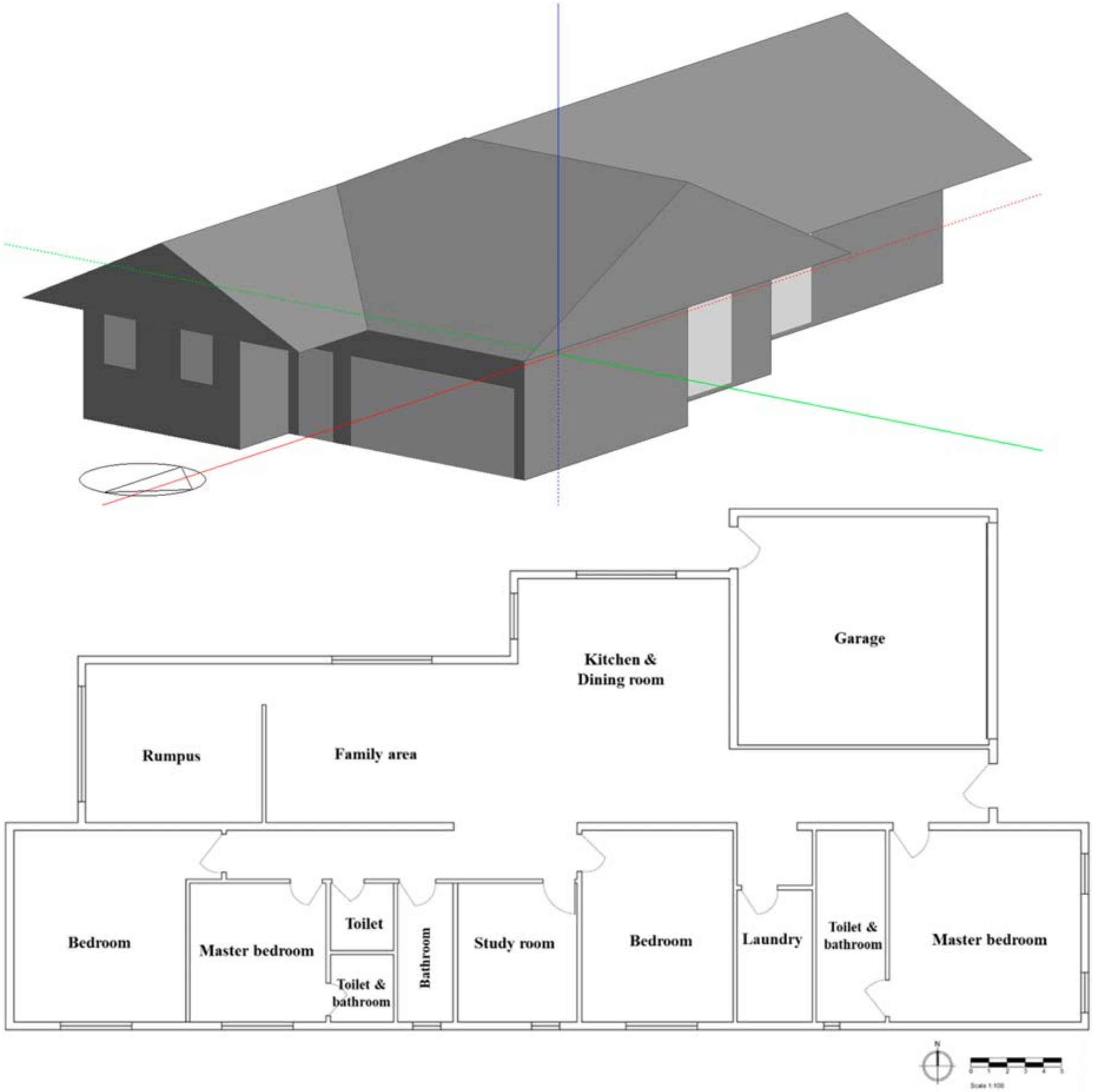

Figure 3. Base case model used for optimization.

Table 1. Characteristics of the base model.

Parameters	Quantity (m^2)	Value	Descriptions
Gross floor area (m^2)		189.85	
Net conditioned floor area (m^2)		146.78	
Wall height (m)		3.0	
External walls	173.0	U-value 0.659 W/m^2 K	Clay brick; Glass fibre batt insulation; Gypsum plasterboard
Ground floor	206.0	U-value 1.22 W/m^2 K	Waffle pods; Concrete
Pitched roof	383.0	U-value 5.227 W/m^2 K	Clay tile; Roofing felt
Slope of pitched roof (°)		23.0	
Ceiling	147.0	U-value 0.600 W/m^2 K	Glass fibre batt; Gypsum plasterboard
Internal walls	120.0	U-value 0.440 W/m^2 K	Insulated gypsum plasterboard
Windows	32.0	U-value 6.70 W/m^2 K, SHGC[a] $= 0.570$	Single glazed, aluminium frames
Overhang (m)		0.30	
Infiltration (ac/h at 50 Pa)		15.0	
Lighting		2.50 W/m^2-100lux (Normalized power density)	LED
Occupancy		Four people (i.e. a couple with two kids).	
Heating set point		21.0	
Cooling set point		25.0	
Ventilation system			Split

[a]Solar heat gain coefficient.

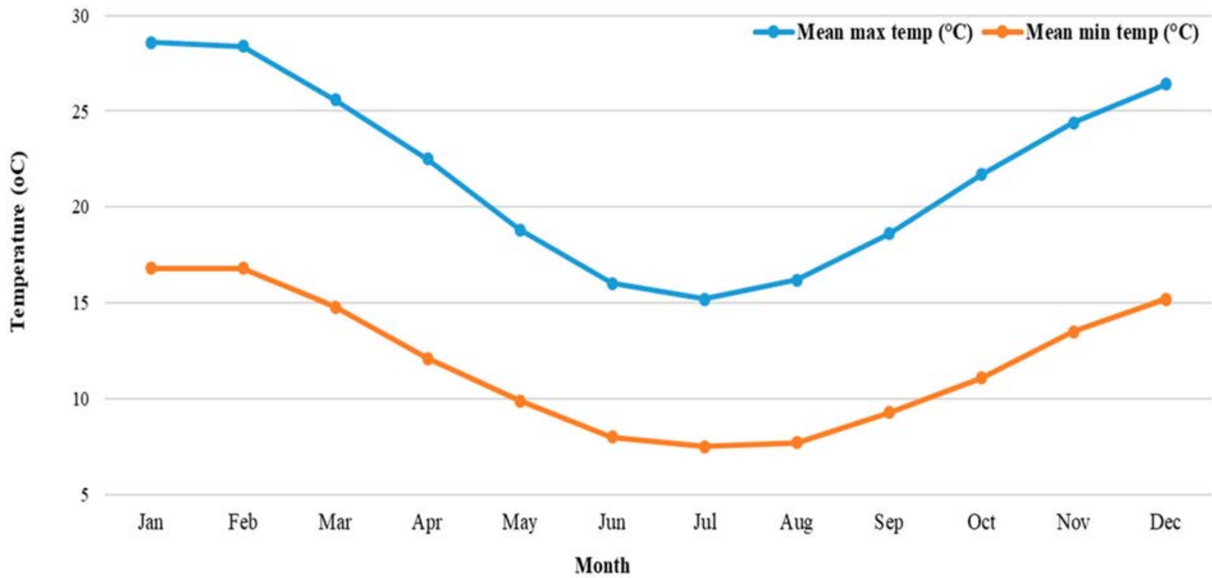

Figure 4. Monthly average ambient air temperature (Australian Government Bureau of Meteorology 2020b).

Table 2. Thermal requirements for NatHERS Star Band for Adelaide city (MJ/m^2.annum) (NatHERS Star Band Criteria 2019a).

		Energy rating (stars)									
Climate zone	Location	0.50	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
16	Adelaide	584.0	325.0	227.0	165.0	125.0	96.0	70.0	46.0	22.0	3.0

and cooling. Figure 4 illustrates the monthly average ambient air temperature for Adelaide airport between 1991 and 2020. According to this figure, February and July are the peak energy demands for cooling and heating, respectively.

Table 2 tabulates the maximum energy usage of thermal loads in Megajoules per metre square (MJ/m^2) for each star band in Adelaide. As shown, the annual thermal performance of a new residential building needs to be 96.0 MJ/m^2 (26.67 kWh/m^2) in order to obtain a 6.0 star rating. In this paper, the thermal performance of the base case model was initially assessed by *AccuRate* to ensure that the building satisfies the obligatory thermal requirements. *AccuRate* is one of the software programmes accredited by the NatHERS framework that can be used for energy rating in Australia. The results showed the thermal performance of the base model was 90.70 MJ/m^2.annum (6.1 Stars), which met the minimum mandatory requirements of EERs.

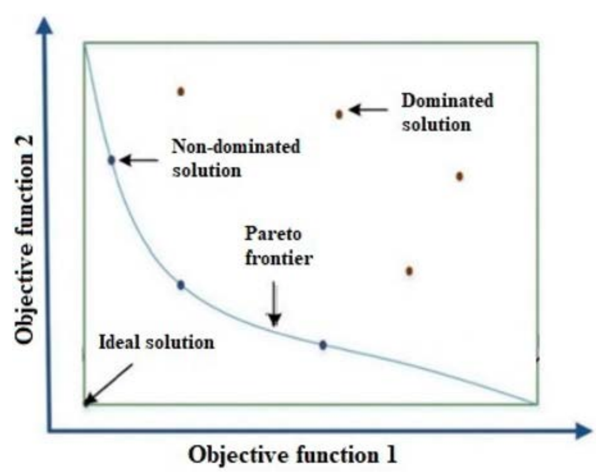

Figure 5. Demonstration of *Pareto* frontier of a multi-objective optimization (Pilechiha et al. 2020).

Multi-objective optimization

Multi-objective optimization differs from single-objective optimization due to the higher complexity driven by the complicated nature of concurrently satisfying several goals, often with conflicting outcomes (Pilechiha et al. 2020). To optimize a function with multiple objectives, a set of circumstances that define the optimal solutions needs to be established, and a *Pareto* frontier is drawn accordingly (Pilechiha et al. 2020). Figure 5 demonstrates a *Pareto* frontier for optimizing a function with two objectives. The *Pareto* front or *Pareto-optimal* refers to a set of best alternatives representing non-dominated solutions, meaning that these solutions are not dominated by other solutions (Kheiri 2018). In this regard, the upper and lower bounds of each objective are represented by the '*ideal objective vector*' and '*nadir objective vector*' respectively (Kheiri 2018). In many multi-objective optimization problems, realizing the ideal objective vector may not be generally possible, and it can only be used as a reference to the trade-off between different alternatives (Deb 2001). Upon identifying non-dominated solutions, decision-makers can select a set of final solutions by which the function can be optimized.

The criteria to select an optimal solution, i.e. a final point amidst the non-dominated points, depending on the application. A standard minimization problem can be converted into a maximization problem or vice versa with the same solution. The minimization problem and its corresponding maximization problem are called duals of each other. This can be expressed as

(Equation 1):

$$max\ \{f_{(x)}\} \leftrightarrow \min\ \{-f_{(x)}\}$$

In addition, a multi-objective optimization problem can be mathematically expressed as (Equation 2):

$$\min_{S.t(g(\vec{x})\leq 0, h(\vec{x})=0)} f(\vec{x}) = [f_1(\vec{x}), f_2(\vec{x}), \ldots, f_m(\vec{x})]^T$$

Where

$$x_i^{min} \leq x_i \leq x_i^{min}\ (i = 1,\ 2, \ldots, n)$$

$$x = [x_1, x_2,\ \ldots,\ x_n]^{\ T} \in \Phi$$

$$y = [y_1, y_2,\ \ldots,\ y_m]^{\ T} \in \psi$$

Where m represents the number of objective functions set to be solved. Φ is the search space with n dimensions and identified by upper and lower bounds of the decision variables $x_i = (i = 1, 2, \ldots, n)$.

$$x^{max} = [x_1^{max}, x_2^{max}, \ldots, x_n^{max}]^T$$

$$x^{min} = [x_1^{min}, x_2^{min},\ \ldots,\ x_n^{min}]^T$$

ψ is the m-dimensional vector space of objective functions and is defined by θ, and the objective function $f(x).g_i(\vec{x}) \leq 0 (j = 1, 2, \ldots, p)$ and $h_{(\vec{x})} = 0 (j = 1, 2, \ldots, q)$ denotes p and q which are respectively the number of inequality and equality constraints (Pilechiha et al. 2020). If both p and q are equal to zero, then the problem is simplified as an unconstrained optimization problem, which is the case of current study.

In this paper, DesignBuilderV6 was employed as the platform to carry out the optimization. The reason for selecting DesignBuilder resides with the capability of this software for carrying out optimization, whereas the NatHERS accredited tools (i.e. AccuRate, BERS, and FirstRate) only allow users to perform 'one-factor-at-a-time' (OFAT) experiments. The OFAT is a design method that involves testing the effects of factors one at a time in lieu of multiple factors at the same time (Tian 2013). DesignBuilderV6 adopts Non-Dominated Sorting Genetic Algorithm II (NSGA-II) for performing optimization (Description of the key features of DesignBuilder Optimization 2020b). The NSGA-II is an evolutionary multi-objective algorithm and offers a non-dominated sorting with a fast searching method towards finding the optimal solutions (Deb et al. 2000). NSGA-II resolves the issues concerned with the former genetic algorithms such as the lack of elitism, the convergence to local optimum, or the lack of genetic diversity (Gagnon et al. 2019). This algorithm is extensively applied in energy and building science as indicated in the literature review conducted by Attia et al. (2013), and it is among the most efficient genetic algorithms (Gagnon et al. 2019).

The key features of a generic algorithm, namely crossover probability (CRP) and mutation probability (MP) are not straightforward to set since they depend on the nonlinearity of the optimization problem, the typology of the input variable (continuous or discrete), the dimension of the problem space, and a trade-off with the available computational capacity of the operating system (Carlucci et al. 2015). There are two main approaches to set the values of these parameters; (i) parameter tuning and (ii) parameter control (Hassanat et al. 2019). The most common approach is the 'parameter tuning', which refers to the process of experimenting with different values for CRP and MP and then selecting the ones with the best results. In the second approach, the initial values of CRP and MP are altered during the run process (Hassanat et al. 2019). This paper adopted the first approach and ran multiple simulations varying CRP and MP in order to find the best values. As a result, the most optimal solutions for reducing heating and cooling loads were achieved when CRP and MP were set 0.75 and 0.10 respectively; thus, these values were selected for the final run of the algorithm. Regarding the population size; 100 was set for this feature that was ten times the number of dimensions (design variables) in the optimization, as recommended by previous studies (Chen et al. 2012; Chen, Montgomery, and Bolufé-Röhler 2015). The 'number of generations' is another important feature of the generic algorithm that is the number of cycles to be run prior to termination (Hassanat et al. 2019). For initial experiments, this feature was set to 180 generations in order to limit the computational time, and it was set to 200 for the final run of algorithms to create enough search space for the algorithm to find the optimal designs.

Optimization objectives and design variables

The objectives set for minimization are heating and cooling loads since the NatHERS energy rating scheme only accounts for these parameters (NatHERS, Software Accreditation Protocol 2019b). The simulation model has also been established via *EnergyPlus8.9*, a simulation engine integrated into DesignBuilder (DesignBuilder, EnergyPlus Simulation 2020a), which considers detailed interactions of all building components and systems such as building envelope, windows, HVAC, and internal heat gains from different systems in order to calculate energy consumption (DesignBuilder, EnergyPlus Simulation 2020a). *EnergyPlus* is among the few simulation engines with the capability of running whole-building simulations. It builds on the most popular features of BLAST and DOE-2, but also includes many innovative simulation capabilities such as time steps of less than an hour, modular systems and plant integrated with heat balance-based zone simulation, multi-zone airflow, thermal comfort, and PV systems (DesignBuilder, EnergyPlus Background Information n.d.).

The design variables inputted for optimization are tabulated in Table 3 along with their respective values. These variables can be categorized into two groups; (i) those that are attributed to the building's physical enclosure i.e. external and internal walls, roof, floor, ceiling, walls, external doors, glazing, and window frames. These variables affect both the thermal performance and embodied energy of the building. The values for these variables are given in U-values (W/m^2-K) that correspond to a particular construction detail defined for each variable. The second group contains variables with an impact limited to the thermal performance of the building, namely air infiltration and orientation. Regarding air infiltration, previous studies showed the average air change rate for Australian new buildings is around 15 ac/h@50 Pa, while 10 and 25 ac/h@50 Pa correspond to very well-sealed and poorly sealed envelopes respectively (Ambrose

Table 3. Design variables considered for optimization.

Design variables	Description	Unit	Range	Increment
X_1	Orientation	(°)	0–180	10.0
X_2	Infiltration	ac/h@50Pa	10–25	1.0
X_3	U-value of external walls	W/m^2-K	0.090–2.770	NA
X_4	U-value of floor	W/m^2-K	0.170–1.220	NA
X_5	U-value pitched roof	W/m^2-K	0.156–5.227	NA
X_6	U-value ceiling	W/m^2-K	0.036–1.499	NA
X_7	U-value of windows	W/m^2-K	2.169–6.700	NA
X_8	U-value of external doors	W/m^2-K	0.323–3.124	NA
X_9	U-value of window frame	W/m^2-K	3.476–5.881	NA
X_{10}	U-value of internal walls	W/m^2-K	0.332–2.632	NA

and Syme 2017). Hence, the value range set for air infiltration was defined between 10 and 25 ac/h@50 Pa with an increment of 1.0.

The optimization converged at 184th generation, where no further improvements on the heating and cooling loads were identified. This led to achieving over 4500 iterations (Figure 6). The results were then exported into *Excel spreadsheets* for further analysis. The next step was to eliminate iterations with thermal loads higher than 96.0 MJ/m^2 (26.67 kWh/m^2), so that a 6-Star rating, which is the minimum mandatory thermal requirement for Adelaide, would be achieved. This process resulted in 2,363 design configurations, in that each one represents a unique building design of a single-storey detached building. Afterward, the remaining iterations were star-rated based on their respective heating and cooling loads. As a result, each star band contained several cases with different building designs. The highest-rated building designs, based on the NatHERS rating scheme, obtained 8.7 stars whereas the lowest building designs yielded 6.0 stars.

The next stage involved calculating the number of PV panels required for each building design to balance out heating and cooling energy. Since the fundamental objective of TLEB is to transition Australian residential buildings to zero energy buildings, this study assumed that all the cases have PV panels to negate their thermal energy demands. To this end, a common type of 220W PV system, with a size of 1.639 m∗0.982 m and an efficiency rate of 80% was assumed to be employed by all the cases. The PV system was assumed to be oriented towards true North, with 30° tilted. The average annual solar exposure in Adelaide was also considered to be 20.39 MJ/m^2 (Australian Government Bureau of Meteorology 2020a). In addition, the inverter efficiency was assumed at 8%. The aforementioned settings were applied for all the cases.

Analysis of embodied and operational energies

Quantification of materials was carried out using technical drawings of the building. Components considered for embodied energy analysis included external and internal walls, ceiling, roof, exterior doors, glazing and window frames, flooring construction (foundation and finishing materials), and PV panels. The embodied energy analysis of this study only accounted for the production and manufacturing of construction materials (i.e. initial embodied energy) (Figure 7).

The end of life and construction stages were excluded due to their minor contributions to the total energy demands, as discovered by previous studies (Dahlstrøm et al. 2012; Cabeza et al. 2014; Crawford et al. 2016). In addition, this study only considered recurring embodied energy (replacement) relating to the PV panels. It is assumed that PV systems have a lifespan of 25 years, thus they are to be replaced once over a life service of 50 years. To quantify embodied energy, SimaPro software was applied using the AusLCI database Version 1.32-2020 as the background life cycle inventory database. The functional unit was also one square metre of gross floor area over a service lifetime of 50 years.

Table 4. Total life cycle energy use of the analyzed cases (GJ).

	Total life cycle energy use∗		Embodied energy% (Min.)	Embodied energy% (Max.)
Star-rating	Min.	Max.	Min.	Max.
6.0	**1,267**.96	**1,843.69**	**19.99**	**39.90**
6.1	1,227.22	1,800.60	20.57	46.52
6.2	1,177.34	1,788.91	21.98	47.92
6.3	1,165.44	1,720.14	22.90	48.36
6.4	1,158.06	1,709.63	23.04	49.06
6.5	**1,137**.07	**1,766.26**	**22.98**	**51.72**
6.6	1,090.71	1,720.69	23.15	51.78
6.7	1,070.62	1,696.27	23.92	52.33
6.8	1,052.10	1,643.68	24.10	53.11
6.9	1,049.01	1,359.18	25.35	53.92
7.0	**993.22**	**1,563.50**	**26.09**	**54.89**
7.1	980.13	1,554.24	27.95	55.27
7.2	940.95	1,538.65	28.47	56.98
7.3	899.28	1,524.15	29.21	57.39
7.4	881.23	1,512.43	29.47	58.44
7.5	**857.85**	**1,497.27**	**30.06**	**60.04**
7.6	844.53	1,460.31	30.63	61.01
7.7	804.61	1,433.95	32.34	61.61
7.8	783.65	1,360.49	34.30	64.35
7.9	753.61	1,346.37	34.46	64.54
8.0	**737.88**	**1,370.38**	**36.83**	**69.11**
8.1	703.13	1,311.35	37.34	69.93
8.2	671.27	1,279.99	40.53	70.51
8.3	659.05	1,267.81	41.78	72.29
8.4	644.22	1,239.82	43.15	73.92
8.5	**623.21**	**1,185.37**	**47.73**	**74.33**
8.6	600.86	1,171.68	48.75	74.68
8.7	**592.73**	**1,172.66**	**50.47**	**74.75**

Total life cycle energy use presents the sums of total energy use (i.e. heating and cooling) and embodied energy over a 50-year period.

The assessment of operational energy has been carried out considering only heating and cooling loads of the cases. The thermal loads are converted into energy use for heating and cooling by applying the assumed COPs of the heating and cooling equipment (2.25 and 3.0 respectively). After this conversion, the primary energy is calculated using an electricity conversion factor of 3.40 (Stephan, Crawford, and De Myttenaere 2012) in order to capture a more holistic understating of overall energy consumption.

Results and discussion

The analyzed cases are first star-rated based on their thermal performances using the NatHERS energy rating scheme. Then, the embodied impacts attributed to each case are superimposed in order to observe the significance of embodied energy. Table 4 presents total life cycle energy use (i.e. sums of thermal loads and embodied energy) of all the cases that are represented in Gigajoules (GJ) over a 50-year period.

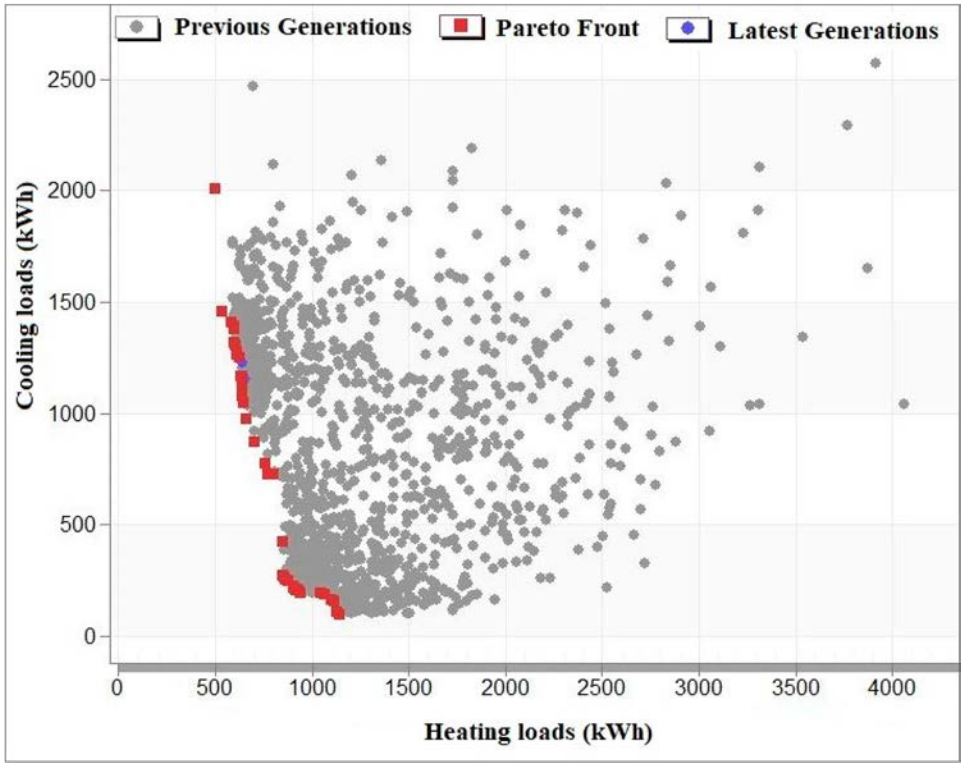

Figure 6. *Pareto* frontier achieved for optimization of heating and cooling loads.

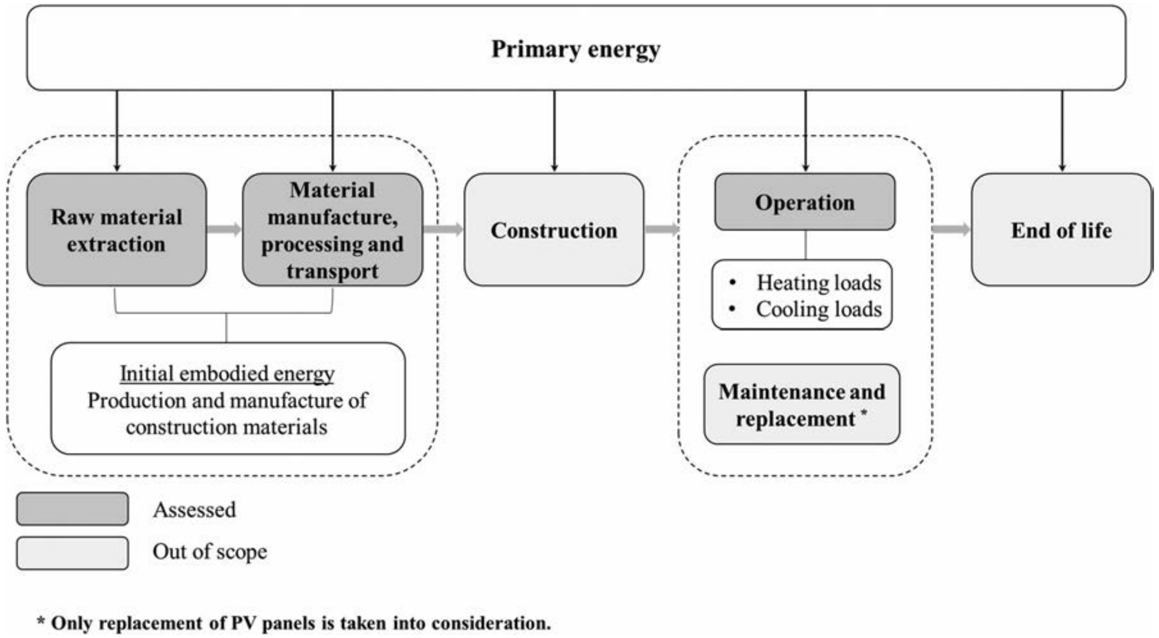

Figure 7. System boundary of the current study.

As shown in Table 4, the improvement of buildings' thermal performance in accordance with the NatHERS energy rating scheme can lead to an overall reduction in total life cycle energy use. However, the embodied energy becomes dominating as the buildings' energy efficiency increases. For instance, the transition from 6.0 stars to 6.5 and 7.0 stars, which is in line with the agenda of TLEB can decrease the total life cycle energy demands by 4–10% and 15–22%, respectively. Nevertheless, this transition results in increasing the share of embodied energy by 23–52% for 6.5 stars and 26–55% for 7.0 stars. Likewise, the comparison of 6.0 stars with 8.7 stars attests to the significance of embodied energy in buildings with higher energy efficiency. It can be seen that improving buildings' thermal performance from 6.0 stars to 8.7 stars leads to reducing buildings' total energy use by 36–53%, whereas embodied energies associated with these bands increase from 20–40% to 50–75%. These findings reaffirm the results of retrospective studies in regards to the significance of embodied energy in the Australian residential

Table 5. Comparison of NatHERS scheme with total energy loads (MJ/m^2.year).

Star-rating	Thermal requirements given by NatHERS	Total life cycle energy use∗	
		Min.	Max.
6.0	96.0	133.57	194.23
6.5	83.0	119.79	186.07
7.0	70.0	104.63	164.71
7.5	58.0	90.37	157.73
8.0	46.0	77.73	144.36
8.5	33.0	65.65	124.87
8.7	28.60	62.44	123.54

Total life cycle energy use presents the sums of total energy use (i.e. heating and cooling) and embodied energy.

buildings (Stephan, Crawford, and De Myttenaere 2012; Crawford and Stephan 2013; Stephan, Crawford, and De Myttenaere 2013b; Crawford 2014; Stephan and Crawford 2014; Crawford et al. 2016). For instance, Crawford (2014) analyzed the life cycle energy consumption of a typical detached residential building in Melbourne, Australia. The results indicated that embodied energy including initial and recurring embodied energy made up 59% of the total life cycle energy use of the building. In another research, Crawford and Stephan (2013) assessed the overall life cycle energy use of a residential building by accounting for operational energy, embodied energy (i.e. initial and recurring embodied energy), and transport energy. The results showed that the embodied, operational, and transport requirements represent comparable shares of the total at 32%, 37%, and 31%, respectively.

Table 5 also compares the thermal requirements specified by the NatHERS scheme for Adelaide with the total energy consumption calculated by this paper. It can be seen that the exclusion of embodied energy associated with each star band has resulted in underestimating the actual buildings' environmental impacts. For instance, a 6-star building can potentially use up to 51% more energy than the amount determined by the NatHERS scheme once the potential embodied impacts are considered. Similarly, an 8.7-star house, which is expected to consume less energy, may actually have the same as or even more environmental impacts than a 6.0-star house due to its high embodied energy.

The findings of this study show that the reduction of operational energy should be addressed in parallel with abating embodied impacts; otherwise, energy consumption or GHG emissions shall be simply moved from one stage of the building life cycle to another without yielding an overall reduction. In this regard, policy can play a vital role in integrating the life cycle embodied environmental impacts into building energy efficiency regulations.

To date, only a limited number of countries have commenced incorporating embodied impacts into their building regulations. The Netherlands is the first country to introduce requirements for the measurement of embodied impacts, though not the reduction, into its building regulations (Building Decree 2012). According to section 5.2 of building decree 2012 (Building Decree 2012), the Dutch jurisdiction requires that the environmental impacts (i.e. GHG emissions and resource depletion) associated with the structural elements of a residential function or an office building with a total usable area exceeding 100 m^2 must be quantified. The enforcement of such a regulatory approach aims to stimulate the builders to utilize sustainable construction materials. However, no restriction has been applied by the Dutch building codes to the amounts of embodied energy associated with the used construction materials. Other countries have also taken their initial steps towards this end such as France (French Ministry of Environment Energy and the Sea 2020), Finland (Kuittinen and le Roux 2018), Norway (Norwegian Standard NS 3720: 2018), Denmark (Frivillig Baeredygtighetsklasse 2018; The Danish Government Strategy for the Circular Economy 2018), and Sweden (Boverket Klimatdeklaration Av Byggnader 2018). Switzerland also opts to implement the target of the '2000-Watt Society', based on which primary energy use per person including embodied energy would be 2000 watts while limiting CO_2 emissions to no more than 1.0 ton of CO_2 equivalent per person per year by 2050 (Frischknecht et al. 2019).

Nevertheless, there are still many countries, including Australia that have been reluctant to recognize embodied energy as a part of their mandatory requirements for EERs. This is mainly attributed to the issues relating to the quantification of embodied energy, in which the varied approaches lead to displaying variations in the results of embodied energy analysis (Moncaster et al. 2019; Omrany et al. 2020a; Omrany et al. 2020b); despite existing several international standards such as ISO 21929-1 (ISO 21929-1 2011), ISO 21931-1 (ISO 21931-10 2010), and the European standards developed by Technical Committee TC350, including EN 15643-2 (EN 15978 2011) and EN 15978 (EN 15978 2011). This was first noted by Sartori and Hestnes (2007) through analyzing 60 cases from 9 countries. More recent studies also highlighted the same issue and identified multiple reasons for such variations e.g. varied definitions of system boundary (i.e. physical and temporal), the use of different methods, buildings' geographic locations, data quality, or manufacturing technology (Pomponi and Moncaster 2016; Anand and Amor 2017; Dixit 2017; Hossain and Ng 2018; Rasmussen et al. 2018; Omrany et al. 2020a; Omrany et al. 2020b). In a study, Moncaster et al. (2018) identified three major categories that contribute to varying results in embodied energy analysis, namely 'temporal differences in the stages considered'; 'spatial differences in the material boundaries'; and 'physical disparities in the data coefficients'.

Apart from the technical issues, there has been a misconception about the significance of embodied energy as to which factors other than operational energy constitute a negligible portion of the total environmental performance of buildings (Ramesh, Prakash, and Shukla 2010; Karimpour et al. 2014); thus, they can be neglected. These challenges have collectively discouraged policymakers from considering embodied impacts as a requirement for energy efficiency.

Proposals for incorporation of embodied energy

This section aims to bring forward proposals for the integration of embodied impacts with the Australian EERs. This study suggests establishing minimum mandatory requirements (energy budget) for 'embodied performance' of new and retrofitted buildings, similar to the current NatHERS scheme. This approach promotes considerations for maximum reduction of embodied

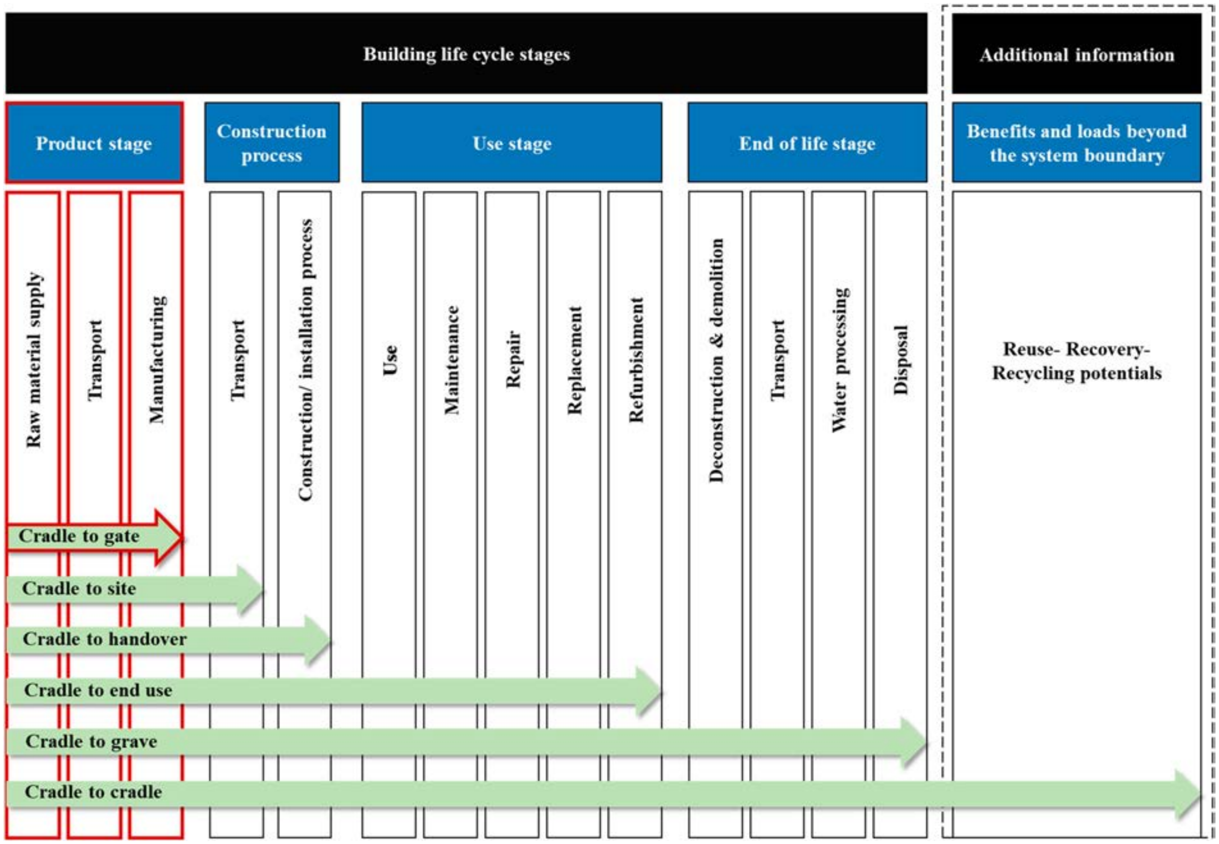

Figure 8. Proposed model for description of system boundary (modular structure adapted from EN 15978:2011 [EN 15978 2011]).

impacts at the earliest design stage. In this regard, the main challenge is to establish standardized boundary conditions in terms of physical and temporal boundaries that can be applied by one Australian climate zone.

The temporal system boundary refers to determining which building life cycle stage is included for the assessment. While it is recommended to account for impacts of all life cycle stages, this study suggests that 'cradle to gate' (i.e. initial embodied energy) should be considered as the minimum mandatory requirement for assessment of embodied impacts at the building level (Figure 8). The initial embodied energy plays a significant role in emitting GHGs into the atmosphere since they are mainly produced by burning fossil fuels (Crawford et al. 2016). It is also widely accepted that initial embodied energy constitutes a high percentage of total embodied energy use (Stephan, Crawford, and De Myttenaere 2013a; Stephan and Stephan 2014; Crawford et al. 2016; Zhan et al. 2018; Omrany et al. 2020a; Omrany et al. 2020b); therefore, taking the impacts of this stage into consideration can capture a significant portion of the total embodied energy use of buildings. For instance, Zhan et al. (2018) endeavoured to calculate the energy consumption of a residential building in Guangzhou, China. The results showed that initial embodied energy made up 85% of the total building's embodied energy use. Similarly, Stephan and Stephan (2014) performed a comprehensive analysis to quantify the life cycle energy performance of a residential building in Lebanon. The results revealed that initial embodied energy represents 69% of the total life cycle embodied energy of the case study.

Additionally, the majority of current LCA databases contain initial embodied impacts of building materials that are calculated based on energy inputs from the entire structure of an economy; thus, the impacts of this stage can be taken into consideration regardless of buildings' locations.

Physical system boundary refers to determining which building components need to be included in the assessment. This study suggests a checklist that can be considered as the minimum requirements for delineating physical system boundaries (Table Table 6). The recommended components are mainly attributed to physical enclosure of buildings. The inclusion of embodied impacts associated with renewable energy systems is also suggested, in the case of zero energy buildings. While recommending to include embodied impacts of other components (e.g. furniture, heating and cooling systems and etc.), considering their impacts by EERs may lead to incomparability since the choice of using these elements depends on a wide variety of factors, e.g. occupants' taste that cannot be predicted at the design stage.

The recommended approaches for standardization of system boundaries should be accompanied by developing embodied energy databases for materials so that designers can readily link their designs with material quantities to carry out embodied energy estimations. It is also important that the environmental product declarations (International Standard 14025/TR: Environmental labels and declarations 2006) for building materials would be enforced in Australia to provide up-to-date quantified environmental data relating to construction materials. A similar approach is being practiced by Dutch jurisdictions in which

Table 6. Recommended approach for delineation of physical system boundary.

Building components	Building sub-components	Recommended for inclusion
Substructure	Foundation	▲
	Basement retaining walls	▲
	Ground floor	▲
Superstructure	Structural building frame	▲
	Exterior walls	▲
	Exterior doors	▲
	Window glazing	▲
	Interior walls	▲
	Floor construction	▲
	Ceiling construction	▲
	Roof construction	▲
	Stairs and ramps	▲
Renewable energy system	Photovoltaic panels; solar collectors; wind turbines; and etc.	▲
Building services	Water system	
	Sewage system	
	Heating system	
	Cooling system	
	Ventilation system	
	Electrical system	
	Conveying systems	
	Fire protection system	
Finishes	External finishes	
	Internal finishes	
	Fixed furniture	
	Furniture	
External	Balcony	▲
	Vegetation	
	Pavement	

a national database (Nationale Milieudatabase) is developed containing different categories of products' environmental data (National Environmental Database 2020). The database subjects to a periodic update every 5 years. Several accredited software are also developed to calculate the environmental performance of buildings based on the data of national database (National Environmental Database 2020).

Limitations and future research

The current study suffers from a number of limitations that need to be highlighted. First, it only considers thermal loads (heating and cooling) for the assessment of building's operational energy and excludes non-thermal loads such as hot water, lighting, and electrical appliances. This is done to reflect on the limited assessment scope of the current regulatory scheme in Australia. However, non-thermal loads can be significant in consuming energy, especially in low energy and zero energy buildings. The statistics show that an average Australian dwelling consumes energy for the following purposes: heating and cooling (40%), water heating (23%), electrical appliances (e.g. laundry appliances or entertainment appliances) (14%), fridges and freezers (8%), lighting (7%), cooking (5%), and standby power (3%) (Home energy use in Australian house 2019). The findings of previous studies also affirm the significance of non-thermal parameters in consuming energy (Stephan, Crawford, and De Myttenaere 2012, 2013b). For instance, Stephan, Crawford, and De Myttenaere (2013b) analyzed life cycle energy and GHG emissions of detached houses in suburban Melbourne, Australia. The analysis showed that heating and cooling constituted 33.3% of total operational energy, while appliances used 47.7% followed by lighting (10.5%), hot water (4.7%), and cooking (3.9%). This limitation can be addressed by future research through considering both thermal and non-thermal loads. Furthermore, the assessment of thermal loads was carried out assuming that the occupational settings (e.g. scheduling and occupancy profile) would remain unchanged over the period of 50 years. The results can be widely affected due to varying occupational settings (e.g. scheduling and occupancy profile).

This study has proposed developing energy budgets for embodied energy performance of new and retrofitted buildings in Australia. The implementation of such an approach requires a thorough consideration of climate impacts on both embodied and operational energies. Studies showed that buildings' life cycle energy demands can be influenced by climatic conditions (Lawania and Biswas 2018; Omrany et al. 2020a; Omrany et al. 2020b). In a study, Lawania and Biswas (2018) endeavoured to design low-carbon houses with the consideration of climate impacts on embodied and operational energies across 18 regional locations in Western Australia. They selected a typical clay brick detached house, and employed Accurate and SimaPro software to calculate operational and embodied energies associated with the building respectively. The results showed that the total life cycle GHG emissions and embodied energy of the houses varied across the 18 selected locations depending on the climate zone of each region. In the end, Lawania and Biswas (2018) recommended a number of strategies that can effectively lead to reducing embodied GHG emissions and embodied energy consumption in Western Australia. The scope of current study is limited to only one climate, i.e. Adelaide, climate zone 16. Future research can expand the current scope to further investigate the effects of climate on embodied energy budgets for each Australian climate zone.

In addition, previous studies pointed out the difference between high-rise and low-rise buildings in terms of their attributed initial embodied energy use (Du et al. 2015; Luo, Yang, and Liu 2016; Wang, Yu, and Pan 2018). Wang, Yu, and Pan (2018) investigated the life cycle energy use of ten real-life buildings in Hong Kong, and reported that initial embodied energy usage of high-rise buildings was twice of low-rise ones. Du et al. (2015) also reviewed 42 case buildings, and conclusively stated that high-rise buildings had almost 50% more embodied energy compared to low-rise buildings. Treloar et al. (2001) highlighted even a larger difference, stating that high-rise buildings may have approximately 60% more initial embodied energy per unit gross floor area than low-rise buildings. The higher embodied energy of high-rise buildings can be related to (i) using more materials, and (ii) using materials with higher energy intensity, e.g. concrete and steel (Wang, Yu, and Pan 2018). The scope of this paper is limited to low-rise buildings (i.e. single-storey detached residential building); therefore, it is expected that variations in building classification will lead to different results. Information regarding building classifications in Australia can be found in (Building Codes of Australia 2014). Thus, the full development of embodied energy budgets requires further analyses of embodied energy associated with different building types.

This study employed the AusLCI database to quantify the embodied impacts of building materials. This database is developed based on the economic input-output method. Although this method improves the incomplete system boundary definition in the process-based method, it still suffers from a lack of product-specific data. Previous studies showed that using a hybrid analysis method for analyzing embodied energy can result in much higher values compared to other methods (Crawford 2011; Stephan and Stephan 2014). Moreover, this research has not studied the relation between building size and embodied energy. The size of a building can directly influence its associated embodied energy use by affecting the quantity of materials needed for its construction. Large buildings inherently consume more embodied energy compared to smaller buildings; however, using the current metrics (e.g. gross, or usable floor area per square metre) to report life cycle energy use of buildings can misrepresent the fact that larger dwellings have more embodied energy. This is echoed in the findings of Stephan and Crawford (2016) that investigated the life cycle energy demands of 90 house sizes and four household sizes for a typical detached house in Melbourne, Australia. The results showed that the life cycle energy demand increased at a slower rate compared to house size; thus, using 'per m^2' to express energy efficiency can favour large houses even though they require more energy.

Conclusions

Over the last decades, Australia has taken several measures to tackle the increasing trend of energy use in residential buildings. In one of the latest attempts, the *Trajectory for Low Energy Buildings* has been endorsed aiming to reduce energy usage in residential buildings by supporting the concept of zero energy building in Australia. This trajectory targets to increase minimum mandatory thermal requirements for new residential buildings in 2022 and 2025. However, the primary focus is given to the reduction of operational energy while excluding the impacts of embodied energy. Therefore, this study aimed to address one primary question; 'can the continued exclusion of embodied energy from the energy efficiency regulations effectively lead to reducing energy consumption in Australian residential buildings?'. The findings indicate that the increase of buildings' thermal performance following the increase of star bands can bring an overall reduction of buildings' energy usage. However, the embodied energy becomes dominating as the star rating increases. It is shown that the transition from 6.0 stars to 6.5 and 7.0 stars can result in reducing the total life cycle energy demands by 4–10% and 15–22%, respectively. Nevertheless, this transition increases embodied energy proportions by 23–52% for 6.5 stars and 26–55% for 7.0 stars. Moreover, the results showed that moving from a standard 6.0 stars building to a highly energy-efficient building of 8.7 stars can result in increasing embodied energy from 20–40% to 50–75%. The findings also point out the necessity of considering the reduction of embodied energy in parallel to operational energy as the limited focus given only to decreasing operational energy may lead to misrepresenting the actual buildings' environmental impacts.

This study suggests that the Australian energy efficiency regulations should introduce minimum mandatory requirements for the 'embodied performance' of new and retrofitted buildings. This approach can potentially promote considerations for maximum reduction of embodied impacts at the earliest design stages. However, the main challenge resides with establishing standardized boundary conditions (i.e. physical and temporal) that can be applied by one Australian climate zone. Recommendations are given in order to standardize boundary conditions for integrating embodied energy with energy efficiency regulations. It is suggested that initial embodied energy should be determined as the minimum mandatory requirements for assessment of embodied impacts at the building level. In terms of the physical system boundaries, this study suggests a detailed checklist that can be considered as the minimum compulsory requirement for assessment of buildings' embodied impacts.

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Appendix IV – Manuscript: A Comprehensive Framework for Standardising System Boundary Definition in Life Cycle Energy Assessments

buildings

Article

A Comprehensive Framework for Standardising System Boundary Definition in Life Cycle Energy Assessments

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Abstract: This paper aims to propose a comprehensive framework for a clear description of system boundary conditions in life cycle energy assessment (LCEA) analysis in order to promote the incorporation of embodied energy impacts into building energy-efficiency regulations (BEERs). The proposed framework was developed based on an extensive review of 66 studies representing 243 case studies in over 15 countries. The framework consists of six distinctive dimensions, i.e., temporal, physical, methodological, hypothetical, spatial, and functional. These dimensions encapsulate 15 components collectively. The proposed framework possesses two key characteristics; first, its application facilitates defining the conditions of a system boundary within a transparent context. This consequently leads to increasing reliability of obtained LCEA results for decision-making purposes since any particular conditions (e.g., truncation or assumption) considered in establishing the boundaries of a system under study can be revealed. Second, the use of a framework can also provide a meaningful basis for cross comparing cases within a global context. This characteristic can further result in identifying best practices for the design of buildings with low life cycle energy use performance. Furthermore, this paper applies the proposed framework to analyse the LCEA performance of a case study in Adelaide, Australia. Thereafter, the framework is utilised to cross compare the achieved LCEA results with a case study retrieved from literature in order to demonstrate the framework's capacity for cross comparison. The results indicate the capability of the framework for maintaining transparency in establishing a system boundary in an LCEA analysis, as well as a standardised basis for cross comparing cases. This study also offers recommendations for policy makers in the building sector to incorporate embodied energy into BEERs.

Keywords: embodied energy; operational energy; net-zero energy building; energy efficiency; conceptual framework

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1. Introduction

High-performance buildings have gained momentum over the recent decades owing to their capacity to curb dependency on fossil fuels [1–4]. These buildings are principally constructed to minimise annual operational energy use so that they can achieve net-zero energy (and carbon) usage by integrating on-site renewable or decarbonised energy systems with the buildings [5]. Thus far, this concept has been introduced into the built environment through two general approaches [1]. The first approach is mainly voluntary, aiming to realise highly energy-efficient buildings by embracing green certification programs. Examples of this approach include Passivhaus in Germany [6], green buildings in Australia [7], and Minergie standard in Switzerland [8]. The second approach is a gradual process by which the performance thresholds to achieve energy-efficient buildings (e.g., nearly-zero energy buildings (NZEBs) or net-zero energy buildings) are progressively increased over time through mandatory building codes. In this approach, building energy-efficiency regulations (BEERs) play a vital role in fulfilling the attainment of high-performance buildings. An example of this approach is the Australian energy-efficiency regulations that aim to achieve zero energy (and carbon)-ready buildings by 2030 through increasing the mandatory thermal performance requirements for new buildings [9].

Nevertheless, previous studies have shown that the implementation of BEERs may lead to increasing the total environmental impacts of buildings due to their limited scopes to account for the impacts of embodied energy [10–12]. For instance, Omrany et al. [12] analysed the effects of enhancing a building's thermal efficiency on embodied energy. To carry out the study, the thermal performance of a residential building constructed in accordance with minimum mandatory requirements of Australia (i.e., 6-star building) was gradually increased to achieve high-performing buildings. The results showed that the share of embodied energy in total life cycle energy consumption increased from 20–40% to 50–75% in transitioning from a standard 6-star building to a highly energy-efficient building. In another study, Stephan et al. [10] analysed the total life cycle energy performance of a passive house located in Belgium and realised that the building's embodied energy constituted up to 77% of the total life cycle energy consumption. It was conclusively stated that the adoption of current energy-efficiency regulatory schemes may not necessarily result in minimising the overall life cycle energy use of buildings owing to the exclusion of embodied energy.

In recent years, literature has witnessed a growing body of research developed to demonstrate the significance of embodied energy attributed to buildings with high energy-efficiency performance. However, this surge of research has been unable to alter the mindset of policy makers about the necessity of abating buildings' embodied impacts when planning for enhancement of sustainability in the built environment [13]. Many studies have attempted to encourage the incorporation of embodied energy into BEERs by increasing the accuracy of embodied energy calculation methods [14–17]; investigating challenges for inclusion of embodied energy into BEERs from the perspectives of building professionals [18,19]; or integrating building information modelling techniques with the life cycle assessment (LCA) approach and building codes [20,21]. Despite increasing attention, the pathway for including the impacts of embodied energy into BEERs is still ambiguous. The chief reason for such an ambiguity resides with the complexity that BEERs encounter in accounting for the impacts of both operational and embodied energies due to various processes and parameters involved.

To address this challenge, the development of a comprehensive framework for a clear description of system boundaries can pave the way towards integrating the life cycle embodied environmental impacts into BEERs. Currently, the literature is lacking such a comprehensive framework. This lack is reflected in the findings of recent studies that reported variations in the results of life cycle energy assessment (LCEA) analyses [22–26]. In a recent study, Pan and Teng [26] conducted a holistic literature review analysis of 244 case studies, aiming to quantify potential variations in embodied energy calculations. The results showed that significant variations may stem from the choice of method for embodied energy assessment, i.e., a 200% increase from process-based to hybrid method. In addition, the varied approaches of studies to account for the effects of parameters influencing the assessments of embodied and operational energy can be critical in varying LCEA results [23,24]. For instance, Pan and Teng [26] found that unclear descriptions of system boundaries for including cradle-to-gate and cradle-to-end of construction embodied energy may cause a 9.2% variation in the achieved results. Retrospective research showed that the primary cause of these variations relates to the subjective delineation of system boundaries in LCEA or LCA analyses [27–29], despite several international standards and frameworks that have been developed towards this end, such as ISO14040:2006 [30] or the European frameworks developed by Technical Committee TC350, e.g., EN 15978:2011 [31]. The subjectivity in defining system boundaries can potentially compromise the quality and reliability of obtained results for decision-making purposes while limiting the possibility for cross comparing LCEA cases.

With the motivation outlined above, this study aims to propose a structured framework through which the system boundaries in LCEA research can be explicitly defined.

The framework proposed by this paper defines system boundaries within six distinctive dimensions, facilitating the possibility for policy makers to set requirements for incorporation of embodied impacts into BEERs at national or regional levels. This framework is also expected to assist with exploring the relative body of research that can lead to broadening our understanding of building energy performance within a global context by comparing LCEA cases. The remainder of this paper unfolds as: first, the research theoretical background is explained in Section 2 in order to provide an overview of the life cycle energy assessment approach, embodied energy, and operational energy. Section 2 also provides a review of previous studies aimed at developing a framework for standardisation of system boundary definition. Section 3 elaborates on the methodological approach of the research. Different dimensions of the proposed framework are then explained in Section 4. The implementation of the proposed framework is described in Section 5, before the discussion and conclusion in Sections 6 and 7, respectively.

2. Theoretical Background

2.1. An Overview of LCEA

The LCA is a quantitative approach to measure environmental burdens associated with processes, products, or services over their life cycles [32]. The International Organization for Standardization (ISO) introduced a framework to perform LCA analysis [33]. This framework consists of four primary steps, including (1) setting the goals and scope, (2) life cycle inventory (LCI), (3) life cycle impact assessment (LCIA), and (4) interpretation. The first step requires setting the overall goals and scope of the project along with establishing system boundaries and determining the inventory data quality requirements. The LCI is the next step whereby the process for obtaining and collating data of energy flows at each stage of a product's life cycle should be determined. This is followed by LCIA, where the environmental impacts correlated with materials and energy flows are quantified and assigned to their respective environmental impact categories. At the interpretation step, the obtained LCA results are interpreted with respect to the defined goals and scope of the research, and recommendations are issued accordingly.

LCEA is a version of the LCA that only accounts for energy usage at all stages of a building's life cycle [6,24]. In this approach, the total energy performance of a building is quantitatively assessed considering both operational and embodied energies. Embodied energy is the amount of energy consumed at the upstream and downstream stages of the building's life cycle, including production of building materials (known as initial embodied energy), building construction, maintenance and replacement (also known as recurrent embodied energy), end-of-life (EOL) processes, and transportation between any of these steps [23,24,32]. The operational energy refers to the amounts of energy used in the forms of thermal (i.e., heating and cooling) and non-thermal (i.e., domestic hot water (DHW), electrical appliances and equipment, ventilation, lighting, and cooking) energy over the life cycle of a building [23,24,32]. The scope of this study is limited to LCEA analysis; however, the final outcome can also be applicable to LCA research.

2.2. Previous Research on Developing Frameworks for System Boundaries

In the wider literature, a system boundary is defined in different ways. In the general system theory, Bertalanffy [8] defined a system boundary as an interaction interface whereby material, energy, or information is transferred in or out of the system. In societal system theory, this concept is described as barriers that differentiate a system from others in the environment through its spatial and temporal boundaries, any surrounding environmental affects characterised by its structure and purpose and expressed in its functionality [34]. In a narrower scope, a system boundary is defined by the ISO as a number of criteria that determine the inclusion of unit processes into a product system [33].

The absence of a standardised framework for defining system boundaries is commonly considered as a principal contributor to varying LCEA results [24,25,28,35–39]. This was first noted by Sartori and Hestnes [40] through analysing 60 cases from nine countries.

Recent studies have also attested to the key role of system boundary definition in deriving variations and identified multiple reasons for such phenomena, e.g., varied definitions of physical and temporal boundaries; the use of different methods for measuring embodied and operational energies; buildings' geographic locations, data source, and data quality; or manufacturing technology [23,24,27,29,40]. For instance, Moncaster et al. [29] identified three major categories that contribute to varying results in embodied energy analysis, namely "temporal differences in the stages considered"; "spatial differences in the material boundaries"; and "physical disparities in the data coefficients".

Despite the significance of a system boundary in determining the quality of LCEA results, a limited number of studies have been undertaken to standardise system boundary definition. Hammond and Jones [41] introduced a four-level regression model for the description of a system boundary. The first level accounts for all of the energy inputs used directly during processes such as construction, prefabrication, maintenance, replacement, demolition, and disposal in order to produce a product. The second level of the regression model promotes the inclusion of energy consumption sequestered into main and all upstream and downstream processes of materials and product manufacturing. The third level captures the amounts of energy use embedded in the production, delivery, and installation of machines that are utilised to manufacture materials, as well as on- and off-site construction processes. The final level represents the amount of energy expelled during the main, upstream, and downstream production processes of manufacturing machinery that in turn produces the machine (of third level regression). Although the proposed model endeavours to disentangle the energy inputs used at each stage of a building's life cycle, it still fails to capture other flows of data requirements for the environmental assessment of a building. Likewise, Fay [42] presented the same ideas about defining system boundary conditions that are composed of multiple levels. A similar boundary condition was also demonstrated by Herendeen [43] through analysing the life cycle energy use of car production. The results showed that 90% of the energy is consumed during processes of producing constituents of car materials such as steel, plastic, glass, etc., whereas only 10% of energy consumption relates to car manufacturing plants.

Dixit et al. [28] also proposed a conceptual framework based on performing a comprehensive literature review and synthesising relevant literature opinions on system boundary definition. The proposed framework primarily aimed to elaborate on the temporal and physical boundaries of a system under research. The study was concluded by recommending several measures that enable conducting the LCEA of a building. Stephan et al. [39] presented a comprehensive framework of a system boundary to capture the energy requirements at both building and urban scales. The framework accounts for operational and embodied energy usage of buildings, as well as embodied impacts related to nearby infrastructures and the occupants' transport energy. Although the framework promotes the integration of energy flows between embodied, operational, and transport requirements, it does not provide tailored data requirements for different dimensions of system boundaries. In another study, Pan [44] proposed a theoretical framework to assist multi-criteria decision making in selecting off-site construction technologies. The framework captures four aspects of system boundaries, namely, ontology, epistemology, methodology, and axiology. Pan's framework enables the theoretical investigation of system boundaries defined in previous studies of LCA and carbon emissions. Later on, Pan [37] developed a conceptual model that consists of eight boundaries including "the policy timeframe, building lifecycle, geographic, climatic, stakeholder, sector, density, and institutional boundaries". This framework provides the possibility of cross comparing different cases within a harmonised context. Despite the great details provided, the life cycle boundary of the framework only elaborates on the temporal dimension of the system boundary without providing detailed information on other facets.

The frameworks developed by the reviewed studies fall short of capturing all the dimensions involved in defining system boundaries. The majority aimed at simplifying the temporal and physical dimensions, and only the study by Pan [37] elaborated on aspects such as building geography, stakeholders, or the relative sector. This highlights the need for a much more comprehensive framework when aiming for the incorporation of embodied impacts into BEERs. The comprehensiveness of such a framework can assist policy makers to set certain requirements and standards for each dimension of the framework at national or regional scales.

3. Methodology

The overall methodological approach of this paper consists of three stages. The first stage involves the identification of variables that contribute to variations in LCEA results. Previous studies have examined a number of parameters with potential influence on the LCEA results, such as data quality, functional units, or calculation methods [27,45]. However, the identified parameters reported in the existing literature were limited and sporadically sorted without any systematic understanding. Hence, comprehensive searching exercises were conducted throughout various scholarly databases, namely, Web of Science, ProQuest, and Scopus, in order to retrieve studies related to the LCEA approach. The literature review approach was a systematic approach; thus, certain limitations were considered. First, the scope of these literature analyses was limited to only residential buildings. Second, only studies that assessed the life cycle energy performance of residential buildings using primary energy were considered for detailed examinations. Despite the limitations considered, the literature review surveys managed to identify 66 LCEA research projects representing 243 case studies in over 15 countries. The findings of the literature review analysis were reported in [23,24]. Thereafter, the approaches of the identified studies to defining system boundary conditions in LCEA research were analysed in depth. The findings identified 12 major parameters attributed to different aspects of LCEA methodology that potentially result in varying outcomes. These parameters were further grouped into the following four categories: "system boundary definition", "calculation methods", "geographical context", and "interpretation of results". Detailed discussion of the findings of the literature review analyses is beyond the scope of this paper; thus, readers are encouraged to refer to [23,24] for further details.

The second stage involves developing a comprehensive framework to standardise system boundary conditions in LCEA research using the parameters identified by analysing the literature. Figure 1 illustrates the development process of the proposed framework that began with (i) reviewing the literature where parameters causing the variations in LCEA results were singled out [23,24], (ii) consolidating the identified variables into six distinguished dimensions, and (iii) allocating each variable to its respective dimension. Since the scope of the literature review was limited to residential buildings, this paper also proposes consideration of "building types" and "building density" (i.e., number of storeys) as distinctive dimensions of a system boundary in LCEA analysis. Section 4 will further elaborate on each dimension of the framework.

The third stage involves demonstrating the implementation of the proposed framework. The applicability of a framework can generally be tested through different methods such as using focused community expert groups, surveys, case studies, experiments, or simulations [46,47]. The current paper employs a simulation approach in order to evaluate the applicability of the proposed framework. To this end, the system boundary conditions of a residential building in Adelaide, Australia, were first defined using the proposed framework. The annual operational energy of the case study was assessed using the EnergyPlus 8.9 simulation engine [48]. Regarding embodied energy, the quantity of materials was assessed through the building's drawings. To assess the embodied impacts of building materials, a database developed by Pullen [49] was utilised in order to calculate the building's embodied energy. The results calculated in this paper were then cross compared with the results of a case study analysed by Crawford [50], aiming to demonstrate the capacity of the proposed framework for cross comparing cases within a standardised context. Afterward, the results are discussed and implications for further research are highlighted.

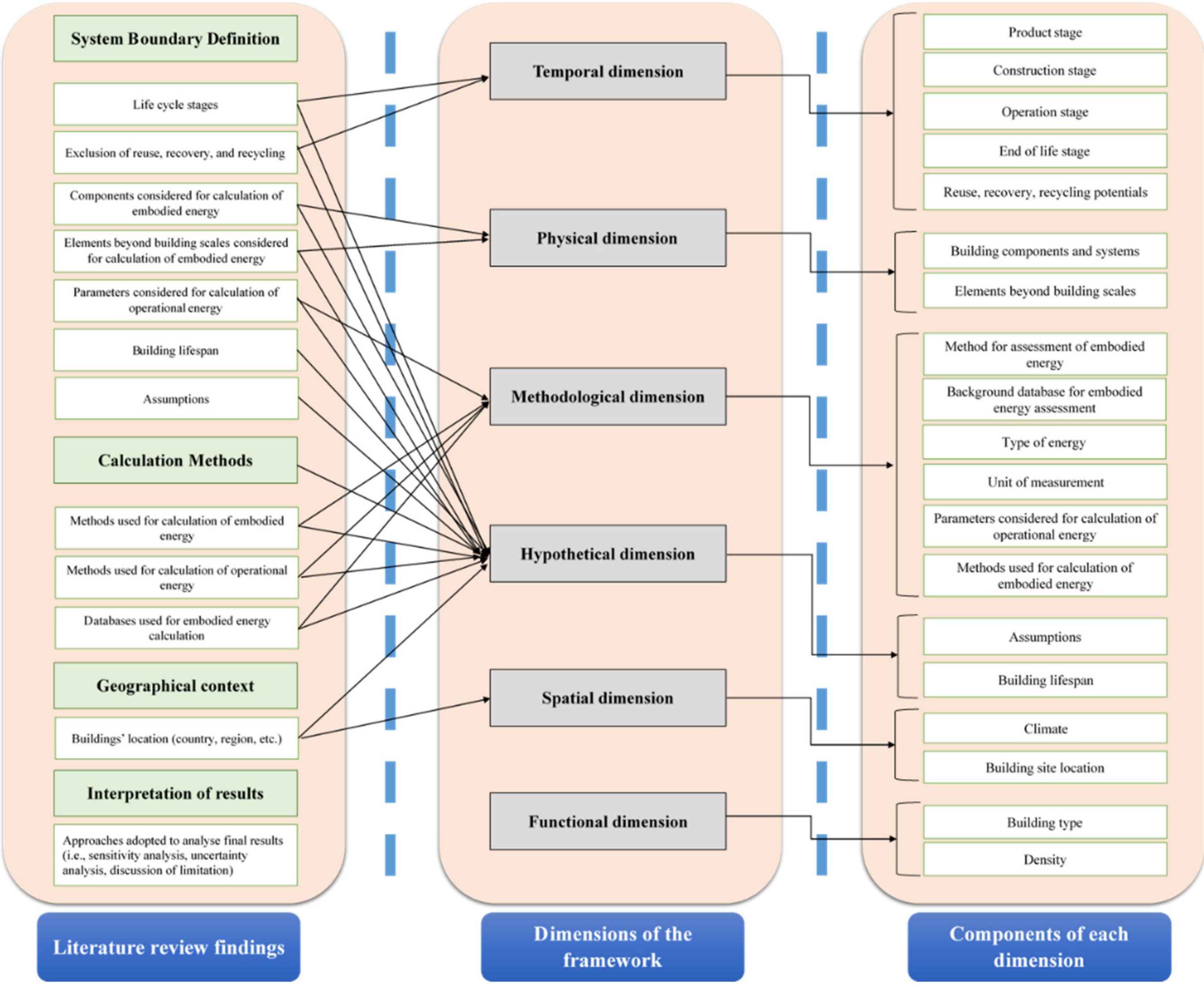


Figure 1. Different aspects of system boundaries in LCEA research.

4. The Proposed Framework

This paper defines a system boundary as a process of characterising attributes that are related to calculations of both embodied and operational energies. These attributes entail a wide array of data regarding the description of temporal, physical, methodological, hypothetical, spatial, and functional aspects of LCEA analysis (Table 1). The proposed framework aims to encourage the incorporation of embodied energy into BEERs by outlining a comprehensive description of system boundaries in LCEA analysis. The objectives of the proposed framework include (i) maintaining transparency in conducting the LCEA, and (ii) establishing a basis for performing cross comparison between cases within a lucid context.

Table 1. Different dimensions of a conceptual framework for system boundaries.

Boundary Dimensions	No.	Components of Boundary	Sub-Components
1. Temporal	(1.1)	Stages of building life cycle	Product; construction; operation; end-of-life; reuse, recovery, recycling potentials.
2. Physical	(2.1)	Building components and systems	Substructure; superstructure; renewable energy system; building services; finishes.
-	(2.2)	Elements beyond building scales	Occupants' transport; external works.
3. Methodological	(3.1)	Method for assessment of embodied energy	Process-based, economic input-output (I-O), and input-output-based hybrid.
	(3.2)	Background database for embodied energy assessment	Literature; publicly or commercially available databases. Age of data.
-	(3.3)	Type of energy	Primary energy; delivered energy.
-	(3.4)	Unit of measurement	Per m^2 of net conditioned floor area; whole building; building component/construction material.
-	(3.5)	Parameters contributing to operational energy assessment	Heating; cooling; DHW; electrical appliances; ventilation; lighting; and cooking.
-	(3.6)	Method for assessment of operational energy	Simulation approach; energy bills; monitoring; national statistics.
4. Hypothetical	(4.1)	Assumptions	Temporal dimension; physical dimension; calculation methods.
	(4.2)	Building lifespan	30–100 years.
5. Spatial	(5.1)	Climate	Tropical; dry; temperate; continental; polar.
-	(5.2)	Building site location	City; suburb; regional; remote.
6. Functional	(6.1)	Building type	Residential; non-residential (e.g., commercial; educational; institutional; industrial etc.).
-	(6.2)	Density	Low-rise, medium-rise, and high-rise.

The first objective promotes enhancing the reliability of LCEA results for decision-making purposes. A detailed definition of system boundary conditions enables the uptake of achieved results with due considerations once the system boundary is subjected to truncation. Previous research [51] asserted that the majority of studies fail to clearly reveal their adopted system boundaries, hence it can be difficult to fully understand the extent to which the data are input to the system boundary.

Cross comparison is important regarding the second objective, as it is widely used as an approach to validate the obtained results. Cross comparing LCEA cases can also lead to advancing our knowledge about the total life cycle energy performance of buildings, i.e., the proportion of either embodied or operational energy used in the total building life cycle. This characteristic can also result in identifying best practices for the design and construction of buildings with low life cycle energy use performance. However, this needs to be done within a standardised context and with respect to the conditions of system boundaries. To date, a wide range of studies have showcased the significance of operational energy versus embodied energy (or vice versa) by cross comparing multiple case studies [32,40,52–55]. For example, Ramesh et al. [52] performed a literature review analysis aiming to cross compare 73 cases of office and residential buildings. They conclusively stated that the operational energy made up 80–90% of the overall life cycle energy usage of buildings, whereas embodied energy constituted 10–20%. Furthermore, they attempted to convey a consolidated understanding of the total life cycle energy requirements of conventional residential buildings and office buildings. It was shown that the overall life cycle energy use of residential buildings can be in the range of 150–400 kWh/m^2 per year and that of office buildings in the range of 250–550 kWh/m^2 per year. These conclusions, driven by cross comparing LCEA cases without delving into their respective system boundaries, can be incomplete due to the varied approaches of studies for establishing system boundaries.

4.1. Temporal Dimension

The temporal dimension refers to determining which stage of the building life cycle is included in the system boundary. In this regard, EN 15978:2011 [31] provides a comprehensive guideline that segregates the building life cycle into five stages (Figure 2).

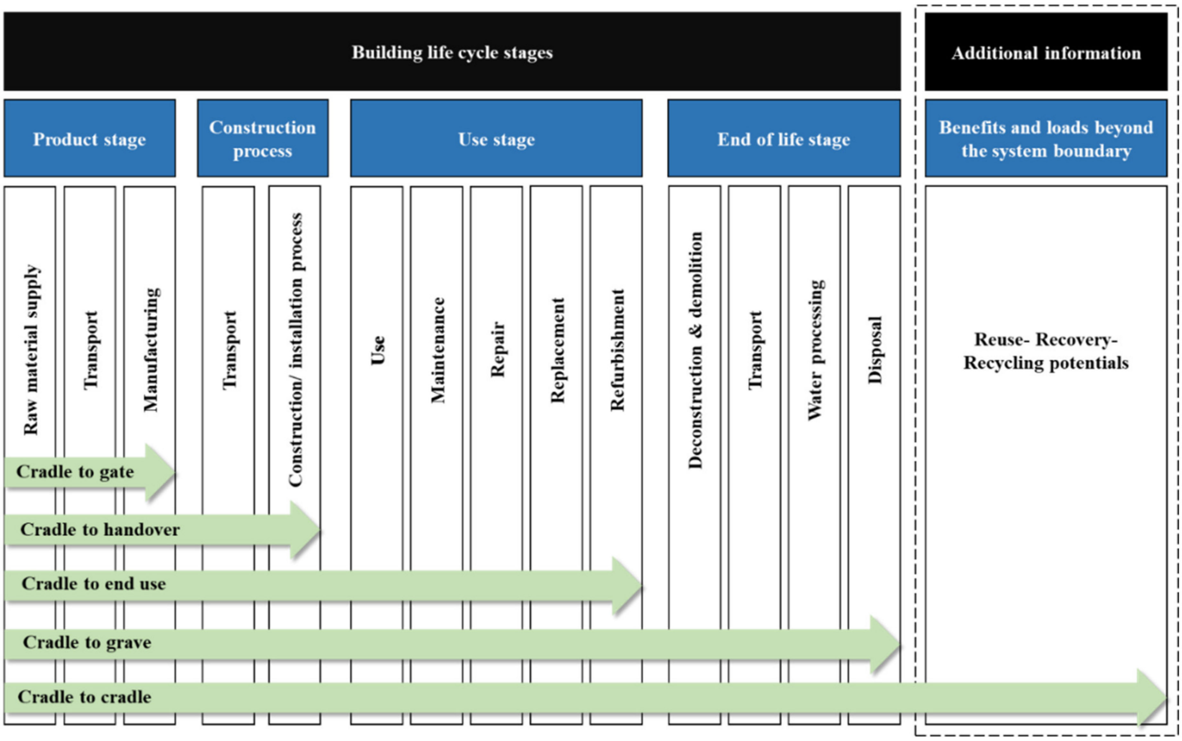


Figure 2. Proposed model for description of a system boundary (modular structure adapted from EN 15978:2011 [31]).

The cradle-to-gate includes energy inputs used for manufacturing construction materials, i.e., mining the materials, transporting the extracted materials to factories, and processing them. The cradle-to-handover includes all the processes from cradle-to-gate along with accounting for energy inputs related to transportation of materials to construction sites as well as on-site construction activities such as assembly, construction, disposal of construction wastages, etc. The cradle-to-end use refers to including energy inputs of product, construction, and use stages into the system boundary. The cradle-to-grave accounts for the amounts of energy used throughout all stages of a building's life cycle, including all the processes of upstream, downstream, and use phase. Finally, the cradle-to-cradle refers to capturing the environmental benefits of construction materials beyond the defined system boundary [23].

4.2. Physical Dimension

The physical dimension refers to determining which building component/systems are included in the system boundary. The current LCA standards, e.g., EN 15978:2011 [31], recommend a number of building elements that can be considered for inclusion into the system boundaries. This paper complements the description of physical system boundaries of the current standards by recommending the inclusion of embodied impacts attributed to renewable energy systems and occupants' transport (Table 2). Studies have shown that embodied impacts of renewable systems, e.g., the photovoltaic system (PV) or wind turbines, can be significant [56,57]. In a study, Wong et al. [56] performed a comprehensive literature review analysis and concluded that the embodied energy required for the production of single-crystalline and multi-crystalline silicon PV systems amounted to 3532 MJ/m^2 and 2876 MJ/m^2 per year, respectively.

Table 2. Recommended components for inclusion in a physical system boundary at building scale.

Building Components	Building Sub-Components
Substructure	Foundation
-	Basement retaining walls
	Ground floor
Superstructure	Structural building frame
	Exterior walls
	Exterior doors
	Window glazing
	Interior walls
	Floor construction
	Ceiling construction
	Roof construction
	Stairs and ramps
Fitments	External finishes
	Internal finishes
	Fixed furniture
Renewable energy system	PV systems; solar collectors; wind turbines; etc.
Building services	Plumbing
	Heating system
	Cooling system
	Ventilation system
	Electrical system
	Lift
	Fire protection system
Furniture and appliances	Furniture
	Appliances
External works	Roads, path, paving and surfaces
	Fencing, railing and walls
	Shed
	Pergola
	External fixtures, drainage, and services
Transportation	Occupants' transport

This study also suggests including energy use relating to occupants' transports within the physical system boundary. Previous research endeavoured to incorporate embodied energies of such elements in the system boundary [10,39,58–60]. For instance, Stephan et al. [39] put forward a framework to measure embodied impacts of nearby infrastructure (roads, water, sewage systems, etc.), combined with the energy usage of occupants' transportation. The framework was then employed to assess the total energy use of two residential buildings in Australia and Belgium. The results revealed that the occupants' transports constituted 25.40 and 33.80% of the entire building life cycle energy use in the Belgian passive house and the Australian building, respectively. Bastos et al. [59] also compared the total life cycle energy demands and greenhouse gas (GHG) emissions of two residential buildings in Lisbon, an urban apartment and a semi-detached suburban house. The analysis accounted for energy use at stages of production and operation, as well as the energy consumed due to occupants' transportation. The results indicated that the occupants' transport made up 51–57% of the entire energy use and GHG emissions for the semi-detached house, whereas operational energy was the largest contributor to energy use and GHG emissions (63–64%) for the apartment.

4.3. Methodological Dimension

As shown in Table 1, the methodological dimension contains six components that represent the key characteristics of a methodological approach for measuring embodied and operational energies. For the first component, embodied energy, there are three principal methods to compute buildings' embodied impacts, namely, the process-based, economic I–O and hybrid analysis methods [23,24]. The process-based method collects and synthesises data relating to various services, products, as well as location-specific data to calculate embodied energy of construction materials [23]. These data can be retrieved from sources such as suppliers, contractors, and manufacturers. The economic I–O method utilises data representing an entire economy to quantify the amounts of energy used to generate a particular service or product. The hybrid method fuses the two methods together in order to capture energy flows from the complete upstream supply chain. Whether the application of hybrid method yields a much higher value for embodied energy, as indicated by [15,58], is still a heated discussion since recent research [61] showed that the use of this method may not necessarily lead to achieving higher values due to restrictive assumptions concerned with it.

The selection of a background database is essential to calculate embodied energy. This database should contain data sets that represent the economic and technical contexts of the case study. In a comprehensive review, Omrany et al. [23] found that the databases needed for the calculation of embodied energy were collected from two main sources: literature (i.e., data published by other researchers) and databases that are available commercially or publicly. It is important to declare the database utilised for calculating embodied energy since the approach of each database towards quantification of embodied energy or embodied carbon emissions of materials can be different. For instance, the Inventory of Carbon and Energy, which contains over 200 construction materials, was developed based on the data collected via surveys and the data reported in the literature [62]. This approach differs from the ecoinvent database, which was developed based on the economic I–O approach and quantifies inputs and outputs to and from the biosphere [62]. In addition, the age of data can affect the quality of the LCEA results and subsequently influence the comparability of cases. The databases with old data represent obsolete manufacturing technologies, hence their energy values can differ from updated ones [63].

The total energy consumption of a building can be measured using either primary energy or delivered (or site line) energy. Primary energy refers to the energy that is directly extracted from nature (e.g., crude oil, or coal) and is unprocessed [24,27]. Delivered energy refers to the energy that is used on-site and produced by processing primary fuels such as electricity [24,27]. The use of primary energy for conducting LCEA research is favoured over the delivered energy since it contains higher amounts of energy; thus, the environmental impacts of buildings can be captured more accurately.

The unit of measurement (also known as functional unit) represents the life cycle energy performance of the main entity (i.e., building) that has been subjected to LCEA analysis. The unit can be expressed in different forms, namely, per m^2 of net conditioned floor area, as a whole building, or it can be a particular building component or a construction material. The proper selection of unit of measurement is of the greatest importance due to its influence on the accurate presentation of the LCEA results. In a study, Stephan and Crawford [64] studied the effect of dwelling size on life cycle energy demands using a parametric approach. It was revealed that the life cycle energy demands increased at a slower rate compared to house size. Hence, the expression of the total energy-efficiency performance of buildings per m^2 would favour large houses, as these require more energy. They recommended that BEERs should utilise multiple functional units to measure the energy-efficiency performance of buildings. de Simone Souza et al. [65] also employed different functional units in order to evaluate their effects on the final LCA results. The selected units included "a building with defined lifetime and occupancy parameters", LCA performance of the building per m^2 over one year, and "the accommodation of an occupant person of the dwelling over a day". This indicated the effects of functional unit selection on the final results.

Energy is consumed in non-thermal and thermal forms in order to retain the comfortability of indoor environments. Thermal energy refers to the amounts of energy used for the purposes of heating and cooling, while the non-thermal includes energies used for domestic hot water (DHW), electrical appliances, ventilation, lighting, and cooking. The estimation of a building's operational energy usage depends on the extent to which system boundaries are set to account for the impacts of these parameters over a building's lifespan [23,24]. Exclusion of each parameter can directly affect the LCEA results by influencing the calculation of operational energy. In a study, Gustavsson and Joelsson [66] showed that the proportion of embodied energy to the total life cycle energy use of a building was reduced from 33 to 25% when the scope of assessment for operational energy was extended from only space heating to include ventilation, DHW, and household electricity.

The method applied to calculate operating energy in an LCEA analysis is another component of the methodological dimension. Recent studies [23,24] revealed that four main methods, namely, "simulation", "energy bills", "monitoring", and "national statistics", have been commonly applied by LCEA studies for computing the operational energy use of buildings. It was found that most reviewed studies applied the simulation approach to calculate the energy usage of buildings. In this approach, the energy consumption of a building is calculated using a simulation engine, then the achieved figure is multiplied by the number of years assumed for building lifespan to estimate the operational energy of buildings. The energy bill is another method in which operational energy consumption is estimated using the actual energy bills of a building. In monitoring, sensors and actuators are employed to record and store the energy consumption of a building on a daily, monthly, or yearly basis. This method is similar to energy bills as both capture actual energy usage, except that monitoring can also provide a detailed breakdown of energy by use whereas the energy bills method only supplies an aggregate value for operational energy consumption [23,24]. However, several challenges are also involved in employing the monitoring method, such as interoperability, high initial cost, and the difficulty in managing and storing the monitored data [67]. National statistics also denotes a method where national or regional statistics on energy consumption in the building sector are used for estimating operational energy. The employment of this method can illustrate the divergence between actual and estimated energy consumption as these data are developed based on the average energy usage in the building sector [23,24].

4.4. Hypothetical Dimension

Making assumptions is inevitable in performing LCEA research. Assumptions are generally made due to the lack of reliable data, or to reduce the complexities involved in calculations of embodied or operational energies [24]. The importance of assumptions is also highlighted by international LCA standards [33], and it is recommended that they should be clearly acknowledged for the sake of transparency. The assumptions are made regarding different aspects of LCEA analysis, namely, temporal, physical dimensions, and building lifespan [23,24]. Regarding the temporal dimension, the assumptions can be grouped as:

- Product stage: assumptions in this category are usually made due to the absence of a locally developed database. Hence, the LCEA researchers adopt the background database of another region/country in order to calculate embodied energy [10,58,68]. This subsequently compromises the accuracy and reliability of embodied energy calculations for decision-making purposes since manufacturing processes, economic sectors, construction technologies, fuel supply structure, and energy tariffs vary from one country to another.
- Operation: the most common assumption in this category relates to assuming that buildings' operational energy use will be constant throughout the entire period of assessment (e.g., for 50 years). This assumption implies that buildings' occupancy profiles will be unchanged in terms of family size or the settings of occupancy schedule, or there will be no depreciation of heating and cooling systems. Another assumption pertains to ignoring the possible effects of future climate change on the heating and cooling demands of buildings. The review conducted by Omrany et al. [23] showed that the majority of the analysed studies calculated operational energy use of buildings considering only the current climatic conditions. However, the findings reported by

recent studies have indicated that the heating and cooling demands of buildings can be affected by climate change [69].

- Recurrent embodied energy: there are also several assumptions made about this stage. The most common assumption is that building materials will be replaced with the same materials as they reach their end of service lives. Thus, they will incur the same amounts of embodied energy as original materials.
- Construction and EOL: due to numerous uncertainties involved, the common approach to account for the embodied impacts of these stages is to assume certain values as their respective contributions to the buildings' total embodied energies [23,24]. For instance, Gustavsson et al. [70] assumed that the primary energy used for the on-site construction of an eight-story apartment equalled 80 kWh/m^2. Devi and Palaniappan [68] also assumed that the EOL stage consumed 3% of the total initial embodied energy.

The assumption of building lifespan is of utmost importance in an LCEA analysis owing to its direct influence on both operational and embodied energies. The embodied energy (i.e., recurrent embodied energy) can be affected by the assumption of building lifespan when assuming a long lifespan leads to frequent substitutions of building materials, while assuming a short lifespan triggers the need for changing the entire building. This assumption can also influence operational energy because extending the lifetime of a building results in an increase in energy consumption over its service life. Recent studies indicated that the range of building lifespans assumed by relevant literature falls within a range of 30 to 100 years [23,24]. The physical dimension can also contain assumptions. This may relate to the process of obtaining and compiling bills of quantity for the calculation of a building's embodied impacts where reliable data are unavailable.

In sum, all the assumptions need to be clearly stated in LCEA research while justifying their contextual applicability.

4.5. Spatial Dimension

The climate directly influences the operational energy use of buildings by affecting heating and cooling demands. In this framework, the spatial dimension is used as a proxy for a building's geographical location to describe the climate zone. This study uses the Köppen climate classification scheme [71] to elaborate on the spatial dimension of system boundaries. This scheme introduces five main climatic conditions, including tropical, dry, temperate, continental, and polar and each has its own subtypes.

The building site location is another component of the spatial dimension that refers to the travelling distance between a building's site location and urban facilities. Disclosure of this component can help with maintaining transparency for calculation of transport embodied energy as well as being a sub-component of the occupants' transport in the physical dimension.

4.6. Functional Dimension

The functional dimension refers to determining the type of building and density. The building types are commonly categorised as residential and non-residential buildings. Non-residential buildings include commercial, educational, institutional, industrial, etc. The number of storeys can also be used to describe the density of buildings, as suggested by Jan et al. [72]. Building density can directly impact LCEA results by affecting initial embodied energy use. Wang et al. [73] investigated the life cycle energy use of ten real-life buildings in Hong Kong and reported that the initial embodied energy usage of high-rise buildings was twice that of low-rise ones. Du et al. [74] also reviewed 42 case buildings and conclusively stated that high-rise buildings used almost 50% more embodied energy compared to low-rise buildings. Treloar et al. [75] highlighted an even larger difference, stating that high-rise buildings may use approximately 60% more initial embodied energy per unit of gross floor area than low-rise buildings. The higher embodied energy of high-rise buildings can be related to (i) using more materials, and (ii) using materials with higher energy intensity, e.g., concrete and steel [73]. Therefore, building density needs to be captured in defining the system boundary.

5. Implementation of the Framework

This section aims to demonstrate the applicability of the proposed framework. To this end, the total life cycle energy performance of an NZEB building that is a single-storey detached residential building located in Adelaide, South Australia, was analysed. The proposed framework was used to define the system boundary conditions of the LCEA analysis. Afterward, the proposed framework was employed in order to compare the achieved LCEA results with the results of a case study reported in the literature [50]. The case study retrieved from the literature was selected based on two principal considerations:

- The total life cycle energy performance of the case study must be analysed, with its results explicitly reported.
- The case study should provide enough data to reflect the six main dimensions of the framework.

The main purpose of this comparison was to illustrate the capacity of the proposed framework for revealing the conditions of system boundaries when cases are horizontally compared. This further helps to make decisions on normalising the identified differences.

5.1. Description of the Case Studies

Figure 3 demonstrates the schematic design of the NZEB-Adelaide case study. Both buildings represent the bulk of the new dwellings that are currently being constructed across Australia. Table 3 shows the main characteristics of the buildings. Further info regarding the Melbourne case study can be found in [50].

Table 3. Characteristics of the case studies.

Characteristics	NZEB-Adelaide Case Study	Melbourne Case Study
Gross floor area (m^2)	189.85	291.30
Net conditioned floor area (m^2)	146.78	254.40
External walls	Brick veneer; glass fibre batt insulation; average U-value 0.659 W/m^2 K	Insulated timber-framed brick veneer walls
Footings/ground floor	Concrete slab on ground consisting of steel, concrete, blinding and membrane	Concrete waffle pod slab
Pitched roof	Clay tile; roofing felt	Concrete-tiled roof
Ceiling	Glass fibre batt; gypsum plasterboard	Not reported
Internal walls	Insulated gypsum plasterboard	Painted plasterboard internal linings
Windows	Single glazed 4 mm window panes with wooden frames. U-value 6.70 W/m^2 K; SHGC [1] = 0.570	Clear float glass 4 mm panes
Infiltration (ac/h at 50 Pa)	15.0	Not reported
Lighting	LED; 2.50 W/m^2–100 lux (normalised power density)	Not reported
Occupancy	Four people (i.e., a couple with two kids)	Not reported
Ventilation systems	Split air conditioner system–reverse cycle	Gas ducted heating system, and an evaporative cooling system

NB: [1] Solar heat gain coefficient.

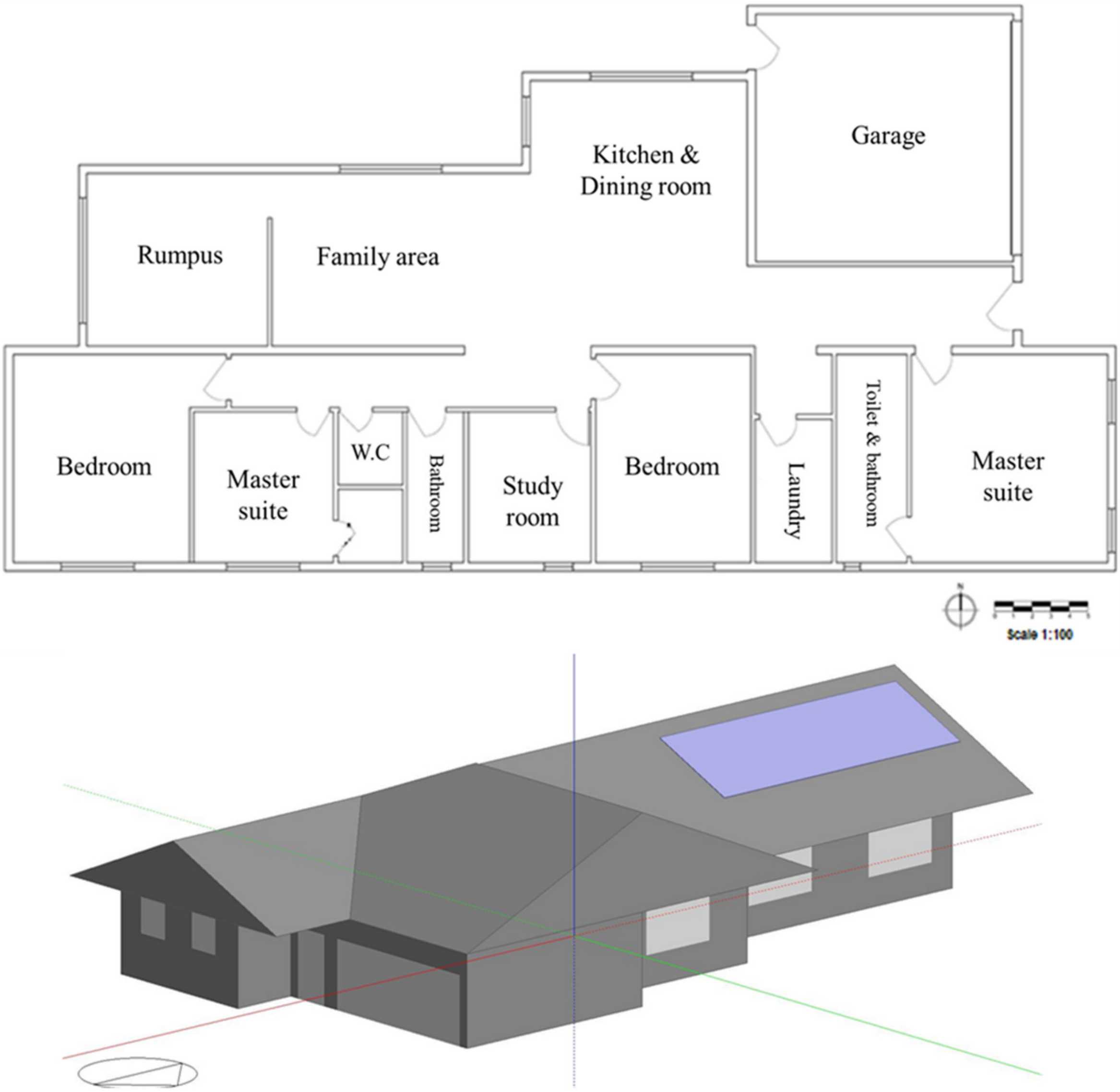


Figure 3. NZEB-Adelaide Case Study analysed by this paper. Details regarding the Melbourne Case Study can be found in [50].

Heating and cooling of the Adelaide case study were provided via a split air conditioner system–reverse cycle using electricity supplied from the grid. The coefficient of performance (COP) of the heating system was assumed to be 2.25, with the maximum capacity of supplying 35.0 °C air temperature. The COP of the cooling system was assumed to be 1.80 with the maximum supply air temperature of 12.0 °C. The Melbourne case study used a gas ducted heating system and an evaporative cooling system. An instantaneous gas-boosted solar hot water system was also used to provide hot water [50].

5.2. Definition of the System Boundary

The main dimensions of the system boundaries defined by both case studies are shown in Table 4. The use of the proposed framework enabled delineating system boundaries within a lucid context so that any truncation with potential effects on the LCEA results could be identified.

Table 4. Demonstrating the implementation of the proposed framework.

Boundary Dimension		Components of Boundary	Sub-Components	NZEB-Adelaide Case Study	Melbourne Case Study
Temporal	(1.1)	Stages of building life cycle	Product	▲	▲
			Construction	-	▲
			Operation	▲	▲
			Recurrent	▲	▲
			End-of-life		▲
			Reuse, recovery, recycling potentials		
Physical	(2.1)	Building components and systems	Substructure	▲	▲
			Superstructure	▲	▲
			Fitments	▲	▲
			Renewable energy system	▲	
			Building services	▲	
			Furniture and appliances		
	(2.2)	Elements beyond building scales	External works		
			Occupants' transport		
Methodological	(3.1)	Method for assessment of embodied energy	Process-based		
			Economic I-O	▲	
			Hybrid analysis		▲
	(3.2)	Background database for embodied energy assessment	Literature		
			Publicly or commercially available databases	Economic I–O data taken from the Australian National Accounts based on work by Pullen [49].	Economic I–O data taken from the Australian National Accounts, and process-based energy data for manufacture of specific materials, obtained from the SimaPro Australian database.
			Age of data	Economic I–O tables 1996–97.	Economic I–O tables 1996–97; process data 2010.
	(3.3)	Type of energy	Primary energy	▲	▲
			Delivered energy		
	(3.4)	Unit of analysis	Per m^2 of net conditioned floor area		
			Whole building	▲	▲
			Particular building component/construction material		

Table 4. *Cont.*

Boundary Dimension		Components of Boundary	Sub-Components	NZEB-Adelaide Case Study	Melbourne Case Study
	(3.5)	Parameters contributing to operational energy assessment	Heating	▲	▲
			Cooling	▲	▲
			DHW	▲	▲
			Electrical appliances	▲	▲
			Ventilation	▲	▲
			Lighting	▲	▲
			Cooking	▲	▲
	(3.6)	Method for assessment of operational energy	Simulation approach	▲	
			Energy bills		▲
			Monitoring		
			National statistics	▲	
Hypothetical	(4.1)	Assumptions	Product		
			Construction		
			Operation	▲	▲
			Recurrent	▲	▲
			End-of-life		▲
			Reuse, recovery, recycling potentials		
			Physical dimension		
	(4.2)	Building lifespan	30–100 years	50	50
Spatial	(5.1)	Climate	Tropical		
			Dry		
			Temperate	▲	▲
			Continental		
			Polar		
	(5.2)	Building site location	City	▲	
			Suburb		▲
			Regional		
			Remote		
Functional	(6.1)	Building type	Residential	▲	▲
			Non-residential		
	(6.2)	Density	Low-rise	▲	▲
			Medium-rise		
			High-rise		

NB: ▲ included in the system boundary.

5.2.1. Temporal Dimension

The total life cycle energy use of the NZEB-Adelaide case study was assessed considering the product, operation, and recurrent stages of the building life cycle. The embodied impacts associated with the EOL and construction stages were excluded from the system boundary due to several uncertainties concerning the calculation of these stages, e.g., difficulty in gathering and documenting reliable data during on-site construction operations or the uncertain fate of materials after deconstructing the building [23]. Moreover, previous studies showed that these stages make minor contributions to the building's overall life cycle consumptions [76,77]. Regarding the recurrent embodied energy, Table 5 tabulates the service lives of construction materials that are assumed by both studies to be replaced over the 50 years of building operations.

Table 5. Service lives of materials subjected to replacement over the buildings' life spans.

Building Materials	NZEB-Adelaide Case Study *	Melbourne Case Study
	Service Life (Years)	Service Life (Years)
Roof tiles	25	25
Paint for external surfaces	15	10
Plasterboard (10 mm)	25	30
Ceramic tiles	25	25
Carpet	10	25
PV panels	25	NA

NB: Source: a Dixit [78].

For the Melbourne case study, the LCEA assessment was undertaken considering all the stages of building life cycle, including product, construction, operation, recurrent, and EOL. Crawford [50] considered the construction stage as a component of initial embodied energy, and to account for its impacts, the material quantities (Q_m) were multiplied by their respective embodied energy coefficient (EC_m) in order to compute the total process-based hybrid embodied energy of the building. Afterward, the total I–O-based energy requirements of the processes for which material quantities were obtained (TER_m) in gigajoule (GJ) per Australian Dollar (AUD) from the I–O model were deducted from the total energy requirement of the residential building sector (TER_{rb}) (0.0106 GJ/AUD) in order to obtain the remainder, thus correcting sideways and downstream truncation errors. To calculate the overall initial embodied energy of the house (IEE), the remainder needed to be converted from GJ/AUD to GJ/house using the estimated costs of the building construction and then added to the process-based hybrid embodied energy value. The approach for calculation of initial embodied energy can be expressed as Equation (1).

$$\text{IEE} = \sum_{m=1}^{M} (Q_m \times EC_m) + \left(TER_{rb} - \sum_{m=1}^{M} TER_m \right) \times C_h \quad (1)$$

where IEE is the initial embodied energy of the building; Q_m represents quantities of delivered materials; EC_m is the embodied energy coefficients of the materials; TER_{rb} is the total energy requirements of the residential building sector in GJ per AUD; TER_m is the total energy requirement of the I–O-based processes representing the materials for which process data were collected, in GJ per AUD; C_h is the cost of the house, in AUD. Regarding the EOL stage, an amount equal to 1% of the total life cycle energy demand of the dwelling was assumed to be added to the final calculated value in order to account for the embodied impacts of the stage.

5.2.2. Physical Dimension

The elements included in the physical system boundaries of both case studies are shown in Table 6. As indicated, the NZEB-Adelaide building has PV panels installed on the sloped roof to neutralise the household electrical energy use. The system was sized considering the average annual solar exposure in Adelaide, which is 20.39 MJ/m^2 [78]. To harvest the maximum solar radiation, the PV panels were oriented towards the true north and tilted 23.0°. The size of PV panels was 1.639 m × 0.982 m, with an efficiency rate of 80%. The embodied energy calculation excludes the balance of system, and only accounts for PV panels.

Table 6. Building elements included in the physical dimension.

Building Components	Building Sub-Components	NZEB-Adelaide Case Study	Melbourne Case Study
Substructure	Foundation	▲	▲
	Basement retaining walls	NA	NA
	Ground floor	▲	▲
Superstructure	Structural building frame	▲	▲
	Exterior walls	▲	▲
	Exterior doors	▲	▲
	Window glazing	▲	▲
	Interior walls	▲	▲
	Floor construction	▲	▲
	Ceiling construction	▲	▲
	Roof construction	▲	▲
	Stairs and ramps	NA	NA
Fitments	External finishes	Paint on external walls	Paint on external walls
	Internal finishes	Ceramic tiles and carpet	Ceramic tiles and carpet
	Fixed furniture	Kitchen cabinet	NA
Renewable energy system	Photovoltaic panels; solar collectors; wind turbines, etc.	PV panels	NA
Building services	Plumbing	Piping; steel sinks; taps/fittings; water services; baths	NA
	Heating system	NA	NA
	Cooling system	NA	NA
	Ventilation system	NA	NA
	Electrical system	NA	NA
	Lift	NA	NA
	Fire protection system	NA	NA
			NA
Furniture and appliances	Furniture	NA	NA
	Appliances/equipment	Oven/hob; air conditioner	Heating, hot water and cooking appliances
External works	Roads, path, paving and surfaces	NA	NA
	Fencing, railing and walls	NA	NA
	Shed	NA	NA
	Pergola	NA	NA
	External fixtures, drainage, and services	NA	NA
Transportation	Occupants' transport	NA	NA

NB: ▲ included in the system boundary.

5.2.3. Methodological Dimension

The background database employed for the calculation of embodied energy in the NZEB-Adelaide case study is based on an economic I–O approach, developed by Pullen [49]. The economic I–O approach utilises the entire structure of an economy as the theoretical boundary of a system in order to compute the amounts of energy used to produce a particular material. This method has a wider approach towards calculating embodied energy compared to the process-based method due to its accounting for both the direct and indirect effects of the upstream supply chain. Cabeza et al. [79] found that studies with an economic I–O approach reported larger embodied impacts owing to the inclusion of indirect effects. On the other hand, Crawford [50] adopted an I–O-based hybrid analysis for calculating the embodied energy impacts of the building. The I–O model of Australian energy use was developed using economic I–O data retrieved from the Australian National Accounts in 1996–97, and the process-based energy data for manufacturing specific materials were acquired from the SimaPro Australian database. To streamline the assessment process, he derived a number of embodied energy coefficients for building materials [15] through which the overall embodied impacts of materials were calculated via multiplying the relevant coefficients by their quantities.

The LCEA analyses for both case studies were carried out based on primary energy consumption while accounting for all parameters contributing to thermal and non-thermal energy use. Regarding the NZEB-Adelaide case study, this study adopted a “simulation approach” to estimate the operational energy usage. To this end, the case study model was first developed in DesignBuilderV6 software, and then the thermal and non-thermal loads (including electrical appliances and lighting) were calculated using the EnergyPlus 8.9 simulation engine. EnergyPlus considers detailed interactions of all building components and systems such as building envelope, windows, HVAC, and internal heat gains from different systems in order to calculate heating and cooling loads [48]. The estimated loads were then converted into energy use by applying the assumed coefficient of performance (COP) of the equipment. After this conversion, the primary energy consumption was calculated using an electricity conversion factor of 3.40 for Australia [39]. Due to the software’s limitation in simulating gas consumption, the amount of natural gas used for cooking and hot water was estimated based on national statistics for South Australia, which is 15 GJ per household per year [80]. Thereafter, a primary energy factor of 1.40 [39] was used to convert natural gas use into primary energy consumption.

The “energy bill” approach was utilised by Crawford [50] in order to calculate the building’s operational energy use. To do this, the total annual delivered operational energy requirement was estimated by averaging energy bills (including both thermal and non-thermal energy use) of the house for three consecutive years. The delivered energy use was then converted into primary energy consumptions using relevant converting factors for electricity and natural gas.

5.2.4. Spatial Dimension

According to the Köppen climate classification, Adelaide has a hot Mediterranean climate (Csa) with cool to mild winters and warm to hot summers that require consuming energy for both heating and cooling. Melbourne has a temperate oceanic climate (Cfb) with ample precipitation and rainfall during the entire year. Similar to Adelaide, energy is needed for addressing heating and cooling demands throughout the year in Melbourne. Figure 4 illustrates the monthly average ambient air temperature for Adelaide airport and Melbourne airport between 1991 and 2020. According to this figure, February and July are the peak energy demands for cooling and heating in both cities, respectively [80].

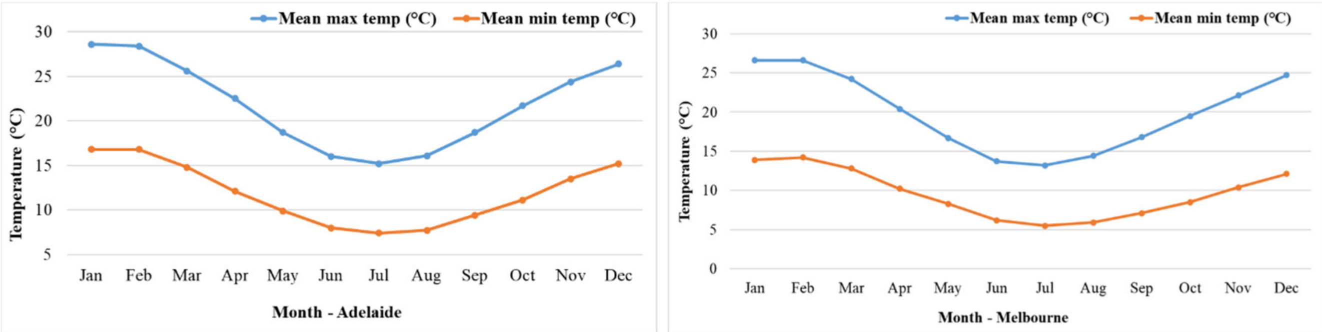


Figure 4. Monthly average ambient air temperature for Adelaide [48], and Melbourne [77].

5.2.5. Hypothetical Dimension

The operational energy for both case studies was assessed assuming that the occupational settings (e.g., scheduling and occupancy profile) would remain unchanged over the period of 50 years. It is also assumed that performance coefficients of electrical equipment and appliances, as well as the efficiency rate of PV panels used in the NZEB-Adelaide case study, would be constant during the entire assessment period. Furthermore, the resource mix supplying electricity to the buildings was assumed for both cases to be unchanged over the 50 years. It is also noteworthy to mention that neither of the cases accounted for the effects of future climate change on heating and cooling energy demands.

In addition, both studies assumed that certain building elements were subject to periodic maintenance and replacement (i.e., recurrent embodied energy) (See Table 5). To calculate the recurrent embodied energy, it was necessary to assume that these materials would be substituted with the same materials, thus incurring the same amounts of embodied energy as the originals. Regarding the EOL stage, Crawford [50] assumed that the energy needed for deconstruction and disposal of materials amounted to 1% of the overall life cycle energy consumption of the building.

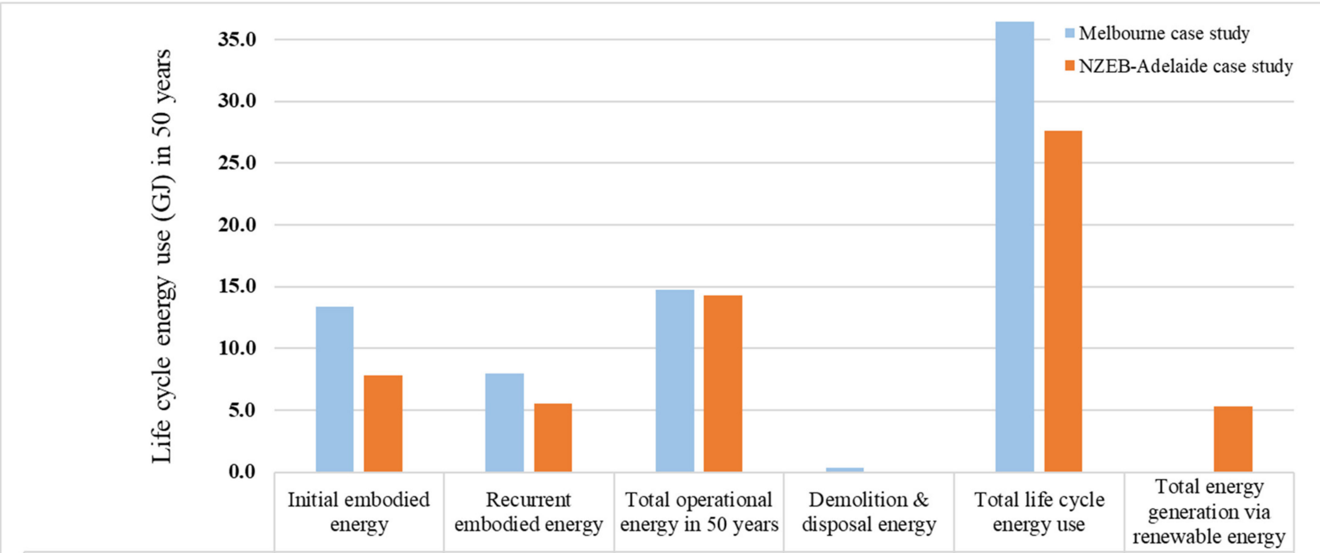
The life span of the NZEB-Adelaide case study was assumed to be 50 years, as recommended by ASHRAE and U.S. Green Building Council (USGBC) [81]. Recent studies have also shown that most of the research analysed considered a life service of 50 years [23,24]. Similarly, Crawford [50] performed the LCEA analysis assuming 50 years of building life service. In addition, the unit of measurements utilised to report the LCEA analysis is "entire building" for both cases.

5.2.6. Functional Dimension

Both of the case studies are single-storey detached residential buildings that belong to the "residential" and "low-rise" sub-components of the functional dimension. The NZEB-Adelaide case study represents the bulk of new dwellings being presently constructed by volume builders in Australia (Figure 4) [82]. Currently, all new buildings need to meet certain thermal requirements the equivalent of 6.0 stars in order to substantiate their compliance with the energy-efficiency regulations in Australia [83]. According to the Commonwealth Scientific and Industrial Research Organisation (CSIRO), most of the accredited buildings fall in the range of 6.0 to 6.9 stars [83]. Being 6.6 stars, the NZEB-Adelaide case study met the minimum mandatory thermal requirements for residential buildings specified by national construction codes in Australia. Detailed information regarding the Australian building energy codes can be found in [84,85].

5.3. Analysis of the Case Studies

Figure 5 illustrates the breakdowns of the total life cycle energy requirements of both cases. For the NZEB-Adelaide case study, it indicates that operational energy use constituted the largest portion of the total life cycle energy use of the building (51.80%), followed by the initial embodied energy (28.3%), and the recurrent embodied energy (19.9%). The amount of operational energy usage estimated for the NZEB case was relatively lower than the Melbourne case. This difference can be explained by the varied approaches of the two studies to the estimation of operational energy use. The use of the energy bills approach allowed to comprehensively capture the variety of occupant behaviours in using energy, thus the potential variability between the predicted (simulated) and actual energy performance of the building was zero. Contrarily, a discrepancy can potentially occur in the simulation approach since it relied on only one pre-defined occupational profile setting in order to quantify energy consumption for an entire year. The study by Van Dronkelaar et al. [86] showed that the magnitude of deviation between simulated and measured energy use in buildings can be +34% with a standard deviation of 55% based on 62 buildings investigated. Another reason may be due to the calculations of natural gas consumption in the two studies. For the Melbourne case, the primary energy consumption of natural gas was estimated to be 8.02 GJ (i.e., 2336.50 GJ) over 50 years of building operation that included cooking, hot water, and heating [50]. However, the natural gas consumption in the case of the NZEB building (i.e., 1050 GJ over 50 years) only accounted for hot water and cooking since heating demand was supplied via electricity [80].



	Initial embodied energy	Recurrent embodied energy	Total operational energy in 50 years	Demolition & disposal energy	Total life cycle energy use	Total energy generation via renewable energy
Melbourne case study	13.4	8.0	14.7	0.4	36.4	0.0
NZEB-Adelaide case study	7.8	5.5	14.3	0.0	27.6	5.3

Figure 5. Life cycle energy use of the case studies normalised per square meter of gross floor areas over 50 years.

The initial embodied energy calculated for the Melbourne case study was significantly higher than the value achieved for the NZEB-Adelaide case study (Figure 5). This difference can be related to the hybrid life cycle approach applied by Crawford [50] to carry out LCEA analysis. Studies by Crawford [15] and Stephan and Stephan [58] showed that the application of a hybrid life cycle approach can yield higher embodied energy values by 3.8 and 3.9 times compared to other methods, respectively. Moreover, Crawford [50] counted the energy usage of the construction stage towards initial embodied energy, as explained in the section on temporal dimension, whereas the NZEB-Adelaide case study excluded the construction stage. The higher recurrent embodied energy of the Melbourne case study can also be explained by the wider approach used by Crawford [50] for calculating the embodied impacts of the building. It is noteworthy to mention that both case studies assumed that materials would be replaced by the same ones when they reached their end of service lives, thus having the same amounts of embodied energy impacts as originals.

In addition, the two studies differed in terms of establishing their temporal and physical dimensions of the system boundaries. Crawford [50] accounted for the impacts of the EOL stage by adding 1% of the total life cycle energy demand to the final figure calculated for the LCEA performance of the building. On the other hand, the NZEB-Adelaide case study included the embodied impacts of PV panels in the physical dimension of the system boundary, which affects both initial embodied and recurrent energies. The PV panels were engaged to zero out the electrical energy demands of the building, which led to generating 1013.844 GJ of energy over the 50 years.

6. Discussion

The importance of reducing embodied energy has become a hostile debate in recent years due to its increasing contribution to energy consumption in the built environment. The World Green Building Council predicted that embodied carbon driven from the embodied energy of construction projects will be responsible for more than 50% of the entire carbon emissions by 2050 worldwide [26]. The results of this study also revealed that embodied energy constituted 60 and 48% of the total life cycle energy demands of the Melbourne and Adelaide case studies, respectively. In this regard, studies discerned that, without immediate action, embodied energy will be an impending environmental concern related to the performance of buildings [45]. Therefore, there has been an increasing demand for mitigation of embodied energy in the built environment over the last decade.

One approach to minimise the impacts of embodied energy is to incorporate such a requirement into current BEERs. Thus far, only a few countries have started incorporating embodied energy into their building regulations. The Netherlands was the first country to introduce requirements for the measurement, though not the reduction, of embodied impacts into its building regulations [87,88]. Other countries have also taken their first steps towards this end such as France [79], Finland [89], Norway [89], Denmark [90,91], and Sweden [92]. However, the abatement of embodied energy as a requirement mandated by BEERs is still being neglected by most countries [45]. One of the main reason for such an exclusion lies with the complexities involved in assessing embodied energy in conjunction with operational energy. The assessment of embodied energy is less straightforward compared to operational energy owing to the various intertwined processes involved, as well as several variables that should be counted towards the assessment of embodied energy. This paper proposed a comprehensive framework to standardise system boundary conditions in LCEA research. The overarching aim of the framework is to encourage the incorporation of embodied energy into building regulations by (i) identifying the main parameters causing variation in LCEA results, and (ii) structuring the identified parameters into six dimensions. Although the case studies analysed by this paper are located in Australia, the framework can be adopted by other countries for the purpose of standardising LCEA analysis.

The proposed framework has two key characteristics. First, its application facilitates defining the conditions of a system boundary within a transparent context. This, in turn, will lead to increasing the reliability of obtained LCEA results for decision-making purposes, since any particular conditions (e.g., truncation, or assumption) considered in establishing the boundaries of the system under study can be revealed. In addition, the use of the proposed framework provides a meaningful basis for cross comparing cases within a global context. This can further result in identifying best practices for the design of buildings with low life cycle energy use performance. In regard to policy making, the framework introduces 15 variables that are categorised into six distinguished dimensions. The policy makers can set certain requirements and standards for each dimension to be practised within a national or a regional level. As an illustration, Birgisdóttir et al. [93] suggested that cradle-to-handover (See Figure 2) should be considered as the minimum requirements for assessing the energy of buildings. The Norwegian Research Centre on Zero Emission Buildings also presented different levels of data requirements for assessment of buildings' embodied emissions [94].

The incorporation of embodied energy impacts into BEERs also requires revising the current mindset of policy making in the building sector. In general, the implementation of energy policies has three components, i.e., "sticks", "tambourines", and "carrots" [95,96]. In the building sector context, sticks represent regulations, codes, and standards through which a benchmarking basis is provided to identify non-compliant buildings with the given requirements. The tambourines are the tools employed to enhance public awareness about compliance requirements and energy-saving strategies such as building labelling. The carrots refer to the incentives considered for encouraging the best practices in the building sector such as subsidies and rebates or loans. The change in mindset should occur in all the three pillars of energy policy implementation in order to accommodate the inclusion of embodied energy into BEERs (Figure 6).

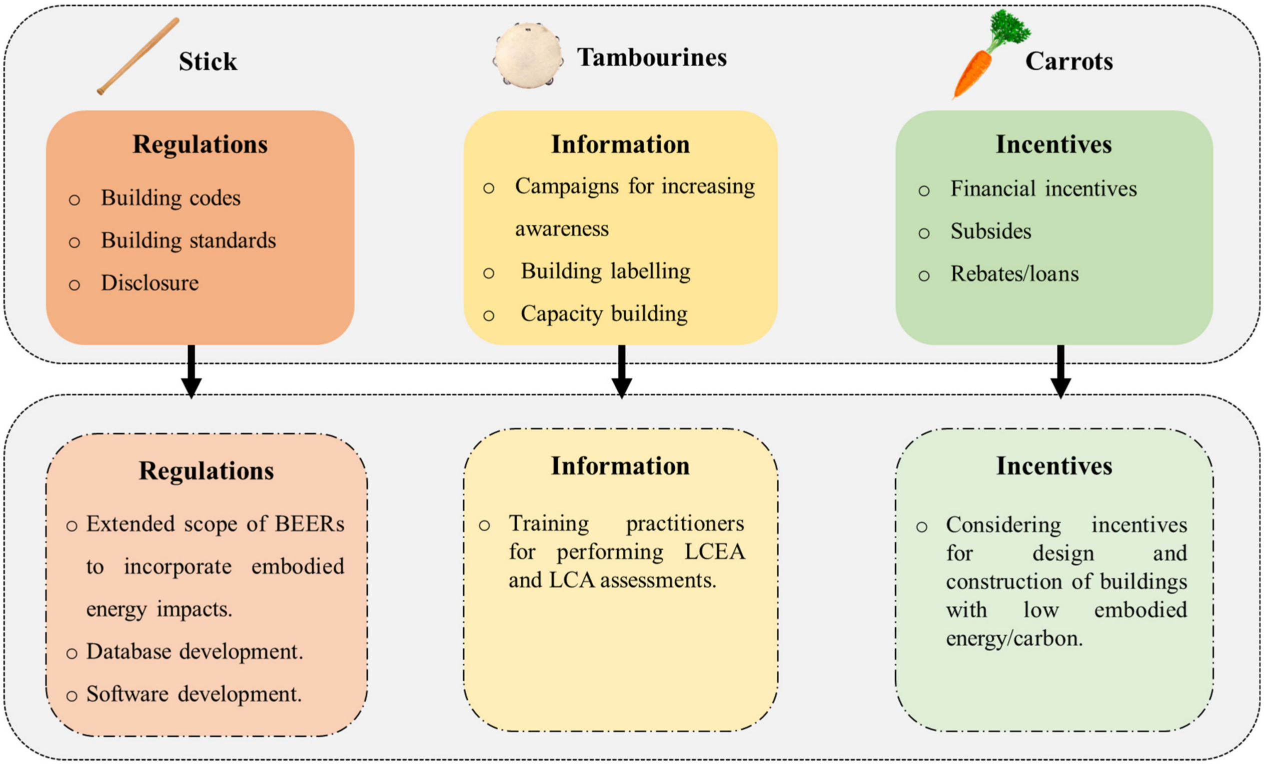


Figure 6. Proposal on further actions for incorporation of embodied energy into BEERs.

Regarding regulations, the scope of current BEERs needs to be extended to include embodied energy. The current scopes of building energy regulations are generally limited to only enhancing the operational energy performance of buildings [45,87]. Hence, the importance of minimising the embodied energy of buildings should be first acknowledged by BEERs and reflected accordingly in the regulatory scheme of building codes. The recommended approach should be accompanied by, first, embodied energy databases to be developed nationally in order to represent the peculiarities of the country, such as economic sectors, construction technologies, manufacturing processes, energy tariffs, and fuel supply structure [23,63]. The Environmental Performance in Construction (EPiC) is an example of such a database that contains the embodied energy coefficients of several building materials in Australia [97]. It is also important that the environmental product declarations (EPDs) [98] for building materials are enforced to provide up-to-date quantified environmental data relating to construction materials. In parallel, investment should be made in developing software with the capacity of pairing with embodied energy databases; thus, designers can readily link their designs with material quantities to carry out embodied energy estimations.

The inclusion of embodied energy into the BEERs will also require launching extensive LCEA or LCA training processes across all professions in the construction industry. This was affirmed by Schwarz et al. [99], who investigated the opinions of building professionals on potential challenges to including embodied energy into BEERs. The interviewees pointed out the necessity of initiating LCA learning programs due to the lack of knowledge in the current industry. Lastly, the design and construction of buildings with low embodied energy or embodied carbon performance should be promoted by BEERs through providing different types of incentives. The integrated policies combining the three pillars mentioned above can effectively instigate the promotion of best practice in constructing low life cycle energy buildings in the sector.

7. Conclusions

The main motivation for this study was inspired by the continued exclusion of embodied impacts from the frameworks of BEERs in most countries. Despite increasing attention, the pathway for including the impacts of embodied energy into BEERs is still ambiguous. The principal reason for such an ambiguity resides with the complexities that BEERs encounter when accounting for the impacts of both operational and embodied energies due to the various processes and parameters involved. To address this challenge, the development of a comprehensive framework for a clear description of system boundaries can pave the way towards integrating the life cycle embodied environmental impacts into BEERs. Currently, the literature is lacking such a comprehensive framework. Therefore, this paper proposed a comprehensive framework for a clear description of system boundary conditions in LCEA analysis with the aim of promoting the incorporation of embodied energy impacts into BEERs.

The proposed framework was developed based on an extensive literature review analysis of 66 studies representing 243 case studies in over 15 countries. The framework consists of six distinctive dimensions, including temporal, physical, methodological, hypothetical, spatial, and functional. These dimensions encapsulate 15 components collectively. The proposed framework has two key characteristics. First, its application facilitates defining the conditions of a system boundary within a transparent context. This can consequently lead to increasing the reliability of obtained LCEA results for decision-making purposes since any particular condition (e.g., truncation, or assumption) considered in establishing the boundaries of the system under study is revealed. In addition, the use of the proposed framework provides a meaningful basis for cross comparing cases within a global context. This can further result in identifying best practices for the design of buildings with low life cycle energy use performance. In regard to policy making, certain requirements and standards can be set for each dimension of the framework to be practised within a national or regional level. This will provide much better control over standardising the process of including embodied energy into BEERs.

The applicability of the proposed framework was tested by applying the framework to assess the life cycle energy performance of a residential building in Adelaide, Australia. To this end, the framework was first employed to define the system boundary conditions of the case study. It was then utilised to cross compare the obtained results with another case study retrieved from the literature. This cross comparison was carried out to illustrate the capacity of the developed framework for cross comparison. The results of these case studies reaffirm the significance of embodied energy consumption associated with buildings. Results showed that embodied energy constituted 48.2 and 60% of the total life cycle energy usage for the Adelaide and Melbourne case studies, respectively. These findings underline the urgent demand for incorporation of embodied energy impacts into energy-efficiency building codes. In this regard, the use of the proposed framework contributed to the clear definition of system boundary conditions as well as to providing a standardised basis for cross comparison of cases.

This study also recommends altering the current mindset of policy making in the building sector in order to embrace the addition of embodied energy to BEERs. First, it is recommended that the current scope of BEERs be extended to include the impacts of embodied energy. This inclusion should be accompanied by developing embodied energy databases. It is also recommended that the environmental product declarations for building materials should be enforced to provide up-to-date quantified environmental data relating to construction materials. Furthermore, software should be developed with the capacity to pair with embodied energy databases so that designers can readily link their designs with material quantities to perform embodied energy estimations. It is also necessity to launch extensive training processes across all professions in the construction industry in order to increase awareness of LCEA or LCA calculations. In addition, it is recommended that different types of incentives should be allocated in order to promote the design and construction of buildings with low embodied energy or embodied carbon performance. The integrated policies combining the three pillars mentioned above can effectively instigate the promotion of best practices in constructing low life cycle energy buildings in the sector.

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