Energy Independent Residential Development for Dhaka City, Bangladesh

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Abstract

Dhaka, the capital of Bangladesh, has been predicted to be the 6th largest megacity in the world by 2030 with about 10 million additional people compared with the current population. This rapid urbanization is accompanied by a fast growing energy demand. On the contrary, the country is far behind in energy sufficiency thus the new developments are unlikely to be supported with adequate energy supply. Moreover, in the face of increasing greenhouse emission and resource depletion, traditional fossil fuel based energy is no longer an option. This research, therefore, is aimed at exploring the possibilities for energy independent residential developments in Dhaka in order to respond to these many challenges.

The research has been conducted by adopting a multimethod approach, which include different quantitative research strategies and techniques supported with a limited qualitative approach. The final outcomes of this research are based on experiments conducted through building performance simulations; however, the simulations are grounded on rigorous monitored data, which included different urban, building, micro-climatic and household parameters that influence household energy consumption. To investigate the urban and building contexts, 70 typical apartment buildings and 93 apartment unit plans were studied. Interviews have also been conducted with representatives from relevant professionals: real estate developers, practicing architects and academicians to understand the background to apartment developments. Micro-climatic conditions were investigated including by using air temperature data loggers. Household contexts were investigated through a questionnaire survey of around 400 residents. The information obtained from the existing situations studied were then analysed and used for the simulations to test various scenarios in order to derive the final outcomes of this research.

The research has identified several existing urban, building and household practices, alterations of which will result in substantial household energy consumption reduction. Best practice modifications of present ways are proposed and the findings indicate that applying these best practices can reduce the current energy consumption by at least thirty-nine percent. It is possible for residential developments in Dhaka to achieve energy independence, after reducing the consumption, by the installation of roof mounted solar photovoltaic systems and battery storage for each household; however, shifting to energy efficient appliances is vital in achieving this. Furthermore, the results indicated that not only the future buildings but also the existing buildings with minor retrofitting and utilizing energy efficient appliances and equipment can achieve energy independence.

The results of this research are expected to have an important impact on the future residential developments of Dhaka as the energy consequences of the current urban and building practices are now known. This will help the professionals to take more informed decisions towards building energy efficient developments in Dhaka. The results also provide a basis for the policy makers to update the existing building construction regulations as well as to develop energy policies to promote energy independent developments.

Although focusing on Dhaka, results from the research will also be useful for other cities in Bangladesh and elsewhere in the world facing similar socio-economic challenges.

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List of Acronyms and Abbreviations

BBS	Bangladesh Bureau of Statistics
BPDB	Bangladesh Power Development Board
BPS	Building performance simulations
BNBC	Bangladesh National Building Code
CR	Canyon ratio
CIA	Central Intelligence Agency
DCC	Dhaka City Corporation
DMA	Dhaka Metropolitan Area
DMDP	Dhaka Metropolitan Development Plan
DESCO	Dhaka Electric Supply Company Limited
DOHS	Defence Officer Housing Society
DPDC	Dhaka Power Development Company Limited
EEA	European Environment Agency
EIA	Energy Information Administration
EPA	US Environmental Protection Agency
FAR	Floor area ratio
GOB	Bangladesh Government
GDP	Gross domestic production
HDI	Human Development Index
GHG	Greenhouse gas
IDCOL	Infrastructural Development Company Limited
IEA	International Energy Agency
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
IPHA	International Passive House Association
IPS	Instant Power Supply

LC-ZEB	Life cycle zero-energy building
MPEMR	Ministry of Power, Energy and Mineral Resources
ZEB	Zero-energy building
PSMP	Power System Master Plan
PV	Solar Photovoltaic
PWD	Public Works Department
RAJUK	Rajdhani Unnayan Kartripakkha
REHAB	Real Estate & Housing Association of Bangladesh
RH	Relative Humidity
SHGC	Solar Heat Gain Coefficient
SHS	Solar Home Systems
SVF	Sky View Factor
SREDA	Sustainable and Renewable Energy Development Authority
TMY	Typical Meteorological Year
UHI	Urban Heat Island
UN	United Nations
UNB	United News of Bangladesh
UNEP	United Nations Environment Programme
UNDP	United Nations Development Programme
WB	The World Bank
WWR	Window to wall ratio

Publications

Publications arising from this research are listed below.

Parveen, R., Soebarto, V. & Williamson, T. (2015, September). *Investigating Urban Heat Island to derive alternative options for energy efficient residential developments, case study: Dhaka, Bangladesh.* Paper presented at the Architecture in (R)Evolution: 31st Passive and Low Energy Architecture (PLEA) Conference, Bologna, Italy.

Parveen, R. (2012, November). *Potentiality of energy-plus urban developments in developing countries. Case study: Dhaka, Bangladesh.* Paper presented at the 46th Architectural Science Association (ASA) Conference, Gold Coast, Australia. Available at http://anzasca.net/wp-content/uploads/2014/02/p60.pdf

Declaration

I, Rehnuma Parveen, 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. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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Rehnuma Parveen

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__In the Far East__, there is a tree called the Chinese bamboo tree. This remarkable tree is different from most trees in that it doesn't grow in the usual fashion. While most trees grow steadily over a period of years, the Chinese bamboo tree doesn't break through the ground for the first four years. Then, in the fifth year, an amazing thing happens – the tree begins to grow at an astonishing rate. In fact, in a period of just five weeks, a Chinese bamboo tree can grow to a height of 90 feet. It's almost as if you can actually see the tree growing before your very eyes.

… pursuing your dream is a sure thing if you just don't give up. So long as you keep watering and fertilizing your dream, it will come to fruition. It may take weeks. It may take months. It may even take years, but eventually, the roots will take hold and your tree will grow. And when it does, it will grow in remarkable ways. - __Eric Aronson__, Para-1 and 7, 2009.

A special thanks to Eric Aronson, who I do not know personally but his words kept me going on during the difficult periods of Ph.D., especially at times when it seemed nothing is progressing.

1 INTRODUCTION

> Energy supply is integral to the economy of a country and thus it is fundamental to national security. Energy is also essential to achieve basic levels of comfort and well-being. Demand for energy is increasing globally … . Yet stocks of coal, oil, gas, uranium and rare earth elements (REE) are declining. (Williams, 2012, p. 3)

1.1 PROBLEM STATEMENT

Bangladesh, the eighth-most populous country in the world (United Nations [UN], 2015a)[1] and one of the fastest-growing developing countries in Asia, is inhabited by 168.96 million people (Central Intelligence Agency [CIA], 2015). Only 34.3% of its current population lives in urban areas (CIA, 2015; UN, 2015b); however, it has been projected that by 2050, this figure will increase to 56% (UN, 2015b). Dhaka, the capital and the most important city of Bangladesh, is growing rapidly, with a population growth rate of 3.6% between 2010 and 2015 (UN, 2015b). Dhaka is also the most densely populated city not only of Bangladesh but also in the world, with an estimated 44,100/km^2 (Demographia, 2016). With a population of 16.98 million people, Dhaka is currently the eleventh-largest megacity in the world and has been predicted to be the sixth-largest city by 2030, with 27.37 million people (UN, 2015b). Consequently, urbanisation is taking place at a rapid annual rate of 3.55% (CIA, 2015; UN, 2015b), resulting in a rapidly growing energy demand, the growth rate of which was 9.84% per year between 2000 and 2012 (Energy Information Administration [EIA], 2013). However, the country suffers from an acute energy scarcity, with one of the lowest per-capita energy consumption rates in the world (293 kWh/year) (CIA, 2015).

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[1] *In this thesis, APA 6th referencing style has been followed.*

Moreover, only a portion (59.6%) of the country's population has an access to electricity (The World Bank [WB], 2015). Blackouts, commonly known as 'load-shedding' in Bangladesh, are a common and daily phenomenon during summer months due to the large gap between energy demand and supply. The inadequate energy system of the country is yet to meet its current energy demand; hence, the burning question is, 'How will the energy demand of the sheer number of new urban developments be met?'

A traditional fossil fuel-based energy system is certainly not the answer, as with depleting fuel resources, it would not ensure energy security. Additionally, it would have a negative effect on the environment. This research argues that since most of the future energy demand of Bangladesh will be from new buildings and urban developments, it is only wise to design them as energy-independent ('zero-energy') buildings, or as developments in which the buildings generate their own energy through on-site micro-generators, using renewable energy sources instead of being fed from a distant energy plant. Not only will this make new developments energy independent, it will also reduce the energy burden of the country in a sustainable way.

Given the above background, this research explores whether future residential developments in Dhaka city can become energy independent and shift from being a consumer to an energy contributor and subsequently, help to ameliorate the energy scarcity of the country.

1.2 RESEARCH BACKGROUND

> It is not an exaggeration to claim that the future of human prosperity depends on how successfully we tackle the two central energy challenges facing us today: securing the supply of reliable and affordable energy; and effecting a rapid transformation to a low-carbon, efficient and environmentally benign system of energy supply. What is needed is nothing short of an energy revolution. (International Energy Agency, 2008, p. 37)

1.2.1 Introduction

Our world is once again into an 'energy crisis'; however, this time the crisis has much wider consequences (Barsky & Kilian, 2004; Droege, 2006; EIA, 2007; Geller, 2003; Williams, 2012). While during the previous crises[2], mostly the industrialised countries were affected, this time, all of the countries of the world will have to pay the toll (Ferrey & Cabraal, 2006; Nandi & Bose, 2010; Williams, 2012). An unprecedented growth in global energy demand, coupled with the depletion of fossil fuels along with their negative effect on the natural environment, are the main reasons behind the current crisis (Droege, 2009; Fell, 2009; Lehmann, 2015a; Pfeiffer, 2004; Pareto & Pareto, 2008; Tillie, Dobbelsteen & Carney, 2015; Williams, 2012). Hence, in the 21st century, the world is facing a unique dilemma where significantly more energy generation is needed but fossil fuel resources are being depleted and more energy generation by burning these fuels means more greenhouse gas (GHG) emissions and consequently, more potential negative effects on the environment.

1.2.2 The Growing Energy Demand and Developing Countries

The huge growth in global energy demand is mainly due to the rapid growth in population and urbanisation in developing countries (International Energy Agency [IEA], 2015a; United Nations Environment Programme [UNEP], 2009). Not only is the

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[2] *In 1973 and 1979, the formation of the OPEC cartel, to maximise group revenue, threatened the energy security of many industrialised countries that were heavily dependent on imported oil.*

world's total population is growing rapidly—1.18% annually, adding 83 million people per year (UN, 2015a)—but also a large portion of the population is becoming urbanised—for the first time in human history, by 2007, more than half of the world's people had become urban residents (UN, 2015b). The proportion of total world population living in urban areas has increased from 30% (746 million) in 1950 to 54% (3.9 billion) at the current time. Between 2014 and 2050, it is predicted to grow by a further 2.5 billion, to 66% (6.3 billion), with 90% of these new urbanites concentrated in the developing countries of Africa and Asia (UN, 2015b). In next four decades, Africa's urban population will increase to twice that of today; Asia's urban population will increase by 61% and Asia will be the home of the majority of global urban population (52%) in 2050 (Asian Development Bank, 2012; UN, 2015b). Thus, a process of rapid urbanisation is taking place, particularly in the developing countries of Africa and Asia.

The rapid urbanisation that is occurring in Asia and Africa is resulting in enormous energy demand, since energy is the most fundamental element for any kind of urban development and activity. However, a large number of people (2.7 billion) are yet to gain access to modern energy systems (IEA, 2015b; United Nations Development Programme [UNDP], 2011). The global demand for energy is growing at an unprecedented rate and according to IEA (2015b), the global use of energy will increase by 33% between 2013 and 2040, primarily driven by Asian and African developing countries.

It is important that the urban developments in developing countries continue without hindrance, as there is a strong positive link between urbanisation and the social and economic well-being of people (Nandi & Bose, 2010; Williams, 2012). The Human Development Index, which measures the average achievement of a country from three basic human development dimensions (health, access to knowledge and per-capita income), has been found to correlate strongly with the level of urbanisation (Nandi & Bose, 2010; UNDP, 2009). Many indicators of poverty, such as infant mortality, illiteracy and low life expectancy, are directly associated with inadequate energy service (UNDP, 2011). Therefore, to break the vicious cycle of poverty and to receive the full benefits of urbanisation, it is essential for developing countries to meet the rapidly growing energy demand with an adequate, reliable and affordable energy supply.

Meeting a fast-growing demand for energy is a difficult task for any country, let alone a developing country with a weak economy and limited resources. Additionally, this only represents one facet of the total energy challenge. In the changed context of the 21st century, focusing only on increasing the energy supply is no longer sufficient; the type and source of that energy is equally important. In the last two decades, the global energy context has changed very rapidly, as fossil fuels, the main energy resources for traditional energy systems, are dwindling while at the same time, global energy demand is increasing (Droege, 2006, 2009; Fell, 2009; Ferrey & Cabraal, 2006; Pfeiffer, 2004; Tillie et al., 2015). In addition, the traditional methods of energy generation by burning fossil fuels emits GHGs, which have serious effects on the natural environment (Droege, 2006, 2009; IEA, 2008; Intergovernmental Panel on Climate Change, 2007; UNEP, 2009; Williams, 2012). An estimation showed that 67% of the world's total GHG emissions are energy related (IEA, 2015b); hence, the fossil fuel-based traditional energy system has become unsustainable, from both the economic and the environmental perspective. An important question is, 'How can the huge energy demand of the future population and urban developments in developing countries be met without having a significant negative impact on the environment?'

1.2.3 Alternative Energy

After the first oil crisis in 1973, renewable energies were developed as an alternative to the use of fossil fuels (Ferrey & Cabraal, 2006; Geller, 2003; Storey & Kang, 2015; Williams, 2012). Renewable energies generate energy (mainly electricity) by harnessing the sun, wind, biomass, hydro, tidal and ocean waves, and geothermal sources. The greatest advantage of renewable energy is it does not emit GHGs while producing energy. Moreover, the energy sources are free to all and abundant (Droege, 2006, 2009; Ferrey & Cabraal, 2006; UNEP, 2012). Renewable energy technologies can be deployed at a large scale (e.g., as an energy plant) as well as at a smaller scale (e.g., as a micro-generator on a building). In fact, deploying renewable energy technology on buildings has some additional advantages over large-scale power plants, as the buildings can provide the necessary infrastructural support and the energy produced can be consumed on spot; therefore, the need for a separate establishment, as well as long-distance transmission, can both be eliminated (Droege, 2006; 2009; IEA, 2006; Williams, 2012). In addition, the energy supply system can be established in a decentralised manner, which many experts advocate as more efficient and sustainable (Appleby, 2011; Droege, 2006; Lehmann, 2015a; Williams, 2012).

Deployment of renewable energy at any scale, however, first requires the reduction of the demand for energy as much as possible (Droege, 2009; Evans, Shui & Delgado, 2009; Laustsen, 2008; Lehmann, 2015a; Lechner, 2015; Yudelson & Meyer, 2013). Alternative building and urban development models that can generate energy have emerged recently in developed countries. These are known as 'zero-energy' and 'plus-energy' models (Bagci, 2009; Charron, 2008; Hernandez & Kenny; 2010; Kapsalaki & Leal, 2011; Kapsalaki, Leal & Santamouris, 2012; Disch, 2009). A zero-energy model refers to a building or development that can generate as much energy as it consumes, while a plus-energy model refers to a building or development that can generate more energy than it consumes through on-site renewable energy sources. Since the zero-energy and plus-energy models generate their own energy from renewable sources, they are by default GHG emission free once at operational stage (Marszal & Heiselberg, 2011a; Pless & Torcellini, 2010; Wang, Gwilliam & Jones, 2009; Williams, 2012). Therefore, zero-energy buildings are often referred to as 'emission-free', 'zero energy-emission' or 'zero-carbon' buildings (Laustsen, 2008; Marszal & Heiselberg, 2011a, 2011b; Torcellini, Pless, Deru & Crawley, 2006).

This research argues that although energy-generating buildings have been developed primarily to address the GHG emission issues of developed countries (Williams, 2012), they have much to offer to developing countries. It is certain that the major share of the future energy demand of developing countries will come from new urban developments; hence, constructing these as energy-generating buildings can be one of the most best ways to meet the fast-growing energy demand of these countries in a sustainable way. Thus, instead of being fed with energy from a distant power plant, the future buildings in developing countries could be energy independent, generating their own energy from on-site renewable energy sources. This would eliminate the need to establish new power plants to feed the new developments and save the limited resources of these countries, as well as significantly reducing the future GHG emissions from these developments. This would ensure a sustainable energy supply in the shortest possible time through a decentralised energy supply system and enable the continuation of much-needed development in the developing world.

1.2.4 Research Need

The deployment of renewable energy requires extensive context-specific research, as energy generation through renewable sources is highly dependent on the geographic location and background climate of an area (Dana & Steemers, 2006; Droege, 2009; Lechner, 2015; Steemers, 2006; Williams, 2012). As mentioned in the previous section, to meet the energy demand of a building solely by renewable energy, it is important to start with reducing its energy demand as much as possible through energy efficiency measures (World Business Council for Sustainable Development, 2007, 2009). However, the energy consumption of a building is a complex phenomenon that is dependent on a number of factors, such as the surrounding urban setting, the building design and construction, the behavioural patterns of the occupants and the energy intensity of the appliances used (Dana & Steemers, 2006; Levine, Urge-Vorsatz, Blok, Geng, Harvey, Lang, … Yoshino, 2007; Steemers, 2006). All of these factors are influenced by the specific social, cultural and economic background in which the building is situated (Banerjee & Solomon, 2003; Williams, 2012, Yao & Steemers, 2005). Thus, it is clear that particular efficiency measures will not work equally for different countries or locations, or even for different parts of the same region. Hence, buildings in different regions with different socio-economic contexts will need to develop their own customised efficiency strategies and renewable energy generation options. Williams (2012) asserts that to be successful, energy-generating buildings must reflect the local contexts in which they are rooted.

This research was conducted in the context of Dhaka, the capital city of Bangladesh and the hometown of the researcher. As noted earlier in this chapter, Dhaka is currently experiencing an acute energy scarcity and a very high rate of urbanisation, on track to become the sixth-largest megacity in the world by 2030 (UN, 2015b). Hence, the city provides an ideal context for conducting this research.

1.3 RESEARCH AIM AND FOCUS

The aim of this research was to explore the possibilities of achieving energy-independent residential developments in the contexts of Dhaka, Bangladesh. In this research, the term 'energy-independent residential development' refers to a typically planned residential district that contains energy-generating buildings (or zero-energy buildings) that are able to generate as much energy as they consume during their operational phase. This is usually achieved by the use of roof-mounted solar photovoltaic (PV) cells.

Although Dhaka city consists of spontaneous as well as planned residential developments, this research focuses on the typical planned residential developments of Dhaka (further explained in Section 3.3.3). Typical planned residential developments are inhabited by the upper- and upper-middle-income sections of society and hence, are more energy intense (Begum, 2010; Seraj, 2012, 2013a). This research argues that since these developments are some of the highest consumers of energy in the housing sector, if energy independence can be achieved in this type of development, it should be possible to achieve energy independence in other types of housing. In addition, a large number of such developments are currently under construction; thus, these developments should be the priority for energy-independent developments.

This research focused on the use of roof-mounted solar PV, since current Government rules stipulate that all new residential buildings must have solar panels to supply 3% of their total energy demand (Bangladesh Power Development Board [BPDB], 2011). This research also investigated whether 100% of the energy use in this type of development could be supplied by roof-mounted solar PVs.

1.4 RESEARCH QUESTIONS AND OBJECTIVES

As already mentioned, to achieve energy independence through renewable energies, two principles must be followed: i) reduce energy demand as much as possible through energy-efficiency measures; and ii) meet the reduced energy demand through on-site renewable energy sources.

This research was conducted under the following three central research questions (RQs):

RQ A. What are the ways to reduce existing household energy (electricity) consumption in typical planned residential developments in Dhaka?

RQ B. To what extent can the existing energy consumption of households in typical planned residential developments in Dhaka be reduced?

RQ C. Is it possible to achieve energy independence through roof-mounted solar PVs after reducing the level of energy consumption?

To obtain the answers for these RQs, six objectives were created. Objectives 1—4 aimed to answer RQ A; Objective 5 aimed to answer RQ B; and Objective 6 aimed to answer RQ C. The objectives are described in detail below.

Objective 1: To identify the parameters that influence household energy consumption in general, through a literature review.

Objective 2: To identify the existing contexts of the energy-influencing parameters (based on Objective 1) in typical residential developments in Dhaka.

The aim of the existing contexts study (Objective 2) was to identify both the dominant practices and the detrimental practices that can contribute to higher energy consumption and the alterations to these that could result in energy saving. The energy-influencing parameters were grouped into three categories, which were investigated separately. Therefore, Objective 2 consists of the following three sub-objectives:

Objective 2.1 To identify the existing contexts of the urban and building energy-influencing parameters in typical planned residential developments in Dhaka.

Objective 2.2 To identify the existing contexts of the microclimatic parameters in typical planned residential development in Dhaka.

Objective 2.3 To identify the existing contexts of household energy-influencing parameters in typical planned residential developments in Dhaka.

Objective 3: To identify the effect of various parameters (urban, building, microclimate and household) on household energy consumption in typical planned residential developments in Dhaka.

Objective 4: To identify the best practice to minimise energy consumption in typical planned residential developments in Dhaka.

Objective 5: To identify the extent to which existing household energy consumption can be reduced after applying these best practices.

Objective 6: To identify whether energy independence can be achieved by the use of roof-mounted solar PVs with the available roof area.

Table 1.1: *Summary Chart: RQs, Associated Objectives and Topics Addressed*

RQ A: What are the ways to reduce existing household energy (electricity) consumption in typical planned residential developments in Dhaka?

Objectives (O)	**Topics Addressed & Associated Chapters**
1: To identify the parameters that influence household energy consumption in general through a literature review.	1: Parameters that can influence household energy consumption in general—includes urban and building design, microclimatic, and household and occupants-related parameters (see Chapter 3).
2.1: To identify the existing contexts of the urban and building energy-influencing parameters in typical residential developments in Dhaka.	2: Current urban design practices in the typical residential developments—includes plot layout, shape, size, dimension & orientation, road width & layout, and vegetation & materials (see Chapter 5).
	3: Current building design and construction practices in the typical residential developments—includes building footprint-plot ratio, canyon ratio, dwelling density, floor & apartment unit plan, apartment size, room size & number, glazing type & size, shading device, external wall and construction materials etc. (see Chapter 5).
2.2: To identify the existing contexts of the microclimatic parameters in typical residential developments in Dhaka.	4: Variation in outdoor air temperature according to different orientations and height (see Chapter 6).
	5: Indoor air temperature patterns and the differences between outdoor and indoor air temperatures of the case study apartments in the case study areas (see Chapter 6).
	6: The urban heat island intensity in the case study areas (see Chapter 6).
2.3: To identify the existing contexts of household energy-influencing parameters in typical residential developments in Dhaka.	7: Existing contexts of household parameters in typical residential developments—includes household composition, affordability of dwelling, occupancy patterns, building characteristics, operational pattern of windows and doors, ownership and use of different appliances (see Chapter 7).
	8: Energy consumption pattern and intensity of households in the case study areas (see Chapter 7).
	9: Relationship between different household parameters and energy consumption as well as dominant household parameters from the energy consumption perspective in the case study areas (see Chapter 7).
3: To identify the effect of various parameters on household energy consumption in typical residential developments in Dhaka.	10: The effect and the extent of the effect of different urban design parameters on energy consumption (see Chapter 8).
	11: The effect and the extent of the effect of different building design parameters on energy consumption (see Chapter 8).
	12: The effect and the extent of the effect of different household parameters such as window operation and

<table>
<tr><td colspan="2">RQ A: What are the ways to reduce existing household energy (electricity) consumption in typical planned residential developments in Dhaka?</td></tr>
<tr><td>Objectives (O)</td><td>Topics Addressed & Associated Chapters</td></tr>
<tr><td></td><td>household appliances on energy consumption (see Chapter 8).</td></tr>
<tr><td>4: To identify the best practice to minimise energy consumption in typical planned residential developments in Dhaka.</td><td>13: The best urban, building, operational and appliances practices (see Chapter 8).</td></tr>
<tr><td colspan="2">RQ B: To what extent can the existing energy consumption of households in typical planned residential developments in Dhaka be reduced?</td></tr>
<tr><td>5: To identify the extent to which existing household energy consumption can be reduced after applying these best practices.</td><td>14: The extent of energy consumption reduction after applying the identified best practices (see Chapter 8).</td></tr>
<tr><td colspan="2">RQ C: Is it possible to achieve energy independence through roof-mounted solar PVs after reducing the level of energy consumption?</td></tr>
<tr><td>6: To identify whether energy independence can be achieved by the use of roof-mounted solar PVs with the available roof area.</td><td>15: The roof area needed to achieve energy independence after consumption reduction with existing density through the use of roof-mounted solar PVs (see Chapter 8).</td></tr>
</table>

1.5 SIGNIFICANCE

This research if the findings are adopted could be expected to have a significant effect on future residential developments in Dhaka city. It provides an insight into the implications of current urban and building design practices on household energy consumption in typical residential developments in Dhaka. It also shows the effect of different operational behaviours, as well as the effect of different household appliances, on energy consumption and highlights the importance of occupants' awareness of reducing residential energy consumption effectively. The outcomes of this research can help both the urban and building practitioners of Dhaka city to make more-informed design decisions and enable them to create residential developments that consume less energy. Additionally, the outcomes of this research can be helpful in increasing public awareness about using energy-efficient appliances.

Further, policy makers can use them as a basis for updating the current building and land development acts to ensure maximum energy saving from future residential buildings and thus sustainable development.

This research can help to reduce the energy burden of the country by shifting the role of future residential developments from being solely a consumer of energy to being an energy generator as well. While the research focused on typical residential developments of Dhaka, many of the findings and recommendations are equally applicable for other types of residential developments.

In the fast-changing global and local contexts, it is important that pathways to alternative developments that are sustainable from both the global and local point of view, as well as suitable to the particular contexts of the country, are researched and established as soon as possible, to allow the rapid initiation of a shift from existing practices. This research is a step in that direction.

1.6 SCOPE OF THE RESEARCH

This research focused on reducing energy scarcity by investigating alternative ways that new urban developments in Dhaka could generate their own energy in a sustainable way and reduce the economic energy burden of Bangladesh. Therefore, this research also addressed some other pressing issues such as inadequate infrastructure, future GHG emissions from the developments and to some extent, environmental degradation in an indirect way.

There are multifaceted challenges within the urbanisation process in developing countries, including economic challenges, slum and squatter development, inadequate infrastructure, social exclusion, urban poverty, environmental degradation, traffic congestion, water stagnation, unmanaged waste, poor sewage and sanitation, and health and well-being. Clearly, not all of these issues could be addressed in this research, which focused only on residential buildings in planned areas and solar PVs as renewable energy source. However, it is acknowledged that to achieve greater success, a holistic approach involving all categories of buildings would need to be adopted and other potential renewable energy sources, such as waste, should be investigated as well.

1.7 METHODOLOGY

This research employed a multimethod approach that predominantly included different quantitative research strategies and techniques, supported by a limited qualitative approach. A brief description of the methodology and methods used are presented here, with a more detailed account in Chapter 4.

The research was conducted in three major phases and mostly followed a linear direction. The first phase was a theoretical study or literature review; the second phase involved field studies; and the third phase involved simulation studies.

1.7.1 Phase 1: Theoretical Studies

The aim of this phase was to build a solid theoretical foundation as well as to identify appropriate methodologies and strategies for conducting the fieldwork and simulation studies. Literature reviews were conducted to obtain an in-depth understanding about the contextual settings of this research, at both the global and local scale. In addition, the first objective of this research was addressed in this phase.

1.7.2 Phase 2: Field Studies

Field studies were conducted to identify the prevailing contexts of different parameters in the typical planned residential areas in Dhaka. They were conducted in three major steps, briefly described below.

Step 1: Urban and building design parameters were investigated by following architectural investigation procedures. Seventy typical apartment buildings and 93 apartment unit plans were studied. Interviews were also conducted with representatives from the relevant professions: real estate developers, practising architects and planners. Urban design parameters such as plot size, shape and layout; road width and layout; plot orientation; and canyon ratio[3] (CR) were investigated. Building parameters, including the building layout, apartment plan layout, room number and size, shading devices, glazing, external walls and construction materials were recorded.

Step 2: Microclimatic parameters (mainly air temperature) were investigated by following climatic investigation procedures. Data were collected using 42 air temperature data loggers for 40 days from the two case study areas.

Step 3: Household parameters were investigated by following survey research procedures. Household parameters included the household composition, income, occupancy patterns, building characteristics, possession of different appliances and their use intensity, as well as the operational pattern of the windows and doors. Data were collected from 392 households from the two case study areas through a questionnaire survey form. Collected data were then analysed statistically.

1.7.3 Phase 3: Simulation Studies

The existing contexts of different energy-influencing parameters in typical residential developments in Dhaka were obtained from the field study results. As the only possible strategy for predicting the effect of different urban, building and household parameters is by building performance simulations (BPS), the outcomes of this research were based on experiments conducted through such BPSs. These simulation studies were conducted in three steps to obtain the answers for the three RQs, using the simulation program Integrated Environmental Solutions-Virtual Environment (IESVE, Version 2015.2.2.0).

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[3] *Canyon ratio refers to the ratio between the average height of two adjacent buildings from the floor and the horizontal distance between the buildings.*

Step 1: The effect and the extent of the effect of different parameters on household energy consumption were tested and the best practice for each of the parameters were identified, to discover the best ways to reduce household energy consumption.

Step 2: The maximum extent of energy consumption reduction was tested to obtain the answer for the second RQ.

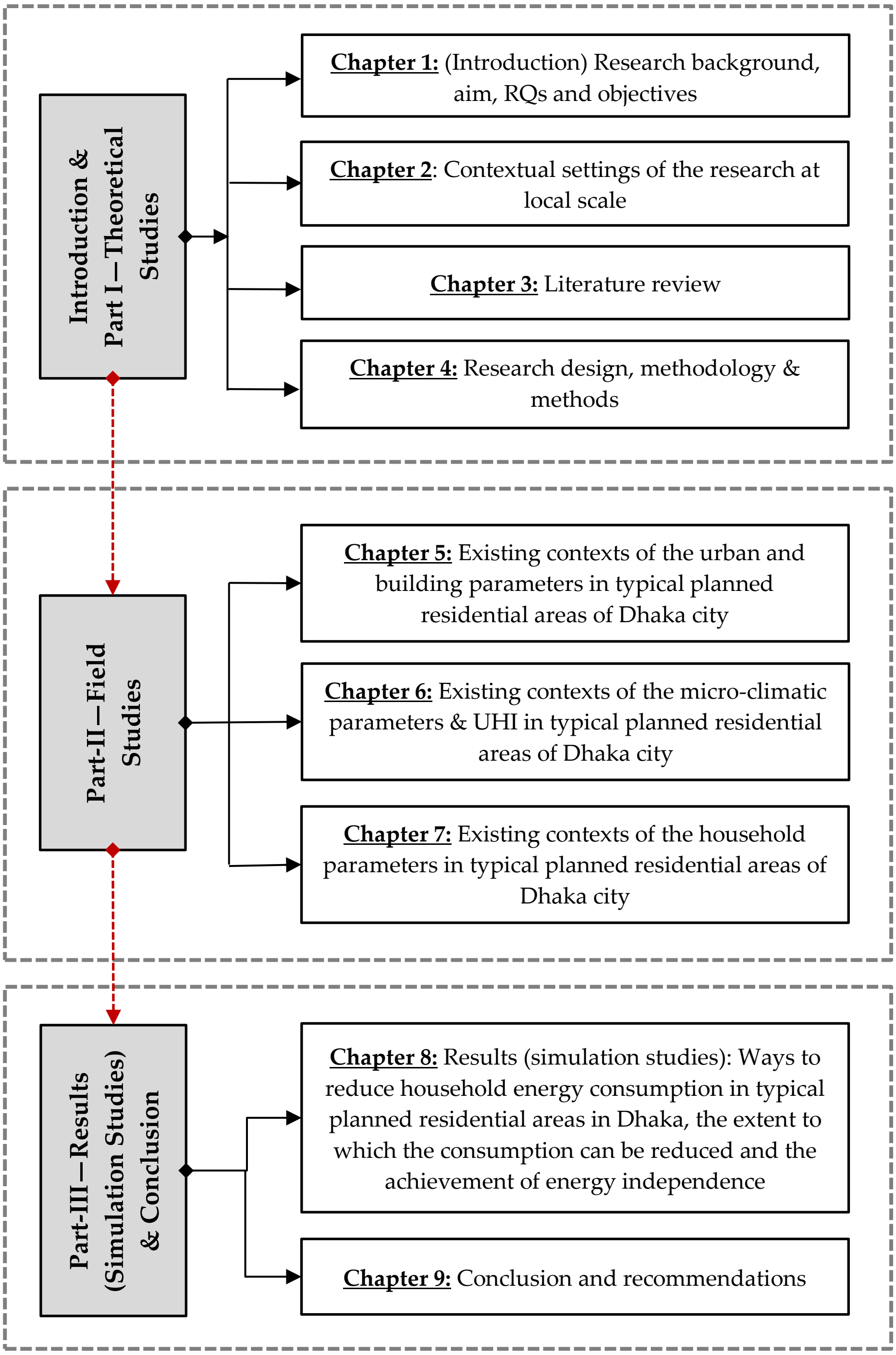
Step 3: Simulation studies were conducted to calculate the maximum energy generation possible through roof-mounted solar PVs with the available roof area and whether it would be possible to energy independence through their use.

1.8 THESIS STRUCTURE

This thesis is organised in nine chapters. The rest of the chapters are grouped into three parts (see Figure 1.1). Part I (Chapters 2–4) presents the findings of the theoretical studies along with a detailed methodology; Part II (Chapters 5–7) includes the findings of the field studies. Part III (Chapters 8–9) presents the research results obtained through the simulation studies, along with the conclusion and recommendations. Brief descriptions of all the chapters are given below:

- Chapter 1 introduces the reader to this research, along with a brief overview of the total project.
- Chapter 2 presents the local contexts of the research, with a particular focus on urban (residential) developments. In addition, the energy contexts and challenges of Bangladesh and how they affect Dhaka have been presented.
- Chapter 3 presents the contextual settings of the research at a global scale. This chapter also includes the answers to Objective 1.

- Chapter 4 contains a detailed account of the methodology followed for conducting this research. The methods adopted at each phase and step of the research, along with the rationale for a particular method, are discussed.
- Chapter 5 presents the findings of the field studies conducted to explore the existing contexts of the urban and building design parameters in typical planned residential areas in Dhaka.
- Chapter 6 presents the findings of the field studies conducted to explore the existing contexts of the microclimatic parameters in typical planned residential areas in Dhaka city.
- Chapter 7 presents the findings of the field study conducted to explore the existing contexts of the household parameters in typical planned residential areas of Dhaka city.
- Chapter 8 presents the results of the simulation studies, the ultimate outcomes and answers to the three RQs.
- Chapter 9 briefly discusses all the key findings of this research. It also presents the study’s limitations and the recommendations for further research that were identified in this research.



Chapter 1: (Introduction) Research background, aim, RQs and objectives

Chapter 2: Contextual settings of the research at local scale

Chapter 3: Literature review

Chapter 4: Research design, methodology & methods

Chapter 5: Existing contexts of the urban and building parameters in typical planned residential areas of Dhaka city

Chapter 6: Existing contexts of the micro-climatic parameters & UHI in typical planned residential areas of Dhaka city

Chapter 7: Existing contexts of the household parameters in typical planned residential areas of Dhaka city

Chapter 8: Results (simulation studies): Ways to reduce household energy consumption in typical planned residential areas in Dhaka, the extent to which the consumption can be reduced and the achievement of energy independence

Chapter 9: Conclusion and recommendations

Figure 1.1: *Thesis Structure*

Part I: Theoretical Studies

Chapter 2: The Research Contexts-Dhaka, Bangladesh

Chapter 3: Literature Review

Chapter 4: Research Design, Methodology and Methods

2 THE RESEARCH CONTEXTS-DHAKA, BANGLADESH

As with the world as a whole, the energy crisis has reached a critical point in Bangladesh. Energy being the lifeline on an economy, the crisis epitomizes the 'development' and 'progress' Bangladesh has been dragged into by relying on the non-renewable energy path. (Kamal, 2010, p. 13)

2.1 INTRODUCTION

For the readers unfamiliar with the situation in Dhaka, Bangladesh, this chapter portrays the contextual settings of this research at a local scale, with a focus on urban development and energy use in buildings and in particular, electricity use. It identifies the gap in knowledge and the issues that need to be addressed to deal with the rapid urban development occurring in Bangladesh and the resulting huge energy-demand challenges. The contexts are presented in two sections: urban development contexts and energy contexts.

The urban development contexts are presented in six sub-sections, the first of which briefly introduces an overview of the overall urban development contexts in Bangladesh. This is followed by detailed investigations into the contexts, presented under headings of Dhaka's growth; development types and patterns; development plans and regulations; and the impact of the city's urban developments on energy use. The energy contexts are presented in two sub-sections. The first critically examines the overall energy contexts of the country, along with a review of the power sector master plan, while the second presents the energy contexts of Dhaka.

2.2 URBAN DEVELOPMENT CONTEXTS

2.2.1 Urban Development in Bangladesh: Overall Scenario

Bangladesh, one of the fastest-growing developing countries in South Asia, is bordered by India, Burma and the Bay of Bengal (see Figure 2.1). Its geographical location is between latitude 20°34′ and 26°38′ North and between longitude 88°01′ and 92°41′ East. The country is comparatively new, having only obtained its independence from the former West Pakistan (now Pakistan) after a bloody war in 1971.

Figure 2.1: *Location of Bangladesh in South Asia. Source: Wikipedia, 2016*

Bangladesh has a small area of land (147,570km^2) but a large number of people (169 million), making it the eighth-most populous country on earth, with one of the highest population densities (1142.29/km^2) (CIA, 2015). Most of this population lives in rural areas (66%); however, this is changing fast due to urbanisation at an annual rate of 2.4% (UN, 2015b). As noted in Chapter 1, by 2050, nearly 56% of the country's total population will be living in urban areas, compared with 34.3% in 2015 (CIA, 2015; UN, 2015b). The signs of this urbanisation are evident throughout the country, with rapidly growing and expanding urban centres. Although there are several major cities in the country with more than 500,000 people, such as Dhaka, Chittagong, Rajshahi, Khulna, Rangpur and Sylhet (Bangladesh Bureau of Statistics [BBS], 2013; Demographia, 2016), Dhaka, the capital, is in every sense the largest and the most important city. It is often referred to as the nucleus of the country (Rajdhani Unnayan Kortripakhkha [RAJUK], 2015) attracting over 300,000–400,000 new migrants each year (BBS, 2013; WB, 2007). Consequently, the city is experiencing a very high expansion and urbanisation growth rate, far greater than the other cities of Bangladesh (BBS, 2013; Corner & Dewan, 2013). According to many researchers, the overall urban development of Bangladesh is influenced significantly by the urban development of Dhaka, as other cities tend to follow the same development pattern as the capital city (Islam, 2005; Seraj, 2013b; Seraj & Tawhid, 2013).

The following sections present the contexts of Dhaka in detail, with a particular focus on residential developments, to provide an in-depth understanding of the development dynamics of the city.

2.2.2 General Contexts of Dhaka

Dhaka is centrally located in Bangladesh. The urbanisation of Bangladesh has always been interlinked with the intense development of Dhaka, since all major political, economic and socio-cultural activities are Dhaka-centric and all major urban facilities are concentrated here (Corner & Dewan, 2013; RAJUK, 2015; Sohag, 2013). The current annual growth rate of Dhaka is 3.55%, which is much higher than the country's overall urbanisation rate of 2.4% (UN, 2015b). Further, the city has nearly five times the population (16.24 million) of the next largest city of the country, Chittagong (3.24 million) (Demographia, 2016). Dhaka alone contains about 10% of the total national population of Bangladesh and 37% of the total urban population (RAJUK, 2015). Additionally, the city is the most densely populated in both Bangladesh and the rest of the world, estimated at 44,100/km^2 (Demographia, 2016).

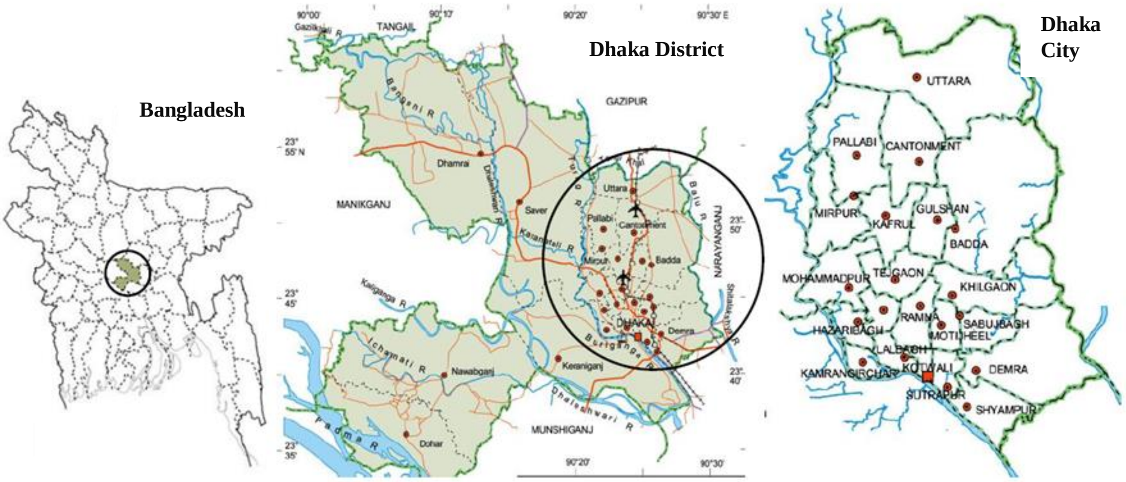


Figure 2.2: *Location of Dhaka city (DMA). Source: Ahmed, 2006*

For Dhaka city, March, April and May are the hottest months, reaching a maximum temperature of 33.4°C in April. From June to October, which is the monsoon period, the average temperature remains steady at around 28.3°C. In the colder period, from November to February, the ambient temperature drops down to around 20.7°C (Ahmed, 1996). Average sunshine hours per day are 7.55 and average global horizontal irradiance is 4.29 kWh/m^2/day (Kabir & Endlicher, 2012). Humidity in Dhaka is high, with mean annual relative humidity (RH) of 77%. The RH during the monsoon months is mostly above 90% and the lowest is in March (60%) during the pre-monsoon season (Ahmed, 1996). Average wind speed during the summer months (March–October) varies between 2.5 and 4.4 m/sec, whereas in colder months, it is between 1.4 and 1.6 m/sec (Ahmed, 1994). The wind is predominantly southerly and south-easterly during the summer months, particularly in monsoon time, and northerly and north-westerly during the winter months (Ahmed, 1996). The background climate of the city is tropical or warm-humid, dominated for most of the year by overheating (Ahmed, 1994; Ahmed, 1996; Mallick, 1994).

Topographically, the city is on flat land that is surrounded by low-lying regions and three rivers: Balu, Buriganga and Turag at the east, south and west respectively. Due to the presence of the rivers and wet lands, the growth of the city was primarily towards the north; however, with urbanisation pressure, the city eventually started to expand in all directions, mostly illegally, by encroaching on the rivers and wetlands (Hoque, 2004; Nilufar, 2010).

The demarcation of the city boundary is somewhat ambiguous. The literature shows three commonly found boundaries for Dhaka city (Corner & Dewan, 2013; Islam, 2005; RAJUK, 2015). According to the Dhaka City Corporation (DCC), Dhaka covers 143km^2; according to the Dhaka Metropolitan Area (DMA), it covers 303km^2; according to the Dhaka Metropolitan Development Plan (DMDP), it covers 1,528 km^2. Although the DCC area is the most consolidated core of the city, according to Islam (2005), the DMA is referred to as 'Dhaka city' by most of the people (see Figure 2.3). It includes the entire DCC area and the eastern and northern fringe areas of the city and is the jurisdiction of the Dhaka Metropolitan Police. In contrast, the DMDP is the planning region of the capital development authority of Dhaka, commonly known as Rajdhani Unnayan Kortripakhkha (RAJUK), and includes the entire DCC area, six adjacent municipality areas (Savar, Narayanganj, Gazipur, Kadamrasul, Siddirganj and Tongi) and a number of adjacent urban areas. Other than these three demarcations, the area for Dhaka megacity was defined by the BBS as being slightly smaller than the DMDP area (1,383 km^2). It is also known as the Statistical Metropolitan Area, which includes the entire DCC area along with the six adjacent municipality areas and 68 unions[4].

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[4] *'Union' is a rural administrative unit.*

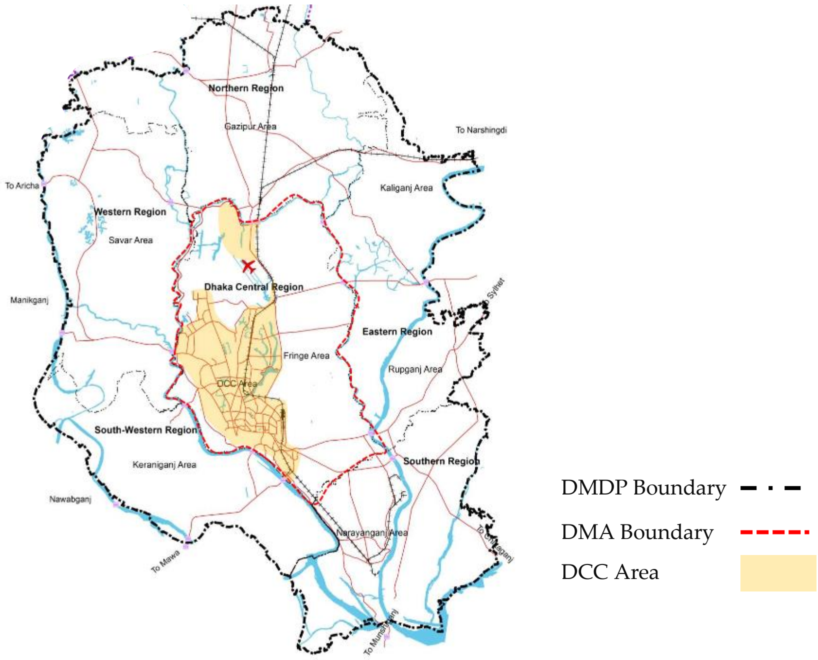

***Figure 2.3:** Dhaka City Boundaries. Source: Adapted from RAJUK, 2015*

2.2.3 The Growth of Dhaka

Before becoming a megacity in the 21st century, Dhaka went through several phases under different rulers, each of which left a mark on the growth of the city. The literature shows five major periods that shaped the growth and development pattern of the city, namely, the Pre-Mughal, Mughal, Colonial, Pakistan and Bangladesh periods (Ahmed, 1986; Ahsan, 1991; Chowdhury & Faruqui, 1991; Chowdhury & Hasan, 2011; Islam, 1996; Nilufar, 1997). In some periods, the city experienced expansion and in others, the opposite (Ahmed 2006; Hafiz, 2011; Nilufar, 2010). The following sections briefly outline the extent of expansion and contraction of the city in each major period.

2.2.3.1 Pre-Mughal Period (Until 1608 AD)

The first urbanised settlement in Dhaka can be traced back to the 7th century, when it was a small Hindu trading centre (Chowdhury & Hasan, 2011; Islam, 1996; Nilufar, 2010). At that time, the city was ruled by the Buddhist kingdom of Kamarupa. In the 9th century, the Sena dynasty took the control of the city, which at that time was known as Bangala. The town consisted of a few market centres and a few localities of craftspeople and businesspeople. After the Sena dynasty, Turkish and Afghan governors descending from the Delhi Sultanate successfully ruled Dhaka until the Mughals arrived in 1608. At that time, the city covered an area of about 2.2 sq. km (Chowdhury & Faruqui, 1991; Islam, 1996).

2.2.3.2 Mughal Period (1608–1764)

The city had no importance until the Mughals arrived in 1608. In this period, the city was known as Jahangirnagar, taken from the name of the Mughal emperor of that time. The city gained the status of the capital of Bengal province in 1608 because of its political and military importance. Centring on the old market, the provincial capital began to grow rapidly in a north-westerly direction (Chowdhury & Faruqui, 1991; Islam, 1996). The greatest urban growth during this period took place under Subadar Saista Khan (1662–1667 and 1679–1689). At that time, the length of the city was 25 km north–south and 15 km east–west and had a population of over a million. However, of when the provincial capital was shifted to Murshidabad in 1717, the city that is now known as Dhaka started to lose its glory and shrank to an area of about 4.5 sq. km with a population of less than a million. The main city was still restricted to a small area on the northern bank of the river Buriganga, where the older part of the city remains today (Chowdhury & Hasan, 2011; Islam, 1996; Nilufar, 1997).

2.2.3.3 Colonial Period (1764–1947)

After the decisive battle of Palassey in 1757, the British East India Company took the control of Dhaka city. The city shrank dramatically between 1757 and1864 and as an after-effect of the war in Palassey, the population dropped from 200,000 in 1800 to 51,000 in 1873 (Chowdhury & Faruqui, 1991). After the British East India Company transferred power to the crown in 1858, Dhaka city began to rise again. In 1905, it became the provincial capital of East Bengal and Assam and experienced a 21% increase in population between 1901 and 1911 (Ahmed, 1986; Nilufar, 1997). The area of the city expanded to 17.0 sq. km and its population increased from some 90,000 in 1901 to over 100,000 in the subsequent decade. Under British rule, many modern educational institutions, public works and the first planned residential area of the city, Wari, were developed along with rail lines, airport and hospitals (Ahmed, 1986; Nilufar, 1997). However, the growth of the city reversed when the proposed partition of Bengal was cancelled in 1911 and the city lost its status of provincial capital. The city again experienced some growth during the Second World War, due to its strategic location. Thus in the colonial period, the city had several expansion and contraction phases.

2.2.3.4 Pakistan Period (1947–1971)

The growth of Dhaka gained significant momentum after the partition and independence of India and Pakistan from the British in 1947, which gave birth to a new Muslim state of Pakistan. Dhaka became the administrative capital of the province East Pakistan, today's Bangladesh. A huge number of Muslims from India migrated to Dhaka city. The need for establishing new administrative and commercial centres as well as residential areas for the new population led to unprecedented growth in the city. During this time, the city grew to occupy an area 125 sq. km and the population increased to 718,766 (Chowdhury & Faruqui, 1991; Islam, 1996).

2.2.3.5 Bangladesh Period (from 1971)

In 1971, Dhaka became the capital city of the independent country Bangladesh. After 1971, the city began to expand in all directions to meet the needs of a newly independent country's capital. Within a decade, one million more people lived in the city within an area of about 510 km^2 (Chowdhury & Faruqui, 1991; Hasan, 2011; Islam, 1996). From 1974 to 1981, the population of Dhaka grew at an annual rate of 9.94%, which the United Nations described as 'exceptional' (UN, 1999). As documented in many studies, during this period, new residential, administration, commercial and business areas were developed and the wetlands and low-lying areas within the city and the fringe areas started to disappear quickly (Hoque, 2004; Islam, 1999; Rahman, 2008; Seraj & Tawhid, 2013; Siddiqui, Ahmed, Siddique, Huq, Hossain, Nazimud-Doula & Rezwana, 2010). Within 45 years (1971–2016), the city area expanded from 125 km^2 to 1,528 km^2.

However, the city was not at all prepared for this sudden growth. There was no appropriate development plan that could address this unforeseen phenomenon nor was the development authority equipped to deal with the situation. Consequently, particularly during the 1970s and 1980s, a large number of spontaneous developments without much planning intervention occurred alongside planned developments. The city still is expanding rapidly. However, the extent of spontaneous growth has become limited due to the activities of organised real estate developers, which are discussed in the next section.

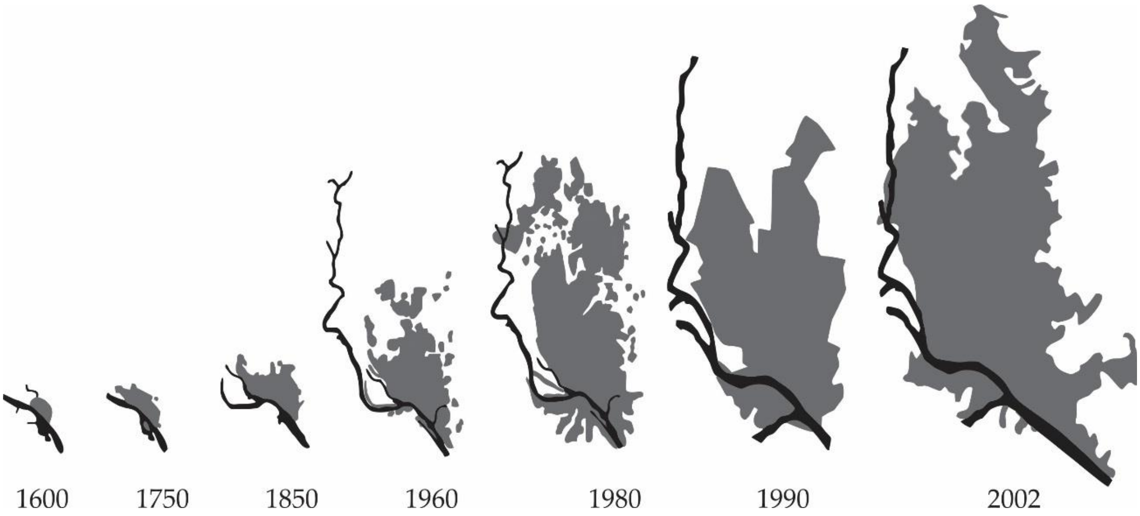

Figure 2.4: *Growth of Dhaka city. Source: Dhaka City Corporation, 2004 (modified by author).*

2.2.4 Development Types and Patterns in Dhaka

Two main types of development pattern can be found in Dhaka city: spontaneous and planned (Hafiz, 2011; Khan & Nilufar, 2009; Nilufar, 2010). According to Nilufar (2010), the city has a composite character, with patches of planned development surrounded by spontaneous ones. The main reason the city developed such a mixed character is that the city grew unexpectedly after the liberation war in 1971, with the development authority unable to keep pace and thus, substantial spontaneous growth occurred alongside planned growth (Islam, 1996; Jahan, 2011; Rahman, 2008). The spatial patterns of the two types of development are different from each other and in general, they house different socio-economic groups. The next sections describe the characteristics of each type of development.

2.2.4.1 Spontaneous Developments

The spontaneous or unplanned developments of the city are often described as informal developments. Typically, they develop at an individual level with independent landowners developing buildings in an incremental way (Nilufar, 2010; Parveen, 2006). During the exceptional expansion of the city in the 1970s and 1980s, these types of developments took place at an extraordinary rate (Islam, 1996; Nilufar, 1997, 2010). Broadly speaking, spontaneous developments are organic in character, with narrow, serpentine streets and irregular, inconsistently sized and asymmetric building plots.

Spontaneous land development is undertaken largely by individual private landowners. The general process of spontaneous developments has been documented in several studies (Enam, 2003; Nabi & Haque, 2003; Nilufar, 2010; Parveen, 2006;), showing that initially, independent private landowners buy land on the outskirts of the city, according to their affordability and aspirations, when the area is under-developed and cheap. Eventually, as the city grows, these areas become an integral part of the city. The streets are narrow and serpentine in nature because landowners mutually leave some of their lands to create an access from the main road network of the city to the plot. Unlike planned developments, civic amenities such as electricity supply, water, sewerage and roads are provided to these developments by the city corporation at a later stage. These areas are generally cheaper than areas of planned development and primarily house the middle- and lower-middle-income section of the city (Nasrin, 2011; Seraj, 2012). Commonly, the landowners develop the buildings in spontaneous developments over a long period, with the help of local contractors and quite often without consulting a professional such as an architect or builder (Enam, 2003; Parveen, 2006) (see Figure 2.5). In some of the spontaneously developed areas of the city that grew a long time ago and already have become an established part of the city, such as Shegun Bagicha, Ramna, Motijheel, Paltan and Kalabagan, the original buildings have been replaced with new apartment buildings that have been developed by formal real estate developers instead of the original land owner. However, these developments are not necessarily illegal; rather, they are developed primarily (particularly the land) without organised developers or proper planning, and initially without proper civic amenities.

Figure 2.5: *Example of Spontaneous Developments. Source: Author(1) & Adapted from Google Earth(2)*

Other spontaneous developments of the city are the slums and squatter settlements, which are illegal and temporary in nature and have been developed on vacant Government and private land. Both legal and illegal (slums and squatters) spontaneous developments account for 50% of the total housing stock of Dhaka (Siddiqui et al., 2010). According to Chowdhury (2013), although spontaneous developments house 50% of Dhaka's population (primarily middle- and lower-income people), the land share by such developments is only 20% of the total.

2.2.4.2 Planned Developments

Planned developments are recognised as the formal developments of the city and are undertaken by the public sector or the formal private sector (Nilufar, 2010; Seraj, 2012). The public sector includes different government organisations, while the formal private sector includes a number of registered real estate developers. A small number of public organisations, such as RAJUK, the National Housing Authority, the Defence Officer Housing Society (DOHS) and the Public Works Department (PWD) are engaged in planned developments; however, RAJUK is the main and key organisation (RAJUK, 2015). The types of planned developments undertaken by the public and formal private sector are described below.

2.2.4.2.1 Public Sector Developments

In Dhaka, land development with serviced plots (land lots) is the only form of planned residential land development by the public sector, apart from site and service projects to rehabilitate slum dwellers. In planned residential land developments, a large area of land is developed with the necessary infrastructure and then divided into varying-sized plots that are allocated and sold to citizens based on quota and lottery (Haque & Asami, 2011; Nasrin, 2011; Hafiz, 2011; The Daily Star, 2009). The plot owners are then responsible for building their own buildings, following the building codes and regulations. The common characteristics of such developments are straight, grid-patterned road networks with symmetric, regularly sized, rectangular plots (see Figure 2.6). Although in earlier developments, 20-katha[5] plots were available, in recent developments, due to land shortage, plot sizes commonly vary from 3 katha to 10 katha, with a growing preference for smaller plots such as 3 katha and 5 katha (Begum, 2010; observation through reviewing master plans of a number of projects). Further discussion of plot size is provided in Section 5.2.2. The public sector also develops

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[5] *Katha is the most commonly used unit for defining plot sizes in Dhaka. 1Katha=720 ft^2 (66.89m^2).*

rental public housing for government employees, which accounts for 10% of the total housing stock of the city (Chowdhury, 2013).

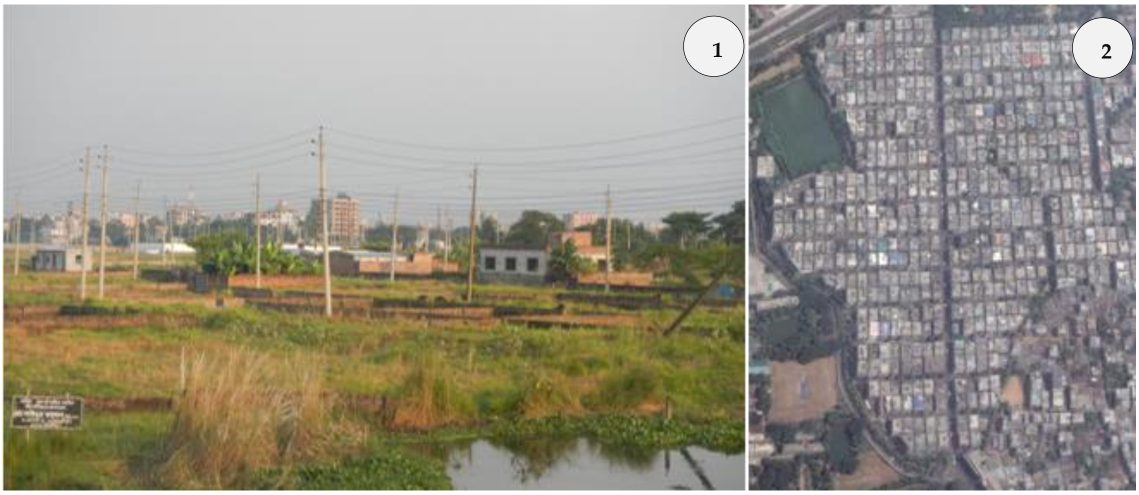

Figure 2.6: *Example of Typical Plot-based Land Development. Source: Author(1) & Adapted from Google Earth(2).*

In 2010, RAJUK initiated the first high-rise apartment projects (16-storeys) in Uttara (RAJUK, 2015). These apartment projects did not receive a positive response from the public. According to Kamruzzaman and Ogura (2007a), apartment units in high-rise buildings are less popular in Dhaka because of their higher price, lower return on investment and the greater preference of the people for owning land. While each plot in the latest projects by RAJUK, on average, would receive five applications, for the apartment projects, 2,500 fewer applications than available apartment units were received (The Daily Star, 2016). To date, none of the apartment buildings have been completed, mostly due to corruption within RAJUK (Naim-Ul-Karim, 2012).

Several studies have suggested that the development of high-rise apartments should be encouraged to address the land scarcity and high urbanisation pressure in Dhaka and plot-based land developments should be discontinued (Chowdhury, 2013; Hafiz, 2011; Nabi, Kamruzzaman, Khalil & Khandokar, 2004;). However, to date, plot-based land developments outnumber high-rise developments (RAJUK, 2015; Real Estate & Housing Association of Bangladesh [REHAB], 2012) and Kamruzzaman and

Ogura (2007b) believe that high-rises are less suitable in Dhaka's economic context. Commonly, it is accepted that given the existing socio-economic and political contexts of Dhaka, the existing plot-based land developments will continue to dominate as the typical type of planned residential development for a significant time.

2.2.4.2.2 Formal Private Sector Developments

The formal private sector, which consists of a number of registered real estate developers, has been present in Dhaka since the 1970s when there were five developers in the city. However, Dhaka's boom in real estate development occurred mainly from the 1990s, with 1,151 developers in Dhaka by 2016 (RAJUK, 2015; REHAB, 2016). In contrast with the public sector, the private sector is involved equally in land and apartment development projects.

The type and pattern of land developments by the private sector is similar to that of the public sector, with the division of a large area of land into varying-sized plots. However, privately developed land projects tend to have more small plots and the plot sizes tend to vary less (observation through reviewing the master plans of a number of projects: Swadesh Valley, Suncity, Green Valley, Asian city, Banasree and Aftabnagar). Many of these land developments have occurred in the city's fringe areas since the 1990s, due to the government policy of accelerating developments in fringe areas (Jahan, 2011; RAJUK, 1997). Therefore, the fringe areas of the current city are occupied overwhelmingly by private land developers with numerous new land development projects under construction. According to RAJUK's website, in 2015, 33 new projects of nearly 4,606 ha of land were under construction by private developers. RAJUK is currently developing the largest township of the city, Purbachal, on 2488.8 ha of land, along with two other projects—Uttara and Jhilmil. As a result, the indigenous spontaneous growth of the city in the fringe areas at an individual level that was dominant until the 1990s has become limited, as private sector land developers buy the land from individual owners to develop small- to large-scale planned residential areas. Such developments predominantly serve the higher- and upper-middle-income section of the city since these are serviced with proper infrastructure from the beginning and hence, are more expensive (Nabi et al., 2004; REHAB, 2012; Seraj, 2012).

The huge growth in land development by the private sector indicates the increased purchasing power of Dhaka city dwellers, as more of them can now afford to buy developed land. At the same time, it indicates the great energy demand of these developments for the near future. The existing typical planned residential areas currently accommodate the top 30% of the city from economic point of view (Chowdhury, 2013); however, this figure is likely to increase with the completion of the huge number of new developments that are under construction.

Apartment developments by the private sector can be divided into three categories: walk-up, mid-rise and high-rise apartments (Begum, 2010; Seraj, 2012). Apartment buildings up to six storeys are referred to typically as walk-up buildings in Dhaka, since the provision of elevator is not obligatory for this height. Buildings between 7 and 10 storeys are defined as mid-rise and those above 10 storeys are commonly referred to as high-rise buildings (see Figure 2.7). The identification of mid-rise and high-rise building is based mainly on the extra provisions that need to be provided after a certain height, according to building rules and regulations (further discussed in the following section). If a building is above six storeys, it must have an elevator with a generator connection that will function during a load-shedding period. If a building is more than 10 storeys high, in addition to the provision of elevator and generator, it must leave wider setback spaces from the side and rear plot boundary line (further discussed in the following section), along with provision for a community space that is equivalent to at least 5% of the building's total floor area.

Until the new construction rules in 2008, buildings in typical planned residential areas were allowed to have a maximum of six storeys. Therefore, the majority of the older planned residential areas primarily consisted of six-storey buildings.

Figure 2.7: *Examples of Walk-up, Mid-rise & High-rise Apartment Buildings. Source: Author(1,3) & Adapted from Google Earth(2).*

Apartment developments by real estate developers primarily are based on an agreed contract between a plot owner and a developer (Begum, 2010; Seraj, 2012). The most common form of negotiations are a 60-40, 50-50 or 40-60 share, which means that the developer will build the apartment building and give 40–60% of the total apartment units to the landowner and sell the rest to make profit. While walk-up apartment buildings are dominant in the planned areas, mid-rise and high-rise apartment projects are primarily undertaken in spontaneously developed inner city areas such as Shantinagar, Shegunbagicha and Ramna, which are and have become an established residential part of the city. As these areas had no height restrictions, the developers usually built high-rise apartments on plots that had better access from the main road network. Since the enactment of new rules in 2008, mid-rise and high-rise buildings are now also being developed in the planned areas (further discussed in the following section).

Although very limited in number, another type of high-rise development by RAJUK, known as 'block-based housing development', can be seen in Dhaka (RAJUK, 2015). In this type of development, a number of closely spaced high-rise apartments are built within a closed boundary. To date, there have been only five such developments; however, there are no regulations in the current building construction rules to control these types of developments (RAJUK, 2015). These projects have been criticised due to their sub-standard indoor living conditions. The target population of these projects is the middle-income section of the society (Nasrin, 2011; Seraj, 2012).

Figure 2.8: *Block Based High-rise Housing. Source: Author*

2.2.5 Development Plans and Regulations

This section reviews the plans and regulations that exist to control developments in Dhaka.

2.2.5.1 Dhaka City Development Plans

Although Dhaka as a town has a rich history of more than 400 years, the first trace of any kind of development plan for the city can only be found in the early 20th century. From the available literature, it could be identified that since then, five development plans have been prepared for Dhaka (Jahan, 2011; Rahman, 2008). The first was the 'DACCA Town Planning Report, 1917', which was prepared during the colonial period but was never implemented. The second plan, 'DACCA Master Plan, 1959' was the first comprehensive plan for Dhaka, prepared during the Pakistan period. Although the plan was intended for a period of 20 years(1959–1978), it lasted nearly double the estimated time until the new plan, the DMDP, was enacted in 1995 (RAJUK, 2015). Between 1978 and 1981, another plan, called 'Dhaka Metropolitan Area Integrated Urban Development Project (DMAIUDP), 1981', was prepared by the Planning Commission, but was not adopted by the Government.

The DMDP, which was prepared by RAJUK for a period of 20 years from 1995 to 2015, proposed development plans and policies for Dhaka covering an area of 1,432 km^{2}. It consisted of three plans: the Structure Plan, the Urban Area Plan and the Detailed Area Plan. While the Structure Plan and the Urban Area Plan provided a long-term and mid-term strategy for the greater Dhaka sub- zone, the Detailed Area Plan provided more-detailed planning proposals for specific sub-areas compliant with the Structure Plan and the Urban Area Plan (RAJUK, 1997). In the DMDP, the magnitude and direction of Dhaka's expansion, along with policy sets necessary to achieve overall planning objectives, were proposed. In addition, it considered the micro environmental aspects of Dhaka, such as the areas necessary to reserve for retention ponds, existing rivers and high-quality wet and agricultural lands. In total, 14 key development policies were proposed in the DMDP, focusing on two major agendas: i) consolidating the existing developments along with the supply of serviced lands to keep pace with the rapid rate of urbanisation and ii) conserving low-lying water-retention areas, including rivers and highly valued agricultural land, to maintain ecological balance and to prevent environmental degradation. The key policies of the DMDP indicate that the primary concern was to keep pace with the high urbanisation rate and to meet the huge demand for housing through consolidating the existing developments as well as supplying new serviced lands in the shortest possible time. In addition, it wanted to preserve the natural drainage system of the city by protecting the rivers, wetlands and retention ponds.

A review of the DMDP in 2015 found that the majority of the policy recommendations (23 out of 31) made in the DMDP Structure Plan under the 14 key development policies were not implemented and the remaining eight were implemented only partially (RAJUK, 2015). Several studies have identified that resource scarcity, undue pressure from vested interest groups and lack of willingness of the development authority are the major reasons for this (Chowdhury, 2013; Hoque, 2004; Rahman, 2008). According to Hoque (2004), the failure in policy implementation led to the uncontrolled growth of Dhaka, which has largely been manifested through a large number of illegal developments encroaching on the wetlands and open fields, particularly in fringe areas, resulting in a serious environmental threat to the city.

In 2016, RAJUK has proposed an updated and revised structure plan for Dhaka for the next 20 years (2016–2035) to cater for an estimated population of 26 million and an area of 1,528 sq.km[6]. The revised plan provides nine strategic directions for the future development of the city, with a total of 14 goals, 55 objectives and 132 policies (RAJUK, 2015). According to the revised plan, nearly 10 million people will be added to Dhaka city by 2035. Therefore, the revised plan still recognises the need for rapid infrastructural development as well as increased housing supply, particularly for the middle- and lower-income group of people; however, unlike the previous structure plan, it also emphasises following a sustainable path. The revised plan includes explicit policies focusing on liveability, functionality and resilience through enhancing land-use maximisation, better communications and other services, better urban living, affordable housing supply, employability, noise and air pollution control, solid waste management, safe water and sanitation, protection and preservation of natural resources. In addition, it focuses on prevention of floods,

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[6] *In the DMDP (1995–2015), the total area of RAJUK jurisdiction was noted as 1,528 sq. km; however, while preparing the revised Structure Plan (2016–2035), GIS calculations found that the total jurisdiction area of the DMDP (1995–2015) was actually 1,432 sq. km. The new Structure Plan has included another 96 sq. km and the total jurisdiction area now stands at 1,528 sq. km (RAJUK, 2015).*

reducing GHG emissions, enhancing energy efficiency and clean energy use, and reducing the impact of natural and manmade hazards (RAJUK, 2015).

While the focus of the previous plan was narrowed down to meet the rapid demand of urbanisation through increasing densities and accelerating serviced land supply, as well as protecting the environment by preserving the natural water bodies, the revised plan seems to reflect wider sustainable development agendas, particularly actions towards reducing GHG emissions and promoting clean energy use. The focus of these aspects are mainly the transport sector and organic waste disposal. There is no particular mention of urban development or buildings. Further, no action plan or directions regarding the urban microclimate as a consequence of the current development process are provided in the new plan. The need for research regarding energy-efficient buildings, industry, transport and consumer appliances is mentioned once as an implementation tool under the Policy-Eng/1.2: Research for Alternative Sources of Fuel/Energy; however, there is no mention of the resource efficiency of the building sector, nor of climate-responsive urban and building development to enhance overall energy efficiency.

Thus, although explicit policies regarding sustainable agendas such as liveability, affordability, better communication and avoiding environmental degradation are provided in the latest development plan for Dhaka, it does not prioritise reducing the future energy demand through urban and building-energy conservation strategies. The absence of such guidelines in the development plan suggests that either the development authority is ignorant of the possibilities of cutting future energy demand through appropriate urban policies or is unequipped to propose such policies due to lack of information, which is somehow reflected through the acknowledgement of the need for research regarding energy-efficient buildings. The review also highlighted the fact that having a policy or action plan is not sufficient in the context of Dhaka; identifying policy implementation strategies is equally important.

2.2.5.2 *Building and Land Development Regulations*

In addition to the overall city development plan, a number of regulations regarding building and land developments have a profound effect on shaping the built environment of Dhaka. At present, building construction and development within the DMDP area are controlled by the Dhaka Mahanagar Building Construction Rule 2008 and Bangladesh National Building Code (BNBC). Private land developments are controlled by the Private Housing Project Land Development Rule 2004. Several other rules, such as the Preservation of Historical Buildings/Infrastructures/Important Locations, the Natural Water Body Protection and Preservation of Open Space and Playground Act 2000, Brick Manufacturing (Control) Act 1989 and the Real Estate Development and Management Act 2010, are also present to protect historical buildings, natural water bodies and the open spaces of the city. They also serve to reduce air pollution due to brick kilns and to ensure the quality of the developments carried out by private sector developers.

RAJUK is the authority responsible for executing the above rules and regulations in Dhaka. Any kind of building or land development within the jurisdiction of the RAJUK area requires approval from the authorised officer or Building Construction Committee appointed by RAJUK. The following sections briefly discuss the three major development rules that are most significant in shaping the built environment of Dhaka.

2.2.5.2.1 *Dhaka Mahanagar Building Construction Rule 2008*

Dhaka Mahanagar Building Construction Rule 2008 was enacted after two short-lived amendments in 2006 and 2007 (RAJUK, 2008). The current rule superseded the Building Construction Act 1996, which was in effect from 1996 to 2006. The first construction rule for Dhaka city buildings was the Town Improvement Act 1953, which, with a minor amendment in 1984, was in effect until 1996 (Seraj, 2012).

Many professionals and experts believe that the Building Construction Act 1996 had the most detrimental impact on the built environment of Dhaka city (M. M. Chowdhury, M. A. Riyaad and R. Hafiz, personal communication, September, 2013). The bases for this belief are that the maximum dwelling-unit density per plot (land lot) in the 1953 rules was much lower and the setback distances between the buildings were higher than those that were allowed in the 1996 rules. For example, until 1996, each residential plot could have one dwelling unit/Katha; therefore, a 5-katha plot could have a maximum of five units. In 1996, the rules were simplified and the rear setback distance was reduced. With a maximum allowable height of six storeys, according to the 1996 rules a 5-katha plot in a planned residential development could have up to 12 units with narrower distance between buildings. According to Islam, Sharmin, Masud & Moniruzzaman (2009), the 1996 construction rules reflect the Government's policy of consolidating existing residential areas to meet the higher urbanisation pressure, as discussed in the previous section, which allowed increased densities. However, the 1996 construction rules were deemed too simple and ambiguous for a megacity like Dhaka, leading to a highly congested and unhealthy built environment with too many hard surfaces. This led to the preparation of a new set of construction rules that came into effect in 2008 (Seraj, 2012).

The new construction rules as specified in the Dhaka Mahanagar Building Construction Rule 2008, are based on floor area ratio (FAR) and maximum ground coverage (RAJUK, 2008). The FAR ratio is derived from dividing the total buildable floor area of a building by the total area of the land plot. Previously, a building simply needed to leave a minimum setback distance from the plot boundary and the maximum height of a building in planned areas was fixed at six storeys. The height of a building in other areas was determined based on the width of the access road, which was double the sum of the access road width and front setback distance. The 2008 rules set different FAR and ground coverage allowances for different-sized plots. Further, the height of buildings in planned areas are no longer restricted to six storeys and a trade-off can be made between the ground coverage and height, which means if the ground coverage of the building is less than that allowed in the rules, the building can go higher than six storeys to attain the maximum buildable area allowed. However, if the building is higher than 10 storeys, the minimum side and rear setback distance requirements increase from 1.25 m and 2 m, respectively, to 3 m.

Table 2.1: *Maximum FAR and Ground Coverage Allowed for Different-sized Plots in the 2008 Rules*

Plot Size (in Katha)	FAR	Maximum Ground Coverage (%)
Up to 2	3.15	67.5
More than 2–3	3.35	65
More than 3–5	3.5	62.5
More than 5–7	3.75	60
More than 7–9	4	60
More than 9–10	4.25	57.5
More than 10–12	4.5	57.5
More than 12–14	4.75	55.5
More than 14–16	5	52.5
More than 16–18	5.25	52.5
More than 18–20	5.25	50
More than 20	5.5	50

Other than specifying minimum setback distances from the plot boundary, maximum ground coverage and FAR, the 2008 rules also require that plots must leave at least 50% of the setback area unpaved or with a permeable ground surface. The rules also specify the minimum size of habitable rooms, kitchen, toilets and bathrooms, minimum window size for rooms and maximum extension of shading devices into the setback area. They also impose further restrictions on building heights, minimum requirements for staircases, elevators, ramps, disability access, fire escapes, boundary walls, utilities, basements and car parking, minimum width of the access road and special control for historic buildings, flood-prone areas and the areas next to wetlands and hills.

One of the main objectives of the new rules are to reduce the impact of flash floods as well as to improve ground water recharge through increasing permeable ground surfaces, since the ground water table of Dhaka city was decreasing alarmingly due to too many hard surfaces (RAJUK, 2008). The primary focus of the rules seems to be to control density through controlling the maximum buildable areas, height and distances between buildings, along with ensuring minimum standards for habitation. However, the 2008 rules do not provide any guidelines regarding the performance of the buildings from an energy consumption point of view. Additionally, even though one of the major goals of the new rules was to create variations in the built environment, a review of a number of plans created following the new rules revealed that the new FAR and ground coverage rules have not really affected the buildings on smaller plots (up to 5 katha). This was further verified during the field study. Interviews with practising architects also supported the fact that with the allowed FAR and ground coverage, a building on a smaller plot cannot go higher (M. M. Chowdhury and M. A. Riyaad, personal communication, September, 2013). Therefore, other than slightly reducing the building footprint area and increasing the permeable ground surface area, the 2008 rule made no significant difference in the built environment in the case of smaller plots such as 3 katha and 5 katha. Previously, the ground coverage of a 5-katha plot could be up to 73%; according to the new rules, the maximum ground coverage has been reduced by 5.5%. Although bigger plots (above 10 katha) in planned areas can now have buildings between 10 and 14 storeys as a result of the new rules, these plots are fewer in number.

A number of professional bodies, such as the Institute of Planners, Institute of Architects, Bangladesh, Institution of Engineers, Bangladesh, Bangladesh Paribesh Andolon and REHAB were involved in preparing the 2008 rules. However, these rules were not based on any first-hand research; rather they were based on subjective measures. No rationale or published documents can be found on why the minimum setback distances between buildings are between one and two metres, which creates narrow canyons between buildings.

2.2.5.2.2 Bangladesh National Building Code

While the 2008 rules are applicable for Dhaka city only, BNBC applies to the whole country. BNBC intends to establish a minimum standard for design, quality of materials, construction, use and occupancy, location and maintenance of all buildings within Bangladesh (Housing and Building Research Institute, 2006). The primary aim of BNBC is to ensure public safety, health and general welfare that are influenced by the construction, alteration, repair, demolition or occupation of a building. It provides specifications regarding general building requirements, such as access to the building, minimum open space, landscaping, natural drainage, damp-proofing, rat-proofing, sanitation and community amenities, as well as fire protection, minimum standards for building materials and fixtures, structural design, building services and construction safety. Specifications are provided according to different building categories, such as residential, institutional, commercial, industrial and educational. Although comprehensive specifications are provided in BNBC to maintain a minimum standard and overall well-being of the occupants, it does not provide any specifications regarding minimum building-energy performance. It is known unofficially that an amended version of BNBC is underway that includes specifications regarding water and energy efficiency, but so far it is not yet available.

BNBC was first introduced in 1993 and was enhanced once in 2006. Although following BNBC is not obligatory in Dhaka, many of the specifications provided in the BNBC are followed.

2.2.5.2.3 Private Housing Project Land Development Rule 2004

Private land development projects in Dhaka are controlled by this rule, which is formulated for Dhaka city only (RAJUK, 2004). This rule was enacted in the context that a large number of land development projects in the fringe areas of Dhaka were being developed rapidly by private developers and some of them did not have enough the public facilities that are required for liveable residential neighbourhoods. Additionally, these projects were encroaching on the valuable wetlands. The rule specifies the minimum width of the primary, secondary and tertiary roads, as well as minimum amenities such as schools, health centres, community spaces, markets and parks. In addition, it requires the developers to show actions taken to protect the surrounding environment and natural drainage system.

It is evident from this review of the key development plans and regulations that the primary focus of the development authority is to meet the pressure for rapid urbanisation, along with ensuring minimum standards for habitation and the protection of natural wetlands. None of the regulations addresses the energy performance of urban developments and buildings, indicating that this is not, as yet, a priority area of the development authority.

2.2.6 Energy Impact of Dhaka's Urban Development

Although several studies in the 1990s pointed to probable higher energy consumption due to rapid urbanisation and urban development practices in Dhaka (Ahmed, 1996; Hossain & Nooruddin, 1993; Karmakar & Khatun, 1993), studies regarding the energy impact of the development practices are scarce. The above studies observed higher air temperatures in several parts of Dhaka compared with the surrounding non-urban areas, which led them to infer that it is likely causing a higher consumption of energy use for cooling, since Dhaka's climate is predominantly warm and humid. However, the studies did not examine the extent to which the higher temperature was affecting energy consumption. A number of later studies have examined the microclimatic impact of the existing urban development practices, primarily focusing on outdoor thermal comfort and the phenomenon known as the 'Urban Heat Island (UHI)' (Ahmed, 2003; Das & Karmakar, 2015; Kakon & Nobuo, 2009; Kushol, Ahmed, Mohataz & Hossain, 2013; Roy, Asaduzzaman & Jahan, 2001; Sharmin & Steemers, 2013; Sharmin, Steemers & Matzarakis, 2015). In addition, a number of studies are available regarding the indoor thermal comfort and indoor thermal performance of different types of urban buildings in Dhaka (Ahmed, 1994; Ali, 2007; Hafiz, 2004; Islam, 2011; Mallick, 1994; Mojumder, 2000). However, none of these studies investigated the impact of the altered microclimate or the indoor air temperature on energy consumption.

Only a few published documents could be identified that investigated the effect of different development practices on energy consumption or the energy consumption in general of Dhaka city buildings. Mondal and Denich (2010) found that the electricity consumption of Dhaka's residential buildings nearly doubled between 2005 and 2011. The main reason for the increased consumption was identified as the increased standard of living of the higher-income group, which led to the use of more air conditioning (AC) (Ahsan, 2009; United News of Bangladesh, 2014). According to UNB (2014), the use of AC accounts for 21% of the country's total electricity consumption. Another study conducted in a typical apartment building with upper-middle-income people found that on average, the use of AC and ceiling fans accounts for 38% of the total household electricity consumption (Ahsan, 2009). The same study recommended that doubling the external wall thickness on east and west walls, using hollow clay tiles on the roof instead of weathering course, and using an appropriate horizontal overhang ratio could all reduce energy consumption by 26%. However, the study results were based on assumptions made through simple numerical calculations and only investigated seven apartment units from a single apartment building; hence, the results lacked generalisation.

A study by Ahmed (2010), which investigated the effect of the surrounding built environment on residential energy consumption, found that apartments that have higher surrounding open spaces or in, other words, are situated in a less densely built environment, are more energy efficient. To demonstrate this efficiency, the study considered the electricity consumed per unit area for a specific period expressed in kWh/m^2/year. Apartments with a consumption of 21–25 kWh/m^2/year were considered efficient; 25–35 kWh/m^2/year was considered moderately efficient; and 35–50 kWh/m^2/year was considered inefficient. The study investigated 112 apartment units from 30 buildings in three types of developments and used statistical methods to analyse the data. Based on the findings, the study suggested that larger areas of surrounding open spaces, greater provision of green areas and water bodies, higher ratios of distance to height of adjacent building and greater access of natural light into the indoor spaces result in higher building-energy efficiency in Dhaka. While the study provided general recommendations based on comparative analyses, it did not specify the minimum distance between buildings or the amount of open space or green space needed to achieve improved performance.

In a study by Sharmin and Steemers (2013), four simple hypothetical urban arrangements were investigated to discover the best arrangement, from an energy-consumption point of view, in Dhaka's climate. The study focused only on consumption of power for cooling and used a building computer simulation for the investigation. According to the study, pavilion-type arrangements are better than enclosed courtyard pavilions, open-square courtyard pavilions and open-rectangular courtyard pavilions. However, this study did not aim to provide recommendations; instead, it focused on obtaining an understanding about the effect of different urban arrangements on energy consumption. The study used simplified single-room models that were not applicable in the real-life, complex situation.

Parveen, Soebarto and Williamson's (2015) study, focusing on the impact of UHI on building-energy consumption in a typical planned residential area of Dhaka, found that the cooling energy consumption of the buildings in the studied area increased by 5.1% for every 1°C air temperature increase. Another study on Dhaka's cooling energy demand change, based on projected temperature increases due to climate change, found that the number of days on which cooling will be required will increase by 41.2%, 54.3% and 71.9% in 2020, 2050 and 2080 respectively, when considering 28°C as the threshold temperature for AC use. Although the major concern of this study was to ascertain the effect of increased temperature due to climate change, it provides a useful insight suggesting that if the urban air temperature elevation due to UHI is not controlled, significantly more energy will be wasted on energy consumption for cooling in the future (Mourshed, 2011).

No other studies were found regarding the effect of different practices on energy consumption or the energy consumption of Dhaka city buildings. This suggests there is a dearth of information in this area, even though many authors have suspected that an inefficient energy-consumption pattern exists in Dhaka due to lack of passive-design considerations both at the urban and building level (Ahmed, 1996; Mallick & Mourshed, 2012). Among the limited number of studies that were found, none were comprehensive; rather, they focused on a particular area.

In contrast, a large number of studies have focused on the social and environmental effects of the rapid urban development in Dhaka. Byomkesh, Nakagoshi and Dewan (2011) showed that the green areas of Dhaka have declined significantly, with Dhaka now having the lowest (8%) green spaces/capita in the world; the ideal tree coverage for a city is 20%. Yamane, Kiguchi, Terao, Murata, and Hayashi, (2013) found that the surface temperature of Dhaka is increasing at 1.9°C/100 years and Chowdhury, Razzaque, Helali and Boden (2010) found that the roadside noise level in a mixed-use area of Dhaka is 82 dB, which is far higher than the acceptable limit (50–60 dB) set by the Department of Environment. In addition, a large number of studies identified social exclusions (Begum, 2007; Hossain, 2006; Siddiqui et al., 2010), slum developments (Corner & Dewan, 2013; Islam, 2005; Rana, 2010), resource inequality (Siddiqui et al., 2010), air pollution (Begum, Biswas & Hopke, 2011; Rabbani, 2009), surface water contamination (Dewan, Kabir, Nahar & Rahman, 2012; Sohel, Chowdhury & Ahmed, 2003); ground water deterioration (Rahman, 2011); solid waste disposal(Hai & Ali, 2005; Huda, 2011), and decrease in wetlands and wetland encroachment (Dewan & Yamaguchi, 2009; Hoque, 2004) as functions of the rapid urbanisation that has occurred in Dhaka.

The available literature suggested that to date, the social and environmental effects of rapid urbanisation have been prioritised in Bangladesh rather than the issue of energy impact. This is reflected in Government policies and regulations as well. While there have been a number of regulations regarding wetland conservation since the early 21st century (Jahan, 2011; RAJUK, 2000, 2004), no regulations are available yet regarding energy conservation in buildings. This could be because Dhaka is still a low-energy-consuming country and insufficient studies are available for developing energy-conservation strategies in Dhaka's contexts; however, the scenario is changing rapidly, as several studies have identified that the standard of living is increasing and hence, the use of AC to deal with the rising urban air temperature. Additionally, a large number of new urban developments and buildings with high energy demands are on the horizon. Therefore, it is imperative that this gap in knowledge is addressed immediately so that energy-conservation strategies can be developed in Dhaka's contexts to ensure the energy security of the future developments, as well as to reduce the economic burden for the country and to have a minimum impact on the environment.

2.3 *ENERGY (ELECTRICITY) CONTEXTS*

This section reviews the overall energy (electricity) contexts of Bangladesh, along with a review of the power sector master plan, followed by a detailed examination of Dhaka's energy contexts.

2.3.1 Energy (Electricity) in Bangladesh: Overall Scenario

The development of Bangladesh, as for many other developing countries, is challenged by acute energy scarcity and poor energy systems. According to the Bangladesh Government (GOB), 76% of the country's population has access to electricity (Ministry of Power, Energy and Mineral Resources [MPEMR], 2016). This includes the 4.5 million rural households without grid connection that are supplied with very basic electricity (45W–120W) through solar home systems (SHS) (Infrastructural Development Company Limited [IDCOL], 2014; Sustainable and Renewable Energy Development Authority [SREDA], 2016). However, other sources have found that only 59.6% of the total population has proper electricity access, mostly within the cities (CIA, 2015; WB, 2015). The country has one of the lowest per-capita energy-consumption rates in the world, at 371 kWh/year according to GOB or 293 kWh according to other sources (CIA, 2015; MPEMR, 2016; WB, 2015). It is commonly agreed that having a grid connection in Bangladesh does not ensure reliable electricity supply. Frequent power cuts, commonly known as 'load-shedding' in Bangladesh, are common, due to the large gap between demand and supply.

Conversely, electricity demand is increasing rapidly at an annual rate of 10% (EIA, 2013; RAJUK, 2015). According to an estimation by Mondal, Boie and Denich (2010), in the cases of a low gross domestic production (GDP) growth scenario (below 5.5%), average (6.5%) or high (above 7.5%), the annual per-capita energy consumption of the country will increase to 658 kWh, 963 kWh and 1451 kWh respectively by 2035. These figures are 2.25, 3.29 and 4.95 times higher than the current annual per-capita energy consumption of 293 kWh. In 2016, Bangladesh is recognised as the world's ninth fastest-growing economy, with a GDP growth of 6.6% (International Monetary Fund [IMF], 2016); hence, it can be expected that the energy demand of the country will continue to increase rapidly. It is important that the increasing energy demand of the country is met immediately through a reliable and affordable energy supply (Masuduzzaman, 2012); however, the current energy supply of the country already cannot meet the peak energy demand (Ahmed, 2011; Kabir & Endlicher, 2012). The current gap between electricity demand and supply is between 600 and 1200 MW; however, it can reach 1500 MW during the irrigation season (March to May), when the energy demand is highest (Rasel, 2015).

The power or electricity sector of the country is state owned and controlled under the MPEMR. The Bangladesh Power Development Board (BPDB) manages the overall generation, transmission and distribution of electricity through multiple different entities. However, it is widely accepted that the power supply system of the country is highly inefficient (Ahmed, 2011; Haque & Rahman, 2010; Imam, 2011;

Uddin, Taplin & Uddin, 2006;), with several studies noting that a substantial amount of energy is wasted due to inefficiency at different levels of the power sector (Alam, Kabir, Rahman & Chowdhury 2004; Barnes, Khandker & Samad, 2010; Sarkar, Ehsan & Islam, 2003). Many of the existing power plants have become old and inefficient and a significant amount of energy is lost during the transmission and distribution phases (Alam & Islam, 2015; Alam et al., 2004). According to a study by Alam & Islam (2015), 13.55% of this is simply due to system loss during distribution. Alam et al. (2004) found that 90% of this distribution loss was due to non-technical reasons such as theft and pilferage by metered consumers, illegal connections, improper operation of meters, illegal use, and manipulation by utility personnel.

Several studies in the 1990s found that in some areas, nearly 50% of the energy was lost during distribution per year, which was enough to establish a 400 MW power plant (Alam et al., 2004; Alam & Islam, 2015). In monetary terms, this average loss was worth US$247 million per year (Alam et al., 2004). Alam et al. (2004) held that since the power sector of the country was built on loans and foreign donations, no one was interested in stopping the pilferage and theft. Additionally, the country does not have a skilled workforce, which led to a daylong blackout in November 2014 (The Daily Star, 2014). Further, the country cannot generate energy to its full installed capacity because of a gas shortage and maintenance issues in the old plants (Alam & Islam, 2015; Munim, Hakim & Abdullah-Al-Mamun, 2010). The current installed electricity generation capacity in Bangladesh is 12,365 MW but to date, the maximum output delivered has been only 8,968 MW (BPDB, 2016).

Heavily subsidised tariffs for residential and agricultural use have been identified as one of the major barriers for the country's power sector, meaning that the BPDB cannot collect enough money for proper maintenance of the power plants (BPDB, 2011; Mujeri, Chowdhury & Shahana, 2014). If these subsidies are withdrawn, the bulk electricity tariff will increase by 330% (BPDB, 2011). Even though experts advise this subsidy withdrawal, it is unlikely to proceed for political reasons (Ahmed, 2011; Gupta, Ferdous & Saleque, 2012; Mujeri et al., 2014).

The existing energy scenario of Bangladesh, as discussed above, highlights that multiple factors are responsible for the existing poor energy system of the country. The biggest problems are resource scarcity, not only in monetary terms but also in skilled labour and shortages of fuel, along with corruption. The existing contexts suggest that even though the demand for energy is rising rapidly, it is unlikely to be met through the existing energy system. Additionally, a large-scale centralised energy system with highly technical power plants that rely heavily on foreign loans and donations and highly skilled labour may not be the most suitable option for Bangladesh. Instead, alternative, decentralised energy systems based on renewables may be more suitable, as the users of energy will be in control of their own energy use instead of being controlled by external forces such as insufficient energy supply and corrupt personnel.

2.3.1.1 Power System Master Plan 2010

To meet the increasing energy demand as well as to improve the energy scenario of Bangladesh, the Power System Master Plan (PSMP) was proposed in 2010 with short-, mid- and long-term goals. Based on the demand forecasted in PSMP, the Government aims to increase the generation capacity from 12,365 MW to 24,000 MW by 2021 and to 40,000 MW by 2030 (BPDB, 2011). By 2021, it aims to provide electricity to 100% of the population. Other major agendas specified in the PSMP are digitising the energy system, increasing the skill of energy personnel and collecting the equivalent of US$24 billion of funds through foreign loans, donations and private investments (MPEMR, 2016; BPDB, 2016).

Half of the targeted 40,000 MW electricity generation capacity in 2030 will be generated by coal-powered plants, 25% by gas, 10% by liquid fuel and the remaining 15% by other sources, such as renewables and nuclear (BPDB, 2011). Currently, only

2.02% of the country's total power is generated by coal, 61.69% by gas, 21.26% by furnace oil, 8.31% by diesel and 1.86% by hydro (along with 4.85% of imported electricity from neighbouring countries) (MPEMR, 2016). To date, natural gas is the only major domestic energy resource; however, the reserves of natural gas are declining rapidly and will last only for another 7–20 years (Kamal, 2010; Sarkar, Ehsan & Islam, 2003). This declining gas resource has been stated as one of the major reasons for the heavy shift towards coal to meet future energy demand (Alam & Islam, 2015; BPDB, 2011). Other major reasons for using coal are that Bangladesh has some good-quality coal reserves (although extraction is yet to be explored) as opposed to minimal liquid-fuel reserves (90% of the country's petroleum is imported from other countries). Additionally, coal is cheaper (Mourshed, 2013; Munim, Hakim & Abdullah-Al-Mamun, 2010). Even though the Government plans to use clean coal technology to minimise carbon emissions, it is certain that the country's overall energy system will be more carbon intense and the future Bangladesh will emit significantly more GHGs than today. Despite having a domestic coal reserve, half of the coal required will need to be imported (BPDB, 2011), which will leave the country dependent on others.

The location of the coal-powered plants is also a major concern (Ahsan, 2011; Chaitanya, 2013). At present, a 1,320 MW coal-powered plant is being constructed at Rampal, which is only 14 km away from the world's largest mangrove forest Sundarbans, a UNESCO world heritage site. Studies have confirmed that such a project at Rampal not only will put Sundarbans at grave risk but also is illegal, according to the Ramsar Convention[7] (Rahman, 2013). In addition, the planning of a 4000 MW nuclear power plant installation has also been criticised, due to the risk of radiation issues, the country's unpreparedness in the case of an emergency such as an

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[7] *The Ramsar Covention is an international environmental treaty for the conservation of wetlands, to which Bangladesh is a signatory (Chaitanya, 2013).*

earthquake, as well as the lack of technical skill and labour to run and manage such large-scale modern technology (Siddique, 2014).

Along with fossil fuels, 10% of the country's total electricity supply has been targeted to come from renewables by 2030. A separate policy, 'Renewable Energy Policy 2008', was adopted in 2010 and a separate agency, SREDA, was established in 2012 under the MPEMR, to support the development of sustainable and renewable energy in Bangladesh. To achieve the goal of 10% of electricity coming from renewables by 2030, a target of 5% was set for 2015; however, this target was not met and currently, renewable energy accounts for only 1.63% (201.9 MW) of the total electricity produced (SREDA, 2016). The majority of the existing renewable supply is through solar PVs (194 MW), with a small contribution from wind, biogas and biomass (SREDA, 2016). 4.5 million off-grid SHS in rural Bangladesh are the primary contributors to the existing solar energies. Generally, the SHS of the country are considered successful, as a large number of rural households now have the basic benefit of electricity (IDCOL, 2014). The use of SHS in rural Bangladesh has created the second-largest solar energy-related job market in the world and it is one of the largest and fastest-growing off-grid renewable energy programmes in the world (IDCOL, 2014; Mondal, 2010; Urmee & Harries, 2009). Due to the past success of SHS, a large number of foreign donors such as WB, ADB, Japan International Cooperation Agency, The United States Agency for International Development and The Department for International Development (DFID) are interested in providing funding to extend the solar programmes in Bangladesh (IDCOL, 2014). Other than the SHS, new buildings in Dhaka are required to meet a portion of their energy demand through solar PVs, which is discussed in further detail in the next section. In general, although solar energy accounts for a tiny portion of the country's total electricity generation, electricity generation through stand-alone solar PVs at small scale is established in the country already.

According to Rahman and Ahmad (2013), the performance of the SHS are quite satisfactory, without any major failures. In addition, both the solar panel components and workforce are available in Bangladesh and the PV modules are now being manufactured within the country (Rahimafrooz, 2016). However, the success of solar PVs has come mainly through off-grid connection in rural or remote areas. Although many government buildings are now installing solar panels, they are the stand-alone type and the technical feasibility of grid-tied solar panels in urban contexts still needs examination (BPDB, 2016).

To improve the serious energy scenario in Bangladesh, the PSMP has also specified policies and actions regarding energy efficiency. It has set a target of conserving 15% of energy through increasing the efficiency of power plants, along with reducing the system loss to single digits by 2030 (MPEMR, 2016). In addition, an energy-efficiency project to implement energy-efficiency standards and labelling for different appliances has been launched with the support of the UNDP (Amin, 2016). This project aims to establish minimum performance requirements for several appliances such as air conditioners, ballast, lights, fans, motors, refrigerators and freezers. Developing the facilities to test these appliances is another goal of the project. The project, which ran from 2012 to 2016, has been successful in increasing the use and production of CFL bulbs and fluorescent T-5 tube lights, as well as in reducing the use of incandescent bulbs. However, the market availability and penetration of other efficient appliances are scarce and there are no incentives to encourage the use of energy-efficient appliances or to stop wasteful consumption of energy. Even though buildings are the major consumers of energy and most of the future energy demand will come from the upcoming buildings, there are no policies to improve energy efficiency in buildings.

2.3.2 Energy (Electricity) Contexts of Dhaka

Dhaka is the primary consumer (55%) of Bangladesh's total generated electricity (Haider & Ahmed, 2016). Half of this is consumed for residential purposes, followed by industries (37%), commercial (10%) and others such as street lighting and agriculture (3%) (Dhaka Electricity Supply Company Limited [DESCO], 2015).

Without exception, the most important city of the country suffers from an unreliable and inadequate energy supply. A study conducted by Kabir, Endlicher and Jägermeyr in 2010 found that the peak electricity demand of the city at that time was around 2000 MW, whereas the city was supplied with only about 1000–1200 MW, resulting in 8–10 hours of daily load-shedding in many parts of the city. The overall energy situation of the city became so serious that the Government imposed several embargos. For example, electricity connection to new residential buildings was suspended between 2009 and 2011 and the trading time for markets and shops was reduced. Although the current power situation of the city is better than earlier, it still experiences 2.5–3.5 hours of daily load-shedding, particularly during summer (DESCO, 2015; Rasel, 2015). However, the timing of load-shedding is now pre-scheduled.

The embargo on new connections was lifted in 2012 on condition that all new residential buildings must manage 3% of their total load (and for commercial buildings, 5% of the total lighting load) through solar PVs or other renewable sources. Additionally, each household can have a maximum 2 KW load connected and must not use air conditioners, which have to be declared on a stamp paper (BPDB, 2011). To obtain a connection of more than 2 KW load per household, special permission needs to be obtained from the electric supply authority, although in reality, this rule is frequently violated (United News of Bangladesh, 2014).

Dhaka Power Development Company Limited (DPDC) and DESCO are responsible for electricity distribution in the city. The electricity demand of the city is growing at an annual rate of 12%, which is higher than the country's overall growth rate of 10% (DESCO, 2016a). However, both in DESCO and DPDC areas, the system loss is claimed to be around 8%, which is lower than the country's overall system loss of 13.55% (DESCO, 2015; DPDC, 2015; MPEMR, 2016). Dhaka city suffers the most from the interrupted and unreliable energy supply, as all major administrative, commercial, institutional and industrial activities of the country are Dhaka-centric.

To deal with the occurrences of load-shedding, every household in the city manages their own emergency power supply through different methods, according to affordability (Parveen, 2012; Rahman, 2011). The most common power sources that are availed by the less affluent section of the city are candles, kerosene lamps and rechargeable lamps and fans. In contrast, the affluent section of the city uses Instant Power Supply (IPS) and diesel or gas-run generators.

IPS, a very common emergency power supply system in Dhaka, is an electrical device that consists of a charging unit, a battery and an inverter (Mehbub, Kabir, Khandaker & Chowdhury, 2012). It is connected parallel to the main power supply and stores electricity from the grid when the power is available, discharging it during blackout periods. However, the use of IPS has been identified as inefficient and having a detrimental impact on the overall power system, since it converts the AC current of the main grid to DC current while storing it into the battery and then converts it back to AC current to be used during the load-shedding period. This results in significant power loss because of the double conversions (Sarwar, 2010). One study found that for 100,000 households using a 400 W IPS, the amount of electricity loss is equal to 123.2 MWh, which is enough to establish a medium-sized power plant (Sarwar, 2010). The same study found that the efficiency of the examined IPSs was only 51.68%, as to discharge 323 W equivalent power, the IPSs consumed 625 W. Several other studies have confirmed that the use of IPS stresses the existing power supply and exacerbates the load-shedding situation (Mehbub et al., 2012). Additionally, the disposal of IPS batteries imposes environmental hazards (Mehbub et al., 2012).

Despite the inefficiency and negative impact of the IPS, it is the most popular and common form of emergency power supply among the middle- and higher-income section of the city. In 2010, more than six of households in an affluent area (Uttara Sector 4) of Dhaka had an IPS (Sarwar, 2010). According to Mehbub et al. (2012), the major reasons behind the popularity of IPS is that it starts working as soon as the main power goes off, it is noiseless and it does not require additional money to purchase fuel.

Generators are used mostly by the higher-income section of the city. According to building construction rules, apartments more than six storeys high must have an elevator and be supported by a generator during the blackout period. However, developer's apartment buildings are usually provided with an elevator and generator even when they are only six-storey buildings (Seraj, 2012). As a result, a large number of apartment buildings in the planned residential areas of Dhaka have generators run by diesel or gas, expelling toxic fumes onto the street while in operation. Many wealthy households have both a generator connection and an IPS. These generators cause a high level of air and noise pollution while in operation. However, the Government does not impose any restrictions on their use or policy to ensure the minimum performance of IPS or generators. There were no studies on the economic and environmental impact of the use of IPS or generators. On the other hand, according to Kabir, Endlicher and Jägermeyr (2010), the available exposed roof-tops of Dhaka can generate nearly 1000 MW of electricity through 75 Watt solar PVs, which could effectively be used to reduce the city's power demand gap.

It is clear from the above discussions that the overall energy scenario of Dhaka is poor, with an unreliable and inadequate energy supply. Further, energy wastage prevails in different forms at different levels, particularly through the use of an inefficient emergency power supply by the middle- and higher-income section of society. However, city dwellers are used to managing their own energy already and new buildings are obliged to manage some of their energy demand through renewables such as solar PVs. Hence, a decentralised energy system based on renewables seems to be a potential option to meet the huge energy demand of the new buildings of Dhaka.

2.4 CONCLUSION

This chapter has outlined the urban development and energy contexts of Bangladesh in general and of Dhaka in particular. The key development plans and regulations that exist to control the developments in Dhaka have been reviewed, along with the energy master plan for Bangladesh. Certain gaps and issues pertaining to this research have been identified, as summarised below:

1. A phenomenal growth in population has been taking place in Dhaka, particularly since 1971, resulting in a large number of new urban and building developments. However, the dominant growth pattern of the city has shifted significantly from spontaneous to planned, plot-based land developments. The upcoming buildings in these new developments will pose a high energy demand and to address that, reduction in the energy consumption of future buildings through conservation strategies is of utmost importance. None of the existing key plans, policies and regulations address this issue explicitly and the country still does not have any building energy code. Additionally, very few studies exist regarding the energy impact of current urban developments, energy consumption of buildings in general, or building-energy conservation strategies in Dhaka. This suggests an urgent need for substantial research on this topic.
2. The poor energy system of Bangladesh is characterised by heavy system loss, wasteful use of energy, inefficient old power plants, resource scarcity, dependency on foreign loan and donations, an unskilled workforce and corruption. This is a strong indication that the future energy demand of the country is unlikely to be met through the existing energy system in a traditional

way. Hence, traditional large-scale centralised energy system does not seem to be the best option for Bangladesh; rather, an alternative, decentralised renewable-based energy system, in which the users of the energy have more control over their energy use, seems more appropriate in the given contexts of the country.

3. The review of the power sector master plan for Bangladesh revealed that the country is investing heavily in large-scale coal-based power plants, guaranteeing significantly higher CO_2 emission in the future as well as weakening energy security, since half of the coal will have to be imported. In addition, it has been identified that the coal power plants will put the only mangrove forest of the country and the largest in the world at grave risk. Only a tiny portion (10%) of the country's future energy demand has been targeted to be met through renewables and the deployment of renewable energy is primarily rural based, as grid-connected PV is not yet available. While the energy efficiency of power plants and some major appliances are on the agenda for improvement, the energy efficiency of buildings has not been addressed in the PSMP, even though the majority of the future demand is likely to come from buildings. Given the current global energy contexts of depleting fuel resources and global warming due to GHG emissions, it can be said that the country's future energy plan is very regressive. While a large number of foreign donors are interested in investing in renewable energy systems, funding for coal and other traditional plants will have to be managed primarily from domestic reserves and sources. In contrast, instead of establishing new power plants, the majority of the future energy demand could be met by using the new buildings as infrastructure for deploying renewable energy systems.
4. It is certain that to address Bangladesh's huge energy demand challenge, which is due to rapid urbanisation, buildings will have to reduce their energy consumption significantly. To achieve that, it is essential to identify the parameters that influence the energy consumption of buildings and the way

they operate. Therefore, an investigation of the existing literatures was conducted to identify the parameters that influence the energy consumption of buildings. The findings of this investigation are presented in the next chapter.

3 LITERATURE REVIEW

> Energy is the number one sustainability issue … .To be sustainable, a city must be energy efficient, and for a city to be energy efficient its buildings must be energy efficient. (Lechner, 2015, p. 97)

> The challenge now is for all nations to support their building industries by mainstreaming energy efficient and low-GHG emissions building. (Lemmet, 2009, p. 3)

3.1 INTRODUCTION

The primary aim of this chapter is a review of the existing relevant literature to address the first objective of this research; that is, to identify the parameters that influence the energy consumption of buildings as well as the relevant details of these parameters. First, the relevant literature will be examined to obtain further understanding of the contextual settings of this research at a global scale, with a particular focus on energy and buildings.

The chapter consists of two sections. The first section describes the energy challenges of the 21st century at a global scale, along with the role of buildings in these challenges. The second section critically explores the parameters that influence the energy used by buildings, in three sub-sections: urban-level parameters, building-level parameters and occupancy-level parameters.

3.2 THE GLOBAL CONTEXTS

3.2.1 Energy Challenges

'Energy' has been identified by many researchers as the most significant challenge of the 21st century (Bose, 2010; Droege, 2002, 2006, 2009; Lechner, 2015;

Lehman & Thornton, 2015; Williams, 2012). As discussed in Chapter 1, the main reasons for this are the rapidly growing global energy demand set alongside depleting global energy resources, as well as the negative effect this growing demand has on the environment. According to the International Energy Agency (2015a), the global demand for energy will grow by 33% between 2013 and 2040. Further, it has been estimated that by 2050, consumption of energy for cooling will increase by 150% globally and 300–600% in developing countries, due to an increase in the use of AC (IEA, 2013). At the same time, common fuel sources such as oil and gas are due to expire before 2050 and coal by 2100 (Asif & Muneer, 2007; Droege, 2002; Lehmann & Thorton, 2015; Lior, 2008; Thielemann & Gerling, 2007; Shafiee & Topal, 2009). Moreover, energy-related CO_2 emissions are projected to be 16% higher in 2040 than at present (IEA, 2015b).

It is known that the demand for energy is growing primarily due to rapid population and urbanisation growth in Asian and African developing countries. For the sake of continued development in those regions, it is important that the growing energy demand is met (Nandi & Bose, 2010). However, how this energy demand can be met is a dilemma. The majority of developing countries still investing largely in traditional fossil-fuel-based power plants, which are a cheaper option than other methods of generating energy. It has been recommended strongly that developing countries should shift significantly towards renewable energy sources (IEA, 2015a, 2015b). Not only is this shift needed for better energy security in the face of resource depletion but also it is essential to reduce the negative impact of fossil fuels on the environment (Hong et al., 2007; Nandi & Bose, 2010). Droege (2006) argues that even if there were no issues of resource depletion, consuming fossil-fuel-based energy would not be an option because of its effect on global warming.

Global warming, or the increase in average global air temperature, is widely accepted to be occurring due to the increased emission and concentration of GHGs in the atmosphere as a result of various human activities such as the combustion of fossil fuels to produce energy (IEA, 2008; IPCC, 2007). At present, the global air temperature is 0.5°C higher than what it was at the time of the industrial revolution (Stern, 2008; Williams, 2012). Studies have predicted that during the 21st century, the global temperature is likely to increase further by 0.3–1.7°C in the case of the lowest GHG emission scenario and by 2.6–4.8°C in the case of the highest GHG emission scenario (Stocker, Qin, Plattner, Alexander, Allen, Bindoff, … Wuebbles, 2013).

It is now an accepted fact that if global warming is not controlled, it will affect humanity catastrophically. If the global temperature rises more than 2°C, a large number of species will become extinct and a significant depletion of ocean fish stock will occur due to ocean acidification (Stern, 2008; UNEP, 2009; Williams, 2012). In addition, the frequency of extreme weather events such as heat waves, droughts, heavy rainfall with floods, heavy snowfall and cyclones will increase, along with sea-level rise, putting a large number of peoples' lives under threat (IPCC, 2007; Williams, 2012). Further, several studies have claimed that even an increase of 1°C will result in crop failure in arid regions and a significant reduction in the amount of productive land that is available, which will threat the world's food security (IPCC, 2007; Williams, 2012). A changing pattern of diseases, severe water shortages and the loss of tropical forests will be likely consequences of global warming (IPCC, 2007; UNEP, 2009).

The overall situation has been recognised as alarming and it is generally agreed that a deep cut in GHG emissions is urgently required to limit global warming to no more than 2°C more than pre-industrial temperatures (United Nations Framework Convention on Climate Change, 2015). According to UNEP (2009), to avoid the worst-case scenarios of global warming, a reduction in GHG emissions of at least 25% is needed by 2035 and of 50% by 2050. As the world's energy sector is the largest GHG emitter (accounting for 67% of global GHG emissions), it will play the most important role in limiting global warming (IEA, 2015a, 2015b).

3.2.2 Energy and Buildings

Buildings, as one of the three major consumers of energy (along with transport and industry), are of particular importance in relation to reducing GHG emissions in the energy sector (Hong, Chiang, Shapiro & Clifford, 2007; UNEP, 2009). Buildings not only consume a significant amount of primary energy but also, once built, last decades and hence, decisions made today have a long-lasting impact on future energy consumption. If a building is built without considering energy efficiency[8], it will continue to consume energy wastefully for many decades (Hong et al., 2007; IEA, 2008). Unfortunately, this is the case for the majority of the world's existing building stock. In general, optimising the energy efficiency of buildings has never been a priority as the fuel has been cheap and the environmental consequences of burning fossil fuels were unknown (Buttera, 2010; Lehmann, 2015). At present, buildings account for 40% of the total global primary energy consumption and 33% of total GHG emissions (IEA, 2015a). Further, the GHG emission share by buildings increases from 33% to 50% if the embodied energy of the materials is included (Hong et al., 2007). This figure is likely to increase as a large number of buildings are being constructed in developing countries. According to Lemmet (2009), if there is no change, GHG emissions from the building sector will more than double by 2030.

To reduce the effect of GHG emissions on the environment, it has been estimated that overall, buildings need to reduce their emissions by 50% by the year 2050 (UNEP, 2009) and in particular, buildings in developed countries need to reduce their emissions by 60% within the same time frame (World Business Council for Sustainable Development, 2007). Most experts agree that to meet the desired targets for

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[8] *'**Energy efficiency** is a way of managing and restraining the growth in energy consumption. Something is more energy efficient if it delivers more services for the same energy input, or the same services for less energy input' (IEA, 2016). For example, an insulated building is often predicted to be more energy efficient than an uninsulated one as it usually consumes lower energy due to heating or cooling to achieve and maintain a comfortable indoor temperature.*

the reduction of GHG emissions, buildings must reduce their share of GHG emissions (UNEP, 2009).

Building consumes energy at five different stages: i) during the manufacturing of the materials used in the building; ii) transportation of the materials to sites; iii) construction of the buildings; iv) building operation; and v) building demolition. However, 80% of energy consumption (and therefore contribution to GHG emissions) occurs during the operational stage (UNEP, 2009, Williams, 2012). It is obvious that to reduce GHG emissions from the building sector meaningfully, buildings must increase their energy efficiency; that is, their operational energy consumption due to heating, cooling, lighting and use of appliances. Additionally, reducing energy use will save money, which is vital for a developing economy with limited resources (Hong et al., 2007; Nandi & Bose, 2010).

In response to the urgent need of increased energy efficiency in buildings, many countries (particularly developed ones) have introduced mandatory building energy codes. In addition, building types such as 'passive houses' and 'low-energy buildings', which consume less energy than standard buildings, have come into existence (Laustsen, 2008).

'Passive house' is a term mostly used in European countries, referring to buildings that achieve comfortable indoor conditions without significant use of energy. Although this style of building has gained a significant momentum in recent years, it was actually developed during the 1970s as a response to the oil crises of that period (International Passive House Association, 2014; Williams, 2012). This building type was developed originally in the cold climate of Scandinavian countries and Germany, where heating is essential. The required heating is primarily achieved by harnessing passive solar heat gain (Gröndahl & Gates, 2010; Feist, 2006; Rosenthal, 2008). The vast majority of passive houses are concentrated in Europe—in 2010, there were 25,000 such certified buildings in Europe and several dozen in the US (Zeller, 2010). In passive-house buildings, the total primary energy consumption due to heating, hot water and electricity can be up to 120 kWh/m^2/year (Laustsen, 2008). Studies have found that the heating energy consumption of a passive house can be 80% lower than that of a standard building in Europe (Fiest, Peper, Gorg & Hannover, 2001). The construction of passive houses is quite different from that of standard buildings, usually using measures such as highly efficient insulation and triple-layer windows, an airtight envelope and controlled mechanical ventilation (Laustsen, 2008; Williams, 2012).

The existing literature suggests that while the standards and definition of a passive house in the cold climates of Europe are well established, this is not the case for a passive house in hot and humid climates, where cooling is required (Hoque & Iqbal, 2015; Laustsen, 2008; Pacheco & Lamberts, 2013; Voss, Musall & Lichtmeb, 2011). The first certified passive house in a hot and humid climate was developed only in 2010 in Louisiana, US (Clearfield, 2011; Defendorf, 2010) and unlike passive houses in cold climates, there are few passive houses in hot climates. Hence, many studies have rightly emphasised the need for passive-house standards in hot and humid climates, since the majority of future buildings will be located in Asian and African developing countries, which have a hot and tropical climate (Laustsen, 2008; Voss et al., 2011).

The term 'low-energy building' generally refers to buildings that have better energy performance than a standard new building that is built by following an energy code (Laustsen, 2008). Commonly, a low-energy building consumes half of what a new standard building would consume. However, the identification of low-energy buildings depends on the energy efficiency standards of new buildings in a country and these can vary significantly between countries (Homod, 2014; Laustsen, 2008; Pérez-Lombard, Ortiz & Pout, 2008). For example, in Germany and Austria, the heating demand and sanitary hot water requirement must not exceed 30 W/m^2 year for a building to be called 'low energy'; in Switzerland, this requirement is 42 W/m^2 year (Laustsen, 2008). Therefore, a building that is identified as low-energy in one country may not be the same in another country that has more stringent efficiency standards. Moreover, with the development of higher efficiency requirements over time, the current low-energy buildings may become standard ones. Therefore, common standards for evaluating low-energy buildings around the world against set criteria have been proposed by Homod (2014) and Laustsen (2008).

In many countries, the construction of low-energy buildings is encouraged by incentives that are provided through certification and labelling. For example, in the European Union, energy-efficient buildings are provided with a certificate and often with a label on a scale ranging from A–G or even A/A+/A++, to indicate the extent of the buildings' efficiency compared with that of standard buildings (Laustsen, 2008). In Australia, star ratings (1–10) are used to indicate energy efficiency, with a higher number of stars denoting higher energy efficiency (Nationwide House Energy Rating Scheme, 2016). In the US, an 'ENERGY STAR' label is used for buildings that have 15% less energy consumption than new buildings built by following energy efficiency codes (Energy Star, 2016).

Some building types have incorporated renewable energies to generate their own energy through GHG-free sources and achieve 'zero-energy' and 'plus-energy'. As briefly discussed in Chapter 1, a ZEB, also known as 'net zero-energy building', generates as much energy as it consumes, while a 'plus-energy' building generates more energy than it consumes, both usually through on-site renewable energy sources. Therefore, these buildings are not only highly energy efficient but also energy generating. The concept of ZEBs is considered one of the best potential solutions to the current GHG emissions problem of buildings at the operational stage (Kapsalaki & Leal, 2011; Marszal, Bourrelle, Musall, Heiselberg, Gustavsen & Voss, 2010; Marszal, Heiselberg, Lund Jensen & Nørgaard, 2012; Marszal & Heiselberg, 2011a, 2011b; Williams, 2012).

The term 'zero-energy' is not a recent one. It can be found in several published documents in the 1970s, when the term was used to describe zero-heating buildings (Besant, Dumont & Schoenau, 1979; Butti & Perlin, 1980; Esbensen & Korsgaard, 1977) such as Vagn Korsgaard Zero Energy Home in Denmark (Esbensen & Korsgaard, 1977) and Saskatchewan Conservation House in Canada (Besant et al., 1979). Although the ZEBs of today are defined differently than those of the 1970s, it is accepted that these early building examples influenced the later development of low- and passive-energy buildings, which adopted some of the energy-saving features of the zero-heating buildings (Hernandez & Kenny, 2010; Marszal et al., 2011b). Further, they contributed in defining the standards for an energy-efficient building as well as in developing building energy codes (Hernandez & Kenny, 2010). However, one of criticism of ZEBs is that they only focus on operational energy use and do not consider the embodied energy of a building. Hernandez and Kenny (2010) include the embodied energy of a building and introduce the term 'life cycle zero-energy building' (LC-ZEB), which they define as follows:

> A LC-ZEB is one where the primary energy used in the building in operation plus the energy embodied within its constituent materials and systems, including energy-generating ones, over the life of the building is equal to or less than the energy produced by its renewable energy systems within the building over their lifetime.

Whether or not the embodied energies are included in the equation, ZEBs are considered the major building type for future, particularly in developed countries (Williams, 2012). To establish ZEBs into the mainstream building industry, many countries have introduced supporting policies and targets (Kapsalaki & Leal, 2011). For example, by 2016, all new residential buildings in the United Kingdom (UK) should be ZEBs; in France, the Netherlands, Hungary and the US, the target date is 2020; and in South Korea, 2025 (Kapsalaki & Leal, 2011).

The concept of ZEBs and other highly energy-efficient building types has become common in developed countries as a response to the GHG emission issue of buildings. While it is vital that such building types gain wide market penetration to be successful, in general, builders and buyers are not interested in voluntarily achieving a higher level of energy efficiency than what is required by the current energy codes

(IEA, 2008; UNEP, 2009). The main reasons for this lack of interest have been identified as economic, unavailability of the services and products, lack of information, too many decision makers in a building project and lifestyle choices. In general, is accepted that the economic barrier is the greatest (UNEP, 2009; Williams, 2012). Therefore, despite the success of ZEBs in addressing both the issues of GHG emissions and fossil fuel depletion, they have not been very successful in creating a market demand in their place of origin (Williams, 2012).

Some studies have suggested that the issues preventing the wide uptake of ZEBs are non-technical (Osmani & O'Reilly, 2009; Sullivan, Mark & Parnell, 2006; Williams 2012; Williams & Adair, 2007). These issues include: i) the need to compromise on the six quality-of-life dimensions (comfort, convenience, privacy, personal freedom, affordability and safety and security); ii) more active involvement of the occupants in energy management; iii) higher initial costs with no corresponding added market value; iv) lack of priority for energy saving; v) people's perception of such projects as aesthetically less attractive and therefore having less market value; and vi) well-supported conventional energy systems and very strong energy lobbies that block the entry of any new competitor. Norton and Christensen (2008) suggested that to achieve zero energy, the behavioural aspects of the occupants may prove more important than any other aspect, as the prediction of the total home energy use is highly uncertain due to individual occupant's choice and behaviour. Similarly, the European Environment Agency (2013) strongly suggested that building occupants needed to be trained, as their behaviour was critical in achieving ZEB goals. Several studies have highlighted the importance of barrier removal to achieve real success in deploying energy-efficient buildings, emphasising that having the right policies, appropriate for a country's context, is vital in this regard (Laustsen, 2008; Williams, 2012).

3.2.3 Energy and Buildings in Developing Countries

While ZEBs and other energy-efficient buildings have become a part of the national agenda of many developed countries, it is not yet common in the developing world, where the majority of new buildings are yet to be built and where there is an acute energy scarcity. In fact, many developing countries, such as Bangladesh, still do not have any building energy codes to ensure minimum energy performance of the buildings. There are very few examples of passive-house, low-energy or ZEB design in developing countries and studies of such building types in the developing countries' contexts are limited. Although it is understood that developing countries' buildings consume much less energy than buildings in developed countries, given the huge volume of future building construction along with the energy scarcity in the developing world, this thesis argues that it is important that new buildings in developing countries are as energy efficient as possible. In fact, all new buildings should be ZEBs, as they can address the energy scarcity issue of these countries.

Many studies have shown that achieving energy efficiency is much simpler and cost effective if it is considered during the planning and design phase of building, instead of retrofitting buildings later. However, due to the different economic and climatic contexts of the areas in which these building types originally developed, efficiency strategies that are specific to a developing country's contexts still need to be developed.

3.3 PARAMETERS THAT AFFECT THE ENERGY CONSUMPTION OF BUILDINGS

This section reviews the relevant literature to identify the parameters that affect the energy consumption of buildings and the way they do this. In its operational phase, a building consumes energy primarily for achieving thermal comfort and for artificial lighting and use of appliances. However, energy consumption in a building is a complex and dynamic process that depends on a number of factors or parameters, acting at three levels: urban, building and occupancy, as discussed in detail in the following sections. In addition, the surrounding climate or microclimate of a building (particularly the dry-bulb temperature) as well as the efficiency of appliances used influence energy consumption (Steemers, 2006; Yildiz & Arsan, 2011; Zhao & Magoulès, 2012).

3.3.1 Urban-level Parameters

Urban parameters such as street width, configuration and orientation, building heights, compactness or dispersion, surface materials, vegetation, open spaces and water bodies have an effect on the energy consumption of buildings (Golany, 1996; Ratti, Raydan & Steemers, 2003; Santamouris, 2006; Steemers, 2003). The existing literature suggests that urban-level parameters affect the energy consumption of buildings both directly and indirectly (Ratti et al., 2003; Raydan & Steemers, 2006).

The direct influence occurs because of direct obstruction or enhancement of solar penetration and airflow, such as a tall structure casting a shadow or obstructing the wind flow, which can result in higher or lower energy consumption. For example, a study conducted in the UK using computer-based image processing found that a 10° increase in obstruction angle increased the energy consumption of an office building by 10%. The same study also found that increasing the plot density ratio from 1.25:1 to 5:1, or spacing the buildings more closely, resulted in 25% more energy consumption (Steemers, 2003). A computer simulation study by Wong, Jusuf, Syafii, Chen, Hajadi, Sathyanarayanan & Manickavasagam (2011) in Singapore found that increasing building height and surrounding density reduces the cooling energy consumption of an office building by 5%, because of the obstruction to direct solar radiation.

The indirect influence occurs due to microclimatic modifications around building as a result of urban design decisions. As Givoni (cited in Ratti et al., 2003) noted:

> The outdoor temperature, wind speed and solar radiation to which an individual building is exposed is not the regional 'synoptic' climate, but the local micro-climate as modified by the 'structure' of the city, mainly of the neighbourhood where the building is located. (p. 763)

Although urban parameters can affect all microclimatic parameters such as air temperature, wind flow, radiation budget and humidity, air temperature is considered the most important parameter in terms of influencing the energy consumption of buildings (Ahmed, 1994; Wong et al., 2011). Hence, the majority of the existing studies are focused primarily on air temperature modification and its effect on energy consumption. The most-studied such phenomenon is known as the UHI.

3.3.1.1 Urban Heat Island

> The urban heat island is one of the most important manifestations of the urban climate, and has been the subject of much research since it was first described for the city of London by Luke Howard in 1818. Its intensity varies significantly and known to be a complex one. (Erell, Pearlmutter & Williamson, 2011, p. 67)

UHI is a phenomenon whereby the air temperature of an urban area is higher than its surrounding non-urban areas. Since the phenomenon increases the ambient air temperature, it results in higher demand for cooling energy or lower demand for heating energy, depending on the geographical location and background climate of the city (Akbari, Bell, Brazel, Cole, Estes, Heisler, … Zalph, 2008; Erell et al., 2011; Oke, 1997; Sailor, 2015; Santamouris, Papanikolaou, Livada, Koronakis, Georgakis, Argiriou & Assimakopoulos, 2001; Wong et al., 2011). As reported by Oke (1997), the annual average air temperature of a city can be 1 to 3°C higher than the surrounding non-urban areas because of the UHI effect.

Two types of heat islands can be identified from the available literature: ‘surface heat island’ and ‘atmospheric heat island’ (Akbari et al., 2008; Erell et al., 2011). While the surface UHI measures the difference between urban and non-urban surface temperature, the atmospheric UHI measures the difference in air temperature. Atmospheric heat island is further divided into ‘canopy-layer heat island’ and ‘boundary-layer heat island’. The canopy layer encompasses the area from the ground to below the top of the trees and roofs; the boundary layer extends from above the top of the trees and rooftops to the point at which the urban landscape no longer disturbs the atmosphere. Most of the current UHI studies focus on the canopy-layer UHI, as this is where people live and it is what has the most influence on the energy consumption of buildings (Sailor, 2015) (see Figure 3.1). The UHI is more pronounced at night under calm, clear conditions; hence, it is often called ‘nocturnal heat island’ (Erell et al., 2011; Oke, 1997). The main reasons for this is that at night, the cooling rate in the city is slower because of its closely spaced buildings hindering radiative cooling through long-wave emission and making the wind speed low and the wind flow erratic (Oke, 1997; Santamouris et al., 2001).

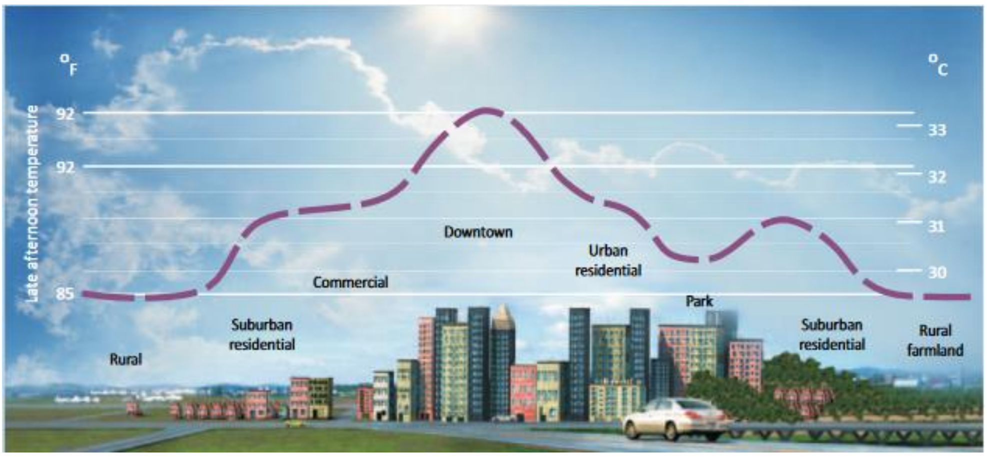

Figure 3.1: *UHI Effect. Source: Lawrence Berkeley National Laboratory, 2013*

A number of factors are responsible for the formation and intensity of UHIs: the urban geometry, the properties of urban materials, reduced vegetation and water bodies and anthropogenic heat emissions along with the background climate, topography and population density (Akbari et al., 2008). Many studies identify urban geometry as the most influential factor in the formation of an UHI (Jusuf, Wong & Chong, 2015; Sailor, 2015; Wong et al., 2011). As Wong et al. (2011) reported, the demand for cooling energy in some parts of Singapore could be reduced by 5 to 10% just by altering the urban morphology or geometry.

The geometry of an urban area is defined largely by the presence of 'urban canyons', which are the spaces in between buildings that are created by streets or setback spaces (Erell at al., 2011). Baik, Park, Chun & Kim (2000) defines an urban street canyon as the space surrounded by a city road and its flanking buildings. Urban canyons in cities are often deep because of the height of the buildings. Canyon geometry also determines the sky-view factor[9] (SVF) from a building's surface or the ground. In a deep urban canyon, the SVF is low; in a shallow urban canyon, the SVF is high. Both the CR[10] and the SVF have been reported to influence the short- and long-wave radiation within a canyon significantly (Oke, 1982, 1997; Sailor, 2015; Santamouris & Kolokotsa, 2015). As described in many studies, deep urban canyons tend to trap heat because of the complex exchange between the buildings and the screening of the skyline keeping the canyons warmer at night (Oke, 1982, 1997; Santamouris et al., 2001; Steemers, 2006). In addition, the geometry may decrease the effective albedo[11] because of the multiple reflection of short-wave radiation between the canyon surfaces (Oke, 1997). The study by Jusuf et al. (2015) in Singapore showed that the lower the SVF value, the higher the nocturnal heat island, and the higher the SVF value, the higher the daytime air temperature inside the canyons. Canyon orientation also affects the wind flow and wind velocity inside the canyon. A study in Greece (Santamouris et al., 2001) found that the wind speed inside a canyon could be up to 10 times lower than that in the open meterological station, particularly during the

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[9] *Sky-view factor refers to the percentage of sky observed from a point compared to the total possible sky hemisphere.*

[10] *Canyon ratio refers to the ratio between the average height of two adjacent buildings from the street level and the horizontal distance between the buildings.*

[11] *Albedo is the 'whiteness' of a surface. It is a reflection coefficient and has a value between zero and one. The albedo of a surface is the ratio of radiation reflected from the surface to the radiation received.*

daytime. The same study also reported that in deep urban canyons, the mean wind speed rarely exceeds 1 m/s.

The thermal properties of urban materials can increase the storage of sensible heat and hence, the UHI intensity. Vegetation, or the amount of greenery, is another important factor. A study in Singapore found that dense greenery could reduce the CBD's temperature by 4.01°C (Wong & Yu, 2005). According to Wong et al. (2011), a low green plot ratio (GnPR) can exacerbate the UHI intensity by 0.9–1.2°C. In addition, dark surface colours and impervious surfaces in urban areas have been found to increase the UHI intensity (Akbari et al., 2008).

3.3.1.2 Energy Impact of the UHI

A number of studies have reported the increased energy consumption needed for cooling because of the presence of UHIs (Akbari et al., 2008; Kolokotroni et al., 2007; Oke, 1997; Santamouris et al., 2001; Wong, Tan, Tan & Wong, 2009). For example, Akbari et al. (2008) reported that the peak energy demand in several US cities (Los Angeles, Washington DC, Phoenix, Tucson and Colorado) increased by 1.5–2% for every 0.6°C (1°F) increase in summertime urban temperature. The same study also found that the peak urban electricity demand rose by 2–4% for each 0.6°C rise in the daily maximum temperature in the studied US cities. Another study in Los Angeles and Atlanta found that for each degree Celsius of increase in the peak air temperature, the peak cooling demand increased by 3% in Los Angeles and by 6% in Atlanta (Santamouris et al., 2001). The same study also reported that the summer UHI in Los Angeles accounts for 1.4 GW of extra peak power, resulting in a loss worth a billion dollars. A study conducted in Singapore, Wong et al. (2009) found that every 1°C increase in temperature results in increasing the demand for cooling energy by 5%.

Many studies have reported on the reduced consumption of heating energy because of the presence of UHIs (Kolokotroni, Zhang & Watkins, 2007; Oke, 1988; Svensson & Eliasson, 2002). Oke (1988) reported that every 1°C increase in temperature in a city at 48° latitude can decrease the space heating costs by 5–7.5%. A study by Svensson and Eliasson (2002) in Sweden reported that urban buildings consume 15% less heating energy than those in rural areas, suggesting that the presence of UHIs is not always negative from an energy consumption point of view.

Several UHI studies have reported mixed influences, such as increased cooling demand but decreased heating demand. For example, a study conducted by Kolokotroni et al. (2007) found that the presence of UHIs increased the cooling load in London by 25%, while at the same time, decreased the heating load by 22%. Santamouris et al. (2001) studied 30 urban sites in Athens and found that the demand for cooling energy was doubled and the peak demand was trebled because of UHIs; however, they decreased the demand for energy for heating by 30%. A similar result also was reported in a study in Adelaide, which found that due to the effect of UHIs, consumption of cooling energy was increased by 75%, whereas energy for space heating was decreased by 22% (Elnahas & Williamson, 1997).

It is clear from the existing literature that although the increased air temperature due to UHIs affects the energy consumption of buildings, the type of influence varies according to the climate and geographical location. In general, UHIs increase the demand for cooling energy in cooling-dominant cities and decreases the demand for heating energy in heating-dominant cities. Thus, increasing the urban air temperature is not always negative from an energy consumption point of view. However, it is generally agreed that UHIs have a detrimental impact on low- and mid-latitude cities, as they can increase the demand for cooling energy significantly (Taha, 1997).

Studies have confirmed that UHI intensity is reduced in the presence of greenery and higher wind flow. For example, a study by Ca, Asaeda & Abu (1998) in Japan found that the presence of a small park (0.6 km^2) can reduce the ambient temperature of the surrounding downtown by 1.5°C, which can result in a 4000 kW reduction in peak demand for cooling energy on hot summer days. A study by Shashua-Bar and Hoffman (2000) in Israel reported that strategically located trees could reduce energy consumption by 25–80%. In the tropical climate of Hong Kong where both air temperature and humidity are high, it was found that UHI intensity decreased by 1.5°C with an increase in wind speed of 1 m/s (Memon & Leung, 2010). In Singapore, an increase in wind velocity by 1–1.5 m/s created a cooling effect equivalent to 2°C temperature drop (Rajagopalan, Lim & Jamei, 2014). Therefore, many studies recommend that to mitigate UHI intensity, more green spaces and increased wind flow through the air paths or breezeways should be used (Davenport, 1965; Erell, 2008; Givoni, 1998; Holmer & Eliasson, 1999; Jusuf et al., 2015; Oke, 1993).

Low-albedo materials that reflect more solar radiation, commonly known as 'cool materials', have been reported to be very effective in reducing UHI intensity (Akbari et al., 2008). Studies suggest that such cool surfaces are more effective in reducing UHI intensity than trees, as it costs little to incorporate colour changes and provides immediate results, whereas trees take time to grow (Akbari et al., 2008). An experiment in Sacramento found that the combined effect of increased albedo and shading by trees could reduce the demand for cooling energy by 43% (Rosenfeld, Akbari, Bretz, Fishman, Kurn, Sailor, & Taha, 1995). According to another study in Florida, increasing a roof's albedo can reduce the demand for cooling energy by 23% (Akbari et al., 2008).

Although green and cool materials can reduce the UHI impact significantly, other studies suggest that in a tropical climate, managing urban geometry, such as the CR between buildings and the canyon direction towards the prevailing wind direction are the best UHI mitigation strategy. This should be enhanced by other strategies such as material composition, surface cover and function of the city (Mills, 2015; Sailor, 2015). Building cities that limit UHI intensity should therefore be the priority, rather than mitigating it afterwards. If mitigation strategies are needed, they must be context-specific. For example, in a cooling-dominated region, the focus should be on reducing the ambient air temperature.

As mentioned above, one of the most important strategies for reducing UHI intensity is urban geometry, which determines the CR surrounding a building and hence, the consumption of energy. The CR determines the direct solar, daylight and wind access to the buildings and affects the SVF, which in turn affects the level of long-wave heat dissipation at night as well as the deposition of pollutants. Deep canyons have been found to trap heat at night, resulting in a higher air temperature and either decreased nocturnal heating demand or increased cooling demand. The shading they create can reduce the demand for daytime cooling energy. Shallow canyons can increase the daytime demand for cooling energy if the buildings do not have proper local shadings (Williamson, Erell & Soebarto, 2009). This means the canyon geometry surrounding a building should be dependent on the use of a building; for example, for an office, which is mostly occupied in the daytime, deep canyons may reduce the demand for cooling energy. Conversely, for residential buildings, which are mostly occupied at night, deep canyons may increase the cooling demand if the heat is not released through natural ventilation or other means at night.

3.3.2 Building-level Parameters

The energy consumption of a building is affected by a large number of building parameters. According to Steemers (2006), these can be grouped into three categories: building form, façade and fabric. The form includes the building shape and size, depth and width, and surface-to-volume ratio. The façade includes the building fenestration, such as the glazing ratio, glazing distribution and shading strategies. The fabric includes the materials (along with their thermal properties) used for different parts of the building, such as the walls, roof, floor, windows and doors. In addition, the zoning of the spaces, natural ventilation strategies and air filtration or air-tightness of a building can all have a significant effect on energy consumption (IEA, 2013; Raydan &

Steemers, 2006; Santamouris, 2006). The efficiency of installed systems such as air conditioners, heaters, boilers and lighting, as well as other appliances, also affects energy consumption substantially (Laustsen, 2008).

The 'building envelope' (also known as the shell or enclosure) consists of the external walls, roofs, floors, ceilings, doors and windows. This boundary between the conditioned interior of a building and the outdoor is considered the most critical in determining the building's energy consumption (IEA, 2013). Each component of the building envelope can affect the indoor comfort level significantly and thus the demand for heating and cooling energy (IEA, 2013). Moreover, the size and ratio of the glazed areas determine the amount of daylight penetration and thus influence the artificial lighting consumption of a building during the daytime. However, glazing also allows more heat loss or gain, which affects indoor comfort, requiring a balance to optimise the energy consumption of a building, considering both thermal comfort and artificial lighting. Nevertheless, it is widely accepted that the building envelope has a key role in determining the heating and cooling load of a building and to achieve meaningful energy efficiency, the building envelope must be efficient.

In most parts of the world, especially in developing countries, the energy performance of the building envelope has been substantially neglected, mainly because of the availability of cheap fuel and the additional money required to achieve higher energy efficiency. Even today, many buildings are built without considering energy efficiency, even though it has been advised that whenever possible, investment should be made in the most energy-efficient envelope that is justified within the context of product availability, cost, climate and energy prices (IEA, 2013). This is because a building will be in place for many years and retrofitting it at later stage is more difficult.

The most common issues regarding the building envelope that affect the energy performance of a building are draughts due to leaky windows; sunlight penetration from inappropriately oriented or unshaded windows; excessive heat gain through east- or west-facing windows; and leaky and uninsulated walls that make it difficult to maintain the desired temperature without higher cooling or heating consumption (IEA, 2013). To improve the energy performance of the building envelope components, a number of advanced options and strategies are available, such as a high level of insulation for walls, roof and floors to reduce heat loss in a cold climate; high-performance windows with low thermal transmittance and climate-appropriate solar heat gain coefficient (SHGC); highly reflective or cool materials for hot climates; and a properly sealed structure with controlled ventilation for fresh air and minimisation of thermal bridges (IEA, 2013). The suitability of a particular energy-efficient option depends on the type of economy and climate of a country. In general, developed countries are encouraged to adopt highly advanced options such as dynamic shading and advanced roofing with building-integrated photovoltaics (BIPVs), wheras developing countries are encouraged to adopt more economical options such as exterior shading and optimised natural ventilation, along with low-SHGC windows (IEA, 2013).

3.3.2.1 Energy Impact of the Building Parameters

Although a number of studies are available regarding the impact of different building parameters on the energy consumption of buildings, most of them have focused on only one or two specific aspects, such as building form and shape, orientation, glazing areas, shading devices and thermal properties of building materials. The following sections present the energy impact of different building parameters and the way they have influence.

3.3.2.1.1 Building Shape, Form and Compactness

Through building performance simulation, Canada Mortgage and Housing Corporation (2014) conducted a study to identify the relative impact of different building shape and envelope parameters on heating and cooling energy consumption in typical multi-unit residential buildings in Toronto and Ontario. Part of the study investigated the effect of different building shapes such as ‘U-shape’, ‘H-shape’, ‘bar-shape’, ’square-shape’ and ‘L-shape’ on heating and cooling energy consumption. The study found that ‘U’- and ‘H’-shaped buildings have a slightly higher heating demand than ‘bar’- and ‘square’-shaped buildings, but a significantly lower cooling demand because of mutual shading. On the other hand, ‘L’-shaped buildings exhibited the poorest performance by having the highest heating and cooling demand because of having larger surface areas but a lower benefit from mutual shading.

El-Deeb, El-Zafarany & Sherif (2012) used computer simulation to compare the effect of different building shapes (square, L, U, H, central-courtyard and rectangular) on the energy consumption of a small-scale residential building in three urban contexts (isolated, linear and compact) in Jeddah, Cairo and Alexandria. Their study found that for all three cities, the isolated square buildings had lower energy consumption than isolated courtyard buildings; however, the saving was more in the extreme climate of Jeddah (15%) than in the milder climate of Alexandria (5%). They found that courtyard-type buildings performed better than square or rectangular buildings when attached to other buildings on three sides; in other words, in a compact urban fabric. The study concluded that the impact of building shape is more pronounced in an extreme climate than in a milder climate. Further, their findings suggested that the same building shape affected energy consumption differently under different climate and urban contexts.

Zerefos, Tessas, Kotsiopoulos, Founda & Kokkini (2012) compared the impact of a prismatic and orthogonal building form on energy consumption in Greece. For this study, a contemporary building with prismatic form was simulated through a building-simulation program. Then the same building was simulated again after changing the prismatic form into a right angle, retaining all the area and volume data of the original prismatic building. The study found that the prismatic form has lower solar heat gain and 7.88% less annual energy consumption.

In Slovakia, Geletka and Sedláková (2012) used simulation to show that a building's energy consumption decreases with an increase in its compactness. The authors concluded that with more compactness, the amount of external wall is reduced and therefore, less heat gain and loss occurs, resulting in lower energy consumption. Gratia and De Herde (2003) found that the heating load of the most compact small-sized domestic buildings in Belgium can be 25% lower than the most sprawling building of the same size. Straube (2012) reported that in Germany, a higher R-value for a building envelope is required if the building is less compact.

In general, it is agreed that building shape can influence building-energy consumption and buildings with a larger surface area are more affected by the external climate than the opposite (AlAnzi, Seo, & Krarti, 2009; Choi, Cho & Kim, 2012; Choi, Kim & Suh, 2007; Fallahtafti & Mahdavinejad, 2015; Marks, 1997). However, several studies have shown that while a strong correlation exists between building shape and energy consumption in cold climates, such as northern Europe (Depecker, Menezo & Virgone, 2001; Marks, 1997), the correlation is weak or absent in milder climates such as in southern France and Italy (Depecker et al., 2001; Albatici & Passerini, 2010). Therefore, several authors have concluded that disregarding building shape in milder climates is appropriate (Albatici & Passerini, 2010; Depecker et al., 2001).

3.3.2.1.2 *Building Orientation*

Several studies have reported the influence of a building's orientation on energy consumption, particularly the orientation of the external surface that has the largest glazed area (Abanda & Byers, 2016; Andersson, Place, Kammerud, & Scofield, 1985; Fallahtafti & Mahdavinejad, 2015; Pessenlenher & Mahdavi, 2003). Through building simulation, Pessenlenher and Mahdavi (2003) showed that in Austria, south-dominant glazing orientation reduces heating demand in winter; however, it increases the overheating period in the summer compared with a north-dominant glazing orientation. Abanda and Byers (2016) used simulation studies and found that a well-oriented domestic building in Hertfordshire, UK could save a considerable amount of electricity in its lifecycle. The study reported that between the best (+180°) and worst (+45°) orientation, the total electricity use difference could be 17,056 kWh over a 30-year period.

Fallahtafti and Mahdavinejad (2015) reported that in Tehran, from a heating energy-consumption point of view, the optimised orientation is between 298° and 318° and the worst orientation is between 171° and 177°. Depending on the amount of glazing, 16–105% energy can be saved annually with the optimised orientation. This study also emphasised that the glazing percentage plays the most important role in determining a building's ideal orientation. When the glazing percentage is low, buildings should be south-oriented in Tehran, whereas when the glazing percentage is higher, buildings should be southwest-oriented.

Andersson et al. (1985) used parametric simulation to investigate the effect of orientation on residential heating and cooling energy consumption for 25 climates in the US. They reported that for all climates in the northern US, the total consumption of south-oriented buildings is 10–20% lower than east- and west-oriented buildings, 20–35% lower in the humid southeast and 30–70% lower in the dry southwest. North-oriented buildings have 25–45% higher energy consumption than south-oriented buildings in the high desert areas and 5–20% higher consumption for rest of the US except for the cooling-dominant climate in the extreme south. In the extreme south, with its dominant cooling demand, north-oriented buildings consume 12% less energy than south-oriented buildings. For all climates, north-oriented buildings also consume less energy than east- and west-oriented buildings; however, the gap is lower for south-oriented buildings. The study also reported that modest changes in thermal mass do not reduce the effects of orientation; however, increasing the amount of shading over windows tends to diminish the effect of orientation.

The findings of these studies suggests that while building orientation can affect the energy consumption of a building, it is notably dependent on the size and shading of the glazing and the degree and type of influence varies according to climatic zone.

3.3.2.1.3 Window Size and Type

A number of studies have examined the effect on building-energy consumption of different window sizes and glazing types (Ghisi & Tinker, 2005; Grynning, Gustavsen, Time & Jelle, 2013; Koohsari, Fayaz, & Kari, 2015; Lee, Jung, Park & Yoon, 2013; Ochoa, Aries, Loenen & Hensen, 2012; Yang, Liu, Shu, Mmereki, Hossain & Zhan, 2015). Yang et al. (2015) used a building-simulation tool to investigate the effect of the window-area-to-wall-area ratio (WWR) and glazing type on residential energy consumption in three cities (Chongqing, Shanghai and Wuhan) in China. The study found that energy consumption increases with the increase of WWR; however, the consumption increase rate is lower in the case of the low-emissivity (Low-E) glazing type than for hollow glass. The study also reported that the energy0saving effect due to reduced WWR is more significant when the use of AC is greater. Hassouneh, Alshboul and Al-Salaymeh (2010), Persson, Roos and Wall (2006), and Stegou-Sagia, Antonopoulos, Angelopoulou and Kotsiovelos (2007) reported that using an energy-efficient glazing type, such as tinted and reflected, instead of clear glazing can reduce the energy consumption of buildings significantly. However, these studies focused only on heating and cooling energy consumption and did not include consumption of energy for artificial lighting.

Koohsari et al. (2015) used parametric simulation to investigate the effect of window size on daytime lighting energy consumption in Iran. The study was conducted by varying window height and width in the model and found that window height had a greater effect on daytime lighting consumption than window width; that is, changing the window height results in more consumption variation than changing the window width. The study concluded that at the initial stage of design, more attention should be paid to determining the height of windows. However, the study did not investigate the visual comfort aspect of increased window height.

3.3.2.1.4 Shading Devices

Shading devices have been reported to decrease the cooling energy demand in hot climates; however, in cold climates, they increase the heating demand due to obstruction of solar heat gain (Tzempelikos & Athienitis, 2005; Dubois, 1997). It is widely accepted that the optimal shading strategy is climate dependent, although disagreement exists on what is the best strategy (Dubois, 1997).

A study conducted by Harkness (1988) in Brisbane showed that the use of exterior precast concrete overhangs can reduce the cooling load by 50%. Brambley, Kennedy and Penner (1981) reported that sunscreens could reduce the cooling load in San Diego by 23%, while Halmos (1974) demonstrated that external shading devices on double-paned windows could reduce the cooling load by 75%. Wong and Li (2007) reported that a horizontal shading device with a depth of up to 0.3–0.9 m could reduce the cooling load of naturally ventilated residential buildings in Singapore by 2.62–10.13%. Bilgen (1994) found that while the use of an automated venetian blind decreased the cooling load by 69–89% in Montreal, it increased the heating load by 4–6%. According to Treado, Barnett and Remmert (1984), net energy saving through the use of shading devices can be achieved only if the saving on cooling exceeds the extra heating demand. In fact, many authors have reported that exterior shadings are often net energy loosers in colder regions because of their interference with direct solar access (Dubois, 1997; Pletzer, Jones & Hunn, 1988).

The existing literature suggests that while external shading devices can reduce cooling energy demand, notably in cooling-dominant regions, they often increase the heating demand in colder regions. Hence, the determination of shading device requires careful consideration, particularly in locations where both heating and cooling is important.

3.3.2.1.5 External Wall Materials

Another important building parameter that affects a building's energy consumption significantly is the opaque part of the building envelope, such as the external walls and roof (Gajda, 2001; IEA, 2013; Long & Ye, 2015; Yao & Yan, 2011). The thermal properties of external wall and roof materials, the type and thickness of insulation and the air-filtration rate all affect heat conduction through the envelope of a building (Gajda, 2001; IEA, 2013; Steemers, 2006). This affects the indoor thermal conditions and hence, heating and cooling energy consumption.

In 25 locations of the US and Canada, Gajda (2001) used building simulation to investigate 11 types of external walls made with wooden and still frames with insulating materials and different types of concrete such as autoclaved aerated concrete block, concrete masonry unit, insulating concrete form and cast-in-situ concrete. The study found that buildings with concrete walls have lower heating and cooling energy consumption than buildings with frame walls. The study also reported that because of the higher thermal mass of the concrete walls, which capture and slow the transfer of heat and cold from outside, buildings with concrete walls require less heating and cooling energy.

Pan, Chan, Deng & Lin, (2012) used simulation to investigate the effect of external wall insulation thickness on energy consumption in office buildings in the different climates of three cities (Guangzhou, Shanghai and Beijing) in China. They found that increasing insulation thickness could significantly reduce heating energy consumption in Beijing. In Shanghai, increasing insulation thickness more than 26 mm did not reduce the total heating and cooling energy demand in a south-oriented building; however, it did in all other orientations. In contrast, increasing insulation thickness in Guangzhou did not result in any reduction of energy consumption. Yao and Yan (2011) used simulation in a study in China. They reported that cooling energy consumption rises and heating energy consumption decreases with an increase in the solar absorption coefficient of the building envelope; every 0.1 increase in the coefficient results in a 2% reduction in the use of heating energy but a 2% increase in the demand for cooling energy.

Several studies have found that while applying insulation to exterior walls can reduce heating energy consumption in cold climates, it increases cooling consumption in hot and warm climates (Kemal & Bedri, 2003; Shariah, Tashtoush & Rousan, 1997; Wu, Ye & Zhou, 2007). Therefore, Kemal and Bedri (2003) recommended that careful consideration is needed to select the optimum insulation thickness for buildings located in areas with a cold winter and a hot summer, such as in Turkey. Bojic, Yik, and Sat (2001) reported that applying insulation did not significantly reduce the cooling energy consumption of a high-rise residential building in Hong Kong.

3.3.2.1.6 <u>Degree of Influence of Different Building Parameters</u>

While a large number of different building parameters that influence building-energy consumption can be identified, several studies have shown that the degree of influence varies greatly from parameter to parameter. Touchie, Binkley and Pressnail, (2013) used statistical analysis to investigate the effect of building height, size, WWR ratio, glazing type, thermal conductance of the glazing, boiler efficiency and occupancy type on the energy consumption of multi-unit residential buildings in Toronto. Among all the parameters investigated, WWR ratio and boiler efficiency were the most significant.

Yildiz and Arsan (2011), through sensitivity analyses, investigated the effects on an existing apartment building situated in the hot, humid climate of Izmir, Turkey of different building form, natural ventilation, air-filtration rate, window area, U-value and SHGC value of the windows, colour of the external walls, space height, specific heat of the external walls, thickness of the insulation, and conductivity of the external wall. The study found that the window area, along with the U-value and SHGC value of the windows, are the most influential parameters from an energy-consumption point of view.

Canada Mortgage and Housing Corporation (2014), through building simulation, investigated the relative impact of different building characteristics on the heating and cooling energy consumption of multi-unit residential buildings in Toronto and Ontario, such as building form, orientation, presence and types of balconies and number of storeys, as well as different envelope parameters such as opaque wall thermal performance, window thermal performance and WWR. The study found that envelope-related parameters have a higher impact on both heating and cooling energy demand than building characteristics-related parameters. However, the impact is much higher for cooling demand (about 80%) than for heating demand (about 60%). The study also found that window-related parameters (WWR and window thermal performance) account for more than 90% of the envelope-related impact for cooling demand, suggesting that windows are more critical in determining cooling demand. The study concluded that to achieve optimum energy efficiency in buildings, the first focus should be on building-envelope performance parameters. Overall, the findings of the above studies suggest that among all building parameters, window-related parameters are the most influential and critical from an energy-consumption point of view.

It is clear from the above discussion that a large number of building parameters not only affect the energy consumption of buildings but also affect it differently in different climate and urban contexts. Many of the building parameters are interrelated and influence one another. Therefore, the existing literature highlights the importance of context-specific decisions regarding building parameters to achieve meaningful energy efficiency. While there are many studies on the effects of different building parameters on building-energy consumption, few studies have investigated the combined effect of all parameters in a single study, suggesting a potential gap in knowledge in this area.

3.3.3 Occupancy-level Parameters

While all of the above studies were based on simulation or numerical studies, without considering occupancy, Yun and Steemers (2011), Firth, Lomas, Wright & Wall (2008) and, Steemers and Manchanda (2010) assert that from an energy-consumption point of view, occupancy-level parameters are more influential than urban- and building-level parameters. In the US, Yun and Steemers (2011) used regression and path analyses to investigate the effect on residential cooling energy consumption of climate, building and equipment characteristics, occupant factors (socio-economic) and occupant behaviour. The study found that occupants' behaviour (related to choices about how often and where AC was used) had the most significant impact on cooling energy consumption, whereas building characteristics ranked low. Firth et al. (2008) reported that dwellings on the same site and with similar built form have significantly different annual electricity consumption owing to differences in household size, occupancy pattern and number and type of appliances used. They concluded that built form is not a strong determining factor of household energy consumption; rather, occupant-related factors are. It has been reported that the energy demand of identical residential buildings in the UK can vary by a factor of 6 or more, owing to dramatically different occupancy patterns for different households, such as single occupant who goes out to work each day or a family with 24-hour occupancy (Steemers & Manchanda, 2010). Many studies in other countries have reported similarly that a considerable variation exists in the energy consumption of buildings with the same physical characteristics due to differences in occupant-related parameters such as household characteristics, lifestyle and perception of comfort (Branco, Lachal, Gallinelli & Weber, (2004); Hirst & Goeltz, 1985; Linden, Carlsson-Kanyama & Eriksson, 2006; Papakostas & Satiropoulos, 2007).

The energy consumption of buildings has been found to depend on the level of control that occupants have on the building's air-conditioning system; buildings with decentralised ACs (e.g., window units) consume less energy than buildings with a centralised air-conditioning system, due to occupants' freedom of choice to adapt their condition in a straightforward and intuitive way (Baker & Standeven, 1996; Leaman & Bordass, 2007).

Several authors have highlighted the importance of understanding the way occupant-related parameters effect the energy consumption of buildings, as their influence is complex and unpredictable and this makes predicting energy demand difficult (Baker & Steemers, 2000; Bordass, Cohen & Field, 2004; Norford, Socolow, Hsieh & Spadaro, 1994). For example, energy use in office buildings in the UK was found to be double that predicted through energy performance simulation, due the difficulty of assuming the behaviour of occupants in the building performance simulation (Baker & Steemers, 2000). Additionally, an energy-intensive lifestyle in a very energy-efficient building can lead to higher energy use than an energy-extensive lifestyle in a less energy-efficient building (Santin, Itard & Visscher, 2009). Several authors have questioned the absolute value of the estimated energy demand of buildings obtained through building performance simulation, unless the occupant-behavioural parameters can be accounted for (Steemers & Manchanda, 2010; Yun, Tuohy & Steemerset, 2009). The most common occupant-related parameters that were identified in the literature as affecting the energy consumption of buildings were occupancy pattern, occupants' behaviour and characteristics, motivation or attitude towards energy saving, awareness about energy saving, occupancy status and household income, age and size (Assimakopoulos, 1992; Santin et al., 2009; Vringer & Blok, 2007; Williams, 2012; Yao & Steemers, 2005; Yun & Steemers, 2011).

3.3.3.1 Energy Impact of Occupant-related Parameters

Most of the existing literature has reported that a positive correlation exists between age and energy consumption; that is, older people consume more energy, particularly for heating (Hayami, Pachauri & Schaeffer, 2006; Lenzen, Wier, Cohen, Lariviere & Lafrance, 1999; Liao & Chang, 2002; Linden et al., 2006; Santin et al., 2009).

This is partly because older people are at home for longer and partly because of their preference for a warmer indoor environment. However, a contrasting result has been reported by Chen, Wang & Steemers, (2013), who found that in Hangzhou city, China, older people consume less heating energy than do younger people. The development history of the country has been assumed to be one possible reason for this contradictory finding. The study explained that when the current older people were young, they experienced constant food and resource scarcity. They are generally very economical and interested in saving money and resources. This may have led them to use less heating than younger people.

A positive correlation also exists between household income and energy consumption. A number of studies have confirmed that the higher the income, the higher the energy consumption (Schuler, Weber & Fahl, 2000). Vringer and Blok (2007) found that in the Netherlands, a 1% increase in income resulted in a 0.63% increase in energy use. However, the variation in energy consumption was also large within the same income category, which led to the conclusion that income alone is not enough to explain energy consumption. Another study found that consumption is higher in rented or social housing, where the bill is paid collectively, than in individually owned houses (Leth-Petersen & Togeby, 2001). Many studies have reported a significant positive correlation between household size and energy consumption; a higher number of occupants results in higher energy consumption (Assimakopoulos, 1992; Vringer & Blok, 2007).

Motivation or attitude of the occupants towards energy saving has been identified as one of the major occupant-related influences (Santin et al., 2009; Vringer & Blok, 2007; William, 2012). Vringer and Blok (2007) reported a 4% increase in energy consumption in less-motivated households in the Netherlands. A study by Haas, Auer and Biermayr, (1998) found that motivation could affect energy consumption as much as mechanical parameters such as the use of efficient appliances.

While it is generally agreed that variation in energy consumption due to occupant-related parameters is complex and difficult to explain, few researchers have investigated the effect of occupant awareness on energy consumption (Ueno, Tsuji & Nakano, 2006; Ouyang & Hokao, 2009). According to a study conducted by Ueno et al. (2006) in Japan, installing an energy-consumption display monitor reduced power consumption by 9%. Increased energy-saving behaviours of the occupants, such as the reduction of standby power, and better control in the operation of appliances also reduced energy use. Ouyang and Hokao (2009) found that providing energy-saving education could save an average of 10% of household energy consumption in China. Examples of energy saving included setting the temperature as high as possible for AC, reducing AC, TV and computer usage time, having more household members staying together in fewer rooms, cleaning filter-dust-net frequently, reducing the time the refrigerator door is open, adjusting the refrigerator temperature according to the season and putting foods into the refrigerator after they have cooled.

Another aspect that affects energy use is the efficiency of appliances. Although the appliances used in a building are not always an integrated part of it, many studies have confirmed that the efficiency of the appliances in a building influences the total energy consumption of the building significantly. Therefore, to reduce energy consumption in the building sector meaningfully, using energy-efficient appliances is important (Laustsen, 2008; EIA, 2013; Pérez-Lombard et al., 2008).

It is clear from the above discussion that not only a number of diverse occupant-related parameters affect the energy consumption of buildings, they are complex and unpredictable in nature, as well as having a greater impact on building-energy consumption than building- and urban-related parameters. Therefore, increasing the understanding of occupant-related parameters and enhancing occupants' motivation and awareness regarding adopting energy-saving behaviour and energy-efficient appliances are likely to result in significant energy saving by the building sector.

3.3.4 Summary

Based on the literature review, the following table summarises the parameters that influence the energy consumption of buildings and the way they influence this consumption.

Table 3.1: *Summary of the Parameters that Affect the Energy Consumption of Buildings and the Ways they Influence this Consumption*

	Parameters	Way of Affecting the Energy Consumption of Buildings
	Urban-level Parameters	
1	Canyon geometry	Deep canyons obstruct direct sunlight as well as trap heat at night, due to the reduction in long-wave heat release. This results in higher artificial lighting consumption in the daytime and higher cooling consumption at night in warmer regions or reduced heating demand in cold regions. During the day, mutual shading inside the canyons can result in lower cooling consumption.
2	Canyon orientation	Either enhances or blocks air movement. Canyons parallel to the prevailing wind direction can channel the wind and act as breezeways; hence, heat is removed, resulting in reduced cooling consumption. Conversely, deep canyons perpendicular to the wind direction create stagnant air inside the canyons, resulting in more trapped heat and deposition of pollution.
3	Vegetation	More vegetation reduces the ambient air temperature, leading to less cooling consumption.
4	Material's albedo and colours	Dark surfaces absorb more solar radiation, resulting in higher cooling consumption. Impervious surfaces reduce evapotranspiration, leading to higher ambient temperatures and cooling consumption.
	Building-level Parameters	
5	Building shape, form and compactness	Building shape influences energy consumption differently under different climate and urban contexts. In general, compact buildings consume less energy due to their lower external surface area. Building shape correlates more strongly in colder climates than in milder climates.
6	Building orientation	In cold regions, buildings oriented towards the sun have reduced heating consumption. In hot regions, buildings should be oriented to avoid direct radiation.

	Parameters	Way of Affecting the Energy Consumption of Buildings
7	Window size and type	The higher the window size, the higher the cooling energy consumption. Low-E glazing types usually result in lower heating or cooling consumption. A balanced WWR is needed for optimal energy consumption, as less window area can result in darker indoor areas and more lighting consumption. Conversely, more windows can result in increased thermal consumption.
8	Shading device	Fixed shading devices reduce cooling consumption in hot regions but can increase heating consumption in cold regions. In regions, where both cooling and heating are needed, a balanced shading device is critical for optimal energy consumption.
9	External wall materials	The thermal properties and air-tightness of the external wall determine the amount of heat conduction through the envelope and hence, the rate of heat loss or heat gain. Higher thermal mass usually results in lower energy consumption. Thick insulation on external walls reduces heating demand but increases cooling demand.
	Occupancy-level Parameters	
10	Household characteristics	Larger household size and higher household income usually lead to higher energy consumption. Aged occupants tend to consume more. If occupants are at home for longer, higher consumption usually occurs.
11	Occupants’ motivation and awareness	Occupants’ motivation regarding energy-saving behaviour, as well as awareness, usually result in energy saving.
12	Appliance efficiency	The higher the efficiency of installed appliances, the lower the energy consumption.

3.4 CONCLUSION

In this chapter, the contextual settings of this research at a global scale have been outlined, with a particular focus on energy and buildings. The chapter has also addressed the first objective of this research by identifying the parameters that influence the energy consumption of building and the way they influence this consumption.

It is clear from the literature review that to address the energy challenges of the 21st century, buildings will have an important role and must have a significantly lower energy consumption. In response to the need to reduce the energy consumption of buildings, a building energy code has been introduced and highly energy-efficient building types, such as passive houses and low-energy building, have been developed. In addition, some building types, such as ZEBs and plus-energy buildings, generate their own energy through incorporating GHG-free renewable energy sources.

In developing countries where the majority of future buildings are upcoming and energy is scarce, highly energy-efficient or energy-generating buildings are not yet common and the relevant studies needed to develop such buildings in the developing country's contexts are scarce. While it is recommended that in the changed context of the 21st century, the buildings in developing countries should be energy efficient and energy generating, the knowledge needed to do this are inadequate. Hence, this review has highlighted the gap in knowledge and the need for in-depth research in the context of developing countries regarding energy-efficient and energy-generating buildings in these countries.

The review has revealed that the energy consumption of building is a complex and dynamic phenomenon, influenced by a large number of parameters that are active at different levels, such as urban, building and occupancy. While the building- and occupancy-level parameters influence the energy consumption of a building mostly directly, the urban-level parameters influence it both directly and indirectly. The surrounding urban setting of a building can interfere with solar and wind access directly, resulting in higher or lower use of artificial lighting and cooling and heating energy. It also modifies the surrounding microclimate, primarily resulting in increased cooling or reduced heating demand. The occupancy-level parameters have been identified as having more impact on energy consumption than the urban-level and building-level parameters. They are also the most complex and unpredictable parameters and are mainly responsible for making the prediction of energy demand difficult.

The literature review also has identified that while many studies are available regarding the impact of building parameters as well as the indirect influence of urban parameters such as UHIs, studies regarding occupancy-level parameters as well as the direct influence of urban parameters are limited. In addition, none of the studies addressed all level of the parameters in a single study. It is understood that a large number of parameters influence the energy consumption of buildings and it is difficult to incorporate them all into a single study. However, the energy challenges of the 21st century mean it is important that further studies are conducted, incorporating all the parameters in a single study, to be able to compare the influence of different parameters at the same time and identify the parameters that are most influential. Such studies can lead to achieving real success in improving the energy efficiency of buildings.

4 RESEARCH DESIGN, METHODOLOGY AND METHODS

> Research is an art of scientific investigation … .Some people consider research as a movement, a movement from the known to the unknown. (Kothari, 2004, p. 1)

4.1 INTRODUCTION

This chapter presents the research approach adopted for the research along with the rationales and philosophical assumptions behind it. This is followed by the research design, methodologies and methods.

The research was conducted in three phases. The first phase was a preparatory phase conducted through a literature review to identify the research problems, questions, objectives and significance, as well as the theoretical background needed for the research. The second phase was the field study conducted to investigate the existing urban, building, microclimatic and household contexts of the case study areas. The third phase was to generate the research outcomes, primarily through simulation studies.

This chapter describes in detail the general and detailed procedures (methodology and methods) that were followed during the different phases.

4.2 RESEARCH APPROACH

The aim of this research was to find out ways to achieve energy-independent residential developments for Dhaka city, to address two of the city's pressing problems: rapid urbanisation and energy scarcity. This research sought to discover sustainable solutions for these problems.

Since the primary goal of this research was to ascertain the level of influence of different parameters on household energy consumption in typical planned residential developments of Dhaka, so that more energy-efficient alternatives can be identified to achieve energy independence, quantitative research approaches were deemed most appropriate for this conduct. Creswell (2014) and Shah and Corley (2006) suggested that if the primary concern of a study is to identify the influence of factors, cause-and-effect relationships, the utility of an intervention, or all kinds of relationships, then a quantitative approach is the most appropriate method. The central RQ of a quantitative approach focuses on 'what is happening?'. This is answered or expressed in numbers or quantitative terms (Creswell, 2014; Firestone, 1987; Gable, 1994; Groat & Wang, 2013; Johnson et al., 2007; Kothari, 2004; MacDonald & Headlam, 2008; Larsson, 1993). In addition, the goal of quantitative research is to attain replicable and generalisable outcomes (Creswell, 2014; Bhattacherjee, 2012; Leech & Onwuegbuzie, 2009; Shah & Corley, 2006; Yin, 2014). This study not only aimed to discover the relationships between the different parameters and household energy consumption but also followed procedures that would produce repeatable outcomes.

In addition to quantitative data, the research used very limited qualitative data to investigate the reasons behind certain factors and existing practices. Hence, this research adopted a multimethod approach; it predominantly employed different quantitative research strategies and techniques that were supported by a limited qualitative approach (Johnson & Onwuegbuzie, 2004).

4.3 RESEARCH DESIGN AND METHODOLOGY

> A research design is the logic that links the data to be collected (and the conclusions to be drawn) to the initial questions of study. (Yin, 2014, p. 26)

This research was based on the three RQs outlined in Chapter 1:

- RQ A: What are the ways to reduce existing household energy (electricity) consumption in typical planned residential developments in Dhaka?
- RQ B: To what extent can the existing energy consumption of households in typical planned residential developments in Dhaka be reduced?
- RQ C: Is it possible to achieve energy independence through roof-mounted solar PVs after reducing the level of energy consumption?

Different sets of procedures were followed to obtain the answers for these questions. Five research steps were designed to obtain answers to the first RQ. First, an extensive literature review was conducted to investigate the parameters that affect household energy consumption in general (not necessarily in Dhaka). As discussed in Chapter 3, this identified a number of parameters that could be grouped into three broad categories: urban and building parameters; microclimatic parameters and household parameters. Investigations were then conducted to identify the existing contexts of these three groups of parameters in typical residential developments in Dhaka. This was followed by investigating better alternatives to the existing practices that could reduce existing household energy consumption. The results of this formed the answers to the first RQ.

The next two research steps were designed to explore the answers for the second and third RQs, which aimed to discover, based on the findings of the previous research step, the best alternative options that could result in the maximum reduction of household energy consumption in typical residential developments in Dhaka. The final step was to ascertain whether, after applying energy-conservation strategies derived from the previous steps, the energy demand of an entire building could be met through installing roof-mounted solar PVs.

The greatest difficulty of this study was to select the appropriate methodology and methods for investigating the parameters that influence energy use in typical residential developments in Dhaka. The difficulty was due to the completely different nature of the three groups of parameters. The urban and building parameters investigations employed architectural investigation procedures in which data collection and analysis were primarily from drawings and observations. The microclimatic parameters investigations employed climatic research procedures and used only 'hard' data that was collected through instruments. The household parameters investigations employed survey research procedures, which collected statistical data through a questionnaire survey.

Experimental research methodology, which often is considered the essence of scientific research (Creswell, 2014; Groat & Wang, 2013; Rajasekar et al., 2013) was employed to conduct the final research steps of this study, in which household energy consumption was considered as the dependent variable and the urban, building, microclimatic and household parameters were the independent variables. To ascertain the best option for each of the investigated parameters from an energy-consumption point of view, independent variables were changed or manipulated one by one, while controlling the other independent variables to evaluate the effect of an option on energy consumption and hence, to identify the best options from the results. The experiments in this research step were conducted through building simulations, which refer to a computational model that closely replicates the real-world context (Groat & Wang, 2013; Hensen & Lamberts, 2011). To find out the best outcome in terms of the largest energy reduction, all of the best alternatives were applied to the same simulated model. Finally, simulations were run to find out the total surface areas needed to achieve energy independence through roof-mounted solar PVs. A conceptual framework has been provided at the end of this chapter to explain the research steps graphically (see Figure 4.9).

4.4 METHODS

This section presents the methods or detailed procedures employed for data collection and analysis at different steps of this study. Apart from Step 1, Steps 2 to 7 were conducted through rigorously collected or generated empirical data by using distinct methods or techniques. Note that ethics approval was obtained from the 'Low Risk Human Research Ethics Review Group' of The University of Adelaide before data collection since some of the research steps of this study involved humans for data collection through survey or interviews. The ethics approval no. for this study is: HP-2012-104 (see Appendix B.1 and B.2 for the ethics approval documents).

The following sections present the detailed data collection and analysis procedures employed for Steps 2 to 7 of this study.

4.4.1 Step 2: Urban and Building Contexts Study

The aim of research Step 2 was to examine the existing urban and building contexts in typical residential developments in Dhaka. Therefore, data were collected on different urban and building parameters from selected case study areas and buildings. Separate procedures were followed to collect the data for urban and building parameter investigations. These are presented below.

4.4.1.1 Data Collection: For Urban Contexts Study

The data collection phase was divided into two parts: selection of the case study areas and data collection.

4.4.1.1.1 Selection of the Case Study Areas

The areas selected for the study were Purbachal New Town, Uttara Model Town and DOHS Baridhara (see Figure 4.1). These are commonly called Purbachal, Uttara and DOHS. The reasons for selecting these case study areas were as follows:

i) All of the case study areas are representative of the typical residential developments of Dhaka city, as discussed in Chapter 2.
ii) Purbachal and Uttara are the two largest residential development projects of Dhaka city.
iii) Purbachal and Uttara (3rd phase) are two of the most current residential projects in Dhaka city. Note: Uttara has been developed in three phases, with the first two phases completed before 2000. The development of Uttara 3rd phase and Purbachal is currently ongoing.
iv) Uttara and DOHS are occupied by wealthier people than other typical developments, such as in Mohammadpur and Mirpur of Dhaka (Seraj, 2012; Begum, 2010). This study argues that since wealthier people live there, these areas represent one of the worst-case scenarios from an energy-consumption point of view; therefore, if these developments could achieve energy independence, so would the majority of the other developments.

4.4.1.1.2 Data Collection

Multiple sources and methods were used to collect the data for investigating the existing urban contexts. Maps and plans of the case study areas were a primary source. The AutoCAD plans of Uttara 3rd phase and Purbachal were collected from RAJUK. The maps of Uttara 1st and 2nd phase and DOHS came from personal collections. Along with the AutoCAD plans, satellite maps of the case study areas were used. These were collected from EGIS and Google Earth. Apart from the maps and plans, additional data were collected through site surveys as well as from photographs and videos taken during the field studies. Observation was used as the main technique to extract data from the maps, plans, photographs and videos.

Interviews with two urban planners at RAJUK (an urban planning professor at Bangladesh University of Engineering and Technology and the chief architect of Purbachal) were conducted to discover the primary motivations and driving factors behind the current urban practices of typical residential developments.

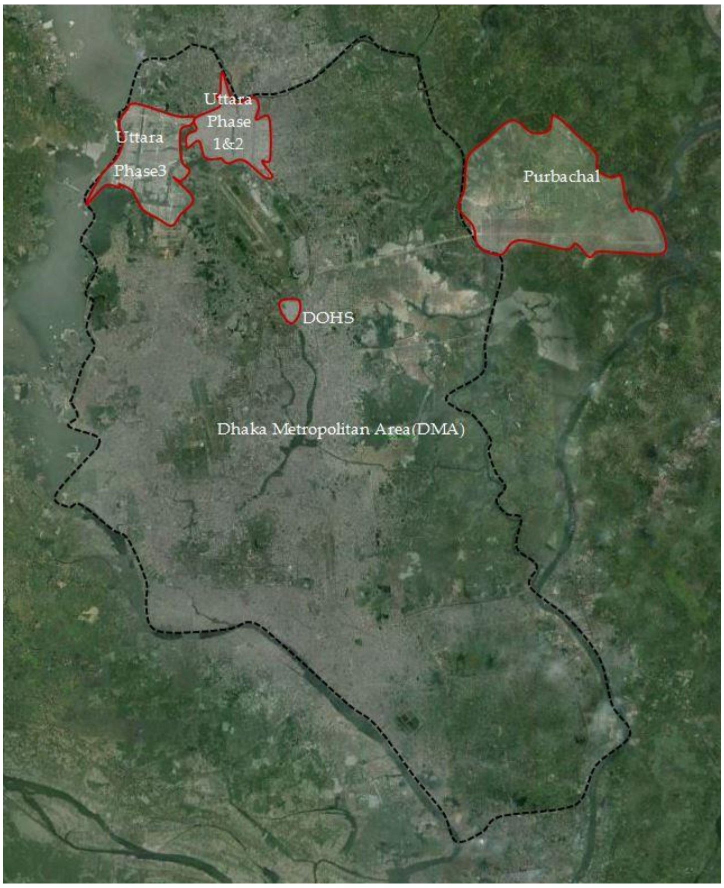

Figure 4.1: *The Location of the Case Study Areas in Dhaka. Source: Adapted from Google Earth*

4.4.1.2 Data Collection: For Building Contexts Study

Data collection for the building contexts study was divided in two steps: selection of buildings and data collection.

4.4.1.2.1 Selection of Buildings for the Study

The building contexts study focused only on the buildings on 5-katha plots, for reasons that are explained below; however, three other plot sizes are common in Dhaka: 3 katha, 7.5 katha and, 10 katha (discussed in further detail in Section 5.2.2). This research studied only buildings constructed under the Building Construction Act 1996 (see Section 2.2.5.2.1). There were several reasons for this. First, when the field study was conducted in 2013, not enough complete buildings under the new rules were available. A preliminary study of building plans, as presented earlier in Section 2.2.5.2.1, found that the buildings on smaller plots had not been affected much by the new rules. Additionally, buildings under the older rules have higher floor areas, which suggest higher energy consumption; hence, if older buildings can achieve energy independence, the newer ones will achieve it too. However, this research acknowledges that further studies with the buildings constructed under the new rules will be needed.

This research also acknowledges that while buildings on all plot sizes need to be studied, time was a major constraint for this research and studying buildings on all plot sizes was not practical. The primary reasons for choosing buildings on 5-katha plots for this study were as follows:

i) A 3-katha plot is too small for a building on it to have double units per floor. As a building on a 5-katha plot usually has double units per floor, a building on a 5-katha plot normally has more dwelling units than a building on a 3-katha plot. This means that the energy demand of a 5-katha building will normally be higher than that of a 3-katha building. Since the ultimate goal of this research was to study energy independence, the 5-katha plot was deemed more appropriate for the study as it presented the worst-case scenario from an energy demand point of view.

ii) 5-katha plots usually occupy the maximum land area of a residential development and are the most popular plot size (Begum, 2010).

iii) Although buildings on a 7.5- and 10-katha plot have a larger floor area and can accommodate more units, making them likely to have more energy consumption than 5-katha buildings, they are much smaller in number compared to the number of 3- and 5-katha plots (Seraj, 2012). Through interviewing several developers and architects who were active in the field, it was found that the size of apartment units in buildings on larger plots were also larger. Therefore, it did not necessarily follow that buildings on larger plots would have more dwelling units and therefore higher total energy demand than those on 5-katha plots.

As outlined earlier, this research focused on buildings built by developers, as these are always built with the intention of profit maximisation; therefore, they always have the maximum allowable built area as well as more glazed surfaces than those built by the occupants or owners of the apartments, to attract potential buyers (see Figures 4.2 and 4.3). This research argues that since the developer's buildings usually have higher glazing surfaces, they are likely to have a higher indoor temperature and hence, a higher energy demand.

Figure 4.2: *Examples of Owner-built Buildings. Source: Field Study*

Figure 4.3*: Examples of Developer-built Buildings. Source: Field Study*

4.4.1.2.2 Data Collection

After setting the criteria for the buildings to be studied, 70 developer-built apartment buildings and 93 apartment unit plans from Uttara 1st and 2nd phase and DOHS Baridhara were collected (Uttara 3rd phase & Purbachal were still under construction). According to Dillman et al. (2009), for a homogeneous population with 2000 members, 60 samples are needed for a representative outcome with a 10% confidence level. Since the total number of 5-katha plots in the case study areas were fewer than 2000 and the buildings were highly homogeneous, the number of buildings (70) and apartment units (93) studied for this study was deemed sufficient.

Building floor plans and apartment unit plans were collected from multiple sources: architectural firms, real estate developers, websites and brochures, as well as personal collections. An effort was made to collect plans from as many diversified sources as possible, to cover as many existing building design and construction practices as possible. In addition to studying the plans, five formal interviews with real estate developers and practising architects were undertaken, along with a number of informal conversations with several architects to find out the primary motivations and driving forces behind several existing practices and choices. The 'Analysis of schedule of rates 2011 for civil works' published by the Bangladesh Government public works department, were also consulted (Public Works Department [PWD], 2011) to augment the information about the available construction practices and materials.

4.4.1.3 Data Analyses

For both urban and building contexts, the data were primarily analysed through simple descriptive statistics such as the frequency, mean, minimum and maximum, using both SPSS (Version 21) and MS Excel 2010, along with observations. Analysis details are presented with the relevant studies in Chapter 5.

4.4.2 Step 3: Microclimatic Contexts Study

The aim of research Step 3 was to find out the existing microclimatic contexts in typical residential developments. The following section describes the data collection and analysis procedures followed in this step.

4.4.2.1 Data Collection

The data collection procedures for the microclimatic study were divided into three steps: instrumentation, selection of case study buildings and data collection. It is important to note that only the modification of air temperature was investigated during the microclimate study. Although it is acknowledged that all four major climatic parameters—air temperature, RH, solar radiation and air speed and direction—can be significantly altered by an urban development, this research only focused on the air temperature because of time and resource constraints. Wong et al. (2011) and Ahmed (1994) argued that air temperature has more effect on the consumption of cooling energy in a building than other environmental parameters; therefore, this research was restricted to investigating the air temperature around and inside the buildings.

Due to time and cost constraints, the data for the microclimatic study were collected from August to October 2013, which are not the hottest months of the year. May to July would have been the best time to conduct this study, as it would have provided the maximum extent of the air temperature modification in Dhaka's contexts; however, the time constraint of this research did not allow the researcher to wait until May of 2014 and the necessary arrangements could not be made before August 2013. Nevertheless, the data from September to October 2013 provide useful information that provides a solid understanding of the effect of the existing urban and building design practices on the microclimate.

4.4.2.1.1 Instrumentation

To collect air temperature data from different locations in the case study areas, non-intrusive data loggers were used (HOBO data loggers from onset) (see Figure 4.4). The number of data loggers used (42) was constrained by the available budget; however, given the fact that the physical contexts of the case study areas were highly homogeneous, this number was deemed sufficient to provide reliable and representative findings about the existing microclimatic contexts. The following table provides the list of the loggers used for the data collection.

Table 4.1: *List of Loggers used for the Data Collection*

#	Type of Logger	Model No.	Total No.
1	Outdoor	HOBO U23-001	12
2	Outdoor	HOBO UA-002-64	12
4	Indoor	HOBO U12-013	16
5	Indoor	HOBO Ux100-003	2

All of the loggers were tested before they were installed. For testing, each logger was set up to measure air temperature at 1-minute intervals through BoxCar Pro (for older loggers) and HOBO ware 3.4.1 (for newer loggers) software programs. They were all put into an airtight container for one night. After that, the data were downloaded from the loggers and plotted using MS Excel 10, to see if there was any anomaly among the loggers' measured data. In total, 46 data loggers were tested, of which four were excluded due to malfunction. The battery life of the loggers was also checked and the loggers with less than 85% battery life were given new batteries.

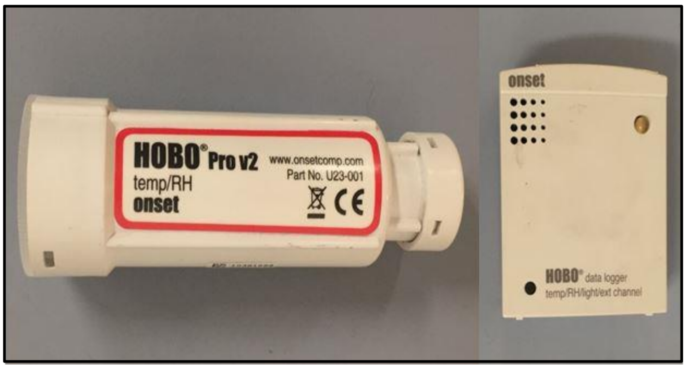

Figure 4.4: *Examples of Loggers used: HOBO U23-001 & HOBO U12-013*

4.4.2.1.2 Selection of Case Study Buildings for Installation of Data Loggers

In the second step of the data collection process, buildings were selected for installing the data loggers. Uttara and DOHS Baridhara were chosen as case study areas for studying the microclimate contexts and were also used for the urban and building contexts study. Loggers were installed from the front, side and rear facades of the buildings so that the impact of current urban development practices on the ambient air temperature surrounding buildings could be investigated. In typical planned residential developments of Dhaka, the building façade next to the access roads is considered as the front façade and the orientation of the front façade is considered as the orientation of the building (see Sections 5.3.2 and 6.2 for further details). Preliminary studies indicated that the front facades of the buildings in the case study areas were mainly located on either one of the four cardinal points; therefore, the aim was to select buildings with four different orientations (north, east, south and west). An effort was made to ensure the case study buildings had similar built-environmental contexts, such as the same distance between buildings and the same height of the building opposite: that is, with a similar CR in the front and side of the selected buildings. It was known from a preliminary survey, as well as from experience, that there was little variation in building materials used.

Although, the aim was to have buildings that were reasonably centrally located in the case study areas, finding appropriate buildings and apartment owners willing to allow the installation of data loggers was not easy. Additionally, security and vandalism is an issue in Dhaka, so serious effort was made to ensure the loggers were installed in visible areas so they would not be stolen easily. Since the security of DOHS Baridhara is better than Uttara, more loggers were installed in DOHS.

Four buildings in DOHS Baridhara and two buildings in Uttara were selected for installing the loggers, primarily because of the availability and willingness of the building owners to participate; however, they were also representative of the built-environmental contexts. Two out of the six case study buildings had a north orientation, two had an east orientation, one had a south orientation and one had a west orientation (see Section 6.2 for further details).

4.4.2.1.3 Installation of Data Loggers and Data Collection

The loggers were set to take half-hourly air temperature measurements. The external data loggers were placed inside shields, painted black in the inside to exclude the effect of solar radiation from the air temperature reading (see Figure 4.5). The loggers were installed on the front façade of the six selected buildings at three different heights; therefore, each orientation (i.e., north, south, east and west) had three loggers at 3 m, 9 m and 15 m above ground level. Loggers were also installed on one side and one rear façade of a building, to measure the temperature at setback areas.

Figure 4.5: *Shielded Loggers*

The loggers were approximately 1 m away from the building façades and were hung with the help of a PVC pipe (see Figures 4.6 and 4.7). The data loggers were not near an AC outlet. Both the installation and uninstallation processes of all the loggers took nearly one week and were dependent on the apartment owners' availability. The loggers were installed between August 12 and 17 2013 and were uninstalled between October 11 and 18 2013.

For indoor temperature measurement, 18 data loggers were placed in the rooms next to the front façade where the outdoor loggers were installed. Although every effort was made to place the loggers in rooms without AC and generally in common spaces, due to the plan of a particular apartment as well as the safety of the loggers, some were put in the rooms with AC. The indoor logger at 15 m of the east-2 building was in an incomplete and under-construction apartment without any doors and windows. However, the indoor contexts of the loggers were carefully considered during the analysis of the indoor temperature data.

Figure 4.6: Loggers at the Side Setback Area and at the South

Figure 4.7: *Loggers at Various Locations*

Interruptions occurred and the logger at the 9 m level of the east-oriented building in DOHS was stolen within two weeks of installation. Therefore, the loggers from that building were shifted to another east-oriented building in DOHS and one of the two extra loggers were installed on 31 August 2013. Because of this mishap, the data analyses are based on measurements for 40 days (from 1 September to 10 October 2013) instead of 54 days. The data from five data loggers were downloaded in the middle of the study period (third week of September) to check whether the loggers were measuring the data correctly and then reinstalled.

4.4.2.2 Data Analyses

The data were analysed mainly through simple descriptive statistics as well as data visualisation and graphical representation using Excel 2010. Detailed analysis procedures are provided with the relevant studies in Chapter 6.

4.4.3 Step 4: Household Contexts Study

The fourth research step was conducted to find out the existing contexts of the household parameters in the residential developments that were the focus for this research. The following sections describe the procedures and methods followed to collect and analyse the data for this study.

4.4.3.1 Data Collection

Primary data for this study were collected through a questionnaire survey, which was conducted between July and October 2013 in Dhaka. The total data collection process was divided into five major steps: identifying the parameters; questionnaire form design; pilot study; sample selection and size; and survey administration and data collection. Energy consumption data for the case study areas for the study period were also collected from DESCO.

4.4.3.1.1 Identifying the Parameters

An exploratory study was conducted through an extensive literature review (research Step 1) and by talking to available residents who lived in the residential developments that were the focus for this research. The parameters identified to influence the energy consumption of the households were divided into two major categories, depending on their nature of influence: indirect parameters and direct parameters.

Indirect parameters refers to the factors that influence the ownership and use of different household appliances and hence, indirectly influence the total energy consumption. They include factors such as household income, total number of occupants, external wall construction and operational practices regarding the doors and windows of a household. The indirect parameters were further divided into three groups: parameters related to the general characteristics of the households, including the number of occupants, income, affordability and occupancy pattern; parameters related to the building, including the orientation, external wall construction, number of windows and external glass doors; and parameters related to the operational practices of opening the doors and windows.

Direct parameters refer to the different aspects of the household appliances themselves, including the ownership, number, type, capacity and use of fans, AC, lights, refrigerator, TV and other appliances. While the direct parameters or appliances directly consume energy to function, the indirect parameters influence the way the appliances are used. The direct parameters (the appliances) were divided into three groups: appliances to achieve indoor thermal comfort, such as ceiling fan, AC and heater; artificial lights; and domestic appliances such as refrigerator, freezer, TV and cooking appliances.

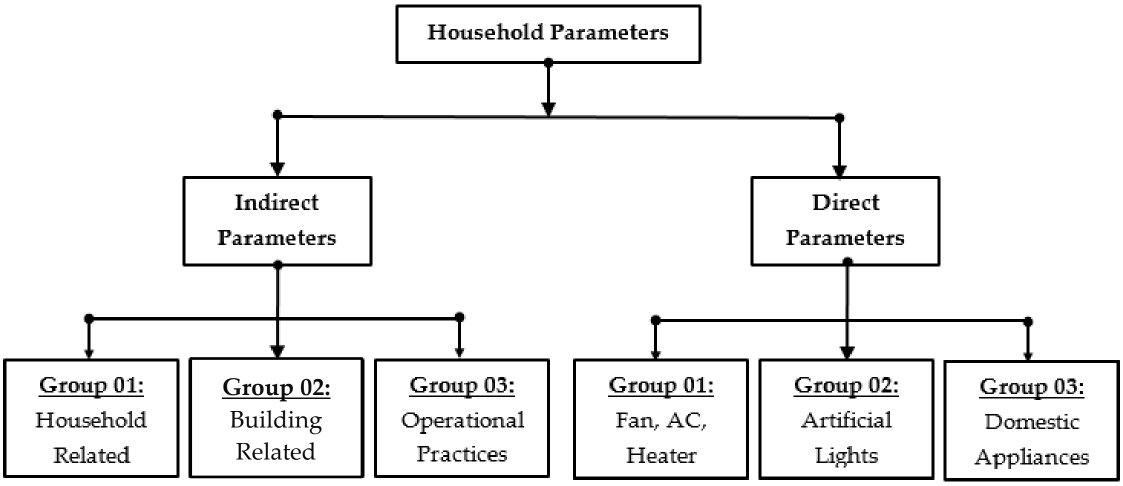

Figure 4.8: *Indirect and Direct Household Parameters Diagram*

The following tables provide lists of the major indirect and direct parameters investigated in this study.

Table 4.2: *Major Indirect Parameters for Household Contexts Study*

Indirect Parameters	
Group 1: Household related	**Group 2: Building related**
Total number of household occupants	Apartment size
Total number of family members	Developer- or owner- built
Total number of full-time maids	Floor levels
Occupancy pattern	Orientation
Occupancy status	External wall & roof construction
Monthly income	Number of glass doors
Apartment vacancy	Window type
Non-residential activities	Cross-ventilation perception
	Mosquito nets on windows
	Presence of indoor plants
	Roof garden

Indirect Parameters	
Group 3: Operational practices	
Window-opening frequency in summer	
Balcony & bedroom door opening frequency (overall)	
Bedroom window-opening frequency (overall)	
Bedroom curtains opening frequency (overall)	
Common-space windows opening frequency (overall)	
Common-space curtains opening frequency (overall)	

Table 4.3: *List of Major Direct Parameters for Household Contexts Study*

Direct Parameters	
Group 1: Thermal comfort-achieving parameters	**Group 2: Artificial lights**
Total number & use of ceiling fans, AC, heaters	Types of lights
AC ownership	Total number & use of lights
AC types & capacity	Total capacity of lights
Total number & use of ACs	
Group 3: Domestic appliances	
Cold appliances: Ownership, total number, age & type of refrigerators & freezer	
Wet appliances: Ownership of washing machine & geyser[12]	
Cooking appliances: Ownership of oven, microwave oven, rice cooker, toaster, etc.	
Brown goods: Ownership, total number, type & use of TV, computer, entertainment	
Miscellaneous: Ownership of iron, vacuum cleaner, IPS, rechargeable items, etc.	

4.4.3.1.2 Questionnaire Design

Once the parameters to be investigated had been identified, as well as the type of information needed for each of the parameters, a questionnaire was designed to collect the necessary data from the subject households. The questionnaire predominantly sought quantitative and categorical responses and included both closed

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[12] *Electric water heater.*

and open-ended questions. General instructions were included at the beginning of the questionnaire, along with a brief explanation for several of the questions as deemed necessary, in both English and Bengali. Care was taken over the wording, legibility and appearance of the questionnaire form. An introductory page in both languages was included to explain the research and the reasons for conducting the questionnaire survey, along with the contact details of the researchers in case of further queries (see Appendixes E.1 and E.2).

4.4.3.1.3 Pilot Study

A pilot study was conducted once the first draft of the questionnaire form was finalised, to find out whether any questions needed to be added, deleted or adjusted and whether the questions and the questionnaire form were clear and legible enough to get the answers needed from the participants. The respondents of the pilot study were the same as the target households, who were known to the researcher. Sixteen people participated in the pilot study. The questionnaire was sent to them as an email attachment. Based on the feedback from the pilot study, the questionnaire form for the final survey was refined and finalised.

4.4.3.1.4 Sample Selection and Size

The target respondents for the questionnaire survey were households living in typical 5-Katha apartment buildings in Uttara and DOHS Baridhara, where the built-environment and microclimatic study was conducted. At the time of this research, there were approximately 16,000 households in Uttara and DOHS. For a population between 10,000 and 25,000 and aiming for a 95% confidence rate and 5% margin of error, 370 samples are required to obtain a representative outcome for the population (Ambrose & Anstey, 2010; The Research Advisors, 2006). Therefore, the questionnaire survey needed to collect at least 370 responses.

4.4.3.1.5 Survey Administration and Data Collection

A questionnaire survey can be administered in several possible ways, such as face-to-face, paper-and-pencil and computerised questionnaire administration (Ambrose & Anstey, 2010; Gable, 1994; Gendall, 1998; Flier, Mellenbergh, Ader & Wijn, 1984). This research used mixed methods such as face-to-face interviews and paper-and-pencil survey. A small number of responses were collected through email. In total, 392 responses were collected from Uttara and DOHS. Post-survey phone calls were made to each paper-and-pencil questionnaire respondent (257) to ensure that the respondents were from the correct samples.

4.4.3.2 Data Analyses

The data were analysed through statistical methods by using SPSS (Version 21). Before running the analyses in SPSS, the data were entered and prepared in Excel and imported to SPSS. Pre-analysis checking and screening of the data were conducted rigorously to cancel the possibility of wrong entries, which could distort the outcomes. Different statistical techniques were used to analyse the data collected through the questionnaire survey. The techniques used included simple descriptive statistics such as frequency, mean, minimum and maximum, as well as complex techniques such as correlation and multiple regression. Details of the analysis strategies are provided with the relevant analyses in Chapter 7.

4.4.4 Steps 5–7: Simulation Studies

The fifth, sixth and seventh steps of this research were conducted through simulation studies. Integrated Environmental Solutions-Virtual Environment (IESVE) (Version 2015.2.2.0) building-simulation program was used for the simulation studies. One of the main reasons for using IESVE was that it is considered one of the most comprehensive and reliable building-simulation programs. It has been tested using the IES ASHRAE 140 and is qualified as a dynamic model for the CIBSE classification system (Sousa, 2012). In addition, it allows a large number of parameters in the simulation analysis for the buildings.

For the simulation studies, a case study apartment was selected based on the findings from the urban and building contexts studies. This apartment was then modelled and used to investigate the answers for all three research questions. To ensure that the model would represent the indoor thermal environment of the actual apartment, the hourly simulated indoor temperatures were compared to measured indoor temperatures. In addition, the monthly electricity consumptions of the case study apartment during the study year (2013) were compared with the simulated monthly electricity consumptions. Inputs to the simulation model were adjusted, particularly on the operation of openings and ACs to reflect the actual practice, until the discrepancies were within acceptable limits. The detailed method and steps of the simulation studies such as the selection of the case study apartment, reproduction of the apartment in the IESVE program, calibration process and data generation and analyses are provided in the Chapter 08.

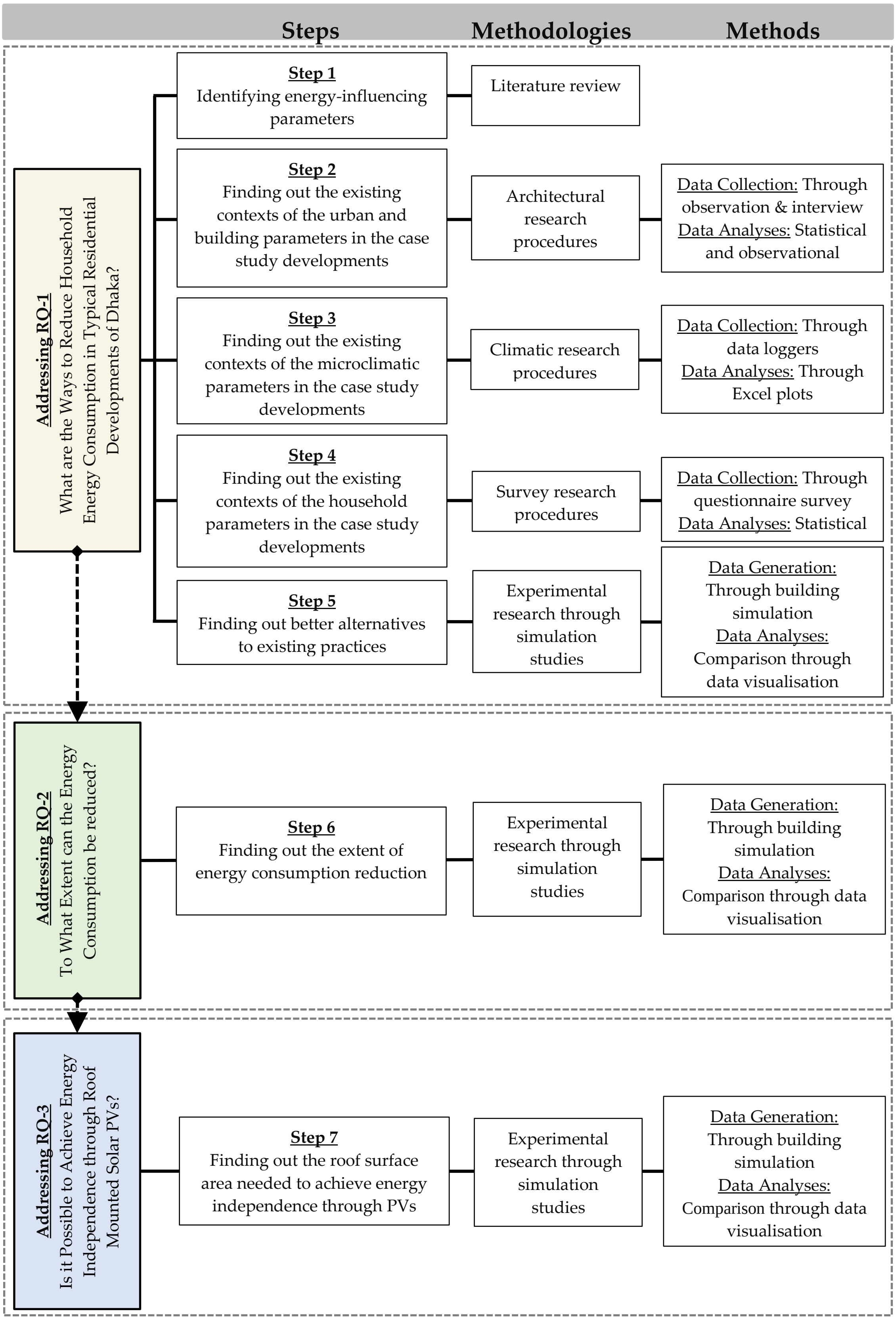

Figure 4.9: Conceptual Framework with Research Steps, Methodologies & Methods

Part II: Field Studies

Chapter 5: Urban and Building Contexts

Chapter 6: Microclimatic Contexts

Chapter 7: Household Contexts

5 URBAN AND BUILDING CONTEXTS

5.1 INTRODUCTION

This chapter presents the findings of the urban and building contexts study, the aim of which was to explore the existing urban and building development practices in typical planned residential developments of Dhaka. The study was conducted in two stages: the urban parameters and the building parameters. The results of the study are presented below in two separate sections for the urban and building contexts.

5.2 URBAN CONTEXTS

The immediate built-environmental contexts of a building are referred to as the urban contexts. The urban parameters were investigated to explore the existing practices in plot layout, plot shape, plot size, plot orientation, road layout, road width, vegetation and road surface materials.

As explained in Section 4.4.1, the investigations were conducted in two steps. In the first step, three case study areas (Purbachal, Uttara and DOHS Baridhara) were selected and data were collected from the plans, maps, photos and a physical survey, primarily through observations. In the second step, the data were analysed through descriptive statistics and observations.

5.2.1 Plot Layout

Plot layout refers to the way the building plots are planned in typical residential developments in Dhaka. The maps and plans of Purbachal, Uttara and DOHS Baridhara were studied to explore the existing plot layout pattern in the case study areas. The typical plot layout pattern was the same for all three case study areas, adhering to the following principles:

i) Two rows of plots were laid back to back, with each plot sharing the same boundary with three other plots at the two sides and the back, except for the plots at the end of rows, which shared the boundary with only two other plots (see Figures 5.1 and 5.2).

ii) The fourth side of a plot (the front side of the plot) was the access road. This means that except for the end plots, each plot was surrounded by three other plots at the back and two sides and the fourth or the front side of the plot was next to an access road. In the case of end plots, one side and the back were surrounded by two adjacent plots and the other two sides were usually next to two roads at right angles (see Figure 5.2).

iii) Therefore, the basic layout of the plots was two rows of plots and then one access road, and then again two rows of plots followed by another access road. Each access road served two rows of plots situated along the two sides of the road.

Although the plot layout pattern in all of the case study areas was highly homogeneous and rigid, the total number of plots per row was not fixed and was found to vary from three plots in DOHS to 20 plots in Uttara 3rd phase. The average number of plots per row at Purbachal was nine, with 16 at Uttara 3rd phase and 10 at DOHS Baridhara. The typical plot layout pattern resulted in two types of plot: i) the middle plots, which were surrounded by three other plots and ii) the end or corner plots, which were surrounded by two plots and two right-angled roads. A frequency analysis showed that 25% of the plots at Purbachal, 16% of the plots at Uttara and 23% of the plots at DOHS were corner plots.

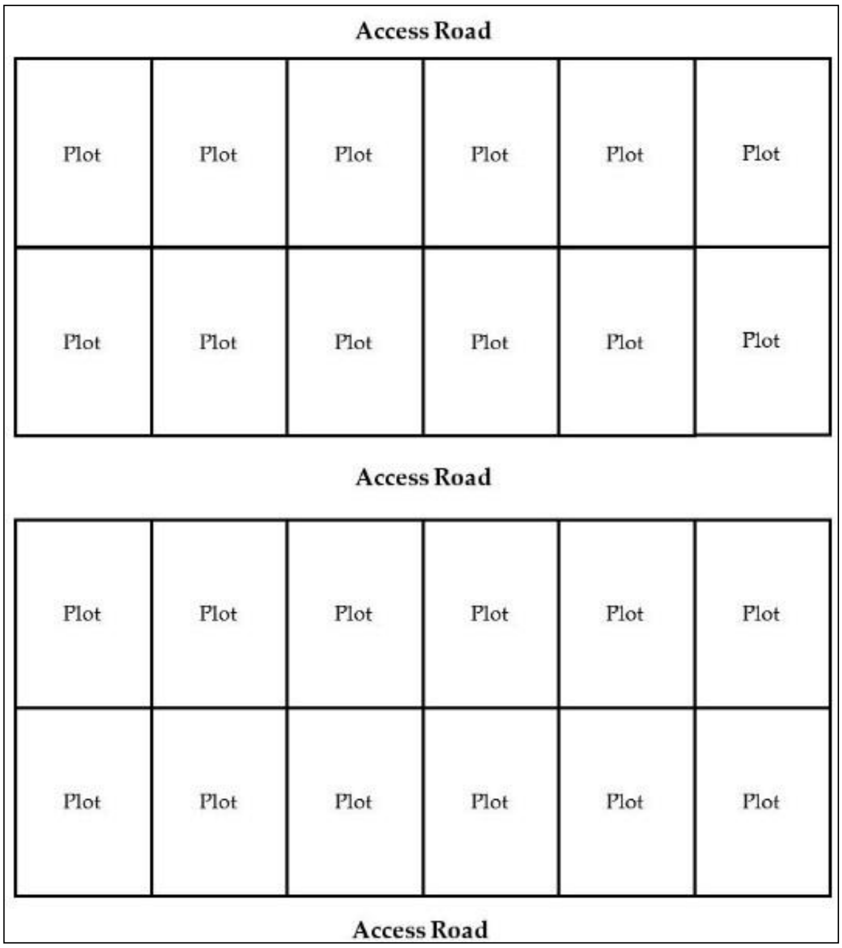

Figure 5.1: *Typical Plot Layout Pattern*

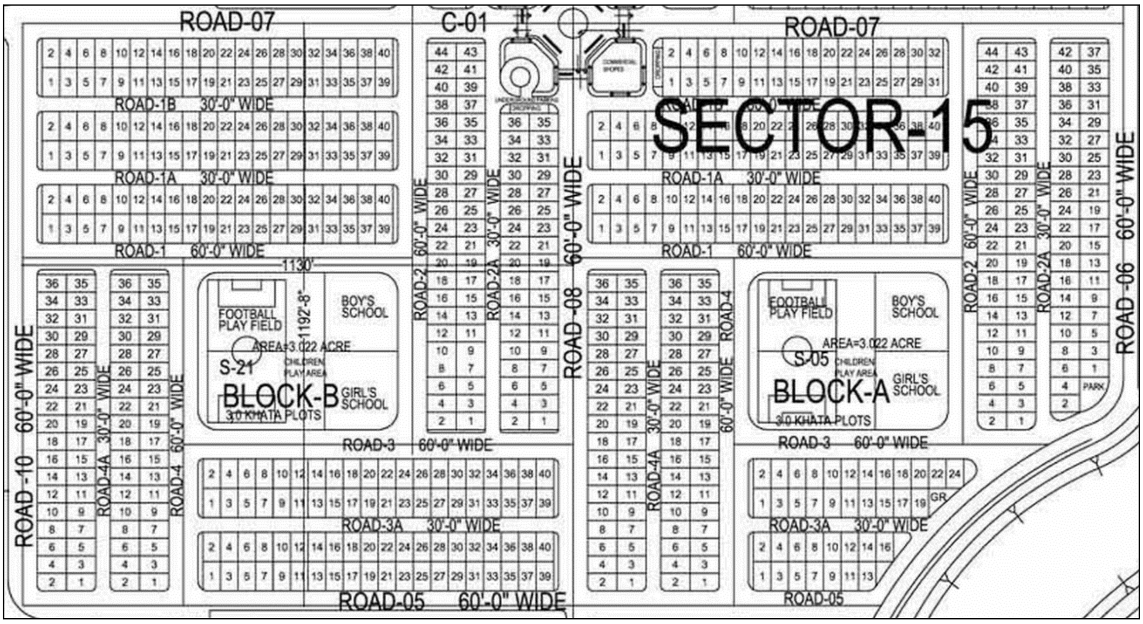

***Figure 5.2**: Example of Plot Layout at Uttara 3rd Phase, Sector 15. Source: RAJUK*

5.2.2 Plot Shape, Size and Dimension

Nearly all of the plots in the three case study areas had a regular rectangular shape. Plots next to the edge of the developments, as well as some plots in Uttara 1st phase, were occasionally found to have a non-rectangular or irregular shape (see Figure 5.3).

Figure 5.3: *Rectangular and Non-rectangular Plot Examples*

The size and dimension of the plots in the case study areas varied. Excluding the irregular plots, all other rectangular plots were found to have six different sizes[13]. The sizes of the plots are detailed in Table 5.1.

Table 5.1: *Different Plot Sizes in the Case Study Areas*

#	Plot Size	Area (ft^2)	Area (m^2)
1	3 Katha	2,160	200.77
2	3.5 Katha	2,520	234.24
3	4 Katha	2,880	267.7
4	5 Katha	3,600	334.62
5	7.5 Katha	5,400	501.93
6	10 Katha	7,200	669.24

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[13] *Bangladesh continues to use the Imperial system of measurement in the building industry. When measurements are shown in this thesis, a metric conversion is also given when appropriate.*

Although six different plot sizes were found, 3.5- and 4-katha plots were scarce (3.1% of the total plots surveyed) and were found only in Uttara 1st phase, which is the oldest area. This is possibly because the Uttara 1st phase was initiated during the pre-independent period (before 1971), with different goals, which after independence were modified according to the new need of a capital city. In the more recent developments such as the DOHS, Uttara 3rd phase and Purbachal, 3.5- and 4-katha plots were non-existent. From the findings, it can be said that the most common plot sizes in typical planned residential developments of Dhaka were 3, 5, 7.5 and 10 katha.

A frequency analysis excluding the 3.5- and 4-katha plots showed that most plots were 3-katha plots, followed by 5-katha, 7.5-katha and 10-katha plots. However, in terms of land coverage, 5-katha plots accounted for the maximum land coverage (1,366 acres), followed by 3-katha (1,049 acres), 7.5-katha (416 acres) and 10-katha (337 acres) plots. While the case study areas mainly consisted of 3-katha and 5-katha plots (85%), the 5-katha plots accounted for the maximum residential land coverage (see Figure 5.4). It is worthwhile to note that according to the building construction rules (RAJUK, 2008), larger plots can further be divided into two or more smaller plots among multiple owners (mainly heirs) but the divided plots cannot be less than 5 katha. Therefore, in future, larger plots can be expected to be divided into further 5-katha plots. This scenario indicates the common practices and preferences regarding plot size and land division; however, due to the high demand for serviced plots and the acute land scarcity, a higher number of smaller plots is being provided in the newer developments.

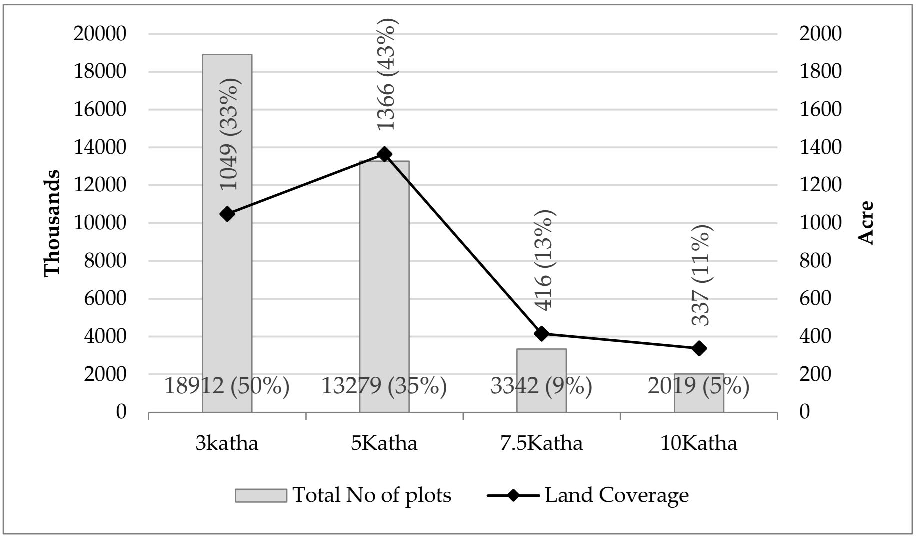

Figure 5.4: *Total Number (in Thousands) and Land Coverage (in Acre) by Different-sized Plots*

Further studies were conducted to ascertain the standard dimensions of the different-sized plots across the case study areas. Only 3-katha plots were found to have two different dimensions, with the rest having only one dimension. The shorter length always faced the access road and the longer lengths shared the boundary lines with the adjacent plots. The standard plot dimensions found from the study are noted in Table 5.2.

Table 5.2: *Plot Size & Dimension*

#	Plot Size	Plot Dimension
1	3 Katha	36′(11m)x60′(18.3m) or 40′(12.2m)x54′(16.5m)
2	5 Katha	50′(15.2m)x72′(22m)
3	7.5 Katha	72′(22m)x75′(23m)
4	10 Katha	72′(22m)x100′(30.5m)

5.2.3 Plot Orientation

Plot orientation refers to the orientation of a plot with respect to its access road. For example, if the access road of a plot is situated at the north of the plot, that plot is identified as a north-facing or north-oriented plot. The common practice of identifying the orientation of a plot in Dhaka was taken as the reference here (see Figure 5.5). Since a common plot was generally surrounded by other plots on three sides, the location of the access road was important in terms of direct solar access or exposure to the prevailing wind flow.

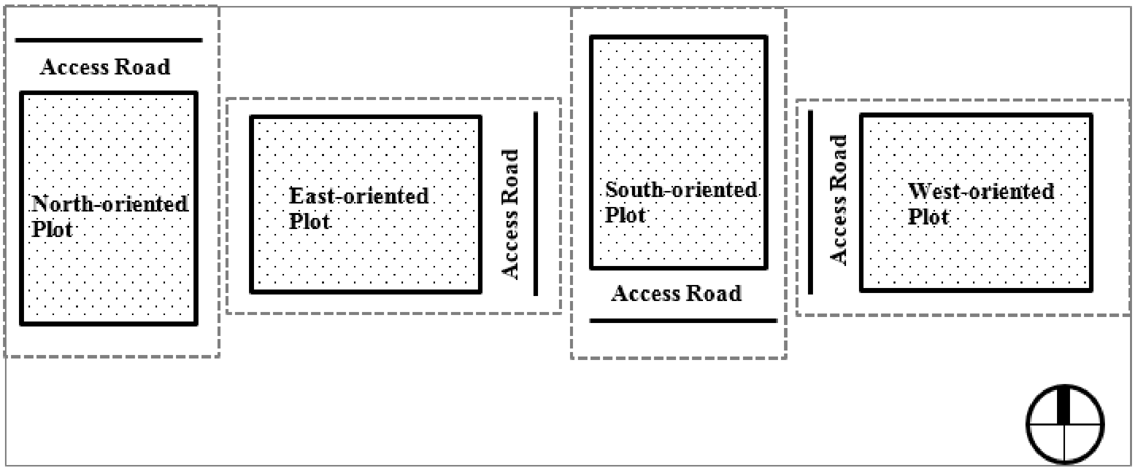

Figure 5.5: *Plot Orientation With Respect to the Access Road*

A frequency analysis showed that 95.2% (24,506) of the total plots in the case study areas faced either one of the four cardinal points (north, south, east or west) and only 4.8 % (1,228) of the plots were oblique with respect to the cardinal points. However, only Uttara 1st phase and Purbachal were found to have oblique plots and from the plans, it seems that they are oblique due to the outline of the site rather than as a deliberate choice. Further analysis found that 58% of the total plots were either north- or south-oriented and 37.6% of the plots were east- or west-oriented. Nearly an equal number of plots were found for two opposite orientations, such as the north (7,388) and south (7,450), and the east (4,851) and west (4,817) (see Figure 5.6). Given the existing plot layout pattern, the plots usually had equal shares for two opposite orientations. The results also showed that there were 21.4% more north- and south-oriented plots than east- and west-oriented plots.

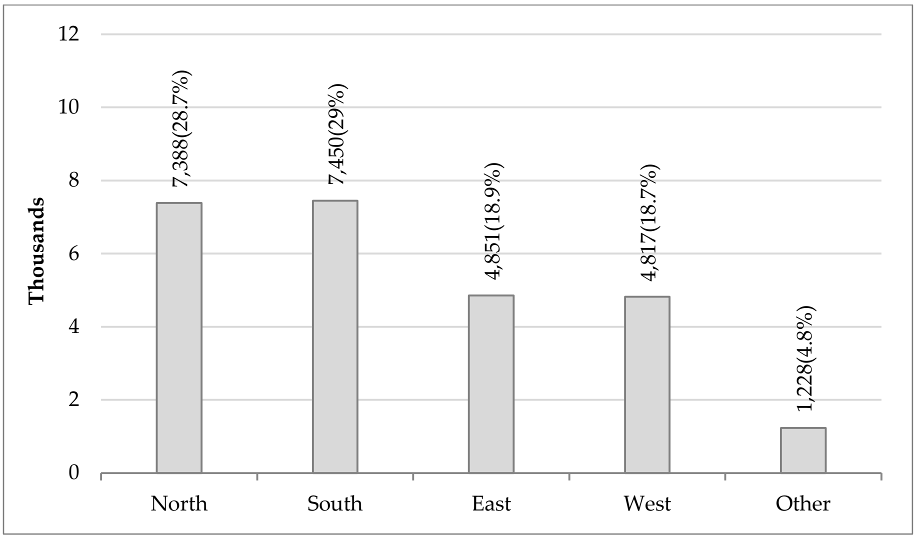

Figure 5.6: *The Frequency of Differently Oriented Plots*

The frequency analysis result supported the anecdotal evidence that in Dhaka, south-oriented plots are the most preferred and west-oriented plots are the least preferred. Further, it was found by studying the brochures of three private residential projects ('Bashundhara Residential Area', 'Ashulia Model Town' and 'Green Model Town') that the unit price of a south-oriented plot was significantly higher than a north- or west-oriented plot—up to 200,000 Taka[14] more per katha. The main reason for preferring a south-oriented plot in Dhaka is the prevailing climatic contexts. Dhaka's climate is predominantly warm and humid; therefore, to achieve comfort, airflow is essential (Ahmed, 1994; Ahmed, 1996; Mallick, 1994). Since the prevailing wind flow during the hot summer months is from the south and south-east, traditionally, a south- or east-facing house is preferred. Similarly, due to the low afternoon sun from the west, which cannot be blocked easily through any shading device, and the absence of wind flow, west is considered the worst orientation in Bangladesh's climatic contexts. An old proverb regarding the orientation of a house in Bangladesh says:

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[14] *1 AUD = 59.44 Taka, as of July 2016.*

'দক্ষিন দুয়ারী ঘরের রাজা
পূব দুয়ারী তাহার প্রজা
উত্তর দুয়ারী কোরো না ভাই
পশ্চিম দুয়ারীর মুখে ছাই'- খনার বচন

The proverb means that the south-facing house is the best, followed by the east-facing house. The north-facing aspect should be avoided if possible and the west-facing is the worst. The proverb is well known to Bangladeshi people and is generally acknowledged; therefore, it can be assumed that the traditional practices as well as the experiences of people have resulted in the preference for south-oriented plots and the avoidance of the other orientations.

5.2.4 Road Layout and Width

The road layout in all three case study areas were found to follow the same grid pattern, with two rows of plots creating one grid. Both N-S and E-W axis roads existed in all three case study areas. However, since the roads and plot layout are interdependent and more plots were north- and south-facing in the case study areas, a higher number of access roads were found along the E-W axis.

In general, three types of roads were found in the case study areas: primary roads, secondary roads and tertiary roads. In smaller developments such as DOHS Baridhara, there were only two types of roads. Primary roads connect the development with the city and therefore are the widest. The plots on primary roads are mainly allocated for non-residential buildings. Different sectors or residential districts in larger developments such as Uttara and Purbachal are connected to the primary road through secondary roads. Tertiary roads are the access roads to the residential plots.

The road width is another important urban parameter from an energy-consumption point of view, as it determines the CR in front of a building and hence, the degree of solar and wind exposure. The width of a primary road in the case study areas was found to vary from 100′ (30.5m) to 250′ (76.2m) and secondary roads were found to vary from 40′ (12.2m) to 72′ (23m). The width of tertiary or access roads did not vary much, with a fixed road width of 30′ (9.15m) in majority of the cases. Only in Uttara 3rd phase, some tertiary roads were found to be 25′ (7.6 m) and 34′ (10.4m) wide.

5.2.5 Vegetation and Materials

As discussed in Section 3.3.1.1, the amount of vegetation and the type of materials used in an urban development can influence the ambient air temperature through enhancing or mitigating UHIs. Investigations aimed to find out the extent of vegetation in the case study areas and the types of materials used. Uttara 1st and 2nd phase and DOHS were physically surveyed (Uttara 3rd phase and Purbachal is under construction). Apart from the parks, fields and neighbourhood community areas, vegetation was found on the road dividers and footpaths of the secondary and primary roads, which are maintained by the city corporation. Vegetation on tertiary or access roads is the responsibility of a plot owner and is dependent on the individual’s choice. Therefore, some tertiary roads had a reasonable amount of vegetation, whereas some were barren. In general, DOHS had more hard surfaces than Uttara.

The materials used for the roads and footpaths in Uttara and DOHS were homogeneous. In both areas, the roads were made of black asphalt and the pedestrian walks were covered either with concrete pavement tiles or with ceramic tiles, in grey or red brick colour (see Figures 5.7 and 5.8). However, the pedestrian walkways were only found along the secondary or primary roads; there were no pedestrian walkways along the access roads. Access roads (asphalt) were 20′ (6.1 m) wide with 5′ (1.5m) setback areas from the front boundary lines of a plot, which were either soil, concrete slab or tiles, dependent on the choice of an individual plot owner (see Figure 5.9).

Figure 5.7: *Example of a Secondary Road with Vegetation in Uttara. Source: Field Study*

Figure 5.8: *Example of a Secondary Road in DOHS. Source: Field Study*

Figure 5.9: *Examples of Access Roads in Uttara (1) & DOHS (2). Source: Field Study*

5.3 BUILDING CONTEXTS

This section presents the findings of the building parameters study, which included the following: i) building footprint-plot ratio; ii) setback rules and CR; iii) dwelling-unit density; iv) floor plan; v) apartment layout; vi) apartment size; vii) room type and size; viii) glazing type and size; ix) shading device; and x) construction practice and materials.

As described in Section 4.4.1.2, the study was conducted in two steps by following architectural investigation procedures. In the first step, the case study buildings were selected and data were collected from 70 typical apartment buildings on 5-katha plots and 93 apartment unit plans. In addition, interviews were conducted with representatives from the relevant professions: practising architects and real estate developers. In the second step, data were analysed through descriptive statistics and observations.

5.3.1 Building Footprint-Plot Ratio

The building footprint-plot ratio refers to the ratio between the building footprint area and the total plot area. The ratio provides useful information on the ground coverage of a plot by the building on it; that is, the ratio between the built and un-built spaces of an individual plot. The higher the ratio, the higher the ground covered by the building. The average building footprint-plot ratio for the case study buildings was found to be 0.73 (SD 0.05), which means that on average, an apartment building on a 5-katha plot occupied 73% of the total plot area at ground level. The results suggested that the plots were mostly built, with very little space left un-built.

5.3.2 Building Orientation

The orientation of a building in the typical developments of Dhaka is identified based on the orientation of its front façade. The façade of the building next to the access road is termed as the front façade and the orientation of the front façade is considered as the orientation of the building. Hence, typically, the orientation of the plot on which the building is constructed is also the orientation of the building. Since majority of the plots in the typical developments are middle plots with one access road, buildings have one front façade with one orientation. However, buildings on a corner plot are usually considered to have two front facades with two orientations as two sides of the building are adjacent to roads.

5.3.3 Setback Rules and Canyon Ratio

As presented in Section 2.2.5.2, buildings in Dhaka are constructed under the building construction rules set by the RAJUK. Setback rules determine the minimum distances a building must maintain from the boundary lines of a plot. The setback rules, along with the maximum allowable building height, determine the CRs surrounding a building.

According to the existing setback rules, a building on a 5 katha plot must have a minimum distance of 5′ (1.5m) from the front, 4′ (1.25m) from the sides and 6.5′ (2m) from the back boundary lines (see Figure 5.10). Due to the existing practice of profit maximisation, all of the studied buildings had been built with the minimum setback distances. It is worthwhile to note that violation of minimum setback distances is quite common in Dhaka and nearly all (60 out of 70) buildings were found to have violated the minimum setback rules to some extent. The most common form of violation was extending a balcony over the setback areas on the setback areas. Therefore, in reality, the actual distance between the buildings was narrower than it should have be (see Figures 5.11 and 5.12). All of the studied buildings had six storeys.

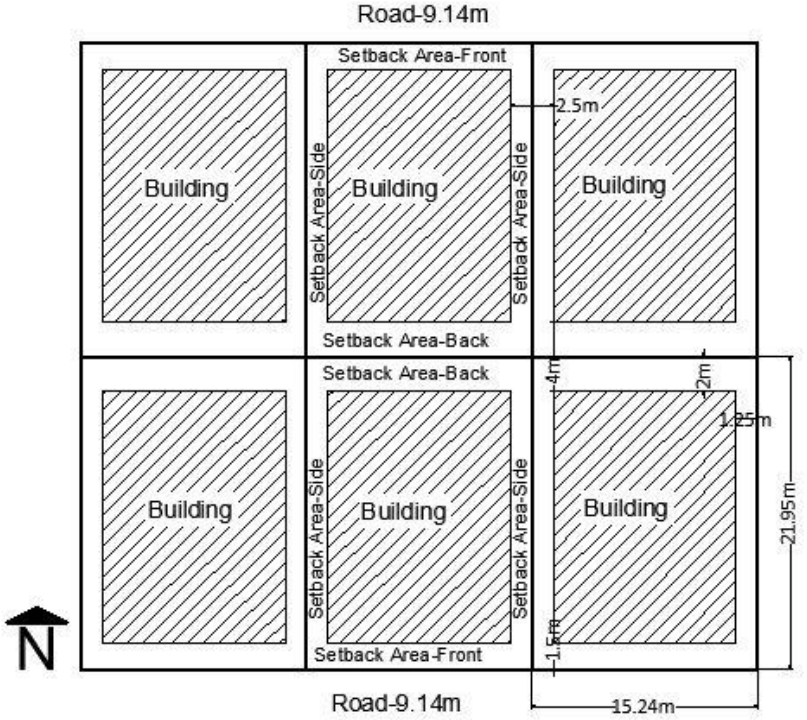

Figure 5.10: *Setback Areas Surrounding a Building*

Figure 5.11: *Distance Between Buildings at the Side. Source: Field Study*

Figure 5.12: *Distance Between Buildings at the Back. Source: Field Study*

As explained earlier, CR refers to the ratio between the average height of two adjacent buildings from the floor and the horizontal distance between the buildings. A high CR suggests a deep canyon between the buildings. In the case study areas, three types of canyons were found around a building: i) the canyon between the buildings created by the access road; ii) the canyons between the buildings due to the side setback distances; and iii) the canyon between the buildings due to the rear setback distances. Therefore, for buildings in this study that had the maximum allowable floor area and height, the CRs around the buildings were as follows i) for the canyons with an access road in between, the CR was 1.63; ii) for the canyons caused by the side setback distances, the CR was 8.13; and iii) for the canyons caused by the rear setback distances, the CR was 5.42 (see Figures 5.13–5.15). However, it should be noted that the CR was calculated from ground level and all the buildings were assumed to have six storeys. The high value of CR, especially between the buildings at the side and back, indicated the density of the developments. It also suggested that the side and rear surfaces of the buildings hardly received any direct solar radiation in the daytime, especially at lower levels. The ground floors of the studied buildings were always found to have car parking, along with all the common utility services of the building and a generator as the emergency power supply. The majority of the plots were had 7′ to 10′ (2–3.1 m) high solid boundary walls made of 125 mm thick brick walls.

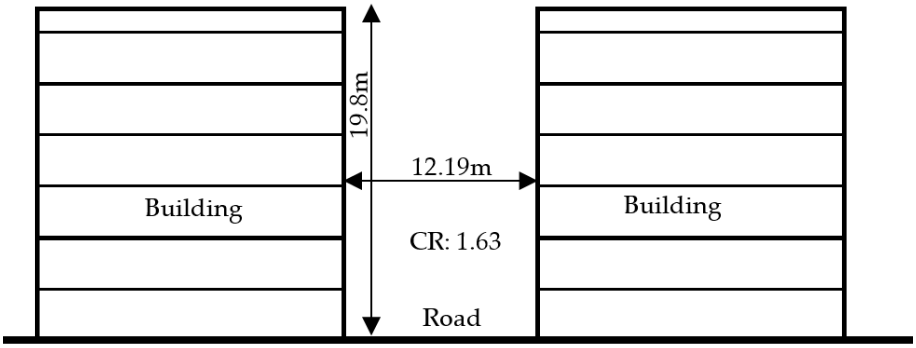

Figure 5.13: *Canyon with an Access Road in Between (CR: 1.63)*

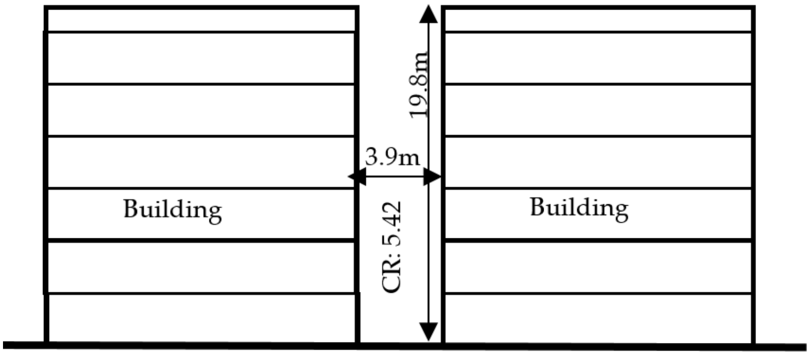

Figure 5.14: *Canyon Due to the Rear Setback Distance (CR: 5.42)*

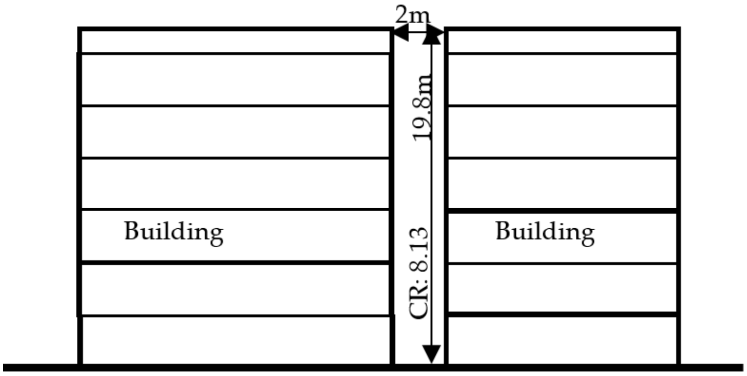

Figure 5.15: *Canyon Due to the Side Setback Distance (CR: 8.13)*

5.3.4 Dwelling-unit Density

Dwelling-unit density refers to the total number of dwelling or apartment units per building. A descriptive analysis found that the average number of units per building in the case study buildings was 8.2, with a minimum of 5 and a maximum of 10 units (SD 2.08) per building. The result suggested that on average, there were about eight units per building on a 5-katha plot. Two types of units were found: single-unit apartments and double-unit apartments. In the case of a single-unit apartment, there was only one apartment unit per floor; in the case of double-unit apartments, there were two units per floor. When the dwelling-unit density of a building was 5, this meant the building had only single-unit apartments and there were five single-unit apartments from the 1st to 5th floor (since the ground floor does not have any apartments). When the density was 10, this meant the building had only double-unit apartments. The average dwelling-unit density of 8.2 for the case study buildings suggested that many of the buildings had both single- and double-unit apartments.

A frequency analysis found that 48.6% (34) of the total studied buildings had only double-unit apartments; 30% (21) had a combination of both single- and double-unit apartments; and 21.4% (15) had only single-unit apartments. In other words, nearly half of the studied buildings had only double-unit apartments, the dwelling-unit density of which is 10. These results were in line with what two real estate developers said during the interviews, that there is a higher demand for the smaller apartment units than the larger, single-unit apartments.

5.3.5 Floor Plan

After studying the floor plans of the 70 case study buildings, it was found that typically, each floor could be divided into two zones: i) the uninhabitable zone, which includes the staircase, lift lobby and lift; and ii) the habitable zone, which includes the apartment units. Depending on the number of units per floor, the habitable zone consisted of one or two apartment units. The uninhabitable zone comprised about 10–

12% (250–300 ft²/23–28 m²) of the total floor area and the remaining 88–90% of the floor area belonged to the habitable zone.

The floor layout pattern did not vary significantly among different buildings. For a floor with a single-unit apartment, only the location of the lift-core varied. For all the cases, the lift-core was found to be placed either at the back or in the middle of a side wall (see Figure 5.16).

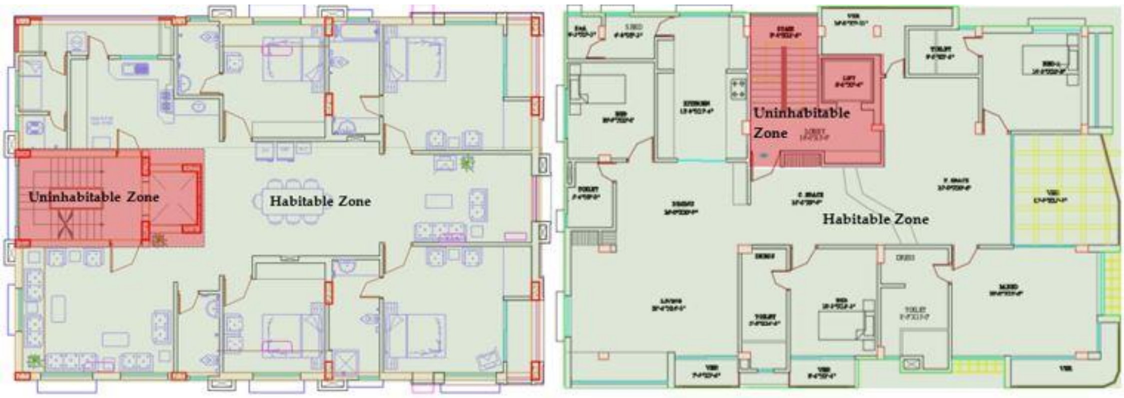

Figure 5.16: *Typical Floor Plans for Single-unit Apartments. Source: Field Study*

Two types of floor layout were found for the floors with double-unit apartments. While the uninhabitable zone was predominantly located either at the back or at the side of the building, the apartment units were placed in two different ways: i) Type A, where the floor was divided across the shorter length of the floor, resulting in two elongated apartments with both of the apartments next to the front façade or the access road (see Figure 5.17); and ii) Type B, where the floor was divided across the longer length of the floor, with one apartment next to the front façade and the other one at the back next to the rear setback area (see Figure 5.18). The lift-core was usually placed at the back of the building in the case of Type A apartment units and for the Type B units, the lift-core was always placed in the middle of a side wall.

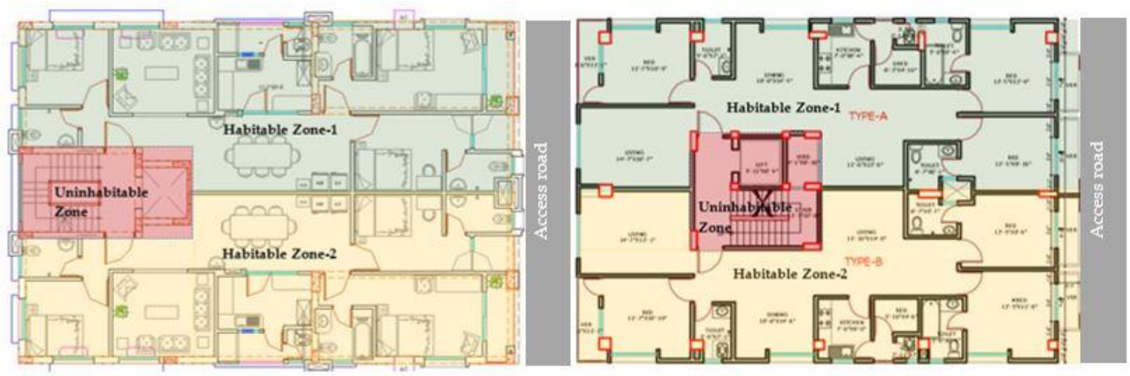

Figure 5.17: *Typical Floor Plans with Double-unit Apartment (Type A). Source: Field Study*

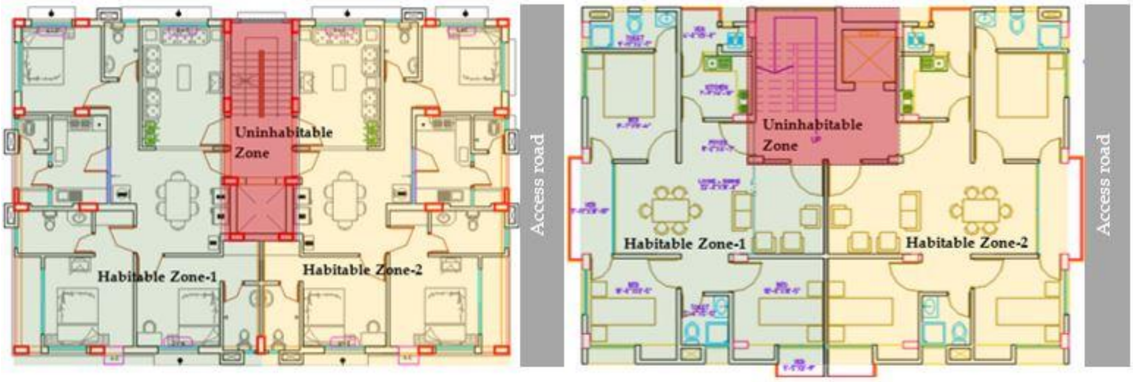

Figure 5.18: *Typical Floor Plans with Double-unit Apartment (Type B). Source: Field Study*

The double units were of nearly equal size and plans mirrored each other in the majority of the cases (82%). Although much fewer in number (18%), some double units had unequal sizes (see Figure 5.19).

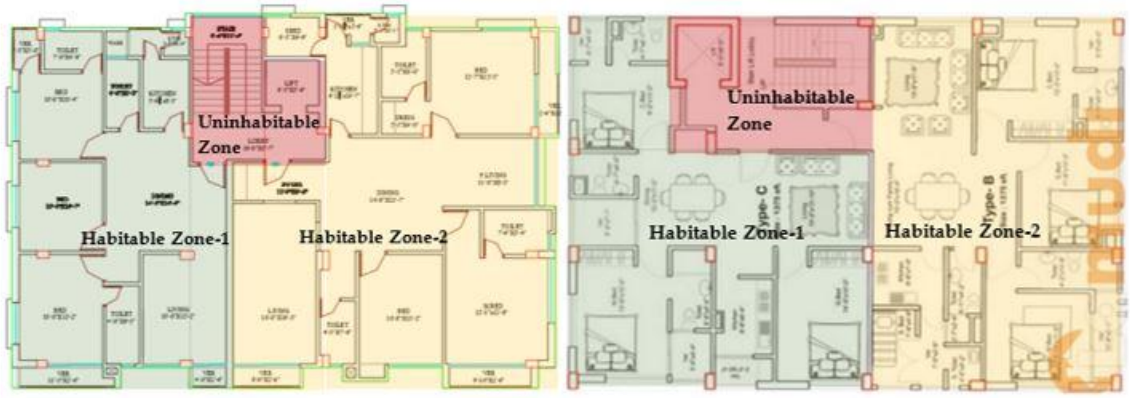

Figure 5.19: *Floor Plans with Unequal Double-unit Apartments. Source: Field Study*

Further investigation found that 60% (44 out of 73) of the studied double-unit apartments were of the Type B category, which means that dividing the floor across the longer length was the preferred option. The results indicated that a considerable number of apartment units in typical residential developments are surrounded by deep canyons, possibly without sufficient daylight, airflow and privacy. From an energy-consumption point of view, it can be assumed that Type B apartments at the back of the buildings would have a higher artificial lighting demand but lower cooling energy demand than the apartments at the front. The Type B apartments at the front or next to the front façade were likely to have the highest indoor temperature of all the double-unit apartments, due to their higher exposure to direct solar radiation. Therefore, the Type B apartments at the front were likely to have higher cooling energy consumption, provided all other parameters were the same for all the apartments.

5.3.6 Apartment Size

A simple descriptive statistics with the 93 case study apartment units showed that the average size of a single-unit apartment was 2,573 ft^2 (239 m^2) and the average size of a double-unit apartment was 1,334 ft^2 (124 m^2). Further study with the equal-sized and mirror-copied double-unit apartments showed that on average, the equal-sized double-unit apartments were 1,311 ft^2 (122 m^2).

Table 5.3: *Minimum, Maximum and Average Size of the Single- and Double-unit Apartments*

		N	Minimum	Maximum	Mean	SD
Single-unit apartment	ft^2	20	2408	2755	2573	115.8
	m^2	20	224	256	239	10.8
Double-unit apartment	ft^2	73	1025	1685	1333.7	146.7
	m^2	73	95	157	123.9	13.6

5.3.7 Apartment Layout

Apartment layout studies were conducted separately for the single-unit and double-unit apartments, since the single-unit apartments were nearly double the size of a double-unit apartment. Twenty out of the 93 studied apartment unit plans were single-unit apartments and 73 were double-unit apartments. It is worthwhile to note that the unit plans of a particular building usually do not vary significantly from floor to floor; therefore, all the single-unit apartments of a particular building usually have the same unit plan for all the floors. Similarly, the same double-unit plans are usually copied for all the floors with double-unit apartments. Therefore, although only 20 single-unit plans were studied, in reality, these plans represented 78 single-unit apartments in 70 apartment buildings in the case study areas. Similarly, 73 double-unit plans represented 305 double-unit apartments in the same 70 buildings.

All the units, both single- and double-unit apartments, followed the same sequence of space arrangements. According to the typical layout practices in Dhaka, dwellings can be divided into three zones: i) the public zone; ii) the semi-public or semi-private zone; and iii) the private zone. The public zone includes the formal living room (and sometimes the guest room); the semi-public or semi-private zone usually includes the dining space, family living, kitchen and guest room; and the private zone includes the bedrooms. Usually the public zones (and sometimes the semi-public zones as well) are located next to the entry point of an apartment and the private zones or bedrooms are located at the farthest point from the entry, especially the master bedroom (see Figures 5.20 and 5.21). The study showed that for all of the cases, the bedrooms were located next to the periphery of an apartment unit. The central space was always the dining space, accessible from all the rooms of an apartment and often without an external wall or window, particularly in Type A apartments. Bedrooms usually had one or two external walls with one to three windows.

Figure 5.20: *Examples of Single-unit Apartment Layout. Source: Field Study*

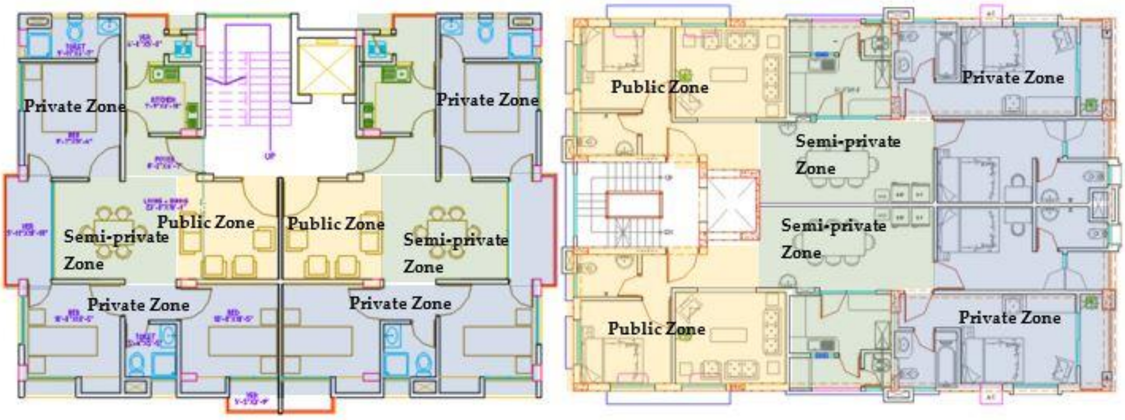

Figure 5.21: *Examples of Double-unit Apartment Layout. Source: Field Study*

A frequency analysis showed that in all of the cases, the location of the master bedroom and bedroom-2, both in single- and double-unit apartments, was next to the front façade. The master bedroom was usually placed at the corner, which meant it had two external walls. For single-unit apartments, the dining-cum-family-living area was next to the front façade in 75% of the cases, followed by the formal living (15%) and bedroom-3 (10%). Bedroom-4, which was usually the guest bedroom, was never found next to the front façade. In double-unit apartments, after the master bedroom and bedroom-2, the dining-cum-family-living space (27%) was placed next to the front façade most commonly, followed by bedroom-3 (17%) and the formal living area (5%). The dining-cum-family-living space often had an external balcony when it was located next to the front façade. The bedrooms at the front also often had external balconies. All of the toilets had an external window and the master bedroom and bedroom-2 always had an attached toilet. The service area, which included the kitchen, servant and storeroom, was usually located either at the back or at the side (see Figures 5.22–5.24)

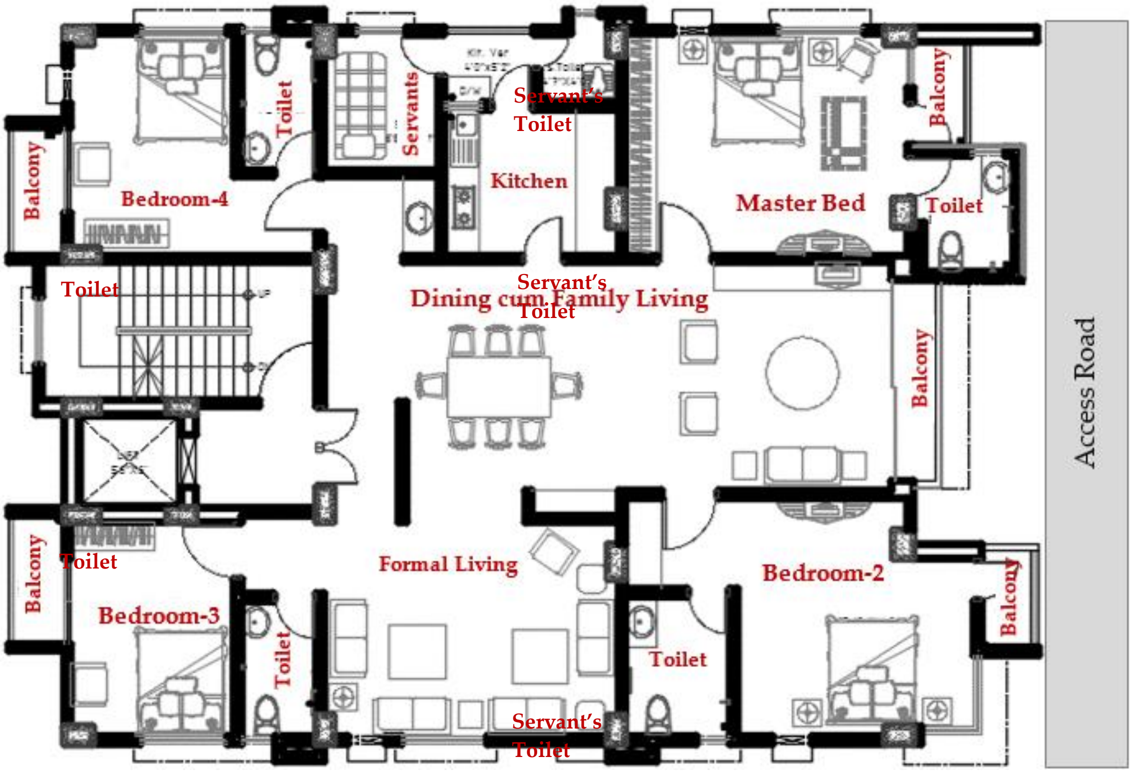

Figure 5.22: *Example of a Single-unit Apartment Layout. Source: Field Study*

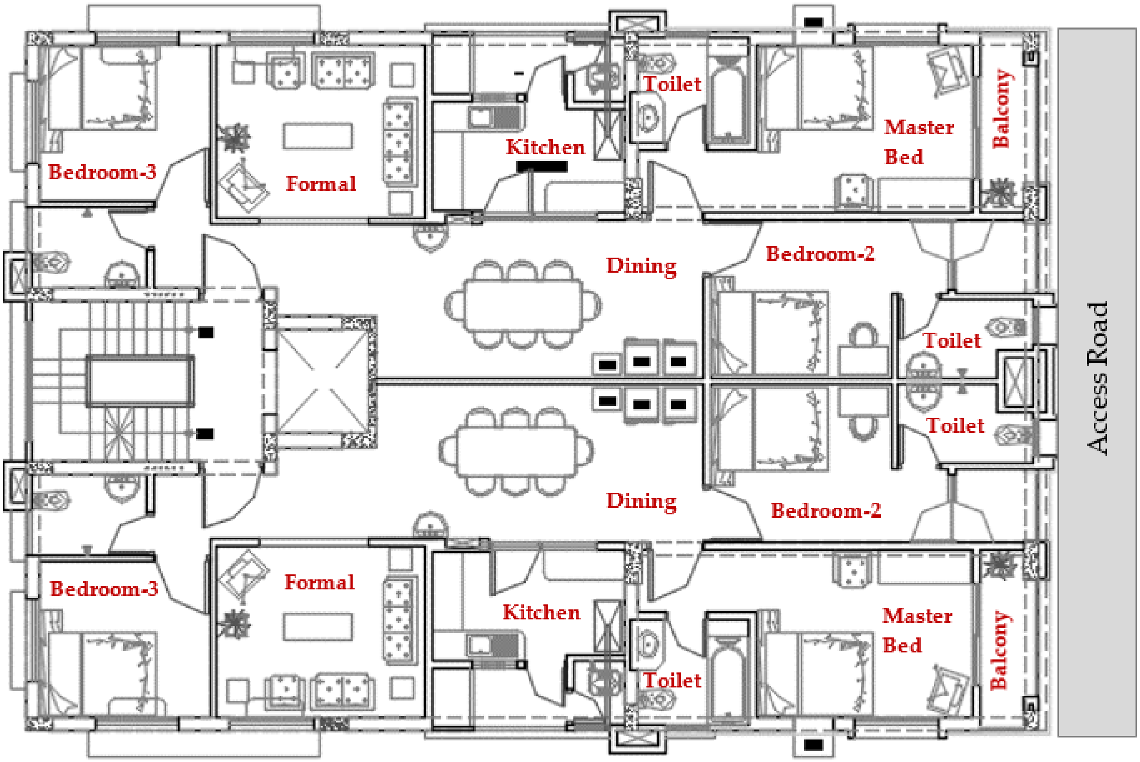

Figure 5.23: *Example of a Double-unit Apartment Layout (Type A). Source: Field Study*

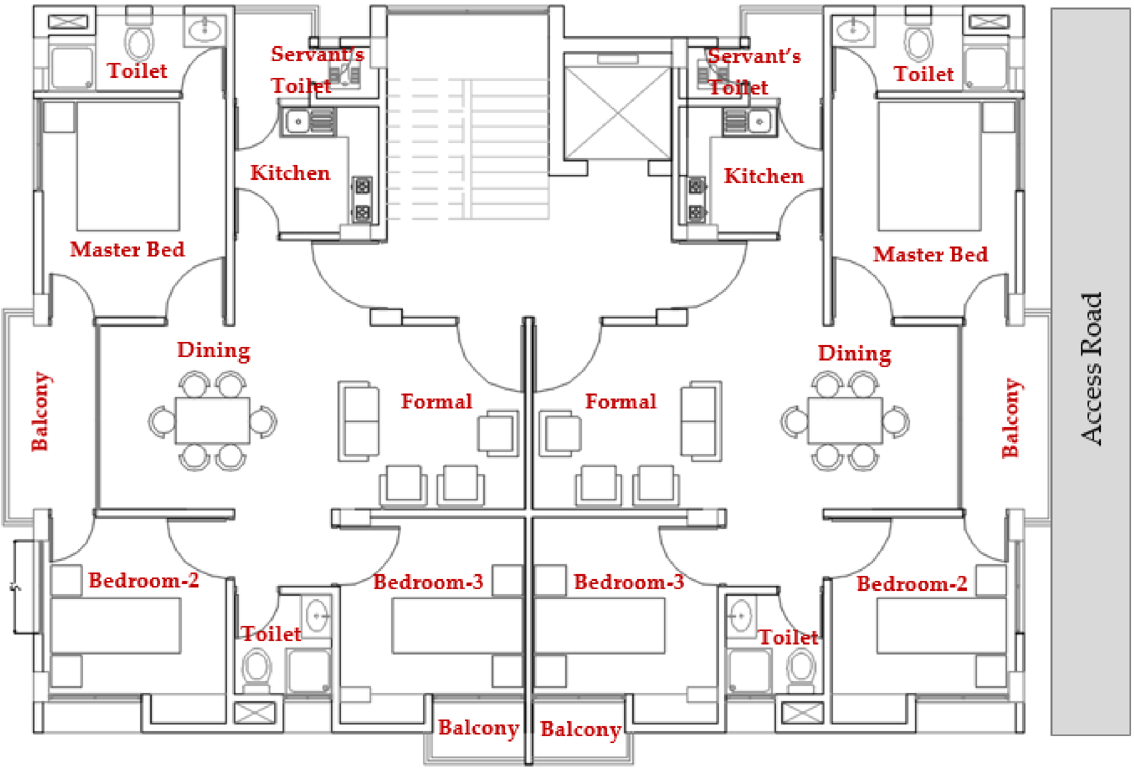

Figure 5.24: *Example of a Double-unit Apartment Layout (Type B). Source: Field Study*

From the plans, it is evident that the master bedroom and bedroom-2 were the rooms most commonly placed next to the front façade; that is, next to the access road. This suggested that these two rooms may have a higher indoor temperature and hence, higher cooling energy demand than other areas of the apartment, due to having more external surface areas and exposure to direct solar radiation.

5.3.8 Room Type and Size

The single-unit apartments usually had one more bedroom than the double-unit apartments. Although the average size of single-unit apartments was nearly double that of the double-unit apartments, the number or size of bedrooms in single-unit apartments were not doubled. Rather, the size of the common spaces and other additional spaces were larger, such as a separate and defined family living area, servant's room and more balconies and toilets. A frequency analysis showed that 90% of the single-unit apartments had four bedrooms and 98.6% of the double-unit apartments had three bedrooms. Three balconies (50%) and five toilets (75%) were most common in single-unit apartments, whereas two or three balconies (48% and 41%) and three or four toilets (74%) were most common in double-unit apartments. For double-unit apartments, 67% of the units did not have any defined family living space and 81% did not have any servant's room. In the single-unit apartments, 95% had a separate family living space and 100% had a separate servant's room. Further analyses were conducted to find out the average room sizes for both single- and double-unit apartments. The following table shows the summary of the findings.

Table 5.4: *Size of Different Rooms in Single- and Double-unit Apartments*

#	Room Name	Apartment Unit Type	Descriptive Statistics				
			N	**Min**	**Max**	**Mean**	**SD**
1	Master bedroom	Single-unit	20	180 ft^2	269 ft^2	211 ft^2	23 ft^2
				17 m^2	25 m^2	19.6 m^2	2.1 m^2
		Double-unit	73	110 ft^2	193 ft^2	144 ft^2	20.7 ft^2
				10 m^2	18 m^2	13.4 m^2	1.9 m^2
2	Bedroom-2	Single-unit	20	130 ft^2	247 ft^2	179 ft^2	32.8 ft^2
				12 m^2	23 m^2	16.5 m^2	3 m^2
		Double-unit	73	90 ft^2	199 ft^2	125 ft^2	20.7 ft^2
				8 m^2	19 m^2	11.6 m^2	1.9 m^2
3	Bedroom-3	Single-unit	20	115 ft^2	189 ft^2	150.8 ft^2	23 ft^2
				11 m^2	18 m^2	14 m^2	2.1 m^2
		Double-unit	73	94 ft^2	189 ft^2	124 ft^2	23.4 ft^2
				9 m^2	18 m^2	11.5 m^2	2.5 m^2
4	Bedroom-4	Single-unit	20	72 ft^2	176 ft^2	128.6 ft^2	26.5 ft^2
				7 m^2	16 m^2	12 m^2	2.3 m^2
		Double-unit	73	--	--	--	--
5	Dining-cum-family living	Single-unit	20	281 ft^2	1221 ft^2	412 ft^2	202 ft^2
				26 m^2	113 m^2	38 m^2	19 m^2
		Double-unit	73	110 ft^2	365 ft^2	206 ft^2	67 ft^2
				10 m^2	34 m^2	19 m^2	6.2 m^2
6	Formal living	Single-unit	20	142 ft^2	416 ft^2	237 ft^2	59.8 ft^2
				13 m^2	39 m^2	22 m^2	5.5 m^2
		Double-unit	73	0	194 ft^2	131 ft^2	57 ft^2
				0	18 m^2	12 m^2	5.2 m^2

For all of the cases, for both single and double-unit apartments, the master bedroom was the bedroom with the highest average room area and the common space (dining-cum-family living) had the largest average floor area. It is worthwhile to note that some of the double-unit apartments did not have a defined formal living area. Rather, it was a single integrated space with dining; for those units, the formal living is shown as ‘0’ floor area in the table. The floor-to-floor height was 10′ (3.1 m) for all units.

5.3.9 Glazing Type and Size

The study found that glazing was used for both windows and doors in the case study apartments. Doors that opened to the balcony on the front façade were usually made of glass 39%. All of the glass doors and windows were single glazed, 5-6 mm thick and sliding with aluminium framing. Three types of glass were used: clear, tinted and reflective. A frequency analysis showed that 56% (44) of the apartments had clear glass, 29% (23) had tinted glass and 15% (12) had reflective glass.

On average, a single-unit apartment had 10 glazed surfaces, with a minimum of six and a maximum of 13 (SD 1.66). The average number of glazed surfaces per double-unit apartment was six, with a minimum of four and a maximum of eight (SD 0.958). It should be noted that the study only counted the glazing of the bedrooms and the common areas (dining and living) and excluded the glazing of the toilets and service areas. The study also found that in both single- and double-unit apartments, the master bedroom had the highest average level of glazing (2). It found that 30% (22) of the apartment units did not have any external glazing in the common areas.

Further analyses were conducted to find out the average size of the glazing in different rooms. The study found that the average glazing area of the master bedroom and bedroom-2 was equal and maximum among all the bedrooms, at 38 ft^2/11.6 m^2 (SD 13.9/4.24). The average glazing size of bedroom-3 was 30.8 ft^2/9.4 m^2 (SD 12/3.5) and for bedroom-4, 34.7 ft^2/10.6 m^2 (SD 18/5.6). The maximum glazing size, 45.9 ft^2/14 m^2 (SD 22/6.7) was found for the dining-cum-family-living space. The average glazing size of the formal living area was 35.9 ft^2/11 m^2 (SD 19.7/6). The average width of a glazing in bedrooms varied from 5.3′–5.7′ (1.62–1.72 m) with a minimum of 2.5′ (0.8 m) to a maximum of 14.5′ (4.4 m). The average height of windows in bedrooms varied from 5.7′–7.2′ (1.72–2.2 m) with a minimum of 4′ (1.22 m) to a maximum of 9.5′ (2.9 m). The average width and height of a common-space window was 6.4′ (2 m) and 6.9′ (2.1 m) and the average width and height of a formal-living-area window was 6.3′ (1.9 m) and 5.8′ (1.8 m), respectively.

Five practising architects and two real estate developers were interviewed to find out the primary motivations behind the design decisions regarding glazed surfaces. All of the architects and developers said that the utility space of a room mainly determined the location and size of the glazed surface. Two architects and one developer also mentioned the increasing preference of clients for large windows or glass surfaces on the front façade, which sometimes forced them to design floor-to-ceiling glass walls (see Figure 5.25). All of the professionals mentioned the strong influence of the market in determining the choice of glass facades and the effect of large glazed surfaces on indoor thermal conditions, which is generally ignored because of the lack of information and not knowing the definite impact of the glazed surfaces. Although in general, the common practice is to provide glazing for 20–30% of the external walls, some apartments now have floor-to-ceiling glass walls on the front façade.

Figure 5.25: *Examples of Floor-to-ceiling Glass on the Front Façade. Source: Field Study*

5.3.10 Shading Devices

Plans and elevations of the case study apartments were studied to find out how many buildings had a shading device, as well as the type and variation of the devices. In addition, five practising architects and two developers were interviewed to find out the existing practices regarding shading device design and the motivations and reasons for using them. It is worthwhile to note that according to the building construction rules, it is not mandatory to provide shading devices for glazed surfaces and they do not provide any detailed guidance regarding shading devices. The only regulation provided about shading devices is the maximum depth (20″/0.51 m) that can be projected into the setback areas.

A frequency analysis showed that 42% (39) of the units did not have any shading devices on the front façade windows. Further, 64.6% (31) of the windows were recessed, which create an 'egg-crate' shading device; 46% (22) had a horizontal shading device; 20.8% (10) had a vertical shading device; and only 6.3% (3) had an L-shaped shading device on front façade windows. The average depth of the shading devices were as follows: horizontal: 1.1′ (0.33 m); vertical: 0.6′ (0.18 m); L-shaped: 1′ (0.31 m); and egg-crate: 1.2′ (0.37 m). The result clearly suggested that when a shading device was provided, the horizontal shading device and the recessed windows were the most popular.

The interviews with the architects and developers revealed that in practice, designing shading devices considering the sun were not a priority design concern. While one of the architects said that for 95% of the time, he tries to provide at least some horizontal shading, the others said that shading devices were not a priority and that some sort of window protection is provided already to protect from rain penetration. One of the architects described these as rain-protection devices rather than shading devices. However, if a shading device was provided, its depth varied between

10″ and 20″ (0.25–0.5 m), mainly due to the building construction rule of allowing a maximum 20″ (0.5m) wide shading device into the setback areas.

Figure 5.26: *Examples of Horizontal Shading & Recessed Windows. Source: Field Study*

The architects usually tried to provide a shading device over the windows if the building was south-facing. However, the depth of the shading device was mainly dependent on the architect’s intuitive choice, which in many cases was driven by the 3-dimensional look of the building from outside and the maximum allowance over the setback areas. The choice of the type and size of the shading devices was more aesthetically driven rather than functional and was not influenced by the orientation of the window. The interviews revealed the following reasons for the lack of priority for the shading devices:

i) The developer-built buildings are highly driven by economy. To maximise the profit and to build with the maximum allowable floor area means that the shading devices cannot be wider than 20″ (0.5m), otherwise the windows have to be recessed inside the floor area, leading to less useable floor area.
ii) Constructing shading devices costs more money.
iii) Providing shading devices for glazed surfaces is not obligatory in the building construction rules.

iv) There is no ready information available about the suitable type and size of shading devices according to different orientations. For an appropriate shading device, architects themselves have to calculate the size by calculating the solar angles.

v) The effect on indoor thermal comfort and hence, on cooling energy consumption, of not having a proper shading device is unknown.

5.3.11 Construction Practices and Materials

The most common construction practices found in these residential developments were a reinforced cement concrete (RCC) structure with solid bricks for both the external and interior walls. The RCC frame includes the columns, beams and floor slabs. The external walls were predominantly made of 5″ (125 mm) or 10″ (250 mm) solid bricks and the internal walls were always made of 5″ solid brick. The walls were always plastered (12–18mm thick) on both sides and painted (see Figure 5.27). The wall thickness was dependent on the standard size of the brick, usually 2.75″ (68.8 mm) x 4.5″ (112.5 mm) x 9.5″ (237.5 mm). Therefore, including the thickness of the plaster, a wall is commonly considered as either 5″ (125 mm) or 10″ (250 mm) thick if laid single layer. It is worthwhile to note that since the construction industry in Dhaka is intensely dependent on half-skilled manual labour, the workmanship is quite poor. Therefore, the brick as well as plaster thickness could vary up to 1″ (25 mm), which could have an effect on the overall thermal properties or the conductance of a wall. A frequency analysis showed that 48% (45) of the case study apartments had 5″ (125 mm) thick external walls and 52% (48) of the apartments had 10″ (250 mm) thick external walls. The toilets and the kitchens usually had tiled walls. The floors were predominantly finished with tiles, or occasionally with marble or granite in the case of luxurious apartments. The tiles were mostly homogenous and sometimes were polished. The roofs were flat, with a 1–2″ (25–50 mm) brick chip layer over the roof slab, finished with a tile or cement layer. No insulation was used for the roof or external walls.

The interviews with the architects and the schedule of civil works (PWD, 2011) revealed several other construction practices in Dhaka, such as ceramic or concrete hollow and solid blocks. Brick facing walls, instead of plastered walls, were not uncommon in the recent past. However, after interviewing the architects and developers, it was evident that the concrete and ceramic blocks were extremely unpopular due to production delays and the concrete blocks were much poorer in quality than the solid bricks. Therefore, the dominant construction practices and materials used for building the apartment buildings in typical residential developments were an RCC frame, solid brick walls with plaster and paint, and tiled floors. Several past practices were identified during the field study, such as the presence of a ventilator, higher ceiling heights and thicker external walls. All of these are now obsolete. The exclusion of passive strategies from building practices may have resulted in increased indoor temperature and hence, a higher demand for cooling energy.

Figure 5.27: *An Under-construction Building, Showing the Common Construction Materials and Practices. Source: Field Study*

5.4 SUMMARY FINDINGS AND DISCUSSION

5.4.1 Summary Findings: Urban Contexts

The urban settings of typical residential developments of Dhaka are highly homogeneous and follow a rigid pattern. The overall development pattern was same for all the case study areas; that is, a large area of land divided into small residential plots. All of the plots were laid in two adjacent rows with an access road. Apart from a few cases, the plots were rectangular and the shorter length of the plot always faced the access road. Although plot sizes varied, the most common plot sizes were 3 katha and 5 katha. However, 3-katha plots were the most numerous and 5 katha plots occupied the largest amount of residential land. The current trend showed an increasing preference for smaller plots. Apart from a few cases, plots faced one of the four cardinal directions: north, east, south and west; however, south was the most preferred orientation.

The road layout strictly followed a grid pattern and the width of the access road was usually 30′ (9.15 m). Apart from the parks, fields and some primary and secondary road dividers, vegetation was the responsibility of the individual plot owners. The roads were made of black asphalt and the pedestrian walkways along the primary and secondary roads were made of concrete tile or slab (grey or red).

5.4.2 Summary Findings: Building Contexts

The overall building contexts of typical residential developments were highly homogeneous. Each plot contained one multi-storey multi-unit apartment building and on average, 73% of the total plot area was occupied by the building. The ground floor of the buildings was used for car parking and the rest of the floors (1–5) were apartment units. The setback distances of the buildings from the plot boundary lines were from the front 5′ (1.5 m), from the sides 4′ (1.25 m) and from the back 6.5′ (2 m). As shading devices and AC outlets were usually projected into the setback areas up to

20″ (0.5 m), the clear distance between the buildings was reduced, especially at the side and the back.

Three types of canyons surrounded the buildings: i) the canyon in front due to the access road plus front setback distances; ii) the canyon due to the side setback distances; and iii) the canyons due to the back setback distances. The CRs at ground level between the buildings were at the front: 1.6; at the side: 8.1; and at the back: 5.4. The dwelling-unit density per building was 8.2; that is, each building on average had about eight apartment units.

There were two types of apartment units: single-unit and double-unit. Single-unit apartments had only one apartment unit per floor. Double-unit apartments had two units per floor. The double units were preferred over single-unit apartments. In the case of double-unit apartments, the floors were divided along either the shorter or the longer length of the floor (the latter option was preferred). On average, the area of a single-unit apartment was 2,573 ft^2 (239 m^2) and the area of a double-unit apartment was 1,334 ft^2 (124 m^2).

The apartment units usually had three functional zones: i) the public zone for formal living (sometimes including the guest bedroom); ii) the semi-public or semi-private zone, being the dining-cum-family and kitchen areas; and iii) the private zone, being the bedrooms. The private zone (bedrooms) was always next to the periphery. The master bedroom and bedroom-2 were always located next to the front façade and the master bedroom was usually on the corner, with two external walls. A single-unit apartment typically had four bedrooms, three balconies, five toilets, a defined family space and a dining and formal living area. A double-unit apartment typically had three bedrooms, two balconies, three or four toilets and a dining and a formal living space. The master bedroom had the highest average room area among all the bedrooms in both the single- and double-unit apartments. However, on average, the central common space (dining-cum-family living) was the largest area.

Glazing was used for both windows and doors. Doors that opened to an adjacent balcony on the front façade were usually are made of glass. All of the windows and glass doors were single glazed, sliding with an aluminium frame. The glass thickness was 5–6 mm and only three types of glass were used: clear, tinted or reflective. On average, the master bedroom and bedroom-2 had the largest glazed surface among all the bedrooms. Shading device design had a low priority and many of the case study apartment units did not have any shading devices. Typically, the shading devices were projected into the setback areas to a depth that varied from 10–20″ (0.25–0.5 m). The horizontal shading device and recessed windows were the most preferred type of shading.

The most typical construction practices were an RCC structural frame (column, beam and floor slab) with 5″ or 10″ (125–250 mm) solid brick wall, plastered and painted on both sides, and tiled floors. Roofs were flat, with a 1–2″ (25–50 mm) brick chips layer over the roof slab, finished with a tile or cement layer. No insulation was used for either the roof or external walls. The construction practices and material choices were highly homogeneous across the case study areas (except for some variation in floor finishes). The thermal properties of the building materials were not prioritised.

The market, profit and the buyers of apartment units in typical residential developments determine the majority of the typical building practices. For example, since the price is dependent on total floor area, a single-unit apartment is too expensive for the majority of buyers; therefore, double-unit apartments are preferred. This is also the reason for the number of bedrooms not varying significantly between a single-unit and a double-unit apartment, despite the single-unit apartment being nearly double the area of a double-unit apartment. Shading devices, one of the most effective passive-design strategies at the building level, were neglected in most typical residential developments. Since buyers preferred more glazed areas, larger glazed surfaces were provided on the front façades of the buildings to increase the aesthetic value (but this surface is the most exposed to direct solar radiation). The choice of a construction material was also driven by economy, such as the 5″ (125 mm) thick external wall, which is cheaper and occupies less floor area than thicker walls, so therefore is preferred for double-unit apartments.

The best building practices in Dhaka's contexts, from an energy-consumption point of view, are yet to be defined and there are no guidelines, enforcement or ready information available for professionals to follow and to initiate energy-efficient building development practices.

5.4.3 Discussion

This study revealed that the existing urban and building development practices in typical residential developments are mainly driven by the social and economic forces and urban development policies. Existing urban and building practices generally do not consider the passive-design strategies. Rather, many of the existing practices, such as the lack of shading devices, were exacerbating the energy effect of the developments.

At the urban level, apart from the effort in laying more plots facing south, no other considerations regarding local climate or passive strategies were found. The effectiveness of such considerations can be questioned, due to the belief that a south-oriented plot is better for thermal comfort, as it has the advantage of the prevailing south wind during the summer months. However, one study found that the typical building CR in residential developments in Dhaka is too high for a south wind to enter into the canyon; therefore, south-oriented buildings in typical residential developments in reality are in a wind shadow, particularly at lower levels, and do not get any advantage from the prevailing south wind (Ahmed, 1996).

This study found an increasing preference for smaller-sized plots, which means that future developments will have even more narrow, deep canyons between the buildings and more external wall surfaces. This finding indicates the higher possibility of intense UHI formation in the future residential developments of the city, which clearly works against achieving energy efficiency in residential developments.

The layout of the apartment units was determined with respect to the front façade (street facing). The master bedroom and bedroom-2, which were the most occupied rooms of an apartment unit, were always located next to the front façade. As mentioned earlier, the front facades usually had larger glazed surfaces irrespective of their orientation, meaning that the most occupied and energy-intense rooms of apartment units were next to these large glazed areas without proper shading devices. The choice of construction materials were also client- and economy-driven and the thermal performance of the materials was not a consideration. Moreover, several passive-design strategies that were common in old buildings, such as ventilators, higher ceilings or thicker walls, have become obsolete in the recent developments.

Considering the effect of different development practices on the microclimate or on the buildings' consequent energy consumption has never been part of the development agendas of Dhaka; therefore, the existing practices do not contain any passive-design or energy-efficient strategies. The reasons for this lack of interest may be: i) due to a high profit-making motivation, no one is interested in leaving land for open spaces or vegetation or spending extra money for passive-design strategies; ii) the energy impact of the existing urban and building practices are unknown, as so far, no research on this topic has been undertaken; iii) as there is no ready information available regarding best urban and building practices from an energy-consumption point of view, the professionals are not equipped to make energy-efficient decisions; and iv) no building energy code is available and buildings are not required to show their energy performance to gain an approval.

Based on the findings of this study, it can be said that several urban and building practices in typical residential developments in Dhaka may have been contributing to higher household energy consumption. The findings of this study also indicate the possibility of reducing energy consumption in future typical residential developments in Dhaka if the current negative practices can be removed. To be able to reduce the energy consumption of typical residential developments successfully, the extent of the effect of these negative practices need to be identified. The best urban and building practices from an energy-consumption point of view in Dhaka's urban contexts also needs to be identified and advocated to the relevant professional bodies, developers and occupants, as well as enforced through the building energy code or building construction rules.

Table 5.5: *Summary Chart with Key Findings: Urban Parameters & Practices*

#	Urban Parameters	Key Findings: Typical Practices
1	Plot layout	Highly homogeneous and rigid. Plots laid side by side in two rows and accessed with an access road.
2	Plot shape	Mostly rectangular with the shorter length facing the access road.
3	Plot size	3 katha, 5 katha, 7.5 katha, 10 katha.
4	Plot orientation	Four major cardinal points: north, south, east & west. South is the most preferred orientation.
5	Road layout	Grid pattern.
6	Road width	Access road 30′ (9.15 m).
7	Materials	Asphalt roads, concrete tile or slab pavements for pedestrians (grey or red).

Table 5.6: *Summary Chart with Key Findings: Building Parameters & Practices*

#	Building Parameters	Key Findings: Typical Practices
1	Building footprint-plot ratio	On average: 0.73 or 73% of a plot is built.
2	Building orientation	Orientation of the façade (front-façade) next to access roads is considered as the building orientation.
3	CR between buildings at ground level	CR (front): 1.6, CR (side): 8.1, CR (rear): 5.4.
4	Dwelling-unit density/building	8.2 units per building.
5	Floor plan	Only one or two apartment units (max.) per floor. The uninhabitable zone (lift-core) is at the back or side of a building (10–12% of the floor area) and the rest of the floor is habitable zone (single- or double-unit apartments). Double-unit apartments are mostly equal sized and mirror each other. For double-units, a floor is divided either across the shorter length or the longer

#	Building Parameters	Key Findings: Typical Practices
		length of the floor; dividing across the longer length is preferred.
6	Apartment size	Single-unit (avg.): 2573 ft^2 (239 m^2). Double-unit (avg.): 1334 ft^2 (124m^2).
7	Apartment layout	Bedrooms are at the periphery of a building. Common spaces (i.e., dining) are in the middle. The master bedroom and bedroom-2 are always next to the front façade.
8	Room types and numbers	Single-unit: 4 bedrooms, 3 balconies, 5 toilets, dining, formal living, separate family living & servant’s room. Double-unit: 3 bedrooms, 2 balconies, 3–4 toilets, dining, formal living.
9	Glazing type	Single glaze, 5–6 mm, sliding & aluminium frame and clear, tinted or reflective glass.
10	Glazing number and size	On average, 10 glazed surfaces/single-unit apartment & 6 glazed surfaces/double-unit apartment (excluding toilet and kitchen windows). Master bedroom & bedroom-2 glazing size (avg.): 38 ft^2 (11.6 m^2). Bedroom-3 glazing size (avg.): 31 ft^2 (9.4 m^2). Bedroom-4 glazing size (avg.):35 ft^2 (10.6 m^2). Common-space glazing size (avg.): 46 ft^2 (14 m^2). Formal living glazing size (avg.): 36 ft^2 (11 m^2).
11	Shading devices	Not a priority design consideration. Mainly for rain protection. Aesthetically & market-driven. Mostly horizontal shadings or recessed windows, 10–20” (0.25–0.5 m) deep.
12	Construction practice & materials	Structure: RCC frame (column, beam & floor slab). External walls: 5–10” (125–250 mm) solid brick (both sides plastered and coloured). Internal walls: 5” (125 mm) solid brick (both sides plastered and coloured). Floor finish: Tiles (mostly homogeneous). Roof: Flat RCC roof slab with cement or tile finish (sometimes treated with an additional layer of brick chips or hollow block over the roof slab). No insulation.

5.5 CONCLUSION

This chapter has presented the findings of the urban and building contexts study, which was conducted to explore the existing urban and building contexts of typical residential developments of Dhaka. The findings of this study have provided in-depth information about the predominant urban and building practices and the primary motivations behind them. They have also provided an insight into which of these practices can be altered or improved to reduce the energy consumption of typical residential developments. Further investigations were conducted to find out the energy impact of the different urban and building practices through simulations, the results of which are presented in Chapter 8.

6 MICROCLIMATIC CONTEXTS

6.1 INTRODUCTION

This chapter presents the findings of the microclimatic contexts study, which aimed to explore particularly the ambient air temperature surrounding the buildings in typical residential developments in Dhaka and the effect of the existing urban development practices on this air temperature. This included analysing the ambient air temperature variation according to different building orientations and heights, and the differences in air temperature patterns and between the outdoors and the indoors, along with their probable impact on energy consumption.

6.2 METHODS

As outlined in Chapter 4, the study was conducted by following climatic research procedures in two major steps: data collection and data analyses. A detailed account of the data collection procedures has been presented in Section 4.4.2. The following section presents the procedures followed for the data analyses, interpretation and presentation.

For the purpose of data analysis, outdoor data loggers were identified according to their locations and the orientation of the front façade of the building in which the loggers were placed. For example, a logger that was installed on a north-oriented front façade was identified as a north-oriented logger. A logger that was placed on the side façade of the building and was situated at the side setback area was identified as the side setback logger. A logger placed on the rear façade of the building and situated at the rear setback area was identified as the rear setback logger. It is worthwhile to note that the space between two buildings, whether at the side or the rear, is termed a setback area in Dhaka.

It was hypothesised that the temperature measured by a logger installed on a façade with a certain orientation would represent the air temperature of other buildings with the same orientation. Comparative analyses between differently oriented and located loggers would then indicate the effect of different orientations and CRs on the microclimate. Due to the narrow setback distances between buildings in the study areas, deep canyons are created in the setback areas. The impact of these deep canyons would be analysed through data from the setback loggers. Descriptions of the setback areas have been presented in Section 5.3.3.

The data from the logger placed at the 15 m level at the side setback area (along the N-S axis) was assumed to represent the air temperature of the west orientation instead of a deep canyon, as the building on the opposite side of the canyon was lower than 15 m (see Figures 4.6 and 6.3). The logger placed at the 15m level at the rear setback area was assumed to represent a south orientation (with 1.1 CR) rather than representing a deep canyon, as it was impossible to place the logger in the middle at that height. Instead, the logger was installed on the south-oriented façade of the canyon (see Figures 4.7 and 6.2). However, to keep the analysis process simple, all loggers placed at the side setback area were identified as side setback loggers and all loggers placed at the rear setback area were identified as rear setback loggers. All anomalies with respect to the surrounding physical contexts among the loggers were carefully considered when interpreting the data after the analyses. The following figures depict the surrounding physical contexts of a building and the loggers installed.

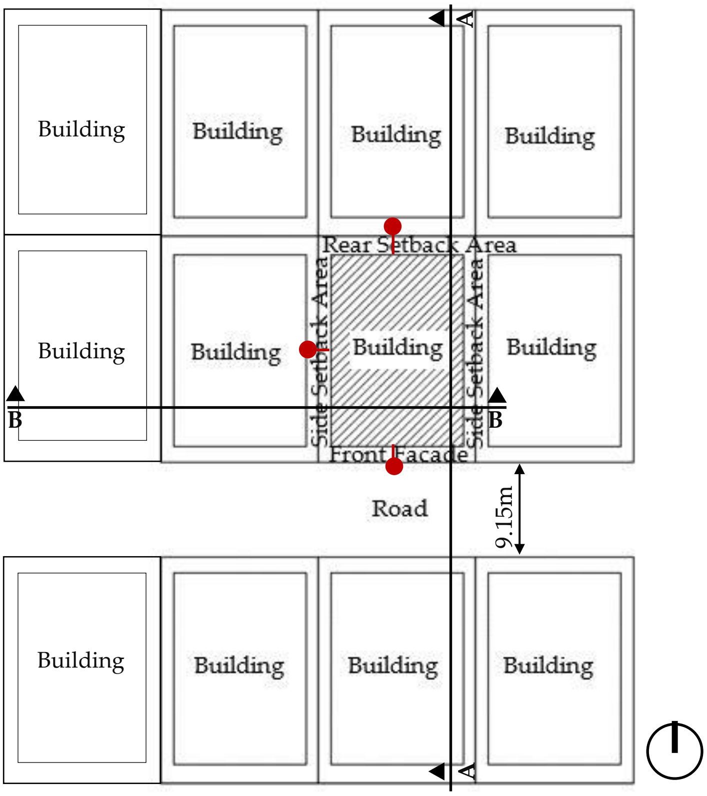

Figure 6.1: *Plan showing the Physical Contexts Surrounding a Building and the Location of the Loggers*

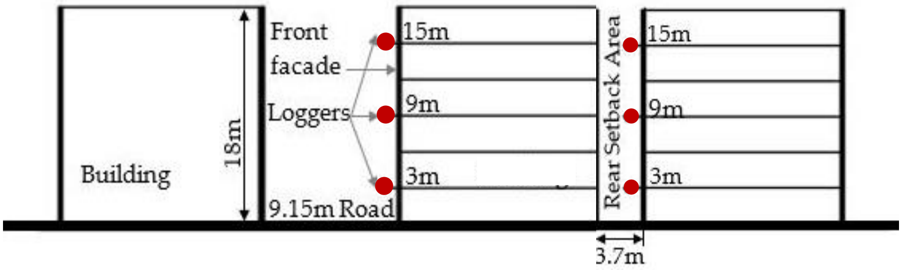

Figure 6.2: *Section A-A: Loggers Installed on the Front Façade & at Rear Setback Area*

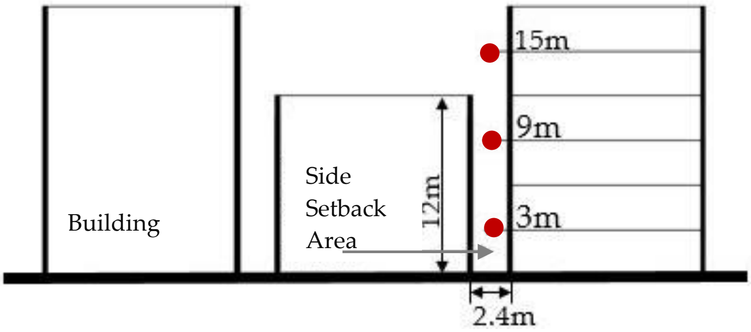

Figure 6.3: *Section B-B: Loggers at the Side Setback Area*

The identifications and IDs for different orientations and locations of the loggers for the data analyses are listed in Table 6.1.

Table 6.1: *The Loggers' Orientations and Locations with Associated ID*

#	Loggers' Orientation/Location	Loggers' ID	Case Study Area
1	North	North-1	DOHS
2	North	North-2	Uttara
3	East	East-1	DOHS
4	East	East-2	Uttara
5	South	South	DOHS
6	West	West	DOHS
7	Side setback area	S-1	DOHS
8	Rear setback area	S-2	DOHS

The loggers were further grouped into three categories according to their heights from the ground-floor level: 3 m, 9 m and 15 m (see Section 4.4.2.1.3). For outdoor loggers, each category had eight loggers at a certain height. Six of the eight loggers were installed on the front façade of a building and hence, represented a certain orientation (north, south, east and west). The other two loggers were at the two setback areas (side setback with N-S axis and rear setback with E-W axis), representing deep canyons. Therefore, category-1 outdoor loggers were labelled North-1, North-2, East-1, East-2, South, West, S-1 and S-2 at 3 m height. Category-2 outdoor loggers were labelled North-1, North-2, East-1, East-2, South, West, S-1 and S-2 at 9 m height. Category-3 outdoor loggers were labelled North-1, North-2, East-1, East-2, South, West, S-1 and S-2 at 15 m height.

The indoor loggers were also identified according to the orientation of the front façade next to which they were placed (see Section 4.4.2.1.3) and were grouped in three categories according to their height. However, in case of indoor loggers, each category had six loggers instead of eight, since the loggers were placed in the rooms next to the front façade on which the outdoor loggers were installed. There were no loggers installed in the rooms next to the setback loggers, partly because of budget constraints and partly because the less used rooms such as guest bed and formal living, and service areas such as kitchen and staircase, are placed next to setback areas. Therefore, category-1 indoor loggers were labelled North-1, North-2, East-1, East-2, South and West at 3 m. Category-2 indoor loggers were labelled North-1, North-2, East-1, East-2, South and West at 9 m. Category-3 indoor loggers were labelled North-1, North-2, East-1, East-2, South and West at 15 m.

Figure 6.4: *Loggers' Location and Orientation with ID at DOHS Baridhara and Uttara*

6.3 RESULTS

The following section presents the results of the microclimatic contexts study. As discussed in Section 4.4.2.1, due to time and cost constraints, the microclimatic study focused only on the ambient air temperature.

6.3.1 Temperature Variation vs Different Orientations and Locations

Figures 6.5–6.7 show the daily average air temperature as measured by the loggers during the study period. The results show that the average daily temperature varied noticeably with respect to different orientations and locations, particularly during clearer days and at the 3 m level (with higher CR). For the majority of the days, at the 3 m and 9 m levels, the south orientation had higher average temperatures than other orientations and locations during the study period, while the north orientations had the lowest temperatures. On the other hand, at the 15 m level, no particular orientation or location dominated consistently, although the setback areas seemed to experience higher temperatures more than the other locations.

A frequency analysis showed that at the 3 m level, the south orientation was the warmest for 85% of the time (34 days) and the north orientations were the coolest for 95% of the time (38 days) during the study period. At the 9 m level, the south orientation had the highest average air temperature for 53% of the days (21 days), followed by the side setback area (42.5%, 16 days). At the 9 m level, the north orientations were found to be the coolest orientation for most of the days (70%, 28 days), followed by the rear setback area (15%), the west orientation (12.5%) and the east-1 orientation (2.5%). At the 15 m level, the warmest locations were the side setback area (42.5%, 17 days) and the rear setback area (40%, 16 days), followed by the east-2 orientation (17.5%, 7 days). Again, the north orientations were the coolest for most of the days (82.5%).

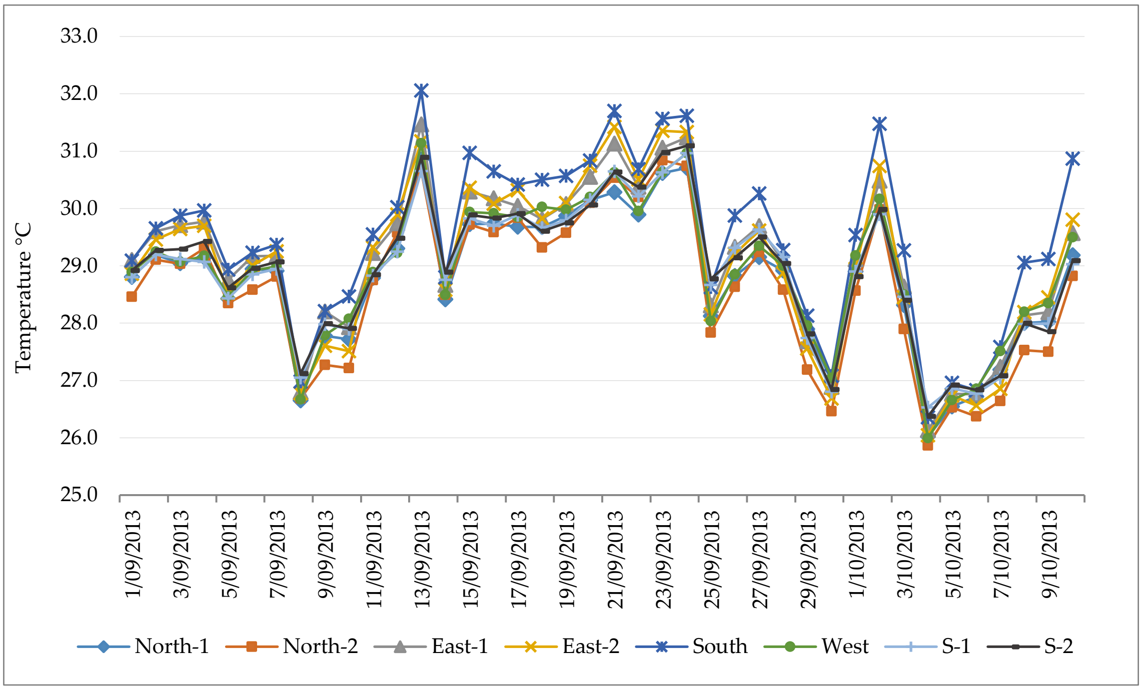

Figure 6.5: *Daily Average Temperature for all Locations at 3 m (1 Sept–10 Oct. 2013)*

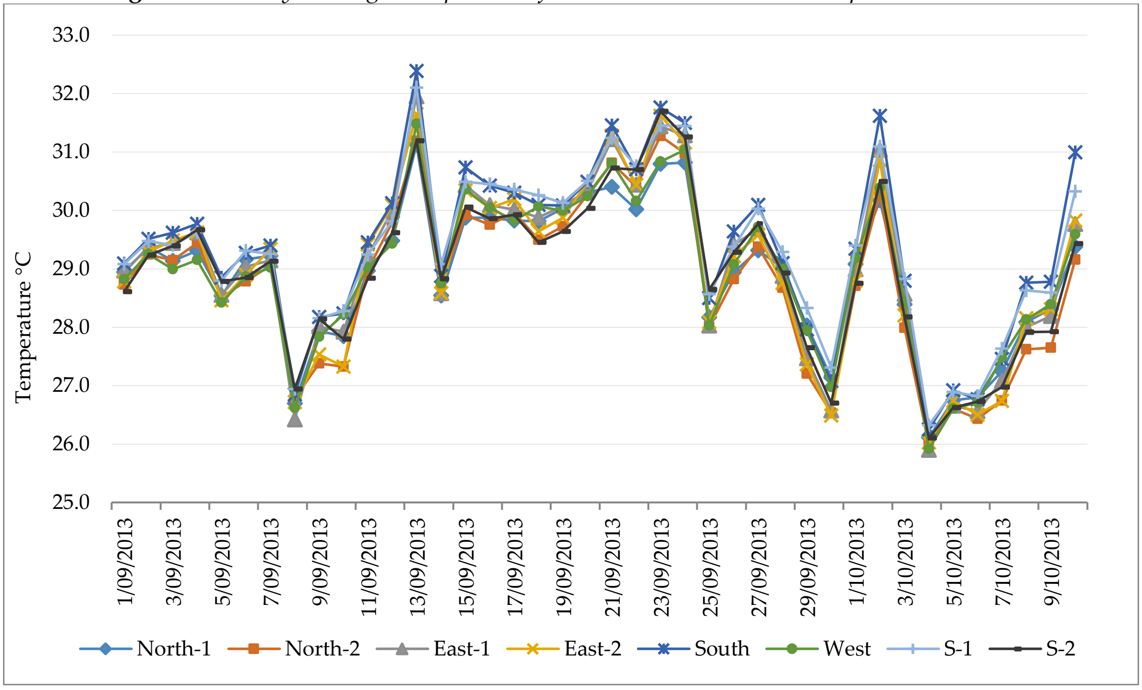

Figure 6.6: *Daily Average Temperature for all Locations at 9 m (1 Sept–10 Oct. 2013)*

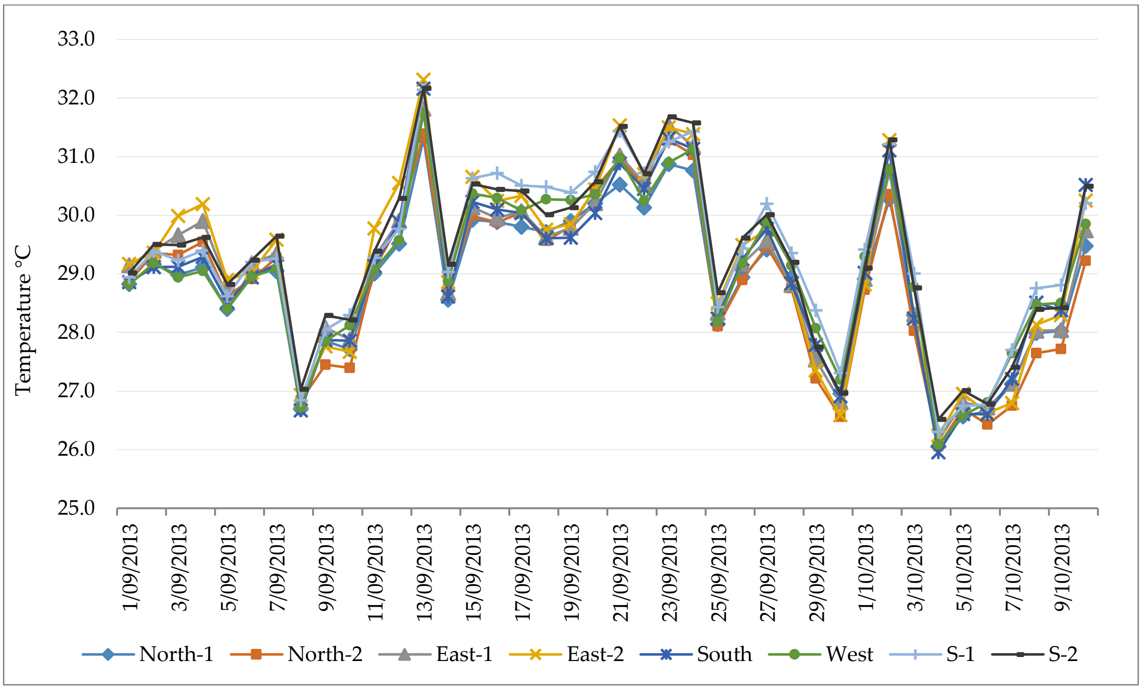

Figure 6.7: *Daily Average Temperature for all Locations at 15 m (1 Sept–10 Oct. 2013)*

Figures 6.8–6.10 show the average air temperature for all the orientations and locations at the 3 m, 9 m and 15 m levels during the total study period (40 days). At the 3 m level, the maximum average air temperature was 29.5°C for the south, followed by the east-1 (29.1°C), east-2 (29°C), west (28.9°C), side setback (28.9°C), rear setback (28.9°C), north-1 (28.8°C) and north-2 (28.6°C). At the 9 m level, the maximum average air temperature was the south orientation (29.4°C), followed by the side setback (29.3°C), east-1 (29.1°C), east-2 (29°C), west (29°C), rear setback (29°C), north-1 (28.9°C) and north-2 (28.8°C). At the 15 m level, the highest average temperature was in the setback areas (29.3°C), followed by the east-2 (29.2°C), east-1 (29.1°C), south (29.1°C), west (29.1°C), north-1 (28.9°C) and north-2 (28.9°C).

The results showed that the highest temperature difference among different orientations and locations was at 3 m and the lowest difference was at 15 m, which indicates the diminishing impact of different orientations on the average air temperature, with decreased effective CR. As described in Section 6.2, it is important to note that the loggers at setback areas at 15 m level actually represented the west and south orientation. Therefore, the higher average temperature reading for the setback loggers at 15 m can be attributed to the facts that the side setback logger facing the west had a very low effective CR (0.05) in front and did not have any shadow benefit from the building in front (due to the lower height of the building in front); and the rear setback logger facing the south had a high effective CR (0.9) due to the narrow distance between the buildings and did not have any benefit of the prevailing wind.

All other orientations (excluding the norths and east-2) at the 15 m level, with an effective CR of about 0.26, showed the same average air temperature during the study period. The east-2 logger showed slightly higher (+0.1°C) average air temperature than east-1, south and west loggers, which could be due to the fact that there was a drop wall next to the east-2 logger at 15 m and this may have contributed to the slightly higher average air temperature. The north loggers always showed lower average temperatures than any other orientations and locations at the same level.

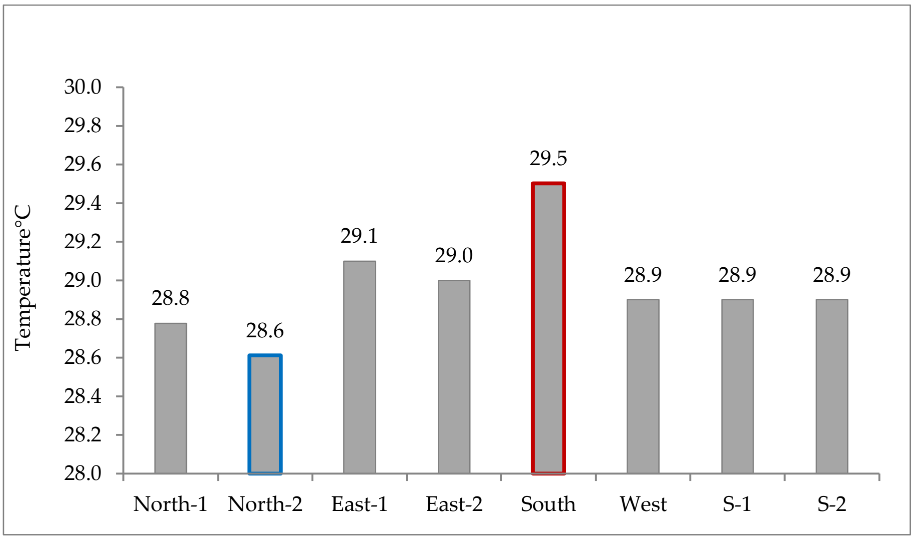

Figure 6.8: *Average Air Temperature at 3 m (1 Sept–10 Oct. 2013)*

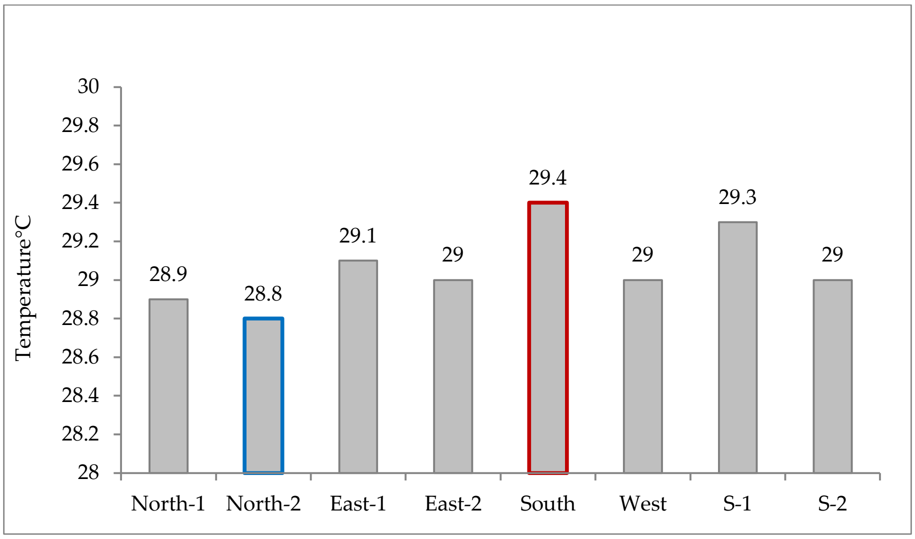

Figure 6.9: *Average Air Temperature at 9 m (1 Sept–10 Oct. 2013)*

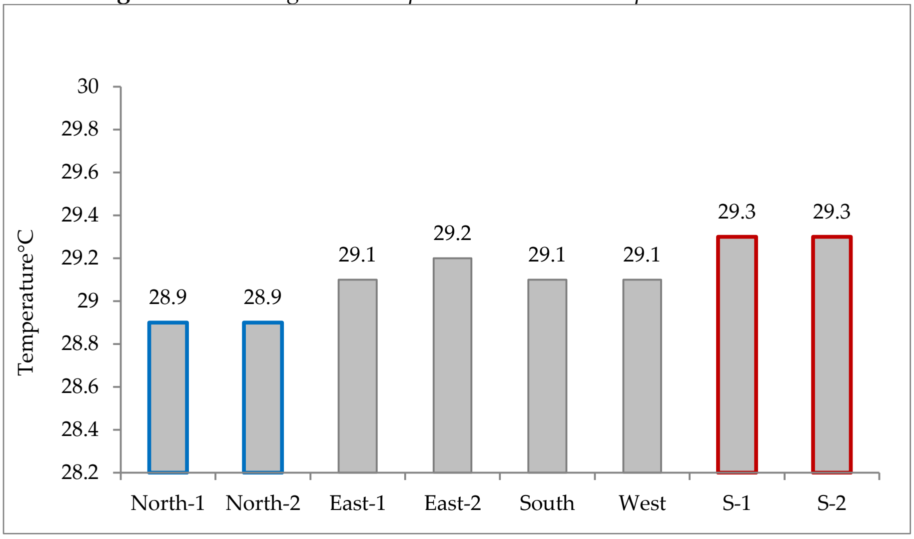

Figure 6.10: *Average Air Temperature at 15 m (1 Sept–10 Oct. 2013)*

The results may suggest that within the given urban contexts of typical residential developments in Dhaka, the average air temperature above 9 m does not vary among different orientations that are exposed to direct solar radiation during the daytime (east, south and west). However, from the results it can be said that the south is the warmest orientation overall and the north is the coolest orientation overall, within the given physical contexts.

The finding from this study that the average air temperature difference between different orientations and locations is greater at lower levels with a higher effective CR and is smaller (or has no difference) at higher levels with a lower effective CR. This could be attributed to the following reasons:

i) At lower levels, the east- and west-oriented facades within the given urban contexts receive the benefit of shadow from the opposite building in the morning and evening sun. However, under the higher midday sun, a south-oriented façade cannot be protected by the shadow of the opposite buildings even at lower levels. In addition, the duration of direct solar access is longer for the south than for the east or west. Since the anthropogenic heat was the same for all orientations in the case study areas, the higher access to direct solar radiation would probably augment the temperature difference between the south and other orientations at the lower level.

ii) At the upper level, where the effective CR is smaller, the east- or west-oriented facades have less shadow benefit, whereas the south-oriented façade starts to receive the benefit of the prevailing wind flow from the south (see Section 5.2.3), which removes some of the heat from the surface.

Both of these reasons are likely to reduce the temperature difference between the south and other orientations.

A previous study regarding outdoor thermal comfort in Dhaka city’s context found that the existing canyons along the E-W axis, perpendicular to the prevailing wind direction, produced still conditions at the pedestrian level inside the canyons (Ahmed, 1996). Other studies have found that a canyon with more than 0.25 ratio and perpendicular to the wind direction produces ‘skimming flow’ and still air conditions inside the canyon (Erell et al., 2011; Oke, 1998; Yim et al., 2009). It should be noted that the effective CR for the loggers at the 15 m level was about 0.23. Therefore, it can be said that the lower levels of a south façade (along the E-W axis) in typical residential developments in Dhaka do not receive the benefit of the prevailing wind flow, due to the high CR. The results further affirm the importance of avoiding direct solar radiation as well as enhancing the airflow to restrict the air temperature rise in Dhaka's contexts and hence, reducing the demand for cooling energy.

Further analyses were conducted to find out to what extent the south orientation was warmer than other orientations and locations during the study period. The average temperature value of each logger at different heights was subtracted from the average temperature value of the south loggers at the same height. The findings showed that the south orientation was on average 0.9°C warmer than the north-2 orientation at 3 m, followed by the north-1 (0.7°C), west (0.6°C), setback areas (0.6°C), east-2 (0.5°C) and east-1 (0.4°C). At the 9 m level, south was 0.6°C warmer than north-2, followed by north-1 (0.5°C), east-2 (0.4°C), west (0.4°C), S-2 (0.4°C), east-1 (0.3°C) and S-1 (0.1°C). However, at the 15 m level, the difference was minimal (0–0.2°C) and the south was cooler than the setback areas and east-2. Given that every 1°C temperature increase can increase the consumption of cooling energy by 5%, the average temperature difference between the south and other orientations at the lower level is significant (Wong et. al., 2011). However, the average temperature differences among other orientations, such as east vs west or north vs east, were insignificant.

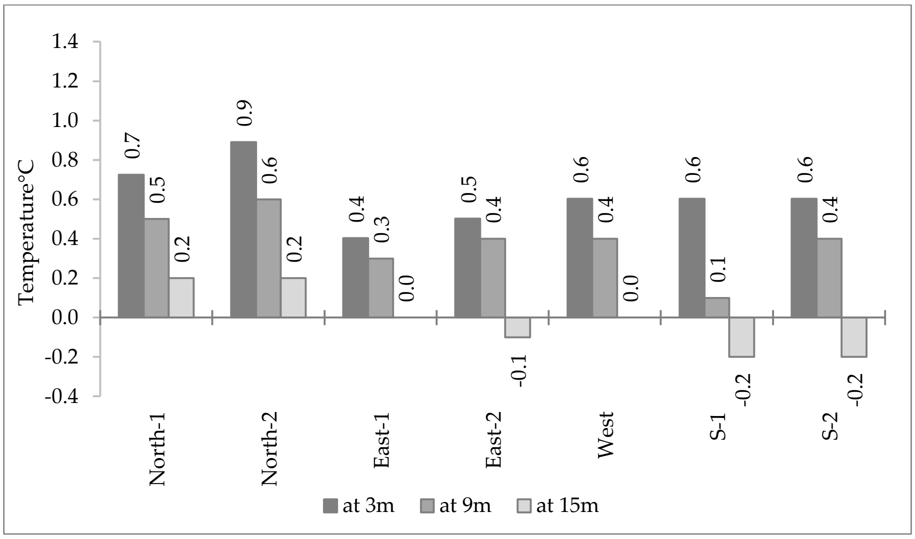

Figure 6.11: *Average Temperature Difference between the South and Other Locations*

The difference between the maximum and minimum daily average temperature during the study period at different levels was also checked. At the 3 m level, the maximum temperature difference between the south and the north-2 logger was 2°C, which means that on average, the south orientation at the 3 m level was 2°C higher than the north-2 orientation on one day during the study period (10 October 2013). At the 9 m level, the maximum difference between the south and north-2 orientation at the 15 m level was 1.8°C. At the 3 m level, the maximum difference between the rear setback area and the north-2 was 1.3°C on the same day. The temperature difference was significant, from both the thermal comfort and energy-consumption points of view, as the average temperature during September and October in Dhaka is about 29°C and the comfortable temperature for people in Dhaka city is 24–32°C (with the neutral temperature at 28°C) (Mallick, 1996; Shajahan, 2012). Therefore, a slight increase in temperature can increase the discomfort hours significantly and as noted earlier, every 1°C temperature increase can increase the consumption of cooling energy by 5% (Wong et al, 2011).

Further analyses were conducted to find out the average daytime and night-time temperature differences among different orientations and locations. It was known from the literature review that dense areas or deep canyons are usually cooler in the daytime due to being shaded by the closely spaced buildings and warmer at night due to the lower SVF, which restricts the nocturnal long-wave emission or radiative cooling (Erell et al., 2011; Oke, 1988; Santamouris et al., 2001). Therefore, it was hypothesised that the setback areas were likely to have a higher night-time temperature. The average daytime (6:00am–5:30pm) and night-time (6:00pm–5:30am) temperatures for all the loggers were calculated and plotted according to their heights.

The results (see Figures 6.12–6.14) showed that at 3 m, the south had the highest average daytime temperature and the setback areas had the highest average night-time temperature during the study period. On the other hand, the side setback area was the coolest in the daytime and the west and the north-2 was the coolest at night-time. At the 9 m level, the south and the side setback area had the highest average daytime temperature and the side setback area had the highest average night-time temperature. The north-2, east-2 and rear setback area had the lowest average daytime temperature and the east-1 had the lowest average night-time temperature. At the 15 m level, the side setback area had the highest average daytime temperature and the rear setback had the highest night-time average temperature. Both in the daytime and at night, north-2 had the lowest average temperature. If we exclude the side setback area at 9 m and 15 m and the rear setback logger at 15 m, as the loggers did not actually represent deep canyon at those levels, it can be said that the results support the assumptions of cooler setback areas in the daytime but warmer setback areas at night, compared to other orientations. Excluding the setback areas, the south was the warmest both in the day and at night at the lower two levels; however, at 15 m, the west was the warmest in the daytime.

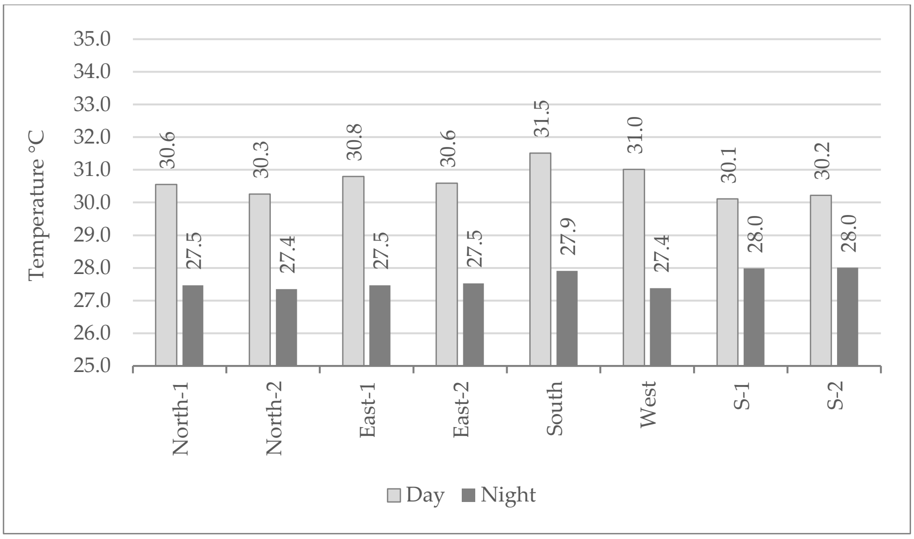

Figure 6.12: *Average Daytime and Night-time Temperature at 3 m*

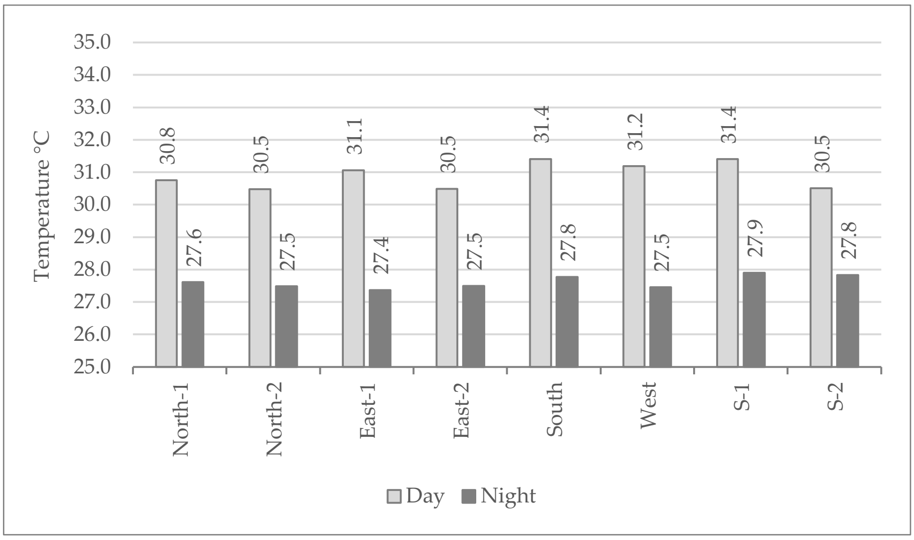

***Figure 6.13**: Average Daytime and Night-time Temperature at 9 m*

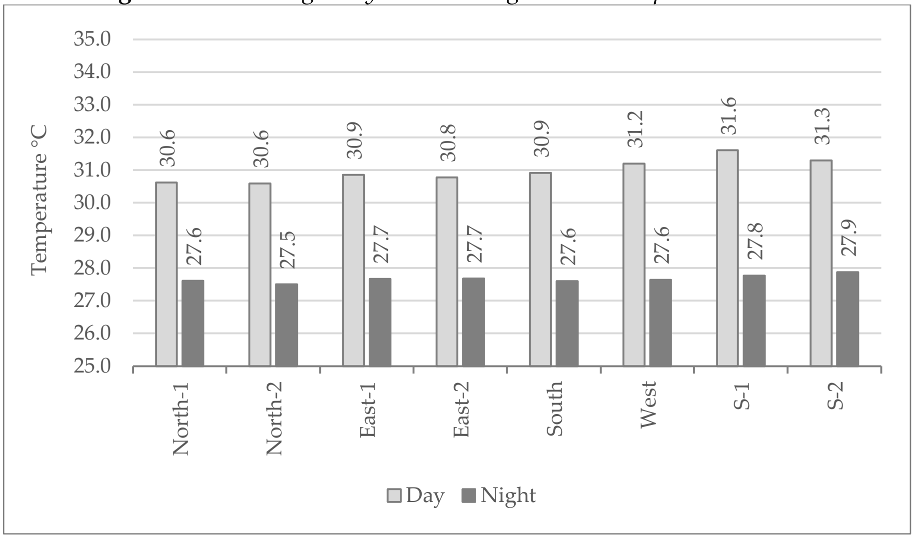

***Figure 6.14:** Average Daytime and Night-time Temperature at 15 m*

Further analysis showed that the maximum daytime temperature difference at 3 m was between the south and side setback area (1.4°C) and the maximum night-time difference was between the setback areas and north-1 (0.6°C). At 9 m, the maximum daytime temperature difference was between the south and north-2 and the rear setback area (0.9°C) and the maximum night-time difference was between the south as well as the rear setback area and east-1 (0.4°C). At the 15 m level, the maximum daytime difference was between the west and the north (0.6C) and the maximum night-time difference was between east-2 and north-2 (0.2°C). For all instances, the daytime difference among the different orientations and locations were larger than the night-time difference, which further affirms the effect of direct solar radiation on temperature rise.

It can be said from the results of this study that in typical residential developments in Dhaka, the south-oriented facades are in general warmer than for any other orientation of buildings, in particular at lower levels. The temperature variation between the south and other orientations is significant at the two lower levels from both the thermal comfort and the energy-consumption point of view; however, excluding the south, the variation among other orientations is insignificant. It has also been noticed that at the upper levels with a lower CR, the temperature variation among all the orientations are insignificant, particularly among the non-shaded orientations. Although the setback areas or the deep canyons are cooler in the daytime, they are warmer at night. From an energy-consumption point of view, these findings suggest that within the given urban settings, the south-oriented apartments are warmer than any other orientation of apartment (excluding the upper floors) and therefore, are likely to require more cooling energy. However, a south-oriented apartment at the upper level may have a lower cooling energy demand than other orientations of apartments if the benefit of the prevailing wind flow can be used. The north-oriented apartments are cooler at all levels and therefore, are likely to have lower cooling energy demand than any other orientation of apartments.

6.3.2 Temperature Variation vs Heights

Analyses were conducted to find out the degree of temperature variation according to different heights for the same orientation and location. The average temperature for all the orientations and locations at all levels during the study period were plotted (see Figure 6.15). Except for east-1 and south loggers, the average temperature during the study period slightly increased as the height increased; that is, as the CR decreased. The ambient temperature slightly decreased as the height increased only for the south loggers, possibly because of the prevailing wind direction, as discussed in the previous section.

The maximum temperature difference between two levels for the same orientation or location was 0.4°C at the south orientation between the 15 m and 3 m level. (The setback areas were excluded from this study due to the inconsistent change in effective CR across the height at setback areas, as described in the previous section.) For all other orientations, the temperature difference between different levels for the same orientation varied 0°–0.3°C, which is minimal. Within the existing urban settings, the temperature did not vary significantly across the height between 3 m and 15 m for the north, east and west orientation and the variation for the south was slight.

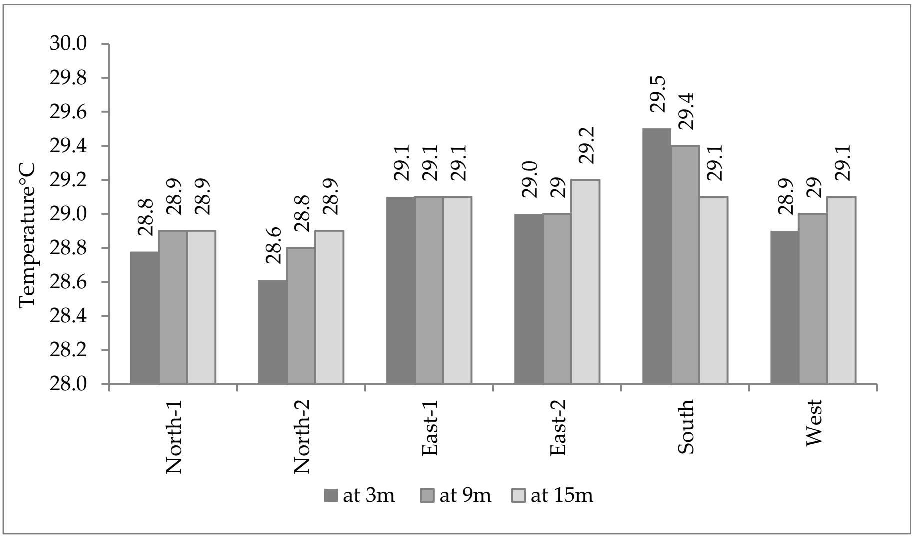

Figure 6.15: *Average Air Temperature Variation at Different Heights*

6.3.3 Outdoor vs Indoor Temperature

Analyses were conducted to explore the differences between the indoor and outdoor temperatures for the 18 case study apartments (as discussed in Section 4.4.2.1.3, most of the indoor loggers were in rooms without AC). The average air temperatures during the total study period for all indoor loggers were plotted against the respective average outdoor temperatures (see Figures 6.16–6.18). For all the cases, the average indoor temperature was much higher than the average outdoor temperature, which varied between 0.7°C and 2.4°C except for the east-facing apartment in DOHS at the 9 m level, where AC was used heavily in the room in which the logger was installed, due to the presence of a child. Except for one case (east-2 at 15 m), the indoor temperatures on the top floors were warmer than the indoor temperatures on the intermediate floors, probably because of more solar exposure.

Although the findings were based on only 18 apartments, because the urban and building design practices, as well as the use of materials, in typical residential developments in Dhaka are highly homogeneous, they were assumed to represent all similar developments. These findings were in line with the study by Ahmed (1994), which also found that the average indoor temperature of Dhaka dwellings was higher than the average outdoor temperature.

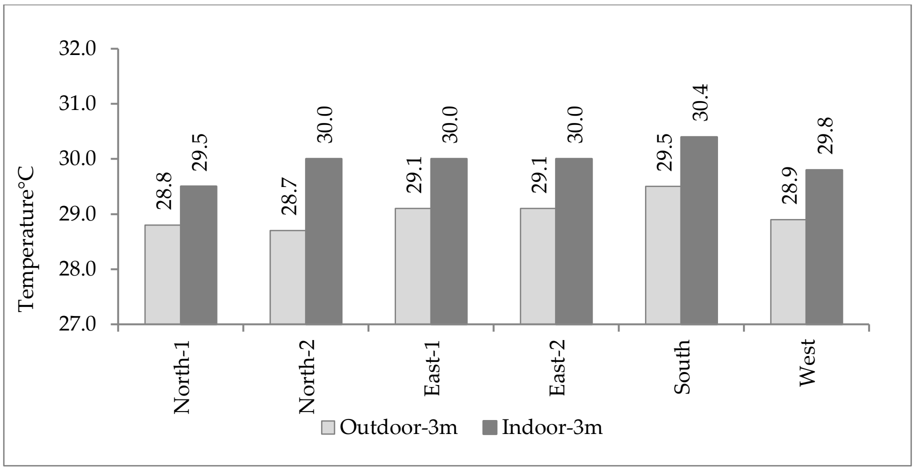

Figure 6.16: *Average Outdoor and Indoor Temperature at 3 m during the Study Period*

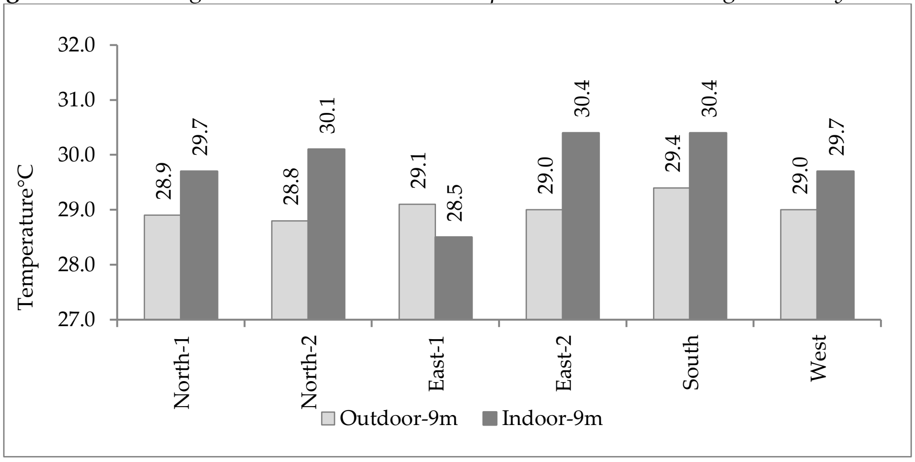

Figure 6.17: *Average Outdoor and Indoor Temperature at 9 m during the Study Period*

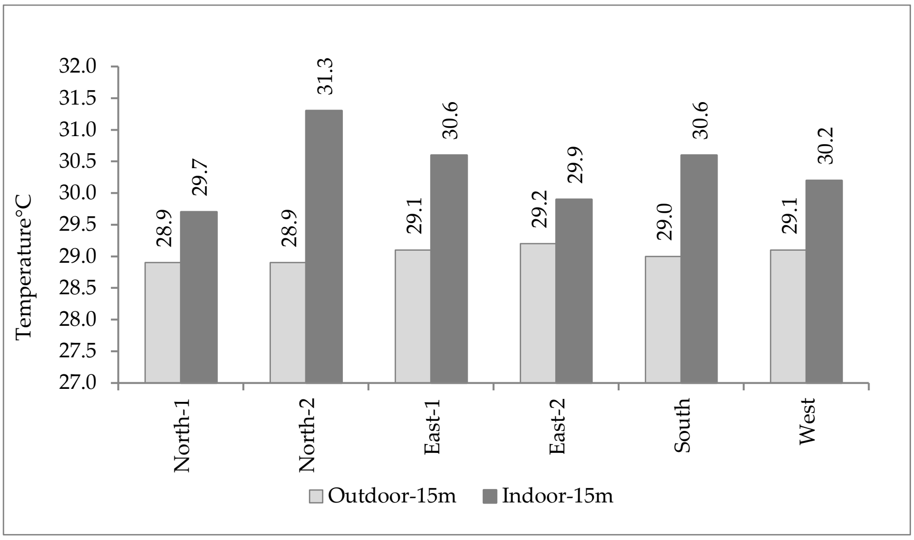

Figure 6.18: *Average Outdoor and Indoor Temperature at 15 m during the Study Period*

There are several possible reasons for the higher average indoor temperatures, such as lack of ventilation or heat release from the indoors as well as the activities of the people and use of appliances such as lights and computers, which generate heat. As described in Chapter 5, Dhaka buildings have a 5″ (125 mm) or 10″ (250 mm) solid brick wall, which provides heavy thermal mass with a time lag of 5–8 hours. This prevents the outside heat transferring to the inside during the daytime; however, it traps the heat inside at night when the outdoors is cooler.

Half-hourly indoor temperature data during the study period, along with its corresponding outdoor temperature, were plotted to compare the temperature patterns between indoors and outdoors. The temperature pattern showed that the daily indoor air temperature did not fluctuate much compared to the outdoor temperature fluctuation (see Figures 6.19–6.22). This means that when the outdoors was hot during the day, the indoors was cooler; however, the indoor temperature did not decrease at night when the outdoors was cooler. These results further confirm the lack of heat release or the occurrence of trapped heat inside the building. Considering the contexts of Dhaka, this finding is not unusual, as for various reasons such as security and privacy, people prefer not to keep their windows open at night.

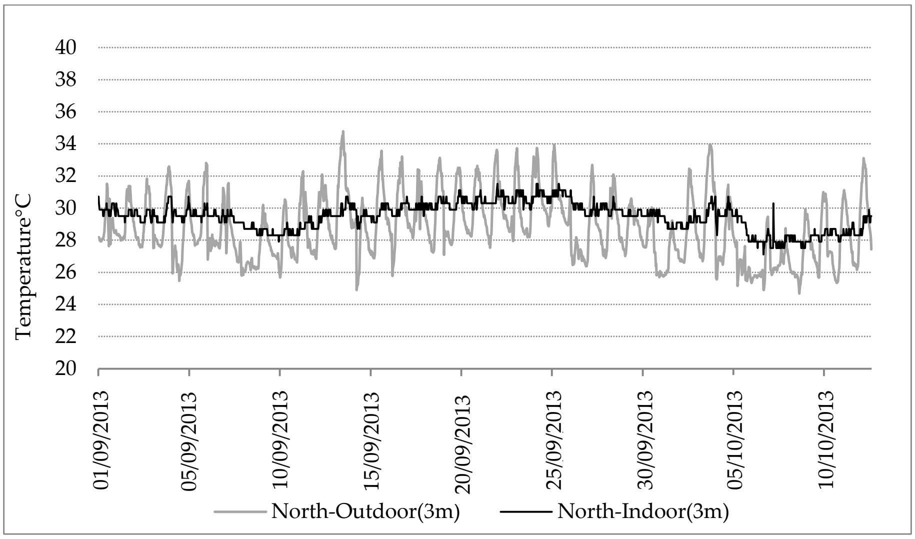

Figure 6.19: *Example-1: Half-hourly Outdoor and Indoor Temperature for North-1 at 3 m*

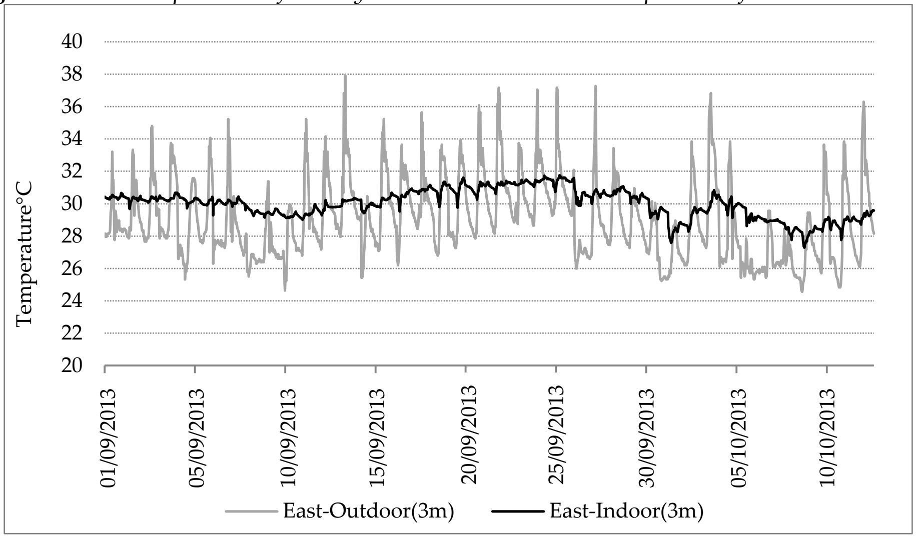

Figure 6.20: *Example-2: Half-hourly Outdoor and Indoor Temperature for East-2 at 3 m*

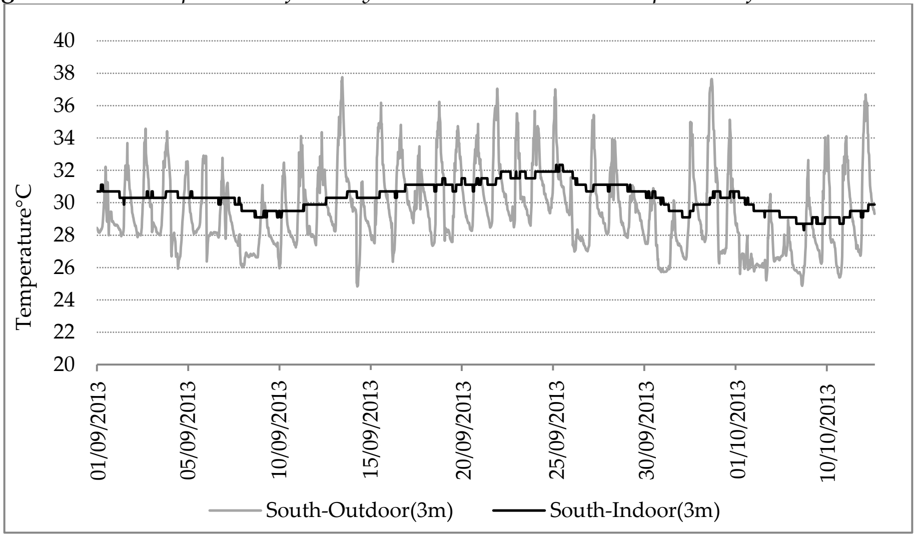

Figure 6.21: *Example-3: Half-hourly Outdoor and Indoor Temperature for South at 3 m*

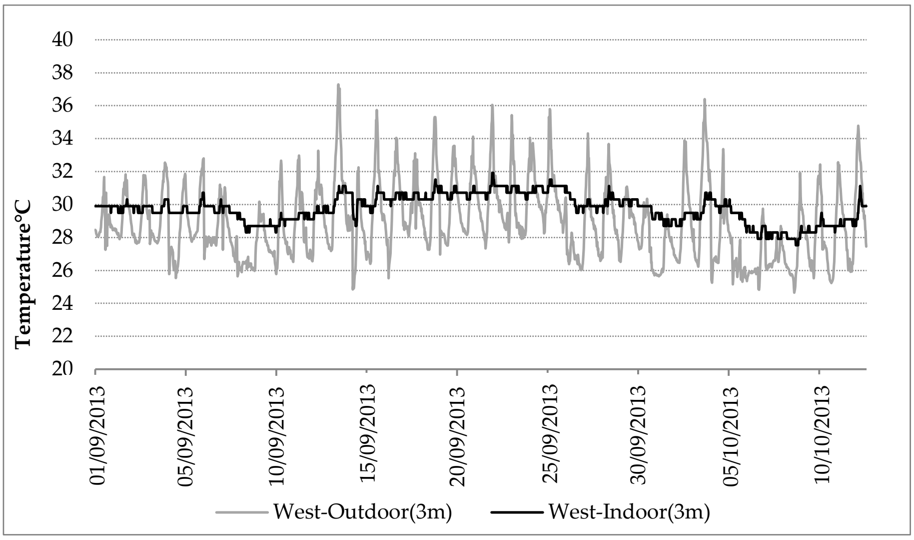

Figure 6.22: *Example-4: Half-hourly Outdoor and Indoor Temperature for West at 3 m*

Further analyses were conducted to find out the variation in temperature patterns as well as the extent of temperature differences between the indoors and outdoors at different hours of the day for four different orientations. This was to find out at which time of day the outdoors started to get warmer or cooler than the indoors for different orientations, as well as the extent of the differences. This information can be used to increase indoor thermal comfort and consequently, cooling energy consumption.

Half-hourly indoor and respective outdoor temperatures of the four different orientations at different levels for 24 hours were plotted for the hottest day (13 September 2013) and the coolest day (4 October 2013) during the study period. It is worthwhile to note that the hottest day was a relatively clear and sunny day and the coolest day was a rainy and heavily cloudy day. Although the north and east orientation had two loggers each (one in Uttara and one in DOHS), only one logger for each orientation was considered for this study, as after some preliminary plots, both of the north loggers and the east loggers showed a similar pattern. Therefore, for the north and east orientations, loggers at Uttara were studied and for the south and west orientations, loggers at DOHS were studied. Only the results of the loggers at the 3 m level are discussed here, as the loggers at other levels with the same orientation showed a similar temperature pattern and difference to the 3 m level. (The plots of the other levels can be found in Appendix D.1).

Distinct temperature patterns were observed for the four different orientations on the hottest day. At north, the outdoor temperature was the lowest at around 5:30–6:00am and was lower than the indoors until around 8:00am (see Figure 6.23). At 8am, the outdoors reached the same temperature as the indoors, after which it became hotter than the indoors and continued to rise until around 11:30am. Figure 6.24 shows that the outdoors reached and stayed at a plateau from 12:00pm to around 5:00pm and then the temperature dropped sharply, levelling with the indoors at about 6:00pm. Apart from a short rise at 9:30pm, it remained lower than the indoors from 6:00pm until the end of that day. The indoor temperature hardly fluctuated throughout the day and shows a slow increase. The peak temperature difference between the outdoors and indoors was 3.1°C when the outdoors was hotter at 2:00pm and 2.39°C when the outdoors was cooler at 5:30am.

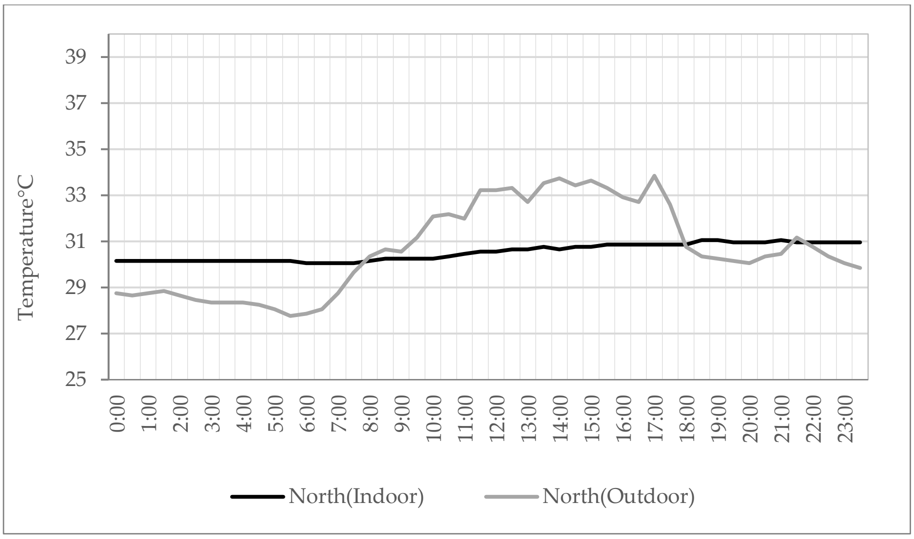

Figure 6.23: *Half-hourly Indoor & Outdoor Temperature on the Hottest Day: North at 3 m*

At east orientation on the hottest day (see Figure 6.24), the outdoor temperature was lowest at 5:30–6:00am, after which it started to increase and reached the level of the indoors at 7:30am. The outdoor temperature surpassed the indoors at around 8:00am and kept increasing rapidly until around 10:00am. At 11:30am, the outdoor temperature reached its peak for the day after a short, sharp drop at around 11:00am, which was due to a quick heavy shower, which lowered the temperature by 4°C. After the peak, it dropped sharply until 1:00pm, after which it remained steady at 33–34°C until 5:00pm. The temperature decreased gradually from 5:00pm to around 7:30pm, after which it remained steady until around 10:30pm, slightly above the indoor temperature. At 10:30pm, the outdoors again levelled with the indoors, after which it became cooler than the indoors. The indoor temperature remained nearly flat throughout the day, with a slight ascend but without any fluctuation. The peak temperature difference between the outdoors and indoors was 7.7°C at 11:30am, when the outdoors was hotter and 1.89°C at 5:30–6:00am, when the outdoors was cooler.

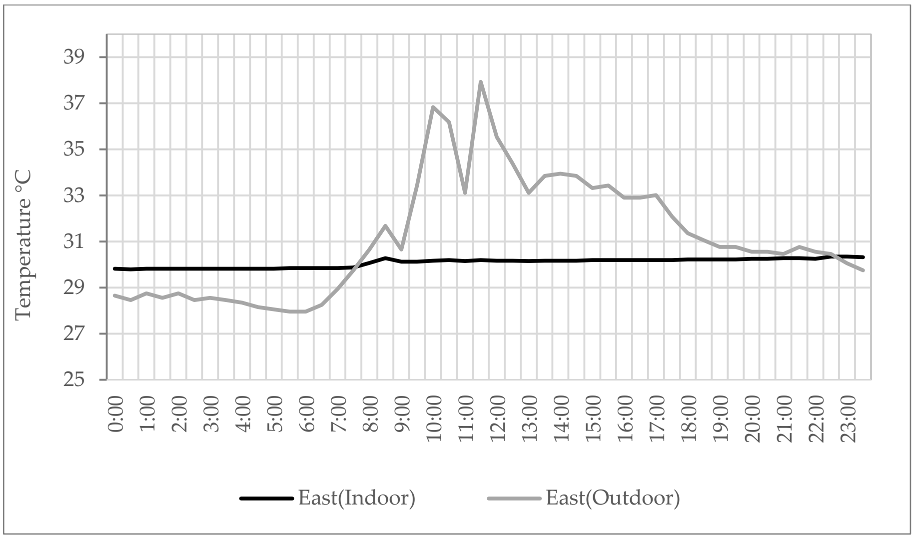

Figure 6.24: *Half-hourly Indoor & Outdoor Temperature on the Hottest Day: East at 3 m*

At south orientation (see Figure 6.25), the outdoor temperature was lowest at 5:30am, after which it started to increase and gradually peaked at around 2:00pm. After a short steady period, it started to decrease after 2:30pm until around 7:00pm. From 7:30pm to around 10:30pm, the temperature remained quite steady, after which it started to decrease relatively steeply compared to the rise before 2:00pm. The outdoors was cooler than the indoors from midnight until 7:30am, when it reached the same level as the indoors and then started to become hotter and remained hotter until 11:30pm. The indoor temperature remained nearly flat, with a slight ascend and without any fluctuation throughout the day. The peak temperature difference between the outdoors and indoors was 7.5°C at 2:30pm, when the outdoors was hotter and 2.1°C at 5:30am, when the outdoors was cooler.

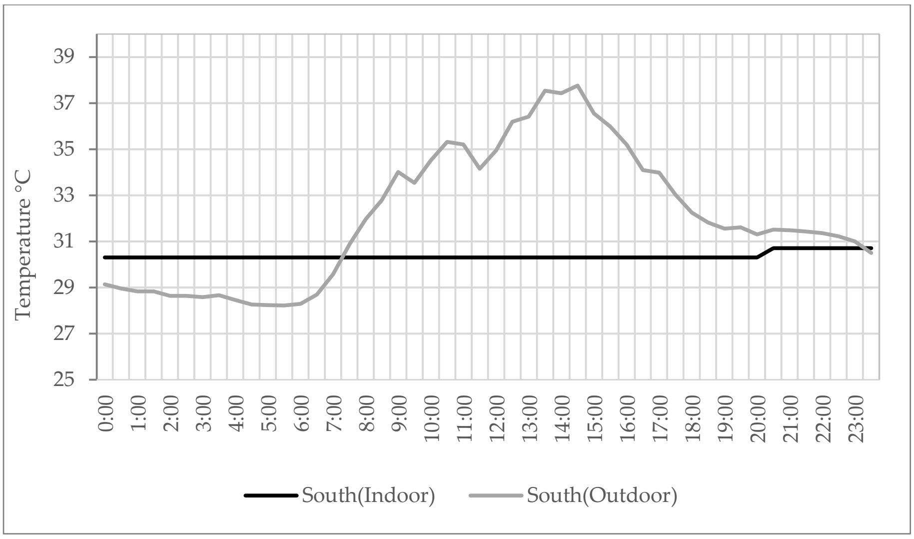

Figure 6.25: *Half-hourly Indoor & Outdoor Temperature on the Hottest Day: South at 3 m*

At west orientation (see Figure 6.26), the outdoor temperature was at its lowest at 5:30am, after which it started to rise gradually until 2:00pm. After 3:30pm, it started to decrease again relatively steeply until around 6:30pm, when it levelled with the indoors. It remained steady and nearly at the same level as the indoors until 10:30pm, after which it decreased again and became cooler than the indoors. The outdoors was hotter than the indoors between 7:30am and 6:30pm on the hottest day during the study period. The indoor temperature showed some small rises and falls compared with the other indoor temperatures as well as an ascension. The peak temperature difference between the outdoors and indoors was 6.3°C at 3:30pm, when the outdoors was hotter and 2.29°C at 5:30am, when the outdoors was cooler.

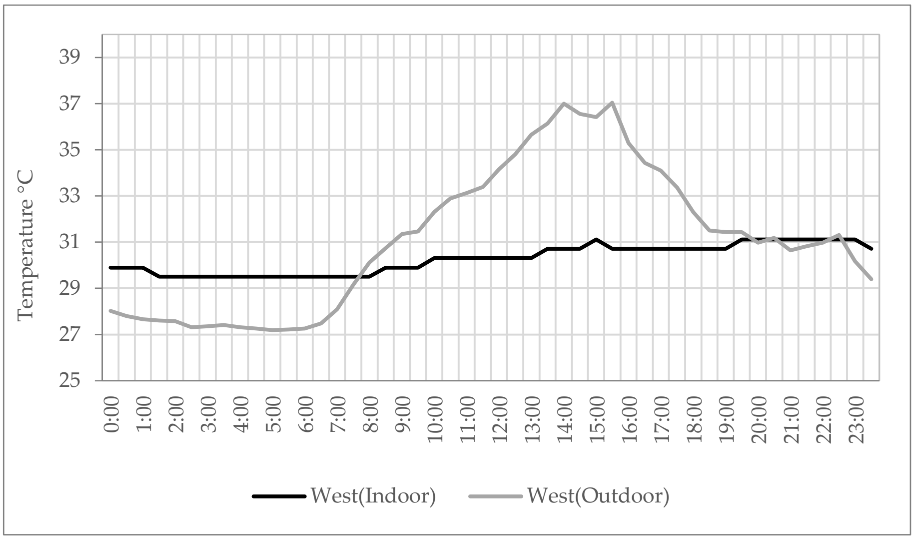

Figure 6.26: *Half-hourly Indoor & Outdoor Temperature on the Hottest Day: West at 3 m*

From these results, it can be said that the indoor air temperature hardly fluctuated, irrespective of its orientation, possibly for two reasons: i) due to the heavy thermal mass of Dhaka buildings, the indoors remains significantly cooler than the outdoors in the daytime for any orientation; and ii) the building mass traps heat that is not released at night through ventilation or any other means, resulting in indoor temperatures that are much higher than the outdoors at night. The outdoors has a distinct temperature pattern for different orientations, with the east reaching its peak in the morning before noon, the south around the middle of the day and the west in the afternoon. In addition, the peak temperature differences between the indoors and outdoors in the daytime for the shaded orientation (3.1°C, north) and non-shaded orientations (6.3–7.7°C for east, south and west) varied significantly.

Figures 6.27–6.30 show the half-hourly temperature on the coolest day during the study period. The coolest day was a rainy day with heavy clouds. The figures show that the indoor air temperature was noticeably higher than the outdoors for all instances on the studied day. For all the orientations, the indoor temperatures also show a slow descend, which clearly depicts the extent of heat trap inside the apartments that was not released even when the outdoor temperature was significantly cooler.

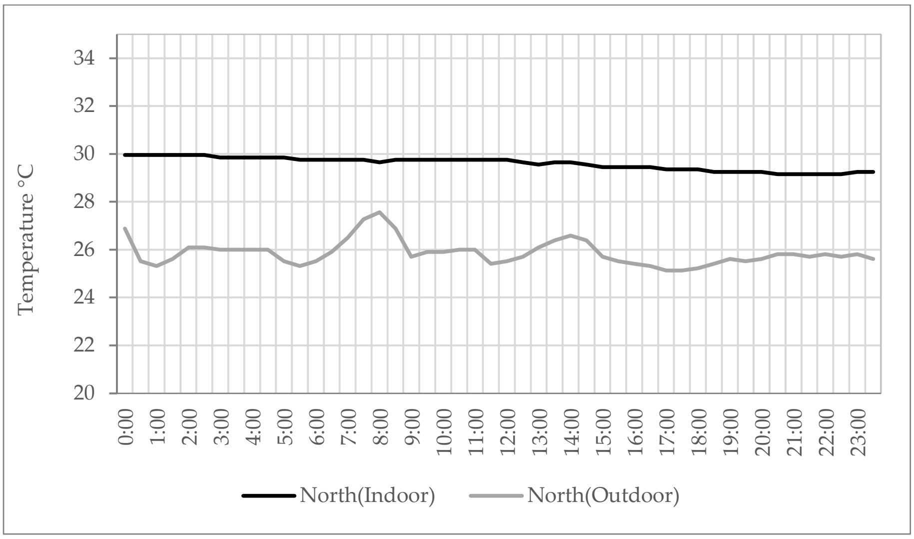

Figure 6.27: *Half-hourly Indoor & Outdoor Temperature on the Coolest Day: North at 3 m*

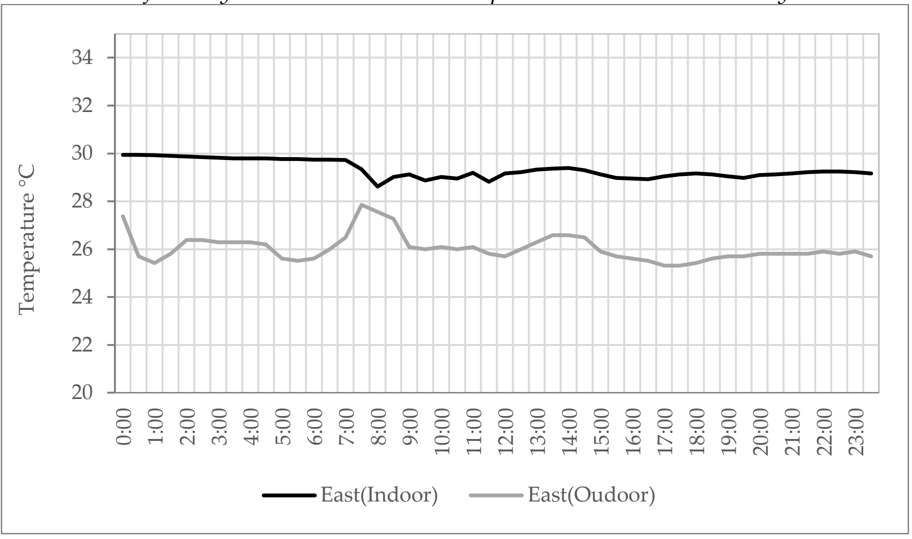

Figure 6.28: *Half-hourly Indoor & Outdoor Temperature on the Coolest Day: East at 3 m*

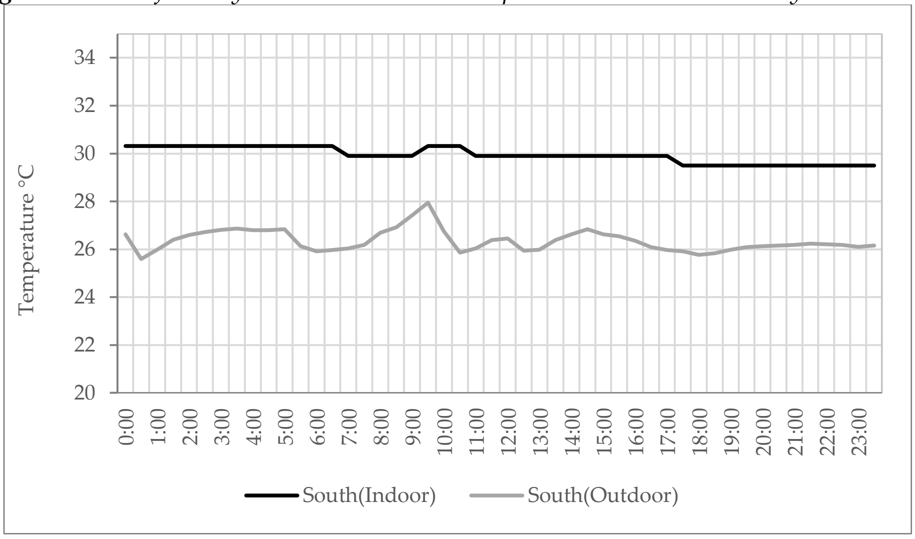

Figure 6.29: *Half-hourly Indoor & Outdoor Temperature on the Coolest Day: South at 3 m*

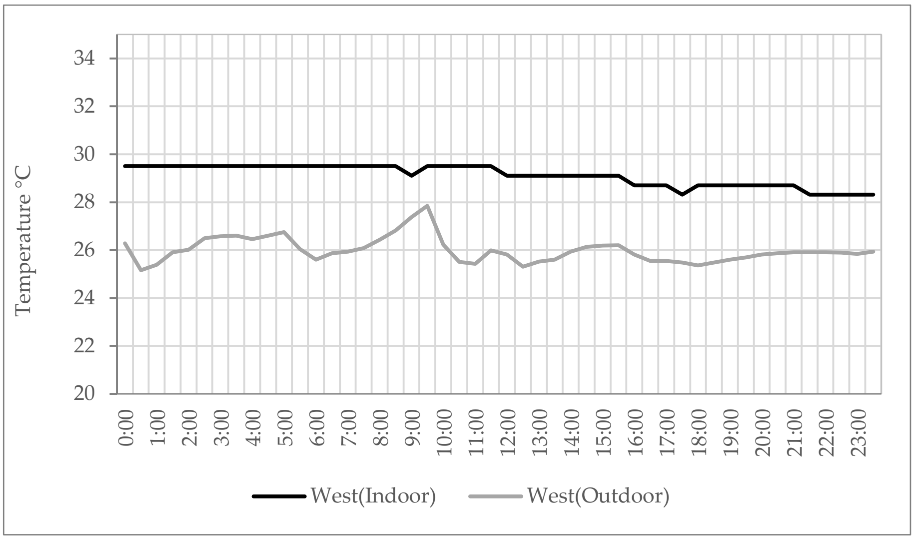

Figure 6.30: *Half-hourly Indoor & Outdoor Temperature on the Coolest Day: West at 3 m*

Further investigations were made to find out the differences between the average daytime and night-time temperature for all indoor loggers, as well as the differences between indoors and outdoors at both daytime and night-time for all orientations at all levels (excluding the east-1 logger at 9 m, because of the use of AC). For this study, the period from 6:00am to 5:30pm was considered the daytime and from 6:00pm to 5:30am was considered the night-time.

The average daytime and night-time temperatures for all indoor loggers and their respective outdoor loggers at all levels during the study period were calculated and plotted (see Figures 6.31–6.33). The results show that except for one case (south at 15 m), the average daytime indoor temperature was either equal to or higher than the average night-time temperature. However, the difference between the daytime indoor temperature and night-time indoor temperature was minimal for most of the cases (0–0.3°C for 14 out of 17 cases). Only the east-1 logger at the 15 m level had a significantly higher indoor daytime temperature (+2°C) than the night-time. This was probably because the apartment was at the top floor and the adjacent building at the south of this apartment was lower and hence, the apartment was more exposed to direct solar radiation in the daytime. The north-1 and east-2 at 9 m had a noticeably higher indoor daytime temperature (0.6°C and 0.8°C, respectively) than the night-time temperature, compared to all other cases. This is possibly because the occupants at east-2 (according to interviews) tended to open the windows more often in the daytime (when the outdoors was significantly hotter) compared to other cases and the north-1 at 9 m was in the formal living room, in which AC was used intermittently in the evening for guests. This may have lowered the night-time temperature and increased the difference between the daytime and night-time temperatures.

The results also showed that the average daytime outdoor temperature was higher than the average daytime indoor temperature for all instances except east-2 at 9 m and north-2 and east-1 at 15 m. The difference for east-2 was lower (see Figure 6.34). North-2 at 15 m was placed in the formal living room of the apartment, which was used only ocassionally and the windows and doors of that room were closed all the time to protect the expensive fabric of the furniture from dust and dirt. The complete absence of ventilation, along with the fact that it was at the top floor, are the likely the reasons for showing not only a noticeably higher daytime indoor temperature than the daytime outdoor temperature but also the highest average night-time temperature among all. East-1 at 15 m was more exposed to direct solar radiation throughout the day, as described in the previous section, which may have contributed to the significantly higher indoor daytime temperature.

In contrast, the average outdoor night-time temperature was always significantly lower than the average indoor night-time temperature for all the cases during the study period. The range varied between minimum 1.9°C and maximum 3.8°C (see Figure 6.35).

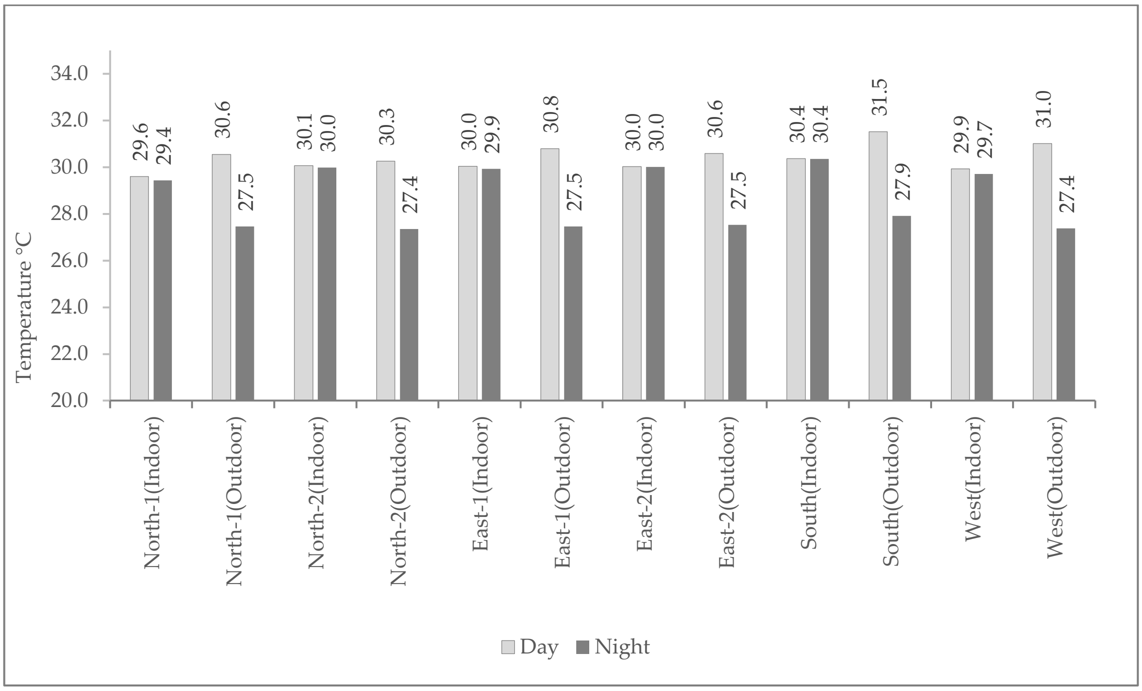

***Figure 6.31:** Average Daytime and Night-time Temperature for all the Loggers at 3 m (1 Sept–10 Oct 2013)*

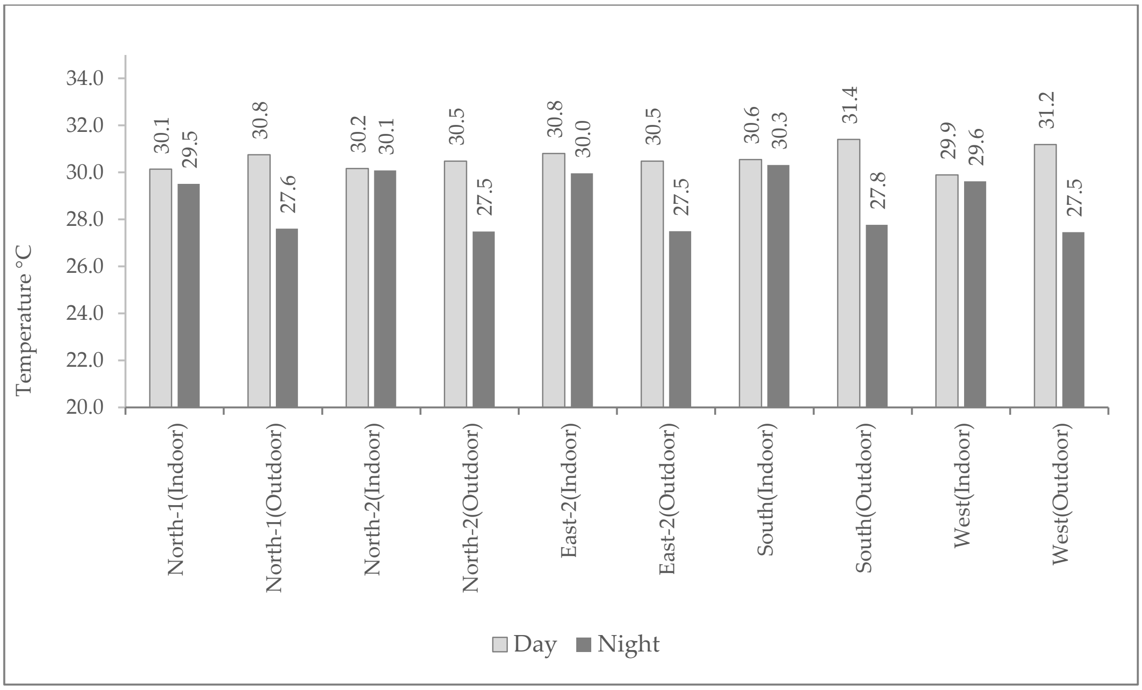

***Figure 6.32:** Average Daytime and Night-time Temperature for all the Loggers at 9 m (1 Sept–10 Oct 2013)*

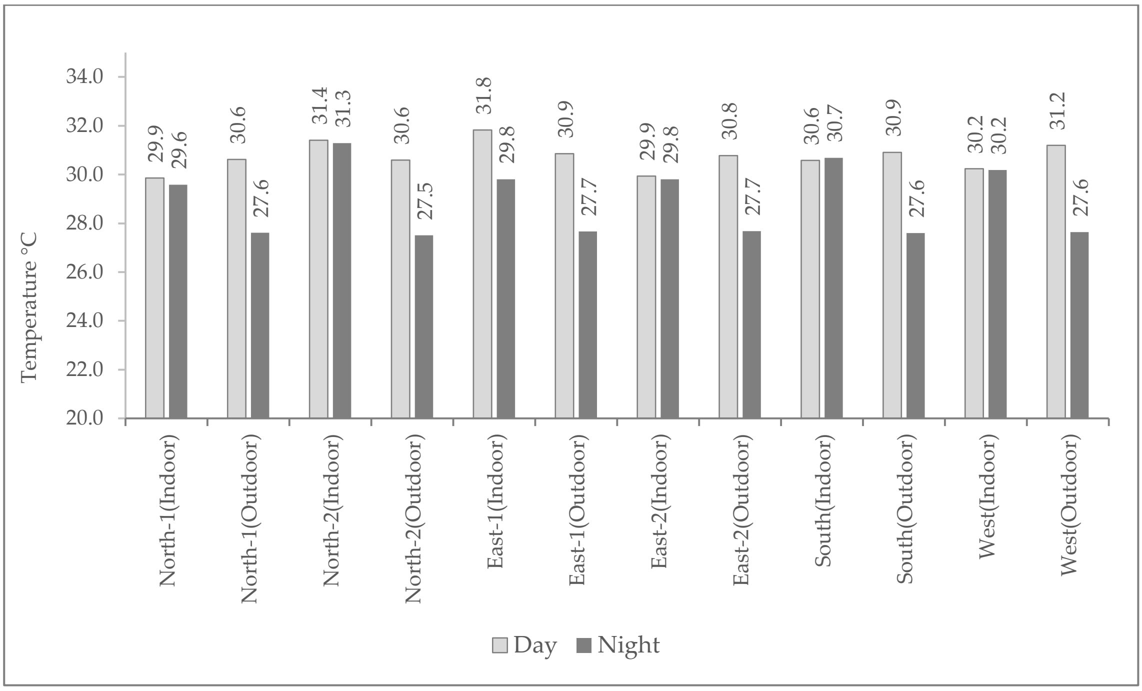

Figure 6.33: *Average Daytime and Night-time Temperature for all the Loggers at 15 m (1 Sept–10 Oct 2013)*

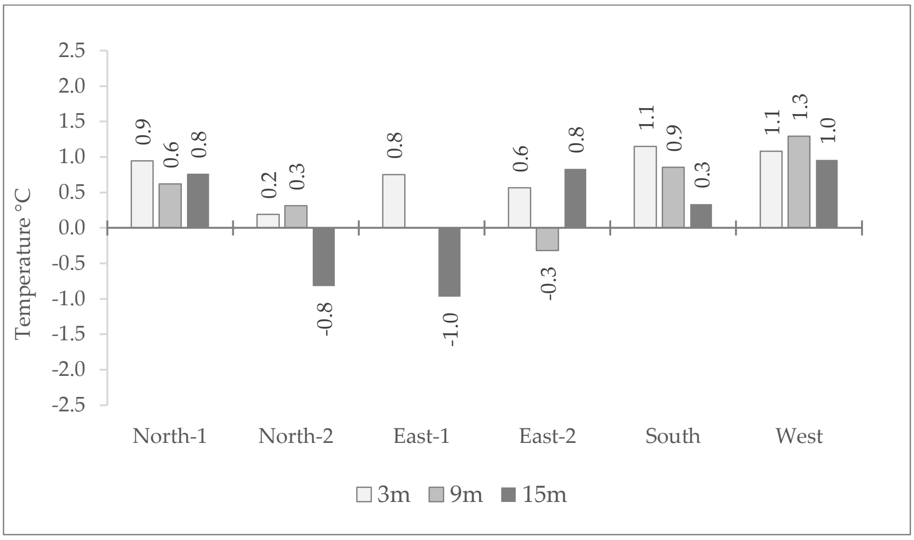

Figure 6.34: *Average Daytime Temperature Differences: Outdoor vs Indoor (1 Sept–10 Oct 2013)*

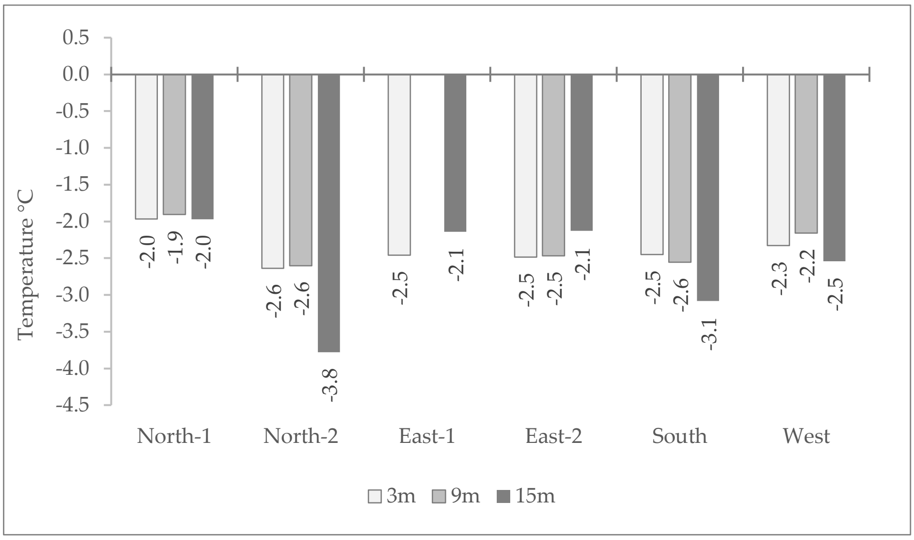

Figure 6.35: *Average Night-time Temperature Differences: Outdoor vs Indoor (1 Sept–10 Oct 2013)*

From the results, it can be said that the indoors of Dhaka dwellings are unnecessarily warmer at night, which could be reduced through sufficient and appropriate ventilation or other heat-releasing means. Based on the findings, from an energy-consumption point of view, it can also be said that the households in typical residential areas in Dhaka are consuming more energy for cooling than needed, as the occupants are at home at night and this is when they use the cooling appliances most. The study also indicates the potential of reducing the existing household consumption of cooling energy through appropriate design strategies, which would enhance night-time ventilation without compromising the other social issues such as the security and privacy of the occupants.

6.3.4 Urban Heat Island Investigation

The UHI intensity and pattern of the case study areas were investigated as part of the microclimate study, with the data loggers' data compared with the data from Bangladesh meteorological department (BMD) for the same period. Although BMD is located within the city and not really a rural in a true sense, it is surrounded by large open spaces and greens; hence, it was assumed it would represent a less urban area for the purposes of UHI study (see Figure 6.36). It should be noted that BMD only provide 3-hourly data; therefore, the UHI analyses are based on 3-hourly temperature data. The data loggers’ data were converted from half-hourly to 3-hourly by considering the data at every three hours.

Figure 6.36: *Locations of Uttara, DOHS & BMD in Dhaka and the Meteorological Instruments inside BMD*

The daily average air temperature data from BMD, along with the loggers’ data at the 3 m level for all the orientations and locations, were plotted to find out the differences in daily average air temperature between different locations of the case study area and BMD during the study period from 1 September to 10 October 2013. Since BMD records data at 1.5 m from ground level, the data of the loggers at the 3 m level were deemed comparable with the BMD data. This aimed to obtain an indication of the extent to which the different locations of the case study areas were warmer or cooler than the nearby meteorological station (a less urban location) on a daily basis during the study period.

The figure shows that on average, all of the locations in the case study areas for most of the days during the study period were warmer than the meteorological station, particularly on clear days. The daily average air temperature difference between the warmest study location and BMD on one of the clear days (2 October 2013) was as high as 2°C (see Figure 6.37).

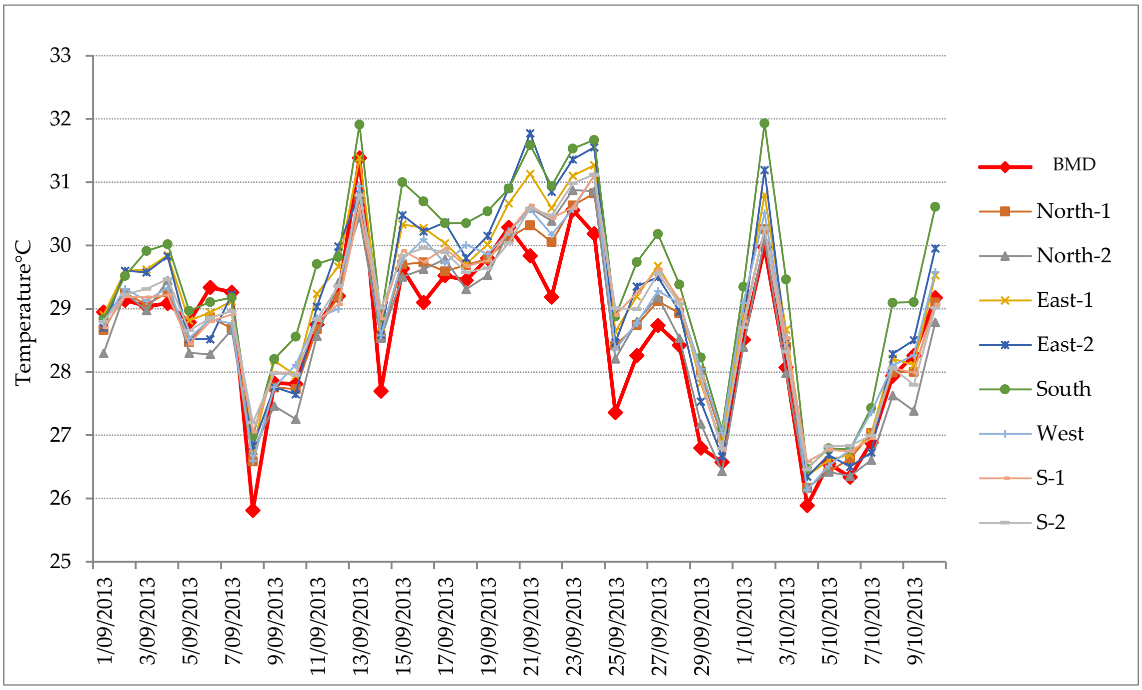

Figure 6.37: *Daily Average Air Temperature of the Meteorological Station and Loggers at 3 m*

The extent of UHI intensity according to different orientation and locations was further analysed. The average air temperature measured at BMD during the total study period was subtracted from the average temperature of all the loggers. The result shows that the highest average UHI intensity during the study period was at south (0.91°C), followed by east-1 (0.52°C), east-2 (0.51°C), setback-2 (0.34°C), setback-1 (0.32°C), west (0.3°C) and north-1 (0.19°C). North-2 did not show any difference (see Figure 6.38).

Since UHIs are more pronounced on a clear day with little wind, further analyses were conducted to find out the extent to which UHI intensity and pattern differs between cloudy and relatively clear days in the case study areas. As no day during the study period was completely clear, the days had to be divided into 'cloudy' and 'less-cloudy'. While on a clear day the cloud cover is equal to or below 2 okta, for this study, the clearer days referred to the days when the cloud cover was below 6 okta (Gordon, 2013). Cloudy days had cloud cover above 6 okta. In total, 22 days were identified as 'clearer' days and 18 days as cloudy days during the study period. The days were calm, as the average wind speed in Dhaka during September and October is

0.48 m/s, which falls under the calm category on the Beaufort scale (Bureau of Meteorology, Australian Government, 2016). Only one day had 1.25 m/s wind speed, which falls under the light breeze category.

The study found that the average UHI intensity during the clearer days was much higher for the south (1.16°C), followed by east-2 (0.75°C) and east-1 (0.62°C). North-2 had minimal UHI intensity during the clearer days (0.09°C) and none on the cloudy days. In contrast, north-1 (0.22°C), setback-1 (0.28°C) and setback-2 (0.41°C) had higher average UHI intensity during cloudy days, although the average UHI intensity gap between the clearer and cloudy days was much smaller (0.06–0.12°C) for the north and setback areas compared to the south- and east-facing locations (0.22–0.57°C). The west (0.3°C) showed no difference in UHI intensity between the cloudy and clearer days (see Figure 6.38).

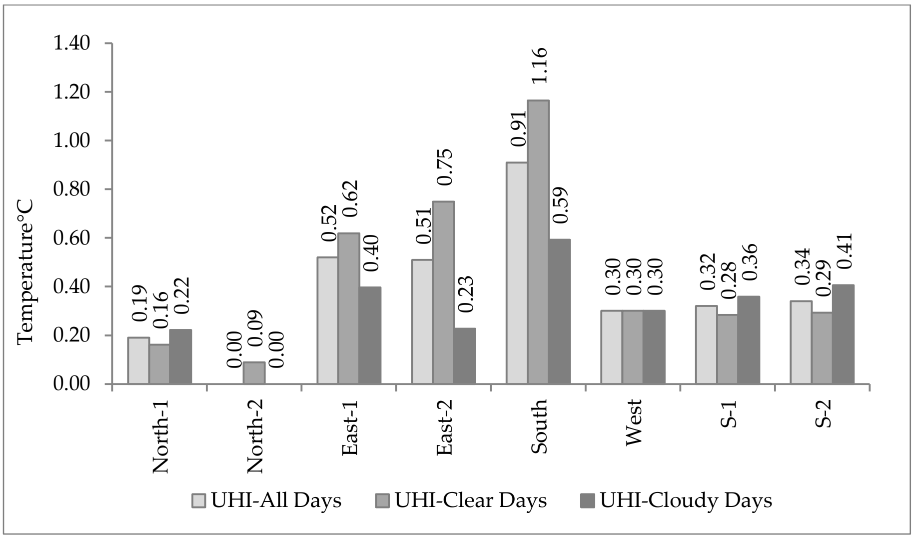

Figure 6.38: *Average UHI Intensity for Different Days and Locations During the Study Period*

Previous studies have also found that UHI intensity is more profound at night, usually occurring several hours after sunset (Erell et al., 2011; Oke, 1988). Therefore, further analyses were conducted to find out the differences in UHI intensity and pattern between the daytime and night-time in the case study areas. The data from 6:00am to 6:00pm was considered daytime and the data from 6:00pm to 6:00am was considered night-time. The average daytime and night-time temperature difference between the meteorological and data loggers' data were then calculated and compared. The daytime and night-time UHI intensity was found to vary noticeably, particularly at locations that were shaded during the daytime. All the locations had positive UHI at night, which was always higher than the daytime UHI for all the locations. The highest average night-time UHI intensity was found for the setback areas (1.02°C, 1.03°C) followed by the south (0.96°C), east-1 (0.77°C), east-2 (0.58°C), north-1 (0.52°C), west (0.48°C) and north-2 (0.4°C). However, along with the UHI, cool islands were present in the setback and north-oriented locations during the daytime, which varied from maximum 0.4°C to minimum 0.1°C (see Figure 6.39). The reason for cool islands can be attributed to the absence of direct solar radiation at the subjected locations.

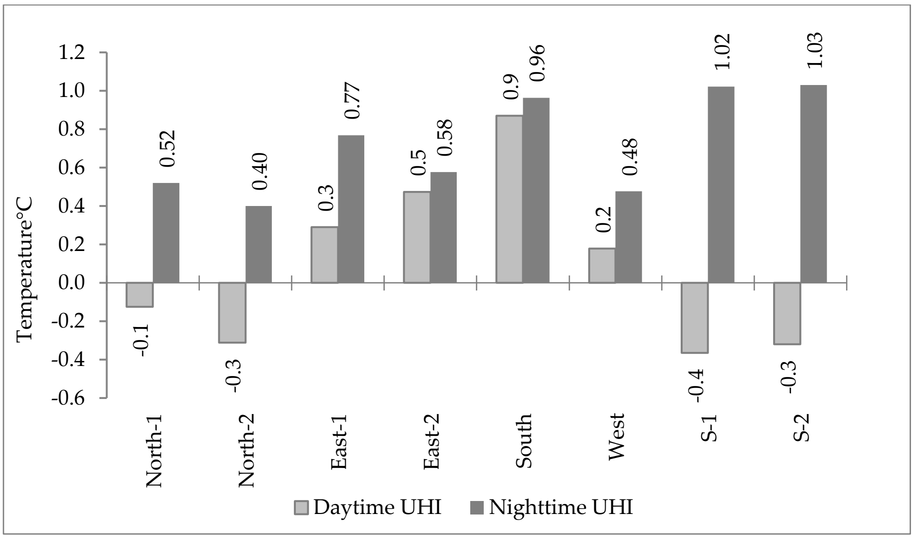

***Figure 6.39:** Average Daytime and Night-time UHI Intensity at Different Locations*

Further analyses were conducted to find out the difference in temperature and its pattern between the meteorological station and other locations at different hours of the day. Three-hourly temperature for 24 hours from all the locations and the meteorological station were plotted for 13 September 2013 and 2 October 2013, as these two days showed the maximum average temperature difference with the meteorological station data.

Figures 6.40 and 6.41 show that on both days, the peak temperature at the meteorological station occurred at 3:00pm. All of the shaded locations (excluding the side setback area on 2 October 2013), such as north-1, north-2 and the rear setback area, also showed a similar pattern to the meteorological station, reaching their peak at 3:00pm. However, east-2 reached its peak at 12:00pm and the south and west reached the peak between 12:00pm and 3:00pm. Again, on both days, the lowest temperature at the meteorological station was at 6:00am, while for all other locations, the lowest temperature was at 6:00am on 13 September 2013 and at 12:00am on 3 October 2013. As the day preceding 13 September 2013 and the day following 2 October 2013 were both rainy, it can be said that on a regular clear day, the lowest temperature in a 24 hour cycle was reached at around 6:00am, which was further confirmed by the plots of two other clearer days (see the Appendix D.2).

The results also showed that while during the daytime (9:00am–6:00pm), all of the shaded locations were cooler on the studied days than those at the meteorological station, the locations that received direct solar radiation were warmer at some point during the day (excluding east-1). The south was nearly never cooler than the meteorological station, east-2 was warmer in the morning until around noon and the west was warmer mainly from midday. The shaded locations that were cooler than the meteorological station in the daytime started to get warmer after sunset, at around 8:00pm on 13 September 2013 and at 6:00pm on 2 October 2013. It is important to note that the UHI analyses were based on three-hourly temperature data; therefore, the interpretation of the data is a close approximation of three-hour intervals.

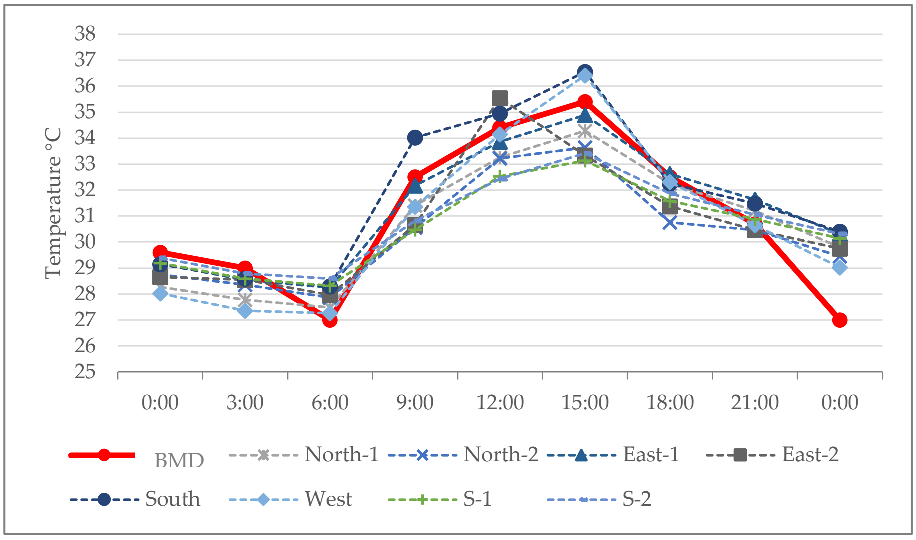

Figure 6.40: *Three-hourly Temperature Plot for 24 Hours: 13 Sept. 2013*

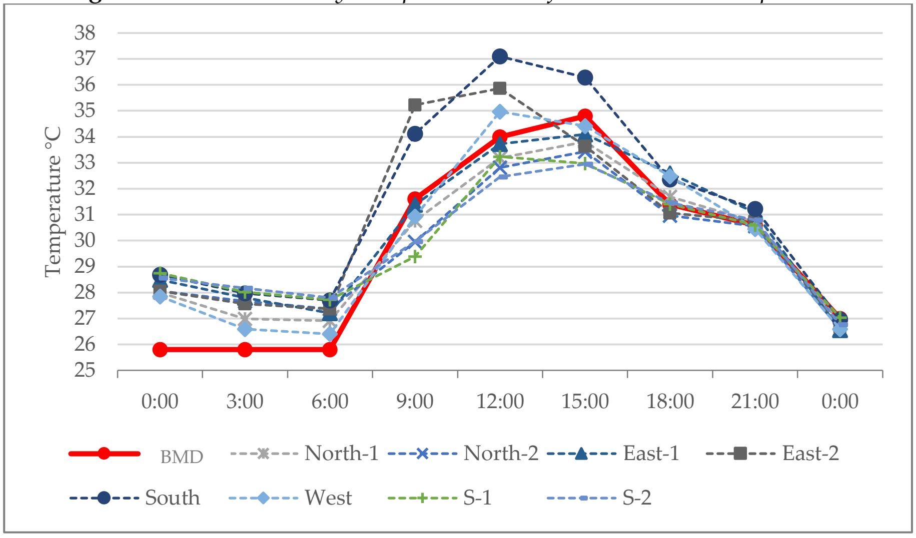

Figure 6.41: *Three-hourly Temperature Plot for 24 Hours: 2 Oct. 2013*

The temperature differences between the meteorological station and other locations at different hours of the days 24 September 2013 and 2 October 2013 were examined to find out the extent of UHI intensity at different hours of the days (see Figures 6.42–6.43). 24 September was the last day of the longest run of clearer days (15–24 September 2013) and the maximum UHI intensity for all the locations was found at 12:00am, 25 September (at the end of 24 September), whereas, the maximum daily average UHI intensity was on 2 October.

Figure 6.42 shows that on 24 September, all of the locations were warmer than BMD from midnight until around 9:00am (only the west was cooler for a short period at around 6:00am) and again after 3:00pm onwards. The shaded locations were cooler from 9:00am–3:00pm (north-1, north-2 and setback areas); however, all other locations were warmer during that time as well. The maximum UHI intensity that was reached at 12:00am of the following day varied between 3.54°C and 4.32°C. The maximum cool island intensity, when the locations were cooler than BMD, was reached at 12:00 noon, with an intensity of between 0.47°C and 1.26°C.

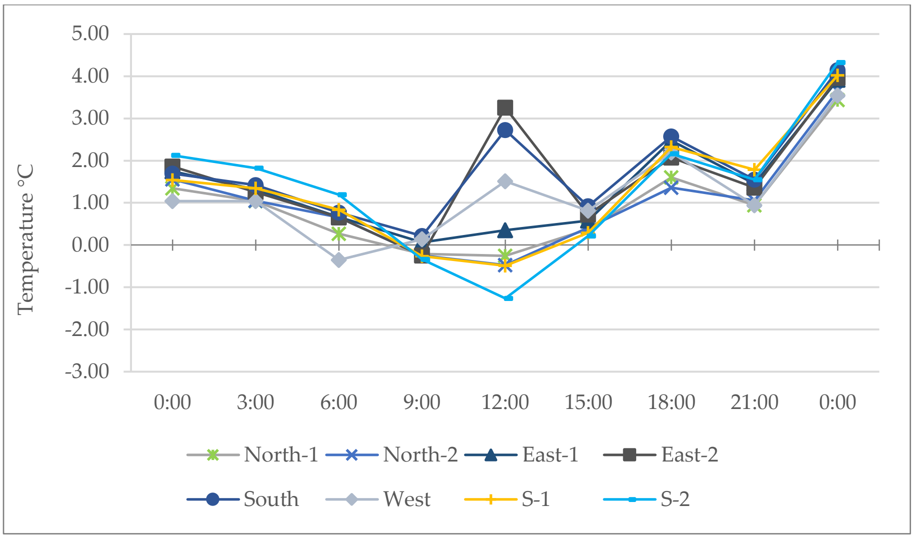

Figure 6.42: *UHI Intensity at all Locations on 24 Sept. 2013*

On 2 October, all of the locations were warmer from 12:00am until around 8:00am. After that, the shaded locations were cooler than BMD until around 6:00pm. However, other locations were warmer than BMD at different times during that period and south was never cooler. After 6:00pm, the intensity started to decrease for all locations, which remained nearly steady from 9:00pm to 12:00am of the following day. As mentioned in the previous section, the following day was rainy and cloudy but it can be assumed that the locations would have been warmer than the meteorological station after 6:00pm as well if there had been no rain and cloud (see Figure 6.43).

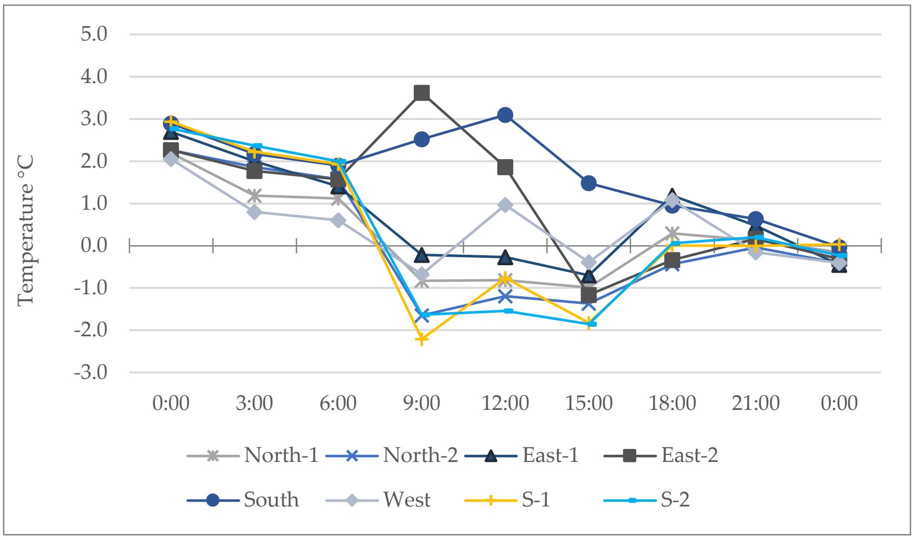

Figure 6.43: *UHI Intensity of all Locations on 2 Oct. 2013*

Figure 6.44 shows the maximum UHI intensity for different locations during the study period, at 12:00am midnight on 25 September 2013 after the longest run of clearer days during the study period. The maximum UHI intensity was found at the rear setback area (4.32°C), followed by the south (4.15°C), side setback area (4.02°C), east-2 (3.96°C), east-1 (3.92°C), north-2 (3.65°C), west (3.54°C) and north-1 (3.4°C). The occurrence of the maximum intensity occurred six hours after sunset, which reflects the densely built characteristics of the case study areas.

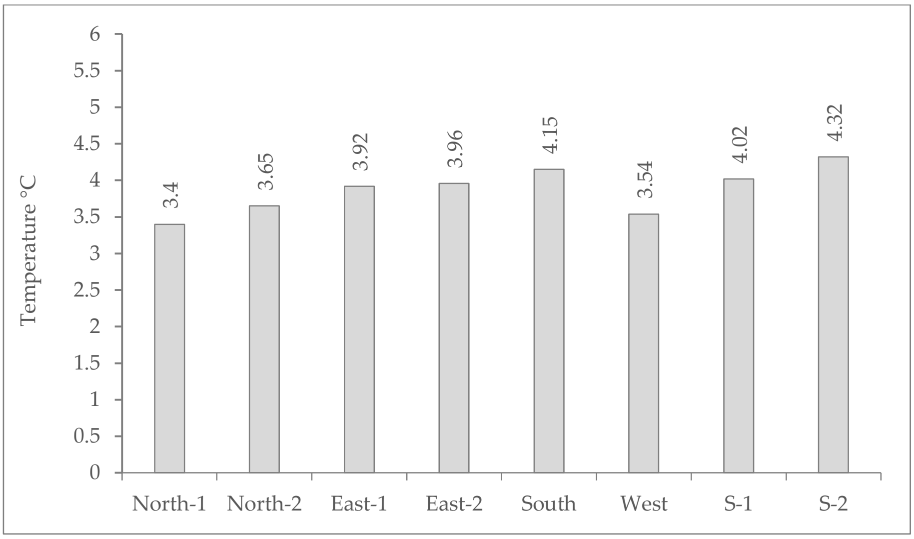

Figure 6.44: *Maximum UHI Intensity During the Study Period for Different Locations*

The findings of the UHI study indicated that while the shaded locations in the case study areas were cooler than BMD during the daytime on a clear day, the south location never got cooler than the meteorological station at either daytime or night-time. The east orientation was mostly warmer from the early morning to midday and the west was mostly warmer after midday. These results affirmed the role of direct solar radiation on UHI formation and intensity, as well as the formation of cool islands at certain times for the shaded locations during the daytime. In addition, the study highlights the extent of heat trap at night-time, which is probably due to the lack of airflow at the urban scale as well as lack of heat release through long-wave radiation in deep canyons. This effect was more intense after a continuous spell of hot days, which shows that not only the formation and duration of a cool island was reduced after a long period of hot days but also the UHI intensity increased significantly.

It is clear from the UHI investigations that the case study areas in general are significantly warmer than the surrounding less urban areas, which can be attributed to the existing urban and building design practices such as the orientation, setback distances, building heights, materials used and possibly anthropogenic heat. It should also be noted that during the study period (September to October 2013), the weather was mostly cloudy, which could have masked the actual intensity. The UHI intensity of the case study areas may be much higher during the hot-dry season from March to May, when the sky is clear, especially at the south- and east-oriented locations.

From an energy-consumption point of view, the results suggest that the presence and intensity of UHI in the case study areas, especially at night, may lead to higher consumption of cooling energy. This also indicates that the use of cooling energy could be reduced through mitigating UHI intensity.

6.4 SUMMARY FINDINGS AND DISCUSSION

6.4.1 Summary Findings: Temperature Variation vs Different Orientations and Locations

The orientation of the front façade of the buildings in the study area had the most dominant impact on the average outdoor temperature within the given urban setting and the degree of impact was dependent on the relevant CR. The south orientation overall was significantly warmer than any other orientation when the effective CR was 0.75 and above. However, with lower effective CR (below 0.25), the average air temperature difference among different orientations was insignificant, particularly among the orientations that received direct solar radiation during the daytime, such as the east, south and west. In addition, the deep canyons such as the setback areas were cooler in the daytime and warmer at night than any other orientations, indicating the effect of shading in the daytime and of the small SVF due to the closeness of the buildings. From the energy-consumption point of view, these results indicate that the lower floors of a south-oriented building in typical residential developments in Dhaka city are likely to experience higher indoor temperatures compared to other orientations and therefore, are likely to require more cooling energy. At the upper floor level, a south-oriented apartment is likely to be more comfortable than any other non-south apartment if the advantage of the prevailing wind can be utilised and thus, should have comparatively less demand for cooling energy.

The north orientation was the coolest among all the orientations. Therefore, a building facing towards the north is likely to require the least cooling energy than any other orientations, provided all other energy-influencing parameters are the same. The maximum average temperature difference between the warmest (south) and the coolest (north) orientation during the study period was 2.4°C at the 3 m level. The maximum night-time temperature difference between the warmest (side setback) and the coolest (north-2) location was 0.6°C. Considering that every 1°C temperature increase can increase energy consumption by 5% and a 0.6°C temperature increase can increase the peak energy demand by 1.5–2% (Wong et. al, 2011; Akbari et al., 2008), the temperature differences found in this study are significant. It is important to remember that the study was conducted during the monsoon months, which are mostly cloudy; the temperature differences are likely to be higher during the hot-dry season with clear skies (March to May), meaning there will probably be even higher requirements for cooling energy.

6.4.2 Summary Findings: Temperature Variation vs Different Height

The average outdoor air temperature varied according to different heights; however, the variation across the different heights was small and insignificant compared with the variation due to different orientations. Excluding the south, all other orientations had either increased or the same air temperature at higher levels compared to the lower level. Only the south had decreased temperatures at higher floor levels, probably because of the influence of advection in removing heat from the upper floors of a south-oriented building, due to the lower effective CR and exposure to the prevailing wind. Based on the findings, from an energy-consumption point of view, it can be said that except for the south, the lower floors are cooler and thus are likely to have a lower requirement for cooling energy compared to the upper floors for any orientation in typical residential developments in Dhaka city. For a south-oriented building, the higher floors are likely to have lower average air temperature and thus lower cooling energy consumption than the lower floors with in the given urban contexts.

6.4.3 Summary Findings: Outdoor vs Indoor Temperature

The average indoor temperature during the study period was higher than the average adjacent outdoor temperature, which varied from 0.7–2.4°C. Irrespective of the orientation of an apartment, the indoor temperature did not fluctuate, which suggests a large time lag due to the heavy thermal mass of the buildings; however, it also indicates the lack of natural ventilation or lack of heat release of the case study apartments at night. In the daytime, the outdoors was usually 0.2–1.3°C warmer than the indoors, excluding the cases where the apartment owners either opened the windows more frequently in the daytime or kept all the doors and windows closed throughout the day. This result indicates the effect of closing doors and windows, increasing indoor temperatures, as well as the negative effect of opening the windows during the daytime. At night, the outdoor temperature on average was lower for all instances, varying from 1.9°C to 3.8°C. This result clearly depicts the extent of heat trap at night inside the apartments of the case study areas.

A distinct outdoor temperature pattern existed for different orientations. For example, the peak temperature was reached at the east orientation in the morning before noon; the maximum outdoor temperature was around midday at the south orientation; and the peak temperature was reached in the afternoon at the west orientation. These results suggest that allowing outside air into the indoors at any time during the daytime would increase the indoor temperature, in particular opening an east-oriented window in the morning, a south-oriented window at midday or a west-oriented window in the afternoon. The results also suggest that keeping the windows open or allowing ventilation from 11:00pm to until 7:00am for any orientation would lead to decreasing indoor temperatures. From the energy-consumption point of view, it can be assumed that the apartments in typical residential developments in Dhaka with any orientation are unnecessarily warm and are consuming more cooling energy than necessary, which could be reduced without much effort if enough ventilation or heat release could be ensured at night.

6.4.4 Summary Findings: UHI Investigation

The study results confirmed the existence of a clear UHI in the case study areas, the intensity of which varied according to different orientations and locations.

Except for north-1, the maximum UHI intensity during the study period was found to be nearly 4°C for all the locations, occurring at midnight. In addition, the study found that the setback areas were much warmer at night than other locations, indicating a possible heat trap due to a deep and narrow canyon. The UHI intensity on clearer days was higher than on cloudy days. In addition, cool islands existed during the daytime for shaded areas, such as the north and setback areas; however, at night, all of the locations in the case study areas were warmer, with an intensity that was much higher than the daytime UHI. The non-shaded orientations such as the south, east and west were always warmer than the nearby less urban area.

These results are similar to other UHI studies, which have also shown that densely built areas that are shaded during the daytime are cooler than surrounding rural or less urban areas. Since the study was conducted during the monsoon months, it can be claimed, based on these findings, that the UHI intensity of the case study areas during the hot-dry season (March–May) may be higher. It can also be said that the presence and the intensity of UHIs in the case study area had a considerable effect on the overall thermal comfort situation and thus on the area's demand for cooling energy, especially at night.

6.4.5 Discussion

This study has identified the effect of the existing urban and building development practices on the ambient air temperatures surrounding a building in typical residential developments in Dhaka. In view of the findings of the urban and building contexts study, the findings of the microclimate study can be considered interesting and contradictory.

As discussed in Section 5.2.3, south-oriented plots are preferred in Dhaka, as they are generally considered the best in terms of thermal comfort in the climatic contexts of Dhaka. This may be true in an open and/or rural setting, where the south sun can be blocked effectively with shading devices and the prevailing wind can be utilised during the summer months. However, given the built-environmental characteristics of the typical residential developments and the current trend of building design practices in Dhaka, this may not be the case in the residential areas. This microclimate study found the opposite scenario: the south orientation in typical developments is much warmer than any other orientation and the advantage of the prevailing wind flow cannot be utilised (excluding the upper floor with lower CR), due to the higher CR.

Moreover, as found in the building contexts study (see Section 5.3.9), the front facades of Dhaka buildings are not shaded properly, irrespective of their orientation. Based on the findings, it can be claimed that the existing urban and building design practices in Dhaka city are counterproductive in terms of thermal comfort and energy consumption. As a result of the existing urban and building design practices, the built environment of typical residential developments in Dhaka city are hotter than necessary, which could be avoided if informed design choices could be made. On a more positive note, it can be said that the existing residential developments in Dhaka could be made more energy efficient through appropriate urban and building design choices and practices, which should be started at the larger urban scale with the mitigation of UHI intensity and eventually incorporate all other micro-urban and building scale factors.

It is important to note that this study observed the positive effect of wind flow at the upper floors of south-oriented buildings, suggesting that urban development incorporating airflow could potentially increase thermal comfort as well as reduce the UHI effect. Hence, this study strongly recommends further research incorporating wind flow and other climatic parameters such as RH and solar radiation.

Table 6.2: *Summary Chart with Key Findings: Microclimatic Contexts*

#	Investigated Areas	Key Findings: Consequences on microclimate (air temperature)	Probable Impact on energy Consumption & Suggestions
1	Effect of orientation	In general, south orientation is the warmest of all, given the	A building with a south orientation will have higher

#	Investigated Areas	Key Findings: Consequences on microclimate (air temperature)	Probable Impact on energy Consumption & Suggestions
		current development practices, particularly at lower levels.	cooling energy demand. Hence, the front façade of a south-oriented building needs special consideration with all possible shading options to reduce the requirement for cooling energy.
		West orientation is warmer in the daytime at the upper floor level.	The upper floors of a west-oriented building need to be treated differently from the lower levels, with additional shading or less glazing, to reduce energy consumption.
		North is the coolest orientation of all within the existing development practices.	Preference may be given for having more north-oriented facades with natural ventilation options.
2	Effect of height	Upper floors are warmer than others for the same orientation, due to lower CR.	Upper floors of the same building will have warmer indoors (except south); therefore, different shading techniques compared to the lower levels should be employed to reduce cooling energy demand.
3	Indoor–outdoor relationship	On average, the indoors is much warmer than the outdoors, due to trapped heat at night. In the daytime, the outdoors is usually warmer than indoors and at night, the outdoors is much cooler than the indoors.	Ventilation during the daytime should be avoided. Natural ventilation at night needs to be ensured, along with different heat-release strategies. Traditional practice of placing ventilators at ceiling height should be revived in a way that is appropriate to the current urban setting, to reduce cooling energy consumption.
		On the east façade, the outdoors is warmest in the morning before noon; the south is the warmest at midday; and the west is warmest in the afternoon.	East-oriented windows should not be opened in the morning; south-oriented windows should not be opened at midday; and west-oriented windows should not be opened in the afternoon.
4	Top floor vs intermediate floors	Top floors are warmer than intermediate floors, due to more exposure to solar radiation.	Roofs should be insulated, shaded or vegetated to reduce cooling energy consumption on the top floors.

#	Investigated Areas	Key Findings: Consequences on microclimate (air temperature)	Probable Impact on energy Consumption & Suggestions
5	Setback areas – deep canyons	Setback areas are cooler during the day but warmer at night than other locations.	Setback areas should be in line with the prevailing wind direction to remove the trapped heat as well as pollution from the deep canyon. Careful consideration is needed regarding which rooms to place next to setback areas.
6	UHI	Clearly present, most profound at night. Maximum intensity on clearer days 6 hours after sunset during the study period.	Urban design approaches to mitigate the intensity of UHI are needed, e.g., through proper layout, vegetation, cool materials, etc. The current trend of developing more smaller plots should be examined immediately, to reduce UHI intensity as well as energy consumption from future developments.

6.5 CONCLUSION

This chapter has presented the findings of the microclimate study, which was conducted to investigate the existing microclimatic contexts surrounding buildings in typical residential developments in Dhaka city. It has also described the effects of the prevailing development practices on the ambient air temperature and the possible consequences of those for energy consumption. Although it is certain from the results that the current development practices affect the microclimate of the area and may have been contributing to higher cooling consumption, the degree of the influence cannot be determined simply from this study.

The extent of different urban and building design choices on energy consumption has been investigated through simulation studies, the results of which will be presented in Chapter 8. However, before this is discussed, the next chapter discusses the impact of different household-level parameters that affect the energy consumption of the households.

7 HOUSEHOLD CONTEXTS

7.1 INTRODUCTION

This chapter presents the results of the analyses conducted to investigate the parameters that affect energy consumption at the household level in typical residential developments in Dhaka. The primary goals of this part of the study were three fold: i) to find out the existing contexts of the relevant parameters; ii) to find out the energy consumption patterns and intensity of the subject households; and iii) to find out the relationship between the household parameters and total energy consumption, as well as the most dominant parameters affecting the total energy consumption. In addition, the study aimed to identify existing practices that require attention to reduce the household energy consumption in typical residential developments in Dhaka.

7.2 METHODS

As outlined in Section 4.4.3, the household contexts study was conducted in two major phases: data collection and data analysis. Data for the study were collected through a questionnaire survey from 392 respondents living in Uttara and DOHS Baridhara. Multiple statistical methods, such as descriptive, frequency analysis, correlation and multiple regression, were used to analyse the data. However, it is worthwhile to note that missing answer is a common phenomenon in any questionnaire survey (Pallant, 2011) and this study was no exception to that. Therefore, the total response number for different questions was frequently less than 392. The associated response number for a particular parameter for a specific analysis has been provided (denoted as N) with the results.

7.3 RESULTS

7.4 EXISTING CONTEXTS

The existing contexts of the different household parameters were investigated separately for the indirect and direct parameters (see Section 4.4.3.1.1). The indirect parameters were grouped into household characteristics, building design and operational practices of the doors and windows; the direct parameters were grouped into thermal-comfort-achieving appliances, artificial lights and other domestic appliances.

Descriptive statistics were used to investigate the existing contexts of the parameters. The distributions of scores for each of the parameters were checked to ensure they were normal (a symmetrical bell-shaped curve); however, many of the parameters had non-normal distribution. Non-normal distribution of the scores is common in social studies but with a large number of samples (200+), violation of normal distribution does not affect the outcomes of statistical analyses severely (Pallant, 2011; Tabachnick & Fidell, 2008). Since the sample size was large enough, the results acquired through this study were deemed adequate to represent the subject households in the case study areas.

7.4.1 Indirect Parameters: Household Characteristics

The study found that on average, there were 4.84 occupants per household, with a minimum of 1 person to a maximum of 13 persons (N=390, SD=1.6). However, it is worthwhile to note that household size and number of family members are not synonymous in Dhaka’s contexts, as many of households have home-stay full-time maids. The study found that 52.1% (187 out of 390) of the studied households had full-time maids at home. Of these, 37.4% (146) had one maid, 12.6% (49) had two maids, 1.5% (6) had three maids and two had four maids living in the house. Further analyses excluding the maids found that the average number of occupants or family members per household was 4.15.

The population distribution of the households showed that 13% (66 out of 387) had 1–2 children aged 0–5 years, 55.3% (214) had 1–3 school-going (6–18 years) children and 8% (30) of the households had 1–2 senior citizens (65+ years) living at home. On average, there were 3.33 adults (18–65 years) per household. The proportion of male and female occupants was 51:49; that is, 51% of the occupants in the studied apartments were male and 49% of the occupants were female.

The average occupancy pattern of the studied households on both working days and holidays was investigated (see Figures 7.1 and 7.2). The figures show that there was always at least one person at home, whether it was a working day or a holiday. On working days, nearly all of the occupants seemed to be at home at night from 10:00pm–9:00am. On holidays, the majority of the occupants (about 90%) seemed to stay at home throughout the day. Considering the socio-economic contexts of the case study areas, it is common to have at least one full-time maid at home and many women stay at home instead of working away from the home.

From the energy-consumption point of view, these occupancy patterns suggested that the difference between the daytime and night-time energy consumption of the households could be small, as most of the households were never completely vacant throughout the day. Peak energy demand data of one of the case study areas (DOHS) also supports this idea, as the highest daytime peak demand in summer in 2013 was 4 MW and the highest night-time peak demand was 4.67 MW (the difference can be attributed to night-time lighting and cooling).

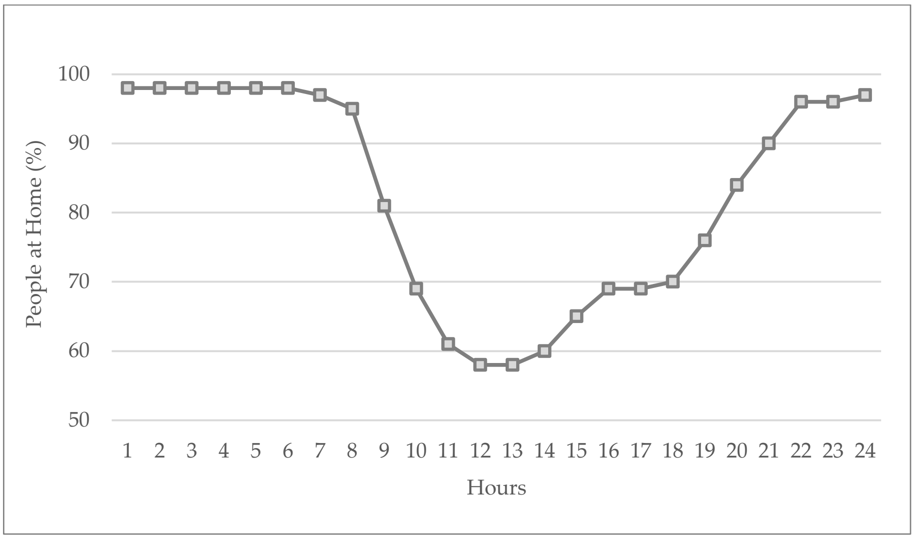

Figure 7.1: *Average Percentage of People at Home on Working Days*

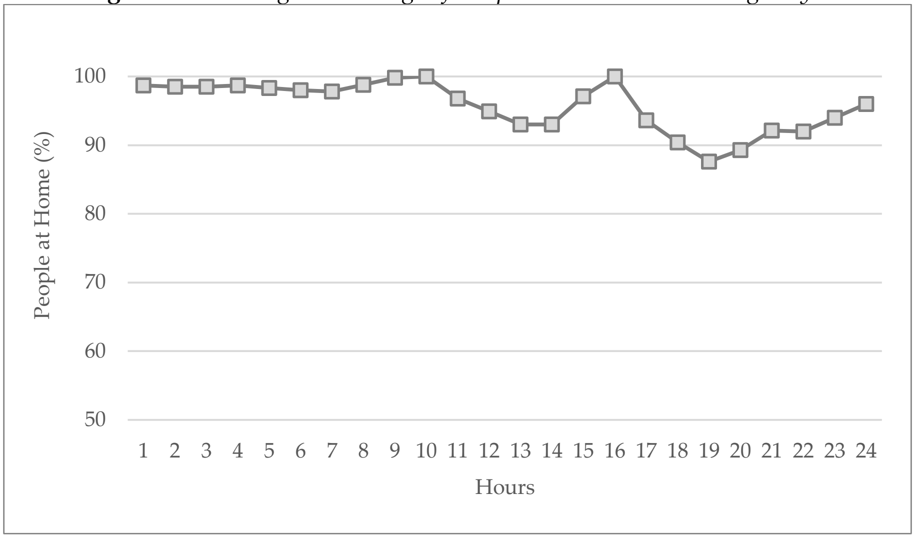

Figure 7.2: *Average Percentage of People at Home on Weekends or Holidays*

7.4.2 Indirect Parameters: Building Design

The average apartment size of the studied households was 1,734 ft^2 (161 m^2), with a minimum of 1,000 ft2 (92.9 m^2) and a maximum of 2,800 ft2 (260 m^2) (N=390, SD=544/50.5). The majority of the households (66.7%, 260 out of 390) were living in double-unit apartments; 33.3% of the households lived in single-unit apartments (see Section 5.3.3). The average apartment size of the single-unit apartments was 2,535 ft^2 (225.5 m^2) and the double-unit apartments were 1,387 ft^2 (128.9 m^2). The average unit area per person was 405 ft^2 (37.64 m^2) for all households, 546 ft^2 (50.8 m^2) for the single-unit apartments and 334.5 ft^2 (31.1 m^2) for the double-unit apartments (see Figure 7.3).

The average number of floors was 5.37 (N=391, SD=1.12), with dwelling-unit density 8.19/building (N=386, SD=2.34), which is consistent with what was found in the building contexts study as presented in Section 5.3.4.

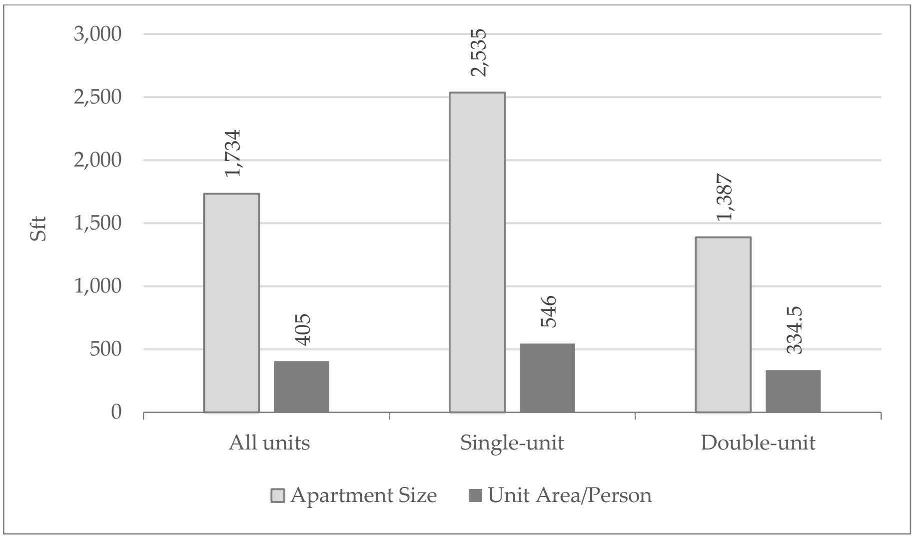

Figure 7.3: *Average Apartment Size and Unit Area/Person of the Studied Households*

Most apartments had either floor tiles or a polished concrete floor commonly called 'mosaic'. The majority of the households had floor tiles (73%, 181 out of 248) as opposed to mosaic (23%). Carpet is not common in Dhaka's residential buildings; only 18.1% (71 out of 392) of the apartments had carpet, usually only in the formal living room.

External wall construction of the households was with either 5″ (125 mm) or 10″ (250 mm) thick solid bricks plastered and painted on both sides. Only 12.3 % (48 out of 390) had an interior wall finish that was different.

The most common type of roof construction was a 6″ (150 mm) RCC slab with water proofing and a thin layer of concrete on top (sometimes with an additional layer of brick chips). Only 2.4% (8 out of 324) of the participants reported that the roof of their apartment building had an additional layer of concrete hollow blocks on top of the regular RCC roof slab. Many of the households (63.1%, 246 out of 390) had indoor plants, while 25.5% (97 out of 379) had a considerable amount of roof garden, covering more than half of the roof.

The study found that there were only two types of windows in the case study areas: sliding windows (aluminium frame) and shutter windows (wooden or aluminium frame) (see Figure 7.4). The majority (94.6%, 371 out of 392) of the bedroom windows were aluminium sliding windows; only 5.4 % (21) of the bedroom windows were shutter windows. In 258 of the responses, 70.9% of the common space had sliding windows, 11.3% had shutter widows and 17.8% had no windows in the common spaces (see Figures 7.5). These results were consistent with the building contexts study, which also found that the predominant types of window in typical residential developments were sliding windows with aluminium frame (see Section 5.3.9). In addition, nearly half of the studied households had mosquito nets on the windows (48.9%, 152 out of 311).

Figure 7.4: *Examples of Aluminium Sliding and Shutter-type Windows. Source: Field Study (1), Google Earth (2)*

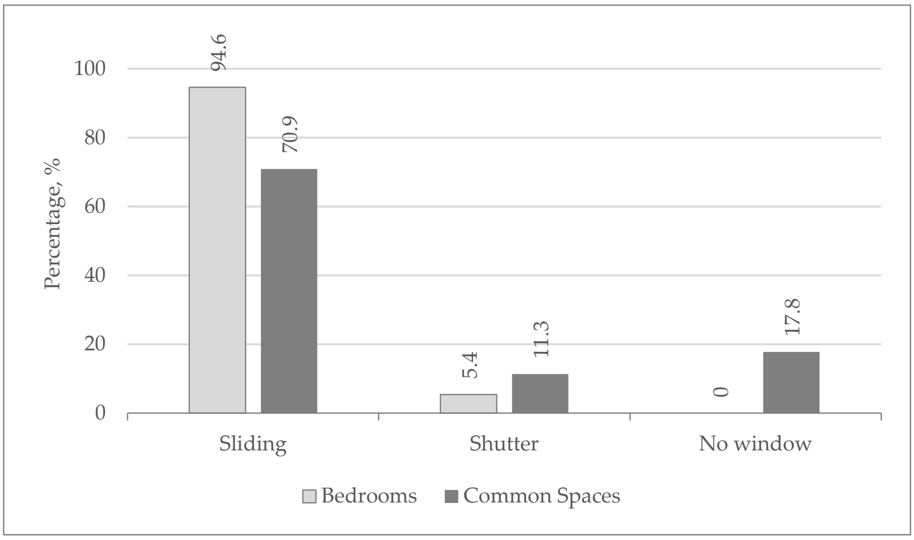

Figure 7.5: *Types of Windows in Different Spaces of the Studied Households*

A frequency analysis also showed that on average, 38.5% (151 out of 392) of the households had glass doors; 21.8% (33) had one glass door, 41.7% (63) had two glass doors, 26.5 % (40) had three glass doors, 3.3% (5) had four glass doors and 2.6% (4) households had five or six glass doors. These results were consistent with the building contexts study, which also found that 39% of the studied apartments had glass balcony doors (see Section 5.3.9).

7.4.3 Indirect Parameters: Doors and Windows Operation

Analyses were conducted to find out the window-opening frequency in the bedrooms and in the common spaces of the studied households. The study found that 29.3% (115 out of 392) of the households opened the bedroom windows quite frequently, 54.9% (215) opened the windows sometimes and 15.7% (62) never opened the bedroom windows. For the common-space windows, 57.4% (140 out of 245) were opened quite frequently, 29.5% (72) were opened sometimes and 13.2 % (33) were never opened. These results suggested that the common-space windows were more frequently opened than the bedroom windows, as 70% of the households did not open the bedroom windows frequently (see Figure 7.6).

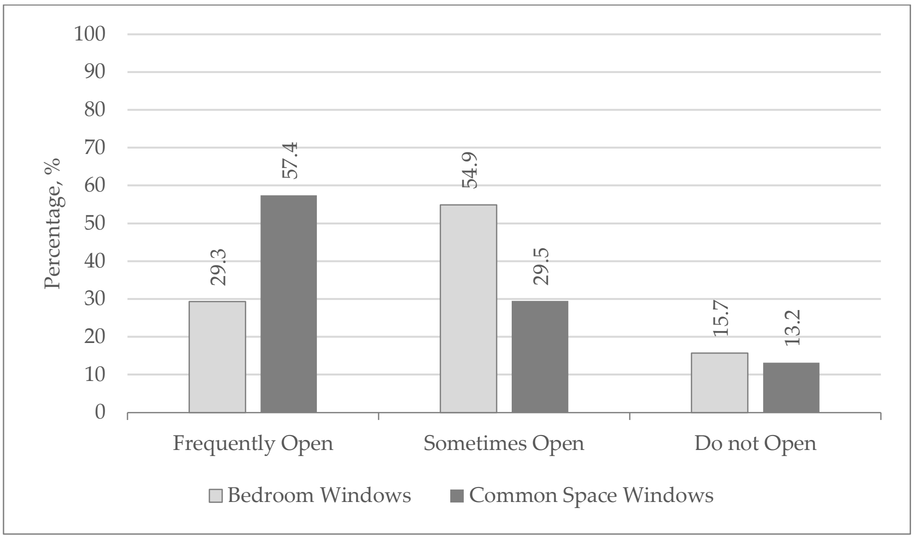

Figure 7.6: *Frequency of Bedrooms and Common-space Window Opening*

Further investigations were made to find out the possible reasons for not opening the windows more often. The study found that 25.1% (98 out of 390) of the households did not open the windows due to dust, 26.3% (103) due to privacy, 16.3% (64) due to noise, 9.2% (36) due to security and 43.9% (172) due to running AC at the same time (see Figure 7.7). The results showed that the majority of the households did not open the windows when using AC.

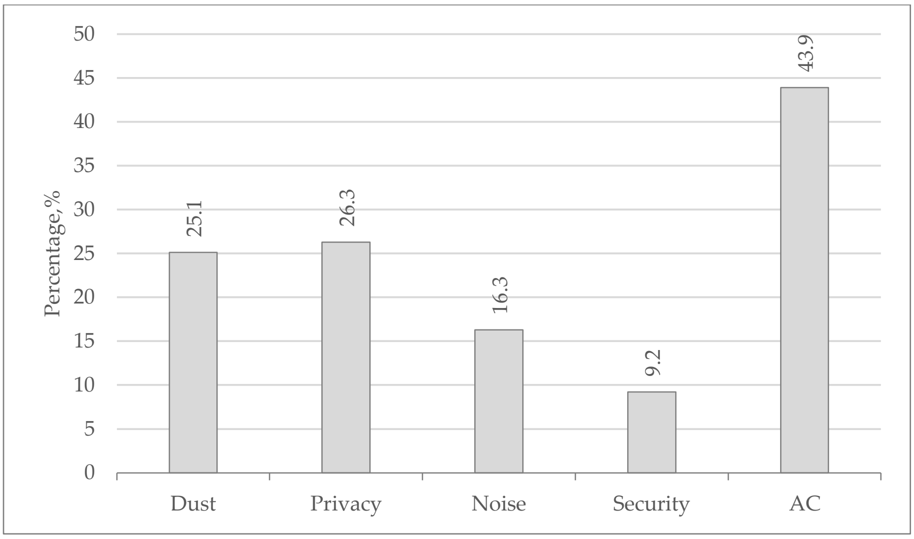

Figure 7.7: *Reasons for not Opening the Windows more Frequently*

Further investigation of the frequency of opening balcony doors found that 40.3% (151 out of 374) of the studied households opened the balcony doors frequently, 37% (159) opened them some times and the remaining 17.1% (64) did not open the balcony doors at all.

Opaque curtain fabric is a common feature in the households of Dhaka; however, curtains can potentially hinder wind flow. Further investigations regarding the operation of curtains found that 29.3% (98 out of 335) of the households opened the bedroom curtains quite frequently, 59.1% (198) opened the curtains sometimes and, 11.6 % (39) never opened the bedroom curtains. Curtains in the common spaces were opened frequently in 53.5 % (144 out of 269) of the cases, 36.8% (99) sometimes and in 9.7 % (26) of the cases, the curtains were never opened (see Figure 7.8). These results suggested that as with windows, the curtains in the common space were opened more frequently than those in the bedrooms were.

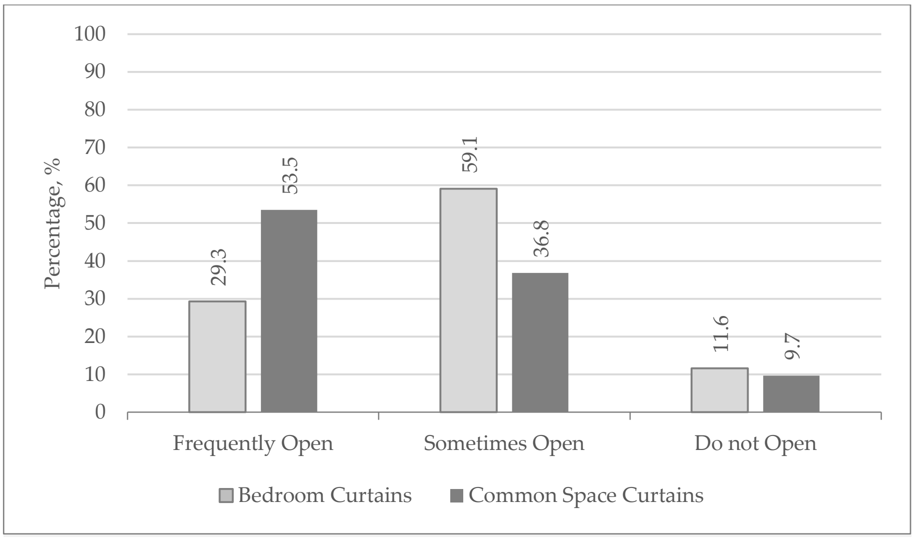

Figure 7.8: *Frequency of Opening Curtains in Bedrooms and Common Spaces*

7.4.4 Direct Parameters: Cooling and Heating Appliances

In most places, cooling and heating appliances such as ceiling fan, AC and heaters account for a significant portion of the total household energy consumption. In Dhaka, cooling appliances are more dominant and usually, heating is not needed. The following presents the existing contexts of cooling and heating appliances in the studied households.

7.4.4.1 Ceiling Fan

A ceiling fan is the most common appliance used to achieve a cooling effect in Dhaka. Every household had ceiling fans. This study found that on average, there were 6.43 fans per household, with a minimum of 4 and a maximum of 16 (N=369, SD=2.49). On average in all the bedrooms, there were 3.54 fans with a minimum of 2 and a maximum of 9 (N=386, SD=1.07); in the common spaces, there were on average 2.26 fans, with a minimum of 1 and a maximum of 6 (N=372, SD=1.3) (see Figure 7.9). A frequency analysis showed that 13.8% (51 out of 369) of the households had 4 fans, 35.5% (131) had 5, 20.9% (77) had 6, 8.4% (31) had 7, 4.9% (18) had 8, 2.2% (8) had 9, 4.6% (17) had 10, 2.4% (9) had 11, 3.5% (13) had 12, 2.2% (8) had 13 and 1.5% (6) had more than 13. These results showed that the majority of the households (70.9%, 259 out of 369) had 4–6 fans (see Figure 7.10).

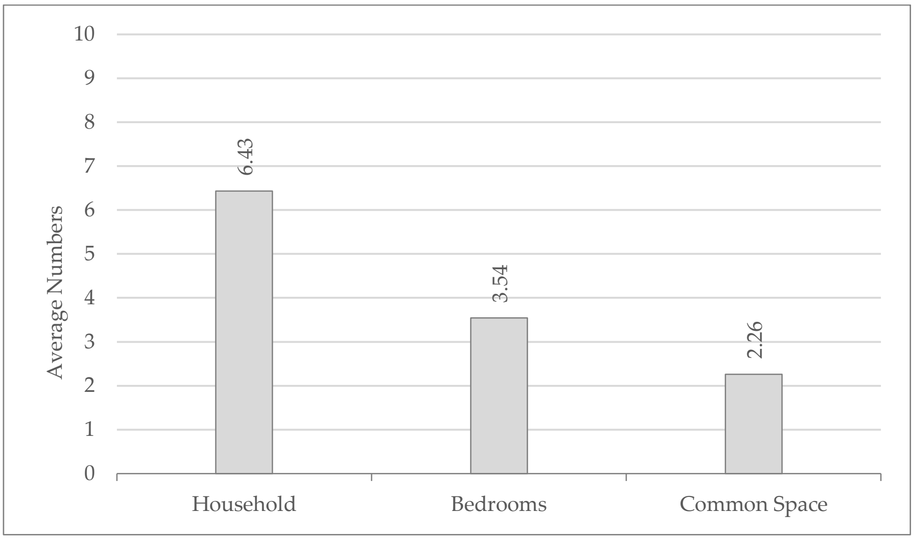

Figure 7.9: *Average Number of Fans in the Studied Households*

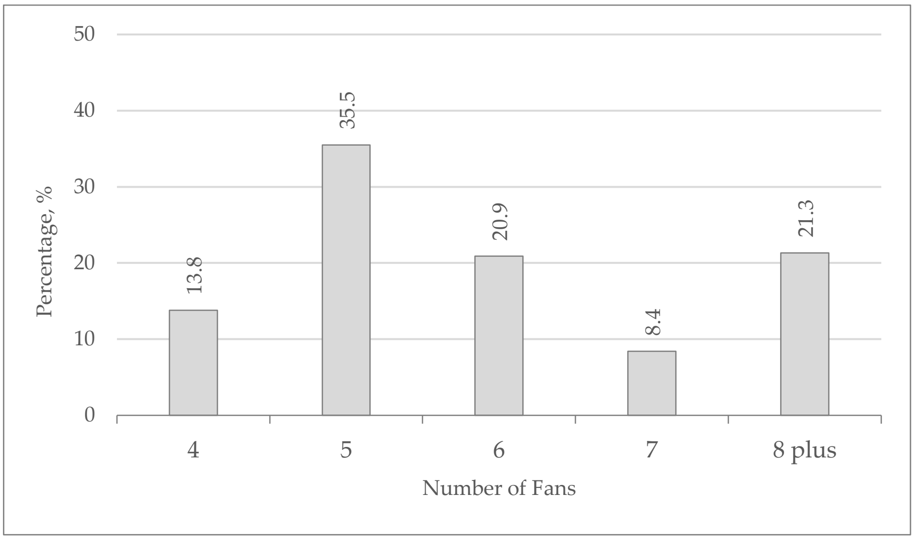

Figure 7.10: *Frequency of Total Number of Fans per Household*

Further analysis found that in the bedrooms, 9.3% (36 out of 386) of the households had 2 fans, 51.3% (198) had 3, 23.8% (92) had 4, 9.8% (38) had 5, 4.4% (17) had 6 and 5 households had more than 6. That is, the majority of households had 3–4 fans in the bedrooms (75.1%, 290). In most cases, each bedroom had one fan and sometimes another fan in the attached dressing room. Bedrooms had double fans in very few cases. The result suggested that the total number of fans in the bedrooms of a household depended on the total number of bedrooms in the household.

In the common spaces, 31.7% (118 out of 372) of the households had 1 fan, 38.4% (143) had 2, 14.5% (54) had 3, 6.5% (24) had 4, 5.1% (19) had 5 and 3.8% (14) had 6. That is, the majority of the studied households had 1–2 fans in the common spaces (70.1%, 261) (see Figure 7.11).

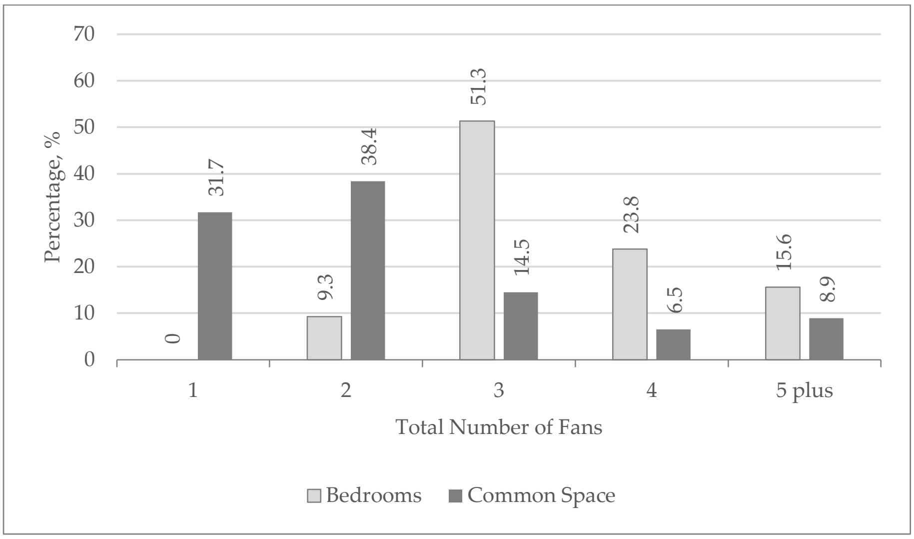

Figure 7.11: *Frequency of Total Number of Fans in the Bedrooms and Common Spaces of the Households*

As the previous result suggested that the total number of bedroom fans was related to the total number of bedrooms in a household, further analyses were conducted to investigate the average number of fans in single-unit and double-unit apartments, as the single-unit apartments have more bedrooms. The results showed that on average, a single-unit apartment had 4.37 fans in the bedrooms (N=124, SD=1.2) as opposed to 3.14 fans in the bedrooms of double-unit apartments (N=260, SD=.74). In the common spaces, there were, on average, 3.2 fans in single-unit apartments and 1.79 fans in double-unit apartments. In total, households in single-unit apartments, on average, had 8.68 fans and in double-unit apartments, had 5.3 fans (see Figure 7.12). These results showed that the total number of bedroom fans was related to the total number of bedrooms in a household.

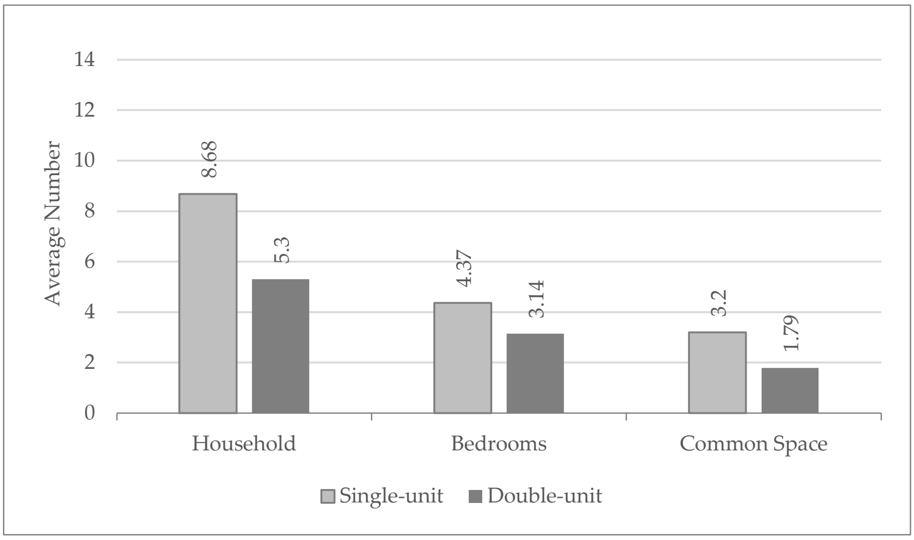

Figure 7.12: *Average Number of Fans in Single-unit and Double-unit Apartments*

Further analyses were conducted to find out the average use of a fan per day in summer. Total fan hours for all the fans were divided by the total number of fans for different spaces. The results showed that on average, a bedroom fan ran for 9.94 hours on a weekday, with a minimum of 1 hour and a maximum of 23 hours (N=292, SD=4.45). On a holiday, a bedroom fan, on average, ran 11.4 hours, with a minimum of 1 hour to a maximum of 23 hours (N=290, SD=4.76). In the common spaces, a fan, on average, ran for 4.42 hours on a weekday (N=277, SD= 2.98) and 5.25 hours on a holiday (N=275, SD=3.34). For the whole household, a fan, on average, ran for 7.55 hours on a weekday (N=283, SD=3.4) and 8.55 hours on a holiday (N=281, SD=3.73). These results suggested that fans in bedrooms were used more than twice as often as fans in the common spaces. The results also suggested that on average, a fan ran more on a holiday than on a working day for all areas. The following table shows the average, minimum and maximum use of a fan in different spaces of the studied households, along with the use of a fan for the whole household.

Table 7.1: *Average Use of a Fan in Different Spaces of the Studied Households (in Hours)*

	N	**Min.**	**Max.**	**Mean**	**Std. Dev.**
Bedroom fan use on a working day	292	1	23	9.94	4.45
Bedroom fan use on a holiday	290	1	23	11.4	4.77
Common-space fan use on a working day	277	1	20	4.42	2.98

	N	Min.	Max.	Mean	Std. Dev.
Common-space fan use on a holiday	275	1	20	5.25	3.34
Fan use of the total household on a working day	283	1	20	7.55	3.4
Fan use of the total household on a holiday	281	2	23	8.55	3.73

Further in-depth investigations were made to find out the average use of a fan in different bedrooms. The study found that on average, a master bedroom fan ran for 11.44 hours on a weekday (N=292, SD=5.3) and 12.94 hours on a holiday (N=292, SD=5.5). The bedroom-2 fan ran for 10.37 hours on a weekday (N=286, SD=5.2) and 11.35 hours on a holiday (N=288, SD=5.5). The bedroom-3 fan ran for 9 hours on a weekday (N=227, SD=5.3) and 10.1 hours on a holiday (N=226, SD=5.7). The bedroom-4 fan ran for 7.3 hours on a weekday (N=56, SD=5.9) and 7.9 hours on a holiday (N=57, SD=6.4). These results showed that the fan in the master bedroom was used most intensely, followed by bedroom-2, bedroom-3, bedroom-4 and common spaces (see Figure 7.13).

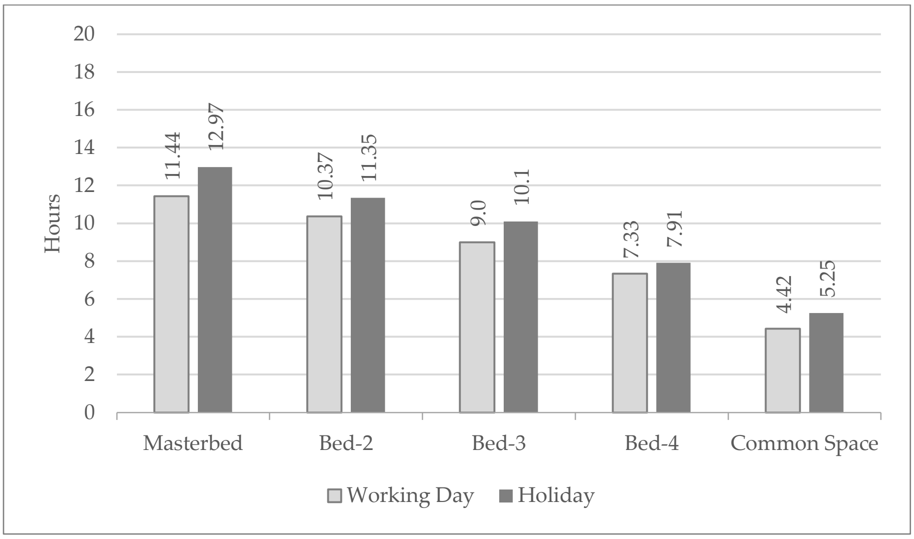

Figure 7.13: *Average Use of a Fan in Different Rooms of the Studied Households*

7.4.4.2 Air Conditioners

As cooling appliances, ACs are more energy intensive than ceiling fans and more expensive. Despite this, the study found that the majority of the studied households owned ACs (70.5 %, 272 out of 387), of which 37.1% (101) had 1 AC, 25% (68) had 2, 19.5 % (53) had 3, 8.5% (23) had 4, 6.3 % (17) had 5, 2.2 % (6) had 6 and 1.8% (5) had 7 (see Figure 7.14). On average, there were 2.4 ACs per household (N=272, SD=1.47).

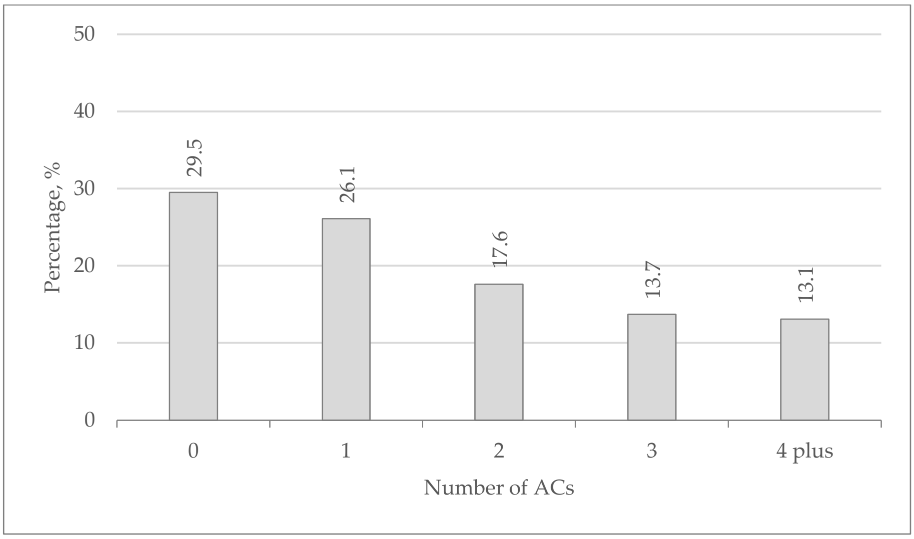

Figure 7.14: *Frequency of Total Number of ACs per Household*

Further analyses were conducted to find out in which rooms the households preferred to install the AC when they had one. The study found that in the case of single AC ownership, it was installed predominantly in the master bedroom (84.2%, 85 out of 101) and for the remaining cases, it was installed in either bedroom-2 or bedroom-3 (14.9%, 15). Where there were two ACs, in 94.1% (64 out of 68) of the cases, one AC was in the master bedroom, 66.2% (45) had one AC in bedroom-2, 17.2% (11) had one AC in bedroom-3 and 20.6% (20.5%) had one AC in the formal living area. The study also found that when a household owned three ACs, in all of the cases one AC was in the master bedroom. When a household owned more than three ACs, in all of the cases one AC was in the master bedroom and one AC was in bedroom-2. It is clear from the results that the first priority of households when installing an AC is the master bedroom, followed by bedroom-2. A frequency analysis showed that the majority of households with an AC (62%, 169) had 1–2 ACs, which were likely to be installed in the master bedroom and bedroom-2 or bedroom-3. From a cooling-energy-consumption point of view, these result suggested that the master bedroom and bedroom-2 are the two most energy-intense rooms of a household in typical residential areas in Dhaka. Only 28.7% (78 out of 272) of the households with AC had it in the common spaces (92.3% of the cases had AC in the formal living area).

Further study found that the ACs were individual cooling units and were either the window type or the split type. Central AC systems did not exist in residential buildings in Dhaka. No dominant preference for a window type or a split-type AC was found, as in 51.2% (163 out of 318) of the cases, the household had a window-type AC and in 48.8% (155) of the cases, the household had a split-type AC.

Further analyses were conducted to find out the average use of AC per day in summer. The total hours of use of all the ACs were divided by the total number of ACs for different spaces. The results showed that on average, a bedroom AC ran for 6.2 hours on a weekday, with a minimum of 0.25 hours (15 minutes) to a maximum of 22 hours (N=199, SD=3.9). A bedroom AC, on average, ran for 6.4 hours on a holiday, with a minimum of 0.25 hours (15 minutes) to a maximum of 22 hours (N=136, SD=4.3). In common spaces, an AC, on average, ran for 2.38 hours on a weekday (N=38, SD=2.28) and 2.7 hours on a holiday (N=38, SD=2.8). For the whole household, an AC, on average, ran for 5.9 hours on a weekday (N=196, SD=4) and 6 hours on a holiday (N=135, SD=4.3) (see Figure 7.15).

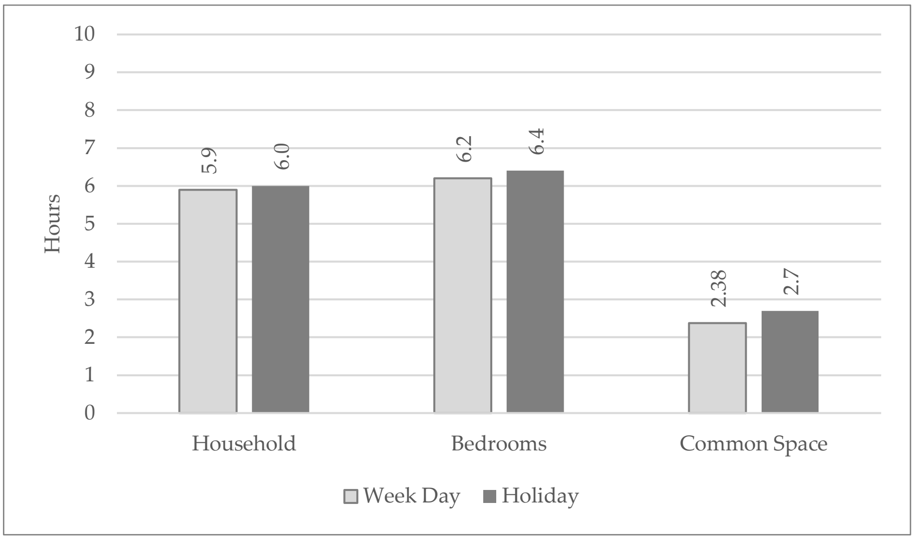

Figure 7.15: *Average Use of an AC in Different Spaces*

Based on these findings, it can be said that both ceiling fan and AC were more used on holidays than on working days. The most energy-intense rooms of the households were the master bedroom and bedroom-2, as both ceiling fans and AC were used most in these two rooms. From an energy-consumption point of view, the overall comfort of the master bedroom and bedroom-2 should be increased so that the use of fan and AC in these rooms can be minimised.

7.4.4.3 Heaters

A heater is not a common appliance in Dhaka, as the climate is predominantly warm for nine months of the year. Only 13.4% (49 out of 367) of the households had a heater, of which 8.7 % (32) had one heater and 3.8 % (14) had two heaters. A fan heater was the most common type of heater and a small number of households had halogen heaters.

7.4.5 Direct Parameters: Artificial Lights

Artificial lights were present in every household and were used every day throughout the year. While the use of artificial lights can vary significantly across the year in some parts of the world where daylight duration varies significantly from season to season, artificial lighting use can be considered fairly constant throughout the year in Dhaka, as the total daylight hours do not vary significantly from season to season, due to the lower latitude of the city.

The average for daylight hours in Dhaka is 12.14 hours, with a maximum of 13 hours 36 minutes in July and minimum 10 hours 40 minutes in January; hence, the difference between the maximum and minimum daylight duration is about three hours. The difference between the sunset time in January and July is about 1.5 hours; the sun sets in January at about 5:11pm and in July at around 6:48pm (Time and Date, n.d.). Therefore, in January, the households used artificial lighting for 1.5 hours more than in July (in the evening). As the sun rises between 5:11am and 6:50am, in general, the households should not need to use much artificial lighting in the mornings. Given the daylight hour availability and variation throughout the year, it can be said that the artificial lighting consumption of Dhaka's households is fairly constant across the year.

The study found that two types of lighting fixtures were used most commonly: CFLs, which are commonly called energy bulbs in Dhaka, and fluorescent bulbs, which are commonly called tube lights in Dhaka. Incandescent bulbs were also common. Some households also had spotlights or halogen lights, mainly for decorative purposes, in formal or family living areas. A frequency analysis showed that 29.2% (114 out of 390) of the households had incandescent bulbs, 96.2% (377) had energy bulbs, 88.5% (345) had tube lights, 19.3% (75) had spotlights and 13.4% (52) had other types of lights such as halogen (see Figure 7.16). The majority of households had mixed types of lights. Only 8.4% (33 out of 392) of the households had one type of light, 50.8% (199) had two types, 28.8% (113) had three types, 10.7% (42) had four types and only 5 households had more than four types (see Figure 7.17).

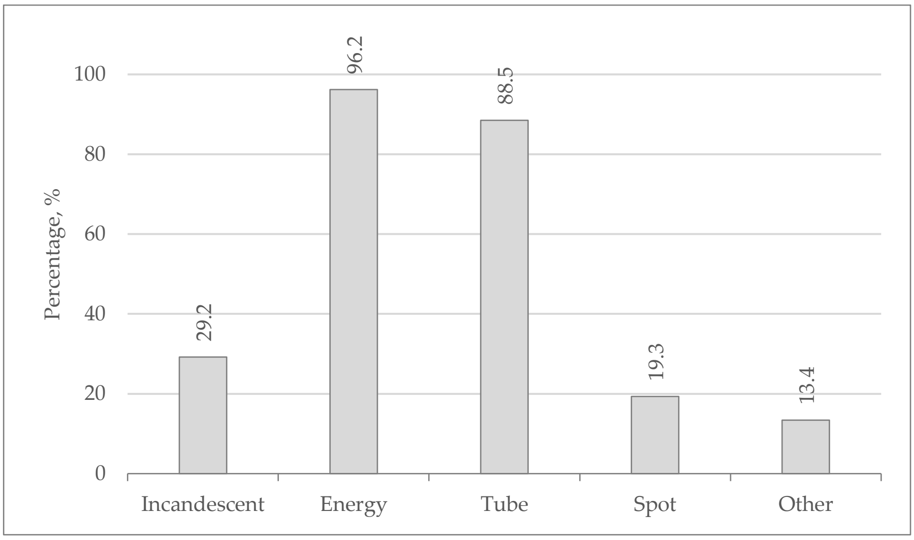

Figure 7.16: *Frequency of Different Types of Lights*

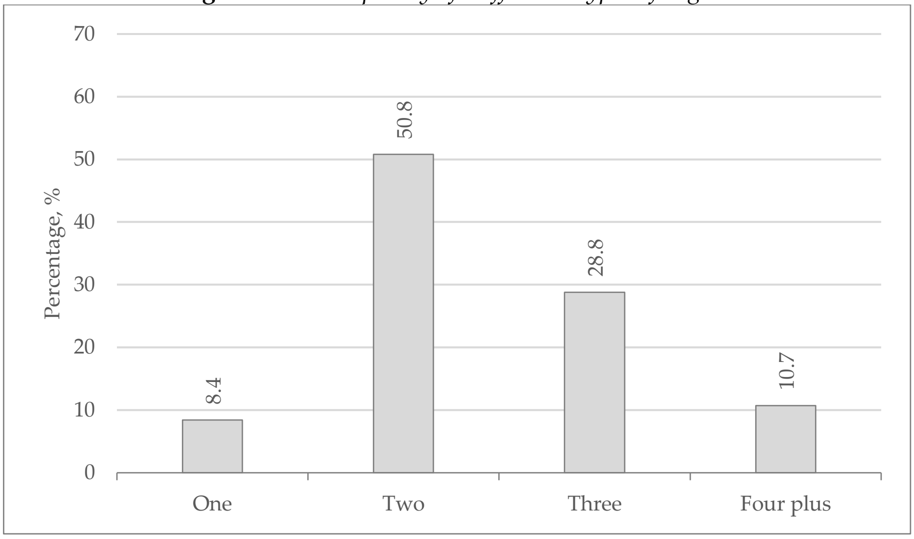

Figure 7.17: *Frequency of Total Types of Lights per Household*

Further analysis was conducted to find out which types of lights were primarily used in certain areas of the house. The results showed that when a household used incandescent bulbs, they were used considerably more in the service areas, including the kitchen, toilets and foyer, compared to the bedrooms and common spaces. The use of energy bulbs was slightly higher in the service areas and slightly lower in the common spaces, compared to the bedrooms. The use of tube light was significantly higher in the bedrooms than in any other areas for the majority of the cases. Spotlights were used more in the common spaces and the other types of bulbs were used more in the bedrooms than in other areas of an apartment (see Figure 7.18). The results showed that energy bulbs were used most; however, in the bedrooms, tube lights were used almost as much as energy bulbs. For the common spaces, energy and tube lights were used most and in the service areas, energy bulbs were used most.

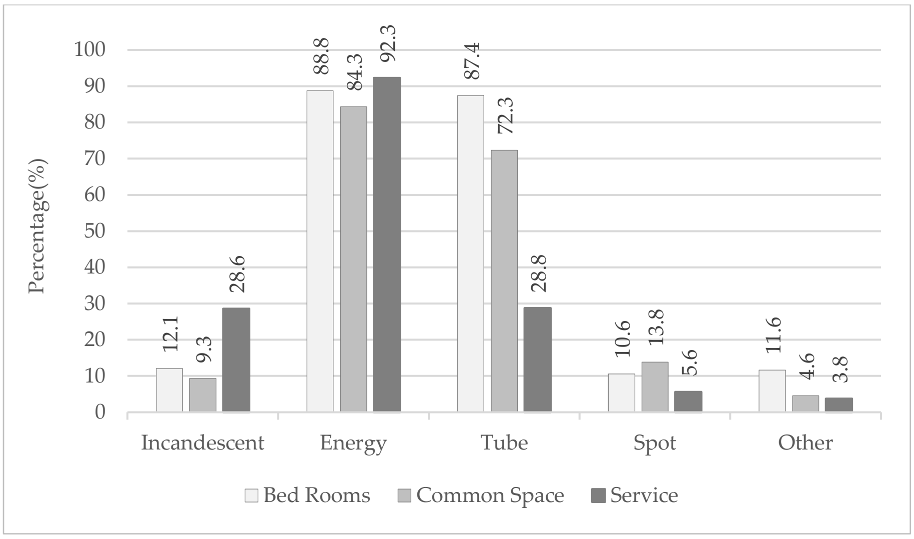

Figure 7.18: *Preferences for Different Types of Lights in Different Areas*

Further study found (see Figure 7.19) that on average, there were 19.5 lights[15] per household, with a minimum of 5 to a maximum of 83 (N=310, SD=11.75). Further detailed investigation found that on average, the bedrooms had 8.93 lights, with a minimum of 3 to a maximum of 27 (N=383, SD=4.5). Common spaces had 6.26 lights (N=313, SD=4.8), with a minimum of 2 to a maximum of 44. Toilets had 3.82 lights (N=376, SD=2.6) and other service areas such as the kitchen, servant's room, foyer had 2.18 lights (N=315, SD=2.3). These result showed that the total number of artificial lights varied significantly from household to household, particularly in the common areas. Some households seem to have a very large number of lights; many higher-income households had a chandelier in the formal living room as well as numerous spotlights, table lamps and stand-alone lamps for decorative purposes.

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[15] *In this study, 'lights' refers to lamps.*

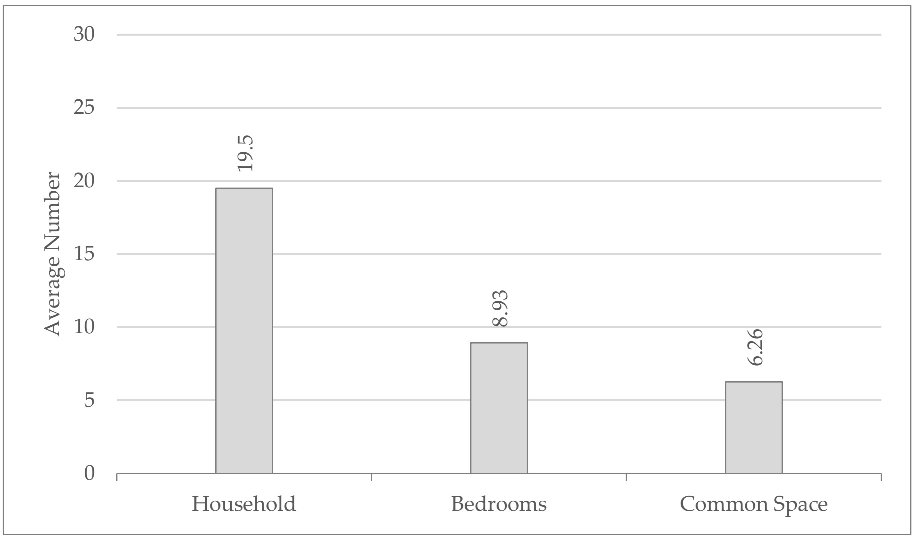

Figure 7.19: *Average Number of Lights (Lamps) in the Studied Households*

7.4.6 Direct Parameters: Domestic Appliances

Domestic appliances, incorporating all other appliances used by a household apart from fans, AC, heaters and artificial lights, were grouped into five major categories by following Yao and Steemers's (2005) classification: i) cold appliances: refrigerator and freezer; ii) wet appliances: washing machine, dryer and geyser; iii) cooking appliances; iv) brown goods: TV, computer, entertainment; and v) miscellaneous: iron, hair dryer, vacuum cleaner and IPS. Investigations were conducted separately for the five groups of appliances.

7.4.6.1 Cold Appliances

All of the studied households owned a refrigerator. Of the total 392 households, 87.4% (343) had 1, 12.3% (48) had 2 and only one household was found to have 3 refrigerators. The average capacity of the refrigerators was 15 Cft (428 L), with a minimum of 7C Cft (198 L) and a maximum of 32 Cft (906 L) (N=265, SD=3.9). A frequency analysis showed that the age of the refrigerators was 5 years for 43% (96 out of 223) of the cases, 5–10 years for 42.5% (95), 11–15 years for 7.2% (16), 15–20 years for 2.2% (5) and more than 20 years for 4.8% (11) (see Figure 7.20). The average age of the refrigerators was 7.22 years, with minimum of 1 year and a maximum of 28 years (N=223, SD=5.1).

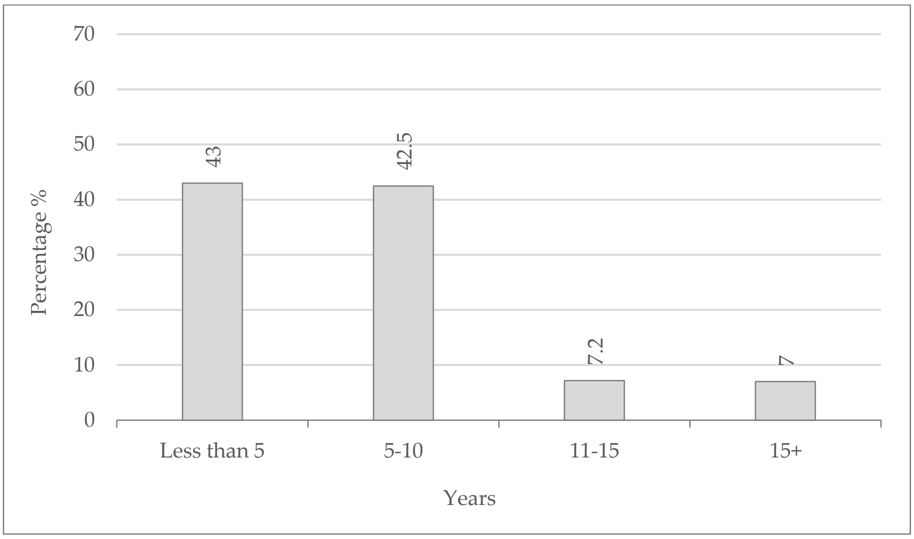

Figure 7.20: *Age Frequency of the Refrigerators in the Studied Households*

More than half (56.7%, 219 out of 386) of the households owned a freezer and 1.8% (7 out of 386) had a double freezer (see Figure 7.21). The average capacity of the freezers was 11.76 Cft (333 L), with minimum of 4 Cft (113 L) and a maximum of 30 Cft (849 L) (N=96, SD=4.7).

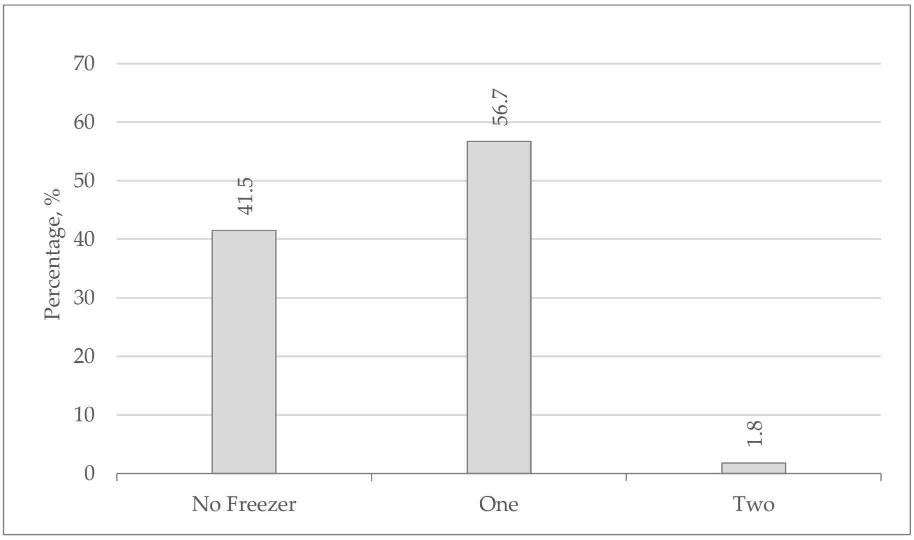

Figure 7.21: *Ownership and Total Number of Freezers per Household*

Further frequency analysis showed that the age of the freezers was 5 years for 41.5% (53 out of 128) of the cases, 5–10 years for 43.1% (55), 11–15 years for 8.6% (11) and more than 20 years for 7.2% (9) (see Figure 7.22). The average age of the freezers was 6.44 years, with a minimum of 1 year and a maximum of 25 years (N=128, SD=4.9).

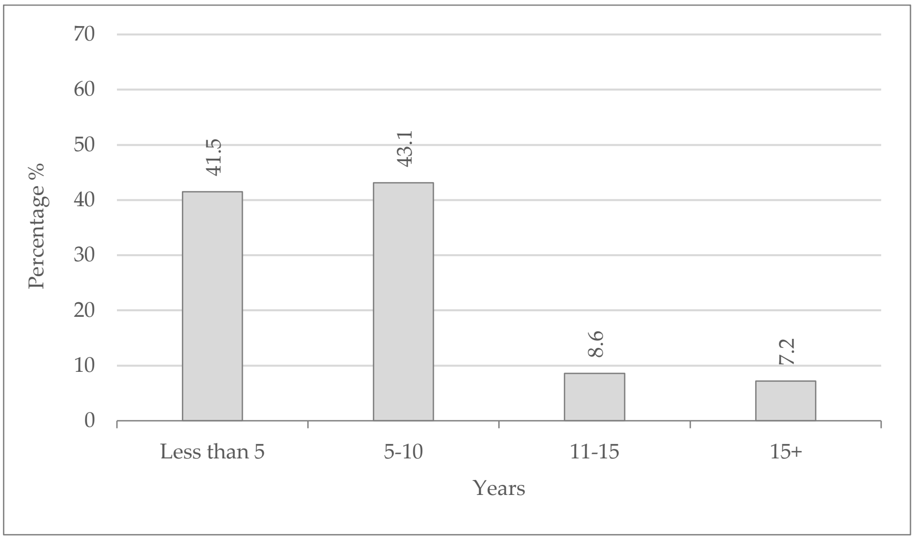

Figure 7.22: *Age Frequency of Freezers in the Studied Households*

Further analyses found that 38.7% (150 out of 388) of the studied households had one cold appliance, 50.5 % (196) had two cold appliances, 10.1% had three cold appliances and 3 of the households had four cold appliances. These results showed that the majority of households had more than one cold appliance.

Since all of the households had a refrigerator, it is certain that when a household had only one cold appliance, it was a refrigerator. From the results, it can also be said that the households with a freezer also had a refrigerator; hence, more than half (56.7%) of the households had one refrigerator and one freezer. Although the ownership and number of cold appliances in the studied households may seem to be high, given the cultural and social contexts of the country, this is not an unusual finding as food storage is very important and hence, ownership of more cold appliances. However, from an energy-consumption point of view, it is possible that cold appliances are the single biggest energy consumer of households in Dhaka, especially for those that do not have AC. Even for the households with AC, cold appliances may account for a substantial amount of total household energy consumption, as it runs throughout the year. Energy-efficient appliances are not yet common in Dhaka, which is understandable given the lack of energy-rated appliances on the market. Replacing the older appliance (5+ years) and promoting energy-efficient refrigerators could help to reduce household energy consumption significantly.

7.4.6.2 Wet Appliances

The use of wet appliances is not very common in Dhaka. Less than one-quarter (23.5%, 91 out of 388) of the studied households had a washing machine and only 3.4% (13) owned a dryer. Given the contexts of cheap labour and the fact that the majority of the studied households had a full-time maid, clothes were usually hand-washed and line-dried. Only 4.6% (18 out of 390) of the households had a dishwasher.

One wet appliance used in Dhaka was the electric water heater (commonly known as a geyser), which is installed independently in the bathrooms, mainly for showering purposes. The study found that only 18% (69 out of 384) of the households had electric geysers in the bathrooms.

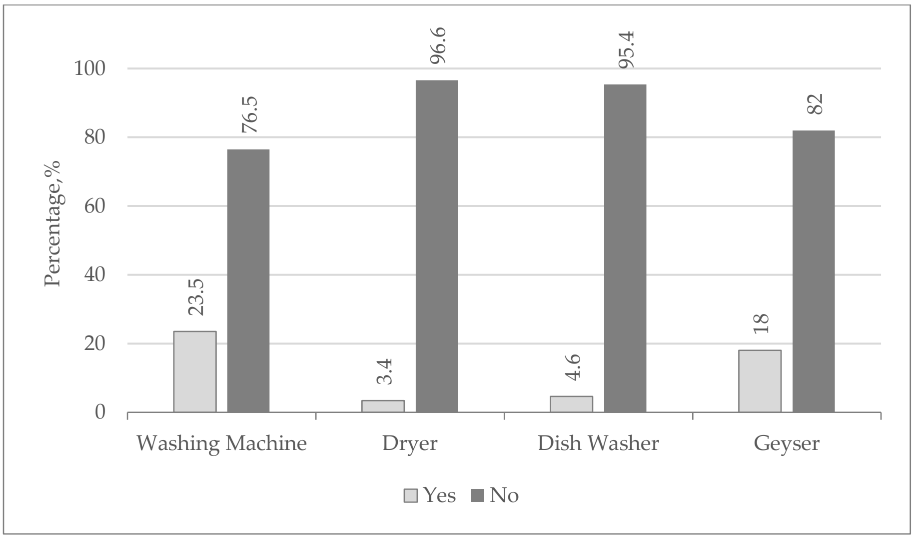

Figure 7.23: *Ownership of Different Wet Appliances*

Given the low number of households that owned and used wet appliances, from an energy-consumption point of view, it can be said that the wet appliances contribute little to the total household energy consumption.

7.4.6.3 Cooking Appliances

A frequency analysis showed that 5.4% (21 out of 390) of the studied households had an electric stove, 23.1% (90) had an electric oven, 67.2% (262) had a microwave oven, 32.3% (126) had a toaster, 34.6% (135) had a sandwich maker, 89.2% (348) had a juicer-blender, and 47.7% (186) had a rice cooker. It is worthwhile to note that the electric stove is not common in Dhaka as for cooking, gas is mainly used. Among the cooking appliances, the juicer-blender was the most common, followed by the microwave oven.

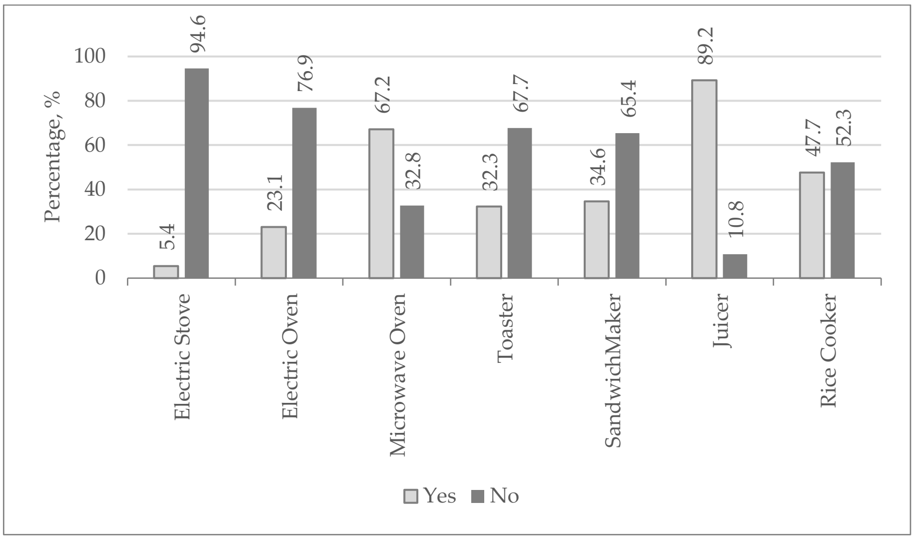

Figure 7.24: *Ownership of Different Cooking Appliances*

7.4.6.4 Brown Goods

The study found that all but three of the studied households owned a television (TV), of which 53.8% (211 out of 392) owned 1 TV, 32.7% (128) owned 2, 9.4% (37) owned 3 and 3.3% (13) owned 4 (see Figure 7.25). Further analysis found that 64.5% (253 out of 392) of the households had CRT TV, 7% (27) had a flat TV, 59.4% (233) had LCD TV and 8% (2) had a plasma TV (see Figure 7.26). The average use of TVs in the households was 5.25 hours, with a minimum of 1 hour to a maximum of 18 hours (N=289, SD=3.5). The average screen size of the CRT TVs was 21″ (53.34 cm), with a minimum of 14″ (35.5 cm) and a maximum of 32″ (81.3 cm) (N=209, SD=3.1). The average screen size of the LCD TVs was 31.75″ (80.65 cm), with a minimum of 16.5″ (42 cm) and a maximum of 55″ (139.7 cm) (N=181, SD=9.6).

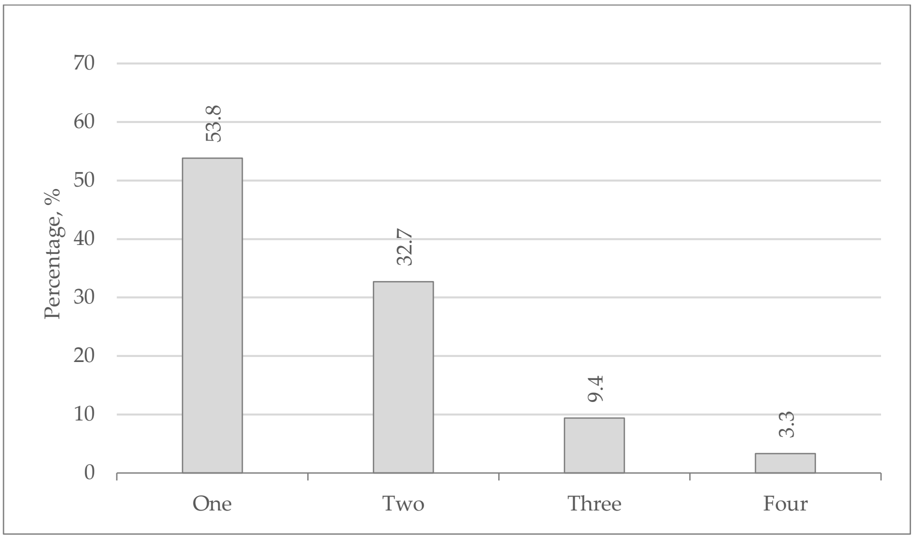

Figure 7.25: *Total Number of TVs per Household*

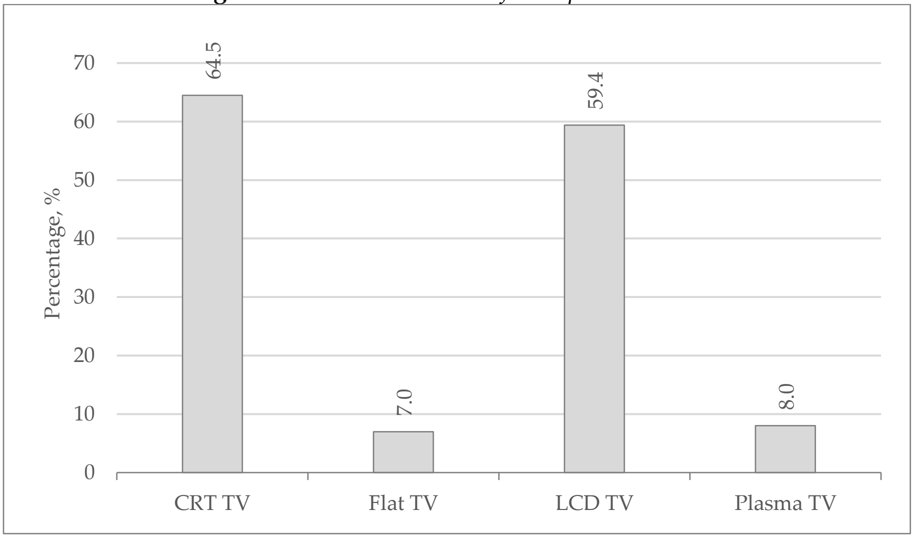

Figure 7.26: *Frequency of Different Types of TV*

From the results, it is clear that CRT and LCD TVs were the most dominant in the studied households, with approximately 5% more CRT TVs than LCD TVs. As TVs ran, on average, for more than five hours per day in the case study apartments and CRT TVs consume nearly twice the energy of LCD TVs, encouraging households to discard their CRT TVs would reduce the energy consumption of the households.

The majority of the households (76.5%, 300 out of 392) owned personal computers, of which 60.7% (182) had 1, 30% (91) had 2 and 9% (27) had more than 2. The average use of computers was about 6.25 hours per day, with a minimum of 1 hour to a maximum of 19 hours (N=213, SD=3.49). These results showed that on average, the computer was more used than the TV.

Excluding TVs and computers, 11.8% (46 out of 390) of the households had a home theatre, 29.8% (116) had a DVD player, 19.5% (76) had a printer, 14.15% (55) had a scanner, 1.3% (5) had a fax machine, and 4 had a projector.

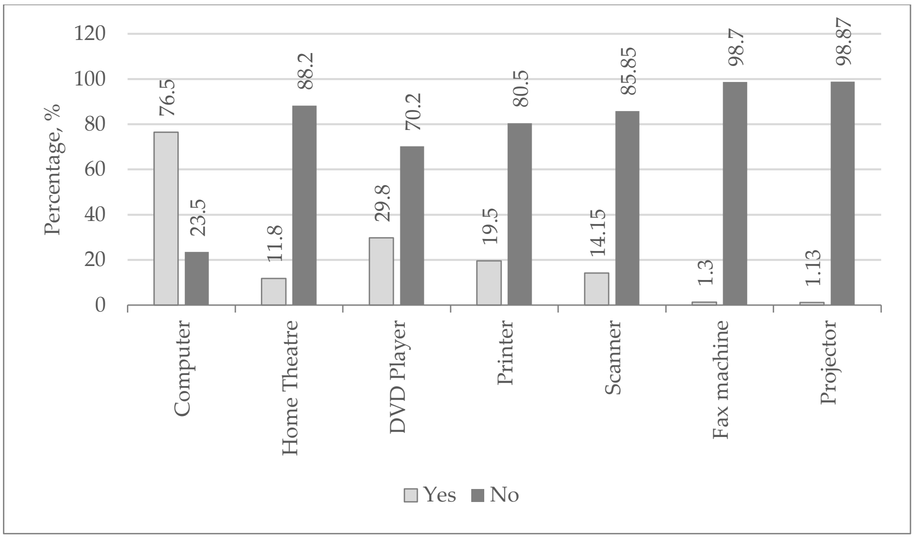

Figure 7.27: *Ownership of Different Brown Goods*

7.4.6.5 Miscellaneous

Apart from the major domestic appliances, 23.3% (91) of households had a cordless telephone, 95.9% (374) had an iron, 10.3% had a vacuum cleaner and 47.9% (186) had a hair dryer (see Figure 7.28). It is worthwhile to note that the vacuum cleaner is not a common appliance in Dhaka as the households do not usually have carpets and the floor is cleaned manually with a handheld broom and a wet mop.

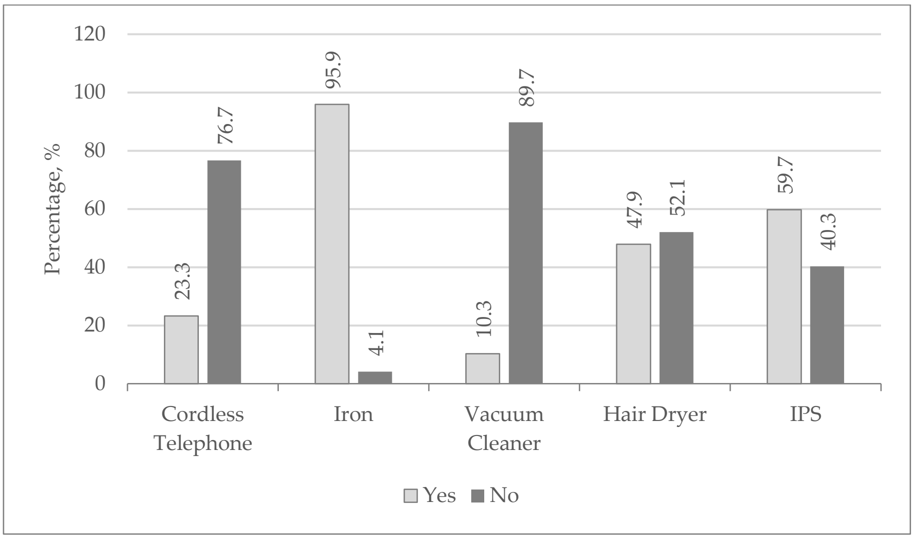

Figure 7.28: *Ownership of Different Miscellaneous Appliances*

Further investigation found that on average, the households had 4.75 rechargeable items, with minimum of 1 and a maximum of 11 (N=366, SD=1.98). A frequency analysis showed that only 2 households had 1 rechargeable item, whereas 9.6% (35) had 2, 18.9% (69) had 3, 21.9% (80) had 4, 15.3% (56) had 5, 18.9% (69) had 6, 5.7% (21) had 7, 6% (22) had 8 and 3.2% (12) had more than 8 (see Figure 7.29).

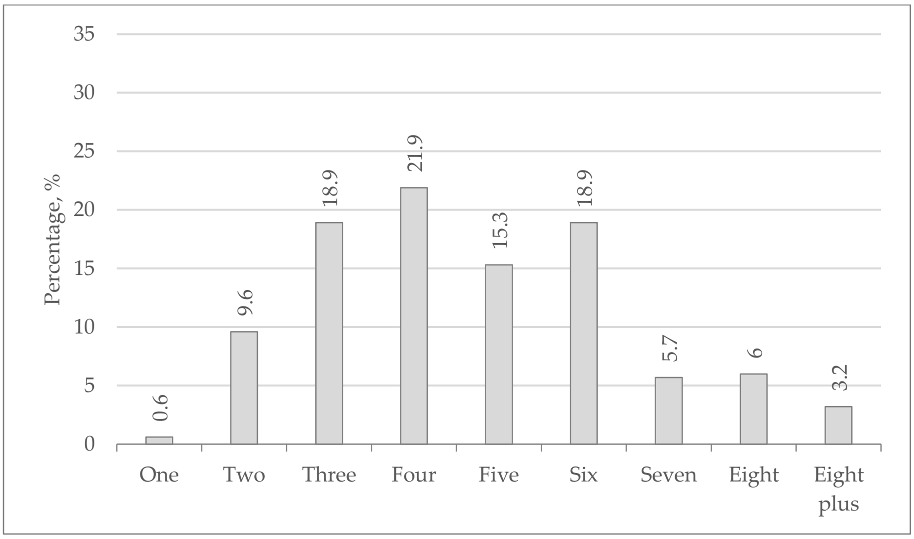

Figure 7.29: *Frequency of Total Number of Rechargeable Items per Household*

Further analyses were conducted to find out if the households switched off the power supply point after using six common appliances that consume energy when they are in standby mode. The result showed that only 30% (113 out of 376) of the households turned off the TV power point when not in use. Only 29.7% turned off the AC switch, 48.6% turned off the scanner-printer switch and 45.7% turn off the DVD player switch. However, the majority switched off the power point for the microwave oven (71.3%, 178 out of 214) and for computers (61.3%, 185 out of 302).

From an energy-consumption point of view, these results suggested that if the occupants could be made aware of the standby power consumption and were encouraged to switch off the power supply point for TVs, the energy consumption of the studied households due to domestic appliances use could be reduced.

7.5 ENERGY CONSUMPTION PATTERN AND INTENSITY

Investigations were conducted to find out the energy consumption pattern and intensity of the households. In this study, ‘energy’ refers to ‘electricity’. It is important to note that not all of the respondents were able to provide the full-year electricity consumption data, as many of the respondents did not keep their electricity records. The respondents who were willing to provide their electricity consumption record provided it in three ways: i) complete electricity data for a year (131 responses); ii) approximate electricity consumption of the coldest and the hottest months of the year (164 responses); and iii) approximate average monthly consumption (62 responses). Electricity data collected from DESCO provided the total monthly electricity sell and the total number of consumers for each of the case study areas for the study year. The monthly electricity consumption of the households with incomplete electricity data was then derived, based on the DESCO data through interpolation. Therefore, the results presented in the following sections are based on the real electricity consumption provided (131 cases) as well as the electricity consumption derived through interpolation (226 cases).

The average total annual electricity consumption per household was found 6,570 kWh, with a minimum of 2,211 kWh and a maximum of 16,048 kWh (N=357, SD=3013.4). This means the households, on average, consumed 18 kWh/day in 2013, with significant variation between households. Further frequency analysis found that for 16% (57 out of 357) of the households, the annual average consumption was 2–4,000 kWh; for 39.5% (141) it was 4–6,000 kWh; for 20.2% (72) it was 6–8,000 kWh, for 11.8% (42) it was 8–10,000 kWh, for 4.8% (17) it was 10–12,000 kWh, for 2.5% (9) it was 12–14,000 kWh and for 5.35% (19) it was more than 14,000 kWh (see Figure 7.30). The results showed that the majority of the studied households (59.7%) consumed 4–8,000 kWh (see Figure 7.30).

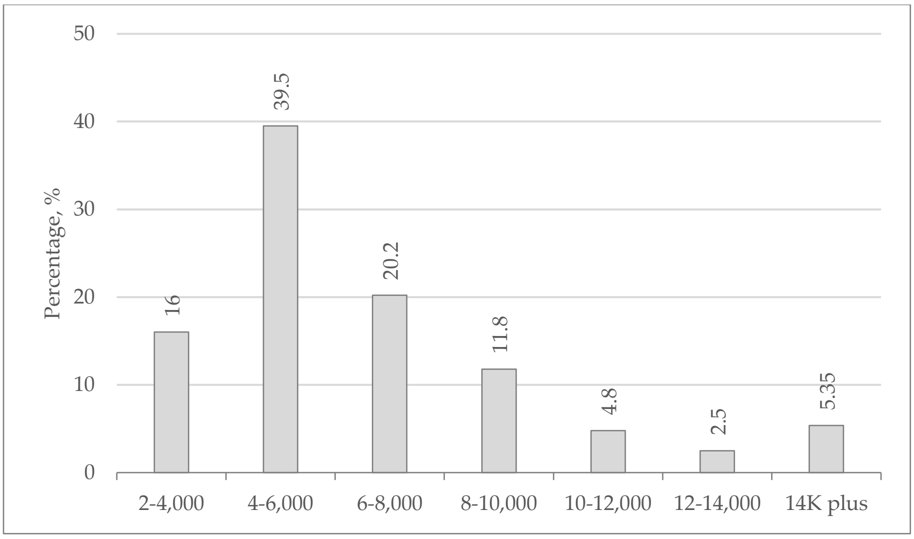

Figure 7.30: *Annual Electricity Use (kWh) Range of the Studied Households*

Further analysis was conducted to find out the difference in average energy consumption between the households with AC and those without AC. This study found that the average energy consumption was 4,381 kWh for the non-AC households (N=117, SD=1198) and 7,648.8 kWh for the households with AC (N=240, SD=3045). These results suggested that the households with ACs on average consumed 43% more total energy than the households without ACs.

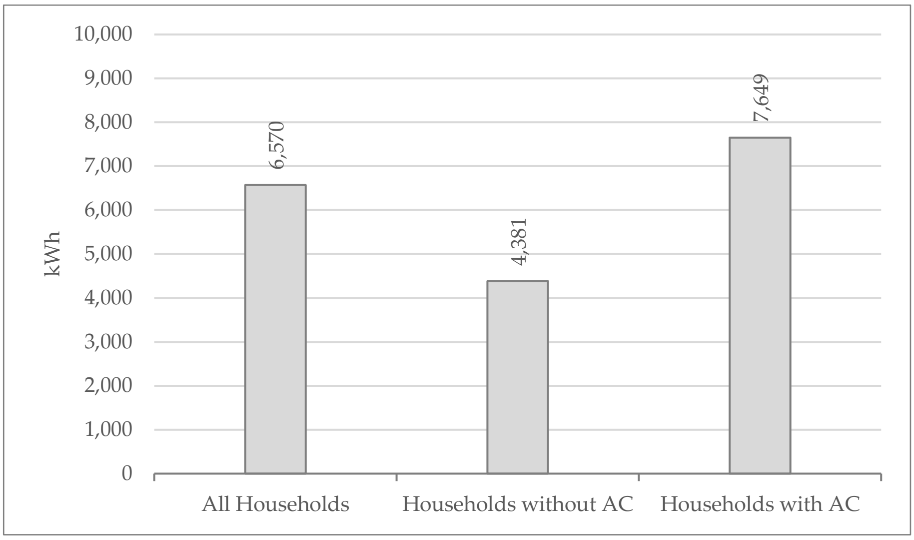

Figure 7.31: *Annual Electricity Use (kWh) of all Households, Households without and with AC*

Further analyses were conducted to estimate the average consumption of cooling energy as well as the proportion of this consumption compared to the total energy consumption of the households. To estimate this, the total base consumption of the households was deducted from the total annual consumption. The base consumption of a household occurs due to the use of artificial lights and domestic appliances, is not climate dependent and is usually constant throughout the year, whereas, the use of cooling appliances is climate dependent and varies across the year. To find out the total base consumption of the households, the daily average consumption in January (which is the month when no cooling is used) was calculated and then was multiplied by 365 to get the total base consumption for a year. The base consumption was then subtracted from the total annual consumption to find the total consumption of energy for cooling. It should be noted that the acquired base and consumption of cooling energy of the households through the above calculation was an estimate, as some of the households may have used heaters and water heaters in January. Therefore, the actual cooling energy consumption of the studied households may be little higher than the figures derived in this study.

The above method resulted in an estimate of average base consumption per household in 2013 of 5012 kWh and an average cooling energy consumption of 1,558 kWh, with a minimum of 113 kWh and a maximum of 6,753 kWh (N=357, SD=1002). The average cooling consumption of the studied households was 14% higher than was found in a previous study conducted in Dhaka's contexts (1,333 kWh) (Ahsan, 2009). On average, the consumption of cooling energy of the studied households accounted for 23.7% of the total energy consumption.

Further analyses were conducted to find out the daily average consumption for different months and seasons, to identify the most energy-intense time of the year. Dhaka has three distinct seasons: cool-dry (December–February), hot-dry (March–May) and hot-wet (June–November). The study results showed that the minimum average daily electricity consumption occurred in January (13.9 kWh), followed by December (14 kWh), February (15 kWh), November (16.1 kWh), March (16.9 kWh), October (18.7 kWh), May (18.2 kWh), April (20.1 kWh), August (20.2 kWh), September (20.6 kWh), June (21 kWh), and July (21.3 kWh). The most energy-intense period is during June and July, which were in the hot-wet season corresponding to the highest humidity (see Figure 7.32). The average daily consumption of the households in July was 35% more than the average daily consumption in January, which can be attributed to the use of cooling appliances in July. If the base case consumption was constant throughout the year then the result also suggests that the households used ACs more intensively during the hot-wet season than at any other time of the year.

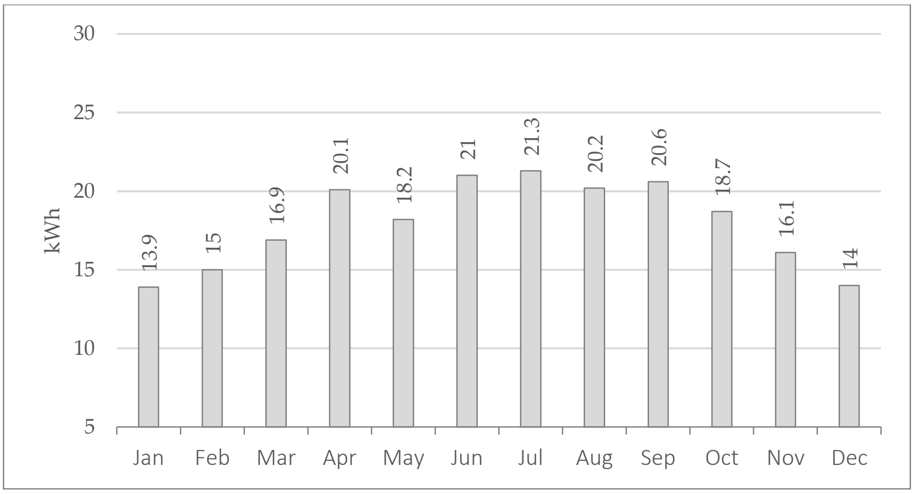

Figure 7.32: *Average Daily Electricity Consumption (kWh) in Different Months*

Further analysis of the daily average consumption during the cool-dry, hot-dry and hot-wet seasons found that the average daily consumption was 14.27 kWh during the cool-dry season, 18.36 kWh during the hot-dry season and 19.65 kWh during the hot-wet season (see Figure 7.33). On average, the daily consumption in the hot-wet season was 27% more than in the cool-dry season and 6.5% more than in the hot-dry season. From an energy-consumption point of view, the findings suggested that to reduce the household consumption of cooling energy, priority should be given to achieving comfort during the hot and humid period, in particular from June to September.

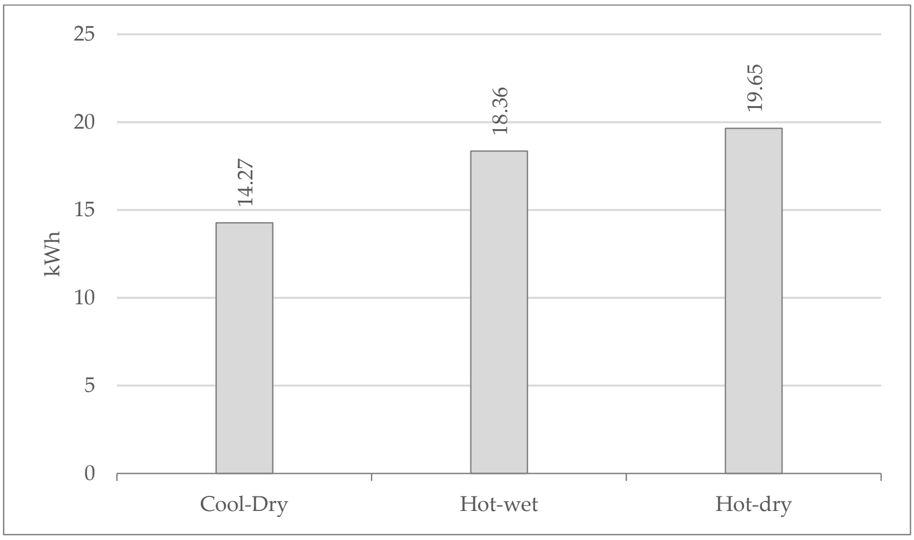

Figure 7.33: *Average Daily Electricity Consumption (kWh) in Different Seasons*

Investigations regarding the difference in average energy consumption between the single-unit and double-unit apartments found that the average annual consumption of a household living in a single-unit apartment was 8,418 kWh (N=118, SD=3620) and for a household in a double-unit apartment was 5,644 kWh (N=237, SD=2150). These results suggested that the households in single-unit apartments on average consumed 33% more total energy than the households in double-unit apartments. Further investigation found that the average consumption per unit area of the single-unit apartments was 3.85 kWh/ft^2 (41.47 kWh/m^2) and in the double-unit apartments, it was 3.91 kWh/ft^2 (42.08 kWh/m^2). These results indicated that the larger apartments may have higher total energy consumption but the consumption per unit area is nearly same for both the single- and double-unit apartments.

7.6 HOUSEHOLD PARAMETERS VS ENERGY CONSUMPTION

In the second phase of this study, a number of correlation analyses were conducted to find out the strength, direction and nature of the relationship between different household parameters and the annual energy consumption of the households. In addition, a number of regression analyses were conducted to find out which of the household parameters had the most effect on household energy consumption. It is worthwhile to note that for both the correlation and regression analyses, the household parameters were the independent variables and the total energy consumption was the dependent variable.

7.6.1 Relationship Between the Indirect Parameters and Energy Consumption

This section presents the results of the correlation analyses between the indirect household parameters and the total energy consumption of the households. The analyses were conducted in three steps for three different sets of indirect parameters: i) parameters related to household characteristics; ii) parameters related to building characteristics; and iii) parameters related to the operational practices regarding doors and windows.

The preliminary assumptions of the correlational techniques were carefully considered. They were: i) a measurement scale of the variables (continuous and dichotomous categorical); ii) related pairs (the response for both independent and dependent variables is from the same subject); and iii) independence of observations (responses were collected independently and separately for different subjects). The assumptions about the distribution of the scores for each of the variables were checked through the following histograms and scatter plots: i) normality (the scores are symmetrically distributed in a bell-shaped curve); ii) linearity (the relationships between the independent and dependent variables are linear); and iii) homoscedasticity (the distribution shows a fairly even cigar shape along its length). For the dichotomous categorical variables, the frequency for each response was checked through bar charts.

Several variables were found to have non-normal skewed distribution, including the dependent variable, which was slightly skewed towards the left. As discussed in the previous section, skewed distribution is a common phenomenon in social science research and authors in general suggest that the statistical procedures are robust enough to endure minor violation of the assumptions, particularly with a large number of samples (200+) and in the case of descriptive statistics (Osborne & Waters, 2002; Pallant, 2011). However, several authors also suggest that any violation of the assumptions can have a considerable effect on the outcomes of the parametric statistical techniques, particularly in the case of correlation and regression analyses and in the case of non-normal distribution. Therefore, either the variables should be transformed until they reach a reasonably normal distribution, or non-parametric techniques, which do not have such strict strings attached, should be used (Osborne & Waters, 2002; Tabachnick & Fidell, 2008). The goal of these analyses was mainly to find out the strength and direction of the relationship between the two variables (independent and dependent) and not to draw a final conclusion based on the statistical analyses. In addition, the response numbers were large enough (300+). Therefore, the skewed variables for this study were not transformed. According to Tabachnick and Fidell (2008), relationship analyses run with non-normal distribution may weaken but do not invalidate the outcome. To deal with missing data (as is common with human responses as well), the option to 'exclude cases pairwise' was chosen, as suggested by many authors (Pallant, 2011).

In correlational statistics, outliers are another issue that can distort the outcome considerably and there has been ongoing debate among authors about whether to retain the outliers or remove them from the analyses (Osborne & Waters, 2002; Zimmerman, 1998). In this study, outliers were kept in the analyses as they were real responses and the response numbers were large enough to withstand the effect of the outliers. In the case of variables with extreme outliers, the non-parametric correlation value was considered.

Finally, both parametric and non-parametric correlational analyses were conducted. For the independent variables with reasonably normal distribution, the parametric correlation coefficient value (Pearson) was considered and for the independent variables with highly skewed distribution, the non-parametric coefficient value (Spearmen's rho), as well as a strict significance level ($p<.01$), were considered for the interpretation.

To interpret the correlation results, different authors suggest different coefficient values to measure the strength of the relationship between two variables. According to Cohen (1988), the strength of relationship is small when r (correlation coefficient) = 0.1 to 0.29, medium when r = 0.3 to 0.49 and large when r = 0.5 to 1. According to Evans (1996), the following is the interpretation for the absolute value of 'r': r = 0.0–0.19 (very weak), r = 0.2–0.39 (weak), r = 0.4–0.59 (moderate), r = 0.6–0.79 (strong) and r = 0.8–1 (very strong). For this study, the recommendations of both Cohen (1988) and Evans (1996) were consulted to interpret the results.

The first set of indirect parameters for the correlation analyses were the total number of occupants, family members, full-time maid, unit area per person, apartment's vacancy for more than four weeks, occupancy status, monthly income and non-residential activities at home. The results showed that excluding the variables 'apartment's vacancy' and 'non-residential activities at home', all the other variables had a statistically significant and positive correlation with the total energy consumption at various degree of strength. The results showed that if the size of the apartment, total number of occupants (including both family members and full-time maids), unit area per person and the monthly income increased, and if the occupancy status of the household was that of an owner, then the total energy consumption also increased. From the strength of the relationships (r), it can be said that the affordability-related parameters such as occupancy status and monthly income had a stronger relationship with energy consumption compared to the occupants' related parameters. Table 7.2 shows the statistically significant indirect parameters, along with the relevant case responses (N)[16], correlational coefficient (r), significance level and whether the analysis was parametric or non-parametric (Pearson/Spearman's rho).

Table 7.2: *Indirect Parameters (Household Characteristics-related) vs Total Energy Consumption*

#	**Parameters**	**N**	**Correlations (r)**	**Sig. (2-tailed)**	**Pearson/ Spearman's rho**
1	Number of occupants	355	.26	$p < .001$	Pearson
2	Total family members	355	.13	$p < .018$	Pearson
3	Total full-time maids	355	.29	$p < .001$	Spearman's rho
4	Unit area per person	355	.14	$p < .009$	Spearman's rho
5	Occupancy status	353	.34	$p < .001$	Parametric
6	Monthly income	324	.35	$p < .001$	Spearman's rho

The second set of the indirect parameters were apartment size, apartments' construction (developer- or owner-built), apartment floor level (on the top or intermediate floors), orientation, external wall construction, window type, presence of indoor plants, presence of external glass doors, presence of mosquito nets, air-tightness of the openings, roof construction and the presence of a roof garden for the top-floor apartments. Although the WWR as well as the presence and depth of shading devices were also important, these parameters were not included in the analyses because of the difficulty in collecting such data through a questionnaire survey and hence, unavailability of the information.

The results of the correlation analyses showed that only the apartment size, the presence of external glass doors and the presence of mosquito nets had a moderate positive correlation with the total energy consumption. This suggested that the energy

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[16] *N in the analysis represents the number of responses for that parameter.*

consumption of a household increased with the increase in apartment size, the presence of external glass doors and the presence of mosquito nets. Although correlational output only indicates the *existence* of a correlation and not the *cause* of it, it can be assumed that the larger apartments in the case study areas indicated higher affordability, as well as a higher number of appliances; hence, a higher energy consumption. On the other hand, the presence of glass doors may indicate both the affordability of the households and the higher indoor temperature due to more glazed surfaces and hence, a higher demand for cooling energy. The presence of mosquito nets may indicate reduced indoor ventilation and hence, more demand for cooling energy—a previous study in Dhaka's contexts identified that mosquito nets can significantly reduce the indoor air velocity and ventilation (Mallick, 1994).

Apart from the above parameters, some other building parameters also showed a significant but weak relationship with the total energy consumption. The apartment floor level and the presence of indoor plants had a statistically significant but weak positive correlation, suggesting that with an increase in apartment height and the presence of indoor plants, total energy consumption also increased. Considering the fact that correlation only indicates a significant relationship and does not ensure causality, it is unlikely that the presence of indoor plants would increase the total consumption of electricity. It is more likely to be an indication of the positive correlation between affordability and increased energy consumption, as usually indoor plants are present in more affluent households, which was further confirmed through a correlation analysis between indoor plants and monthly income ($N=356$, $r = 0.19$, $p < .002$).

The apartments' construction, external wall construction and window type had a statistically significant but weak negative correlation with energy consumption, which suggested that if the building was owner-built and the external walls were 250 mm (10″) thick instead of 125 mm (5″) and the windows were shutter type instead of sliding, then the total energy consumption decreased. This result supported one of the assumptions of the building contexts study, which assumed that the developer-built buildings were more energy intensive than owner-built buildings. The facts that thicker walls have more thermal inertia and that shutter-type windows can be fully opened, unlike sliding windows, may be the reasons for the significant negative correlation with energy consumption, even though the correlation was weak. Apart from the above parameters, the rest of the housing parameters investigated did not show any significant relationship with total energy consumption (see Table 7.3).

Table 7.3: *Indirect Parameters (Building Related) vs Total Energy Consumption*

#	Parameters	N	Correlations (r)	Sig. (2-tailed)	Pearson/ Spearman’s rho
1	Apartment size	355	.43	p < .001	Spearman’s rho
2	Developer-/owner-built	356	-.19	p < .001	Pearson
3	Apartment floor level	348	.13	p < .012	Pearson
4	External wall	356	-.23	p < .001	Spearman’s rho
5	Window type	357	-.14	p < .007	Spearman’s rho
6	Indoor plants	355	.11	p < .038	Pearson
7	Glass doors	357	.39	p < .001	Pearson
8	Mosquito nets	276	.32	p < .001	Pearson

The third set of indirect parameters were cross-ventilation conditions, whether the windows were kept open or closed in summer, frequency of opening balcony doors, the frequency of opening bedroom doors, frequency of opening bedroom windows, frequency of opening common-space windows, frequency of opening bedroom curtains and frequency of opening common-space curtains.

The results showed a positive relationship between the total energy consumption and the cross-ventilation conditions of the apartment, as well as whether the windows were open or closed in summer. This suggested that the total energy consumption increased if the cross-ventilation conditions of a household were poor or if the windows were kept predominantly closed in summer. A negative correlation was found if the bedroom doors were kept open and the bedroom windows and balcony doors were opened more frequently, which suggested that energy consumption decreased if balcony doors, bedroom doors and bedroom windows were opened more frequently. This result indicated either improved indoor ventilation due to more frequent opening of windows and doors and hence, less consumption of cooling energy, or less-frequent opening of doors and windows due to more frequent AC use and hence, higher consumption of cooling energy. Whatever the actual cause, the correlation results suggested that more frequent opening of windows and doors, as well as better cross-ventilation, could decrease the total energy consumption or more precisely, the demand for cooling energy of the households. This supported the findings of the microclimate study, which showed that the closed rooms had a much higher average indoor air temperature than the others (see Section 6.3.3). However, unlike the doors and windows, the frequency of opening curtains did not show any relationship with the total energy consumption (see Table 7.4).

Table 7.4: *Indirect Parameters (Operation of Windows and Doors) vs Total Energy Consumption*

#	Parameters	N	Correlations (r)	Sig. (2-tailed)	Pearson/ Spearman's rho
1	Cross-ventilation	335	.12	p < .032	Pearson
2	Windows open/closed in summer	357	.17	p < .001	Spearman's rho
3	Frequency of opening balcony doors	343	-.15	p < .005	Spearman's rho
4	Frequency of opening bedroom doors	332	-.31	p < .001	Spearman's rho
5.	Frequency of opening bedroom windows	357	-.23	p < .001	Pearson

Based on the findings regarding the correlational strength between the indirect parameters and the total energy consumption of the households, it can be said that the income of the households, followed by the presence of more glazed surfaces and mosquito nets, and the lower frequency of opening doors and windows (i.e., less ventilation) contributed to high energy use by the households. The building design and construction-related parameters showed less correlation with energy use. From an energy-consumption point of view, ensuring ventilation and avoiding the use of unnecessary glazed surfaces would probably provide better success in terms of reduction of cooling energy consumption.

7.6.2 Relationship Between the Direct Parameters and Energy Consumption

Further correlational analyses between the direct parameters, which refer to the possession, number and use of different appliances, and the total energy consumption were conducted. As mentioned earlier, these analyses were conducted in three steps with three different sets of appliances; the same analysis procedures were followed as those described in the previous section. The first set of direct parameters investigated were the total number of fans, total fan hours per week in summer, AC ownership, total number of AC units, total AC hours per week in summer and total number of heaters.

The result showed a large significant and positive correlation between AC ownership and total household energy consumption, which suggested that total energy consumption was likely to be significantly higher if the household owned an AC unit. However, there was a moderate positive correlation between the total numbers of fans per household, total number of AC units per household, the use of AC and AC capacity. There was a small positive correlation between the total household energy consumption and, the use of fans and total number of heaters. The result suggested that the higher the number of fans, ACs, fan use, AC use, AC capacity and the number of heaters, the higher the total energy consumption of a household. Among all the appliances related to achieving thermal comfort, AC correlated more with energy consumption and hence, can be said to affect energy consumption the most. Given that heaters were not commonly owned by the households and were needed only for a very limited period, it was difficult to infer from the result whether the significant positive correlation indicated the higher use of a heater and hence, higher consumption, or rather, indicated higher affluence.

Table 7.5: Direct Parameters (Fan, AC and Heater) vs Energy Consumption

#	Parameters	N	Correlations (r)	Sig. (2-tailed)	Pearson/ Spearman's rho
1	Total number of fans	336	.31	p < .005	Spearman's rho
2	Total fan hours/week	251	.23	p < .001	Pearson
3	AC ownership	353	.60	p < .001	Pearson
4	Total number of AC units	353	.45	p < .001	Spearman's rho
5	Total AC hours/week	167	.33	p < .001	Spearman's rho
6	AC capacity	224	.39	p < .001	Spearman's rho
7	Total number of heaters	332	.26	p < .001	Spearman's rho

The second set of direct parameters were the variety or total types of lights, total number of lights, total length of use (in hours) of lights per day and the total capacity of lights. The results showed a moderate positive correlation between the total number of lights per household and the total capacity (Watt) of lights. Total types and use of lights had a small positive correlation with total energy consumption. The result suggested that the higher the number, variety, use and capacity of lights, the higher the energy consumption of a household. Given the fact that households with higher affluence have a higher number of lights for decorative purposes, it is difficult to infer from the results whether the correlation indicated a higher energy consumption due to the higher number of lights or the higher affluence of a household.

Table 7.6: *Significant Direct Parameters (Artificial Lights) vs Energy Consumption*

#	Parameters	N	Correlations (r)	Sig. (2-tailed)	Pearson/ Spearman's rho
1	Total light types	357	.18	p < .001	Pearson
2	Total number of lights	353	.40	p < .001	Spearman's rho
3	Total use of lights – hours/day	222	.19	p < .005	Spearman's rho
4	Total capacity of lights	356	.36	p < .001	Spearman's rho

The third set of direct parameters was the number of refrigerators, capacity and age of refrigerators, freezer ownership, capacity and age of freezer, washing machine ownership, capacity and use of washing machine per week, ownership of dryer, electric stove, electric oven, microwave oven, dishwasher, cordless telephone, toaster, sandwich maker, juicer, iron, vacuum cleaner, hair dryer, home theatre, home office, total number of appliances per household, total number of rechargeable items, total number of TV and TV use per day, total number of computers and computer use per day and IPS ownership and capacity. The results showed that among all of the common household appliance-related parameters, freezer ownership and capacity and total number of TVs per household had a moderate positive and significant relationship with total energy consumption. Refrigerator capacity, washing machine ownership, ownership of microwave oven, total number of appliances, total number of rechargeable items and IPS capacity also had a medium positive correlation with total energy consumption. Freezer age, ownership of a geyser, toaster, sandwich maker, cordless telephone, iron, vacuum cleaner, hair dryer, home theatre, rice cooker, use of TV and IPS ownership had a small or weak positive correlation with total energy consumption. Apart from the above, no statistically significant relationship was found for the rest of the appliances.

Based on the coefficient (r) values, it can be said that among all of the common household appliances, cold and wet appliances such as refrigerator, freezer and washing machine, as well as total number of TV and IPS capacity, had a significant influence on the energy-use intensity of the studied households. Among the cooking appliances, the ownership of a microwave oven had a significant influence.

Table 7.7: *Direct Parameters (Household Appliances) vs Energy Consumption*

#	Parameters	N	Correlations (r)	Sig. (2-tailed)	Pearson/ Spearman's rho
1	Refrigerator capacity	242	.31	p < .001	Pearson
2	Freezer ownership	351	.45	p < .001	Spearman's rho
3	Freezer capacity	88	.43	p < .003	Spearman's rho
4	Freezer age	113	.28	p < .003	Spearman's rho
5	Washing machine ownership	353	.33	p < .001	Spearman's rho
6	Geyser	349	.18	p < .001	Spearman's rho
7	Microwave oven	355	.38	p < .001	Pearson
8	Toaster	355	.26	p < .001	Pearson
9	Sandwich maker	355	.12	p < .03	Pearson
10	Rice cooker	355	.19	p < .001	Pearson
11	Cordless telephone	355	.19	p < .001	Spearman's rho
12	Iron	355	.16	p < .001	Spearman's rho
13	Vacuum cleaner	355	.15	p < .004	Spearman's rho
14	Hair dryer	353	.27	p < .001	Pearson

#	Parameters	N	Correlations (r)	Sig. (2-tailed)	Pearson/ Spearman's rho
15	Home theatre	355	.22	p < .001	Spearman's rho
16	Total no. of appliances	355	.34	p < .001	Pearson
17	Total no. of rechargeable items	337	.31	p < .001	Pearson
18	Total no of TV/household	357	.41	p < .001	Pearson
19	TV use (hours)	263	.21	p < .001	Spearman's rho
20	IPS ownership	264	.26	p < .001	Spearman's rho
21	IPS capacity	214	.39	p < .001	Spearman's rho

Based on the findings of the correlational study, it can be said that in general, all cooling appliances, whether to achieve thermal comfort or used as common household appliances (e.g., refrigerator, freezer, etc.) along with artificial lights, microwave oven, TV and IPS accounted for the major share of the households' total energy consumption. Therefore, to reduce the energy consumption of the subject households effectively, reducing the use or enhancing the energy efficiency of these appliances would be likely to provide successful outcomes.

7.6.3 Dominant Parameters

Regression analyses were conducted to find out the most influential indirect and direct parameters in terms of affecting the total energy consumption of the studied households in typical residential areas in Dhaka. The analyses were conducted in two steps for both the indirect and direct parameters.

Several procedures were followed and decisions were made before conducting the regression analyses: i) the total energy consumption of the households were considered as the dependent variables and all other indirect and direct parameters were considered as the independent variables; ii) the assumptions of normality, linearity and homoscedasticity of the variables were checked through scatter plots and histograms, and the model was checked through normal P-P plot and scatter plot; iii) for this study, highly skewed continuous variables were transformed to meet the assumption of normality and to be able to derive the best model fit. This research was aware of the issues regarding the interpretation of regression results with transformed variables. However, since the goal of the regression analyses in this study was to find the most influential parameters but not to derive predictive equations to predict the energy consumption of the households, transforming the skewed variables was deemed appropriate for this research. It provided better fit and hence, better information about the dominant parameters (Pallant, 2011; Tabachnick & Fidell, 2008). In addition, it ensured that no multicollinearity and singularity existed between the independent variables. The maximum number of independent variables for a single analysis was determined by the minimum number of case studies required to derive a reliable regression model. According to Stevens (1996), about 15 cases are needed per independent variable for social science research and according to Tabachnick and Fidell (2008), following the formula of $N>50 + 8m$ (m = number of independent variables) should be used to derive the required number of cases. More cases are needed if the dependent variable is skewed and about 40 cases per independent variable in the case of using stepwise regression (Pallant, 2011).

Finally, a standard multiple regression analysis method was used for this study—the stepwise regression method was excluded because of the criticism associated with its use (Pallant, 2011). After checking all necessary assumptions and transformation of variables, multiple regression analyses were conducted with the indirect and direct parameters as the independent variables and the total energy consumption as the dependent variable. To deal with the missing data and outliers, 'exclude case wise' and 'exclude outliers outside 3 standard deviation' options were chosen.

The indirect parameters included for the regression analyses were apartment size, total occupants, unit area per person, occupancy status(owner or rent-payer), monthly income, non-residential activity at home, building's construction (developer- or owner-built), number of floors, top or intermediate floor, orientation, external wall construction, presence of indoor plants, cross-ventilation, presence of external glass doors, frequency of opening balcony doors, frequency of opening bedroom doors, opening the windows in summer, frequency of opening bedroom windows, frequency of opening common-space windows, frequency of opening bedroom curtains, frequency of opening common-space curtains, presence of mosquito nets and window type (sliding or shutter).

A statistically significant model ($p < .001$) with $R^2 = .612$ was derived after the first standard regression analysis, which meant that the model (including the indirect parameters as independent variables) could explain 61.2% of the variance in the dependent variable (total energy consumption). The normal probability plot (P-P) of the regression standardised residual and the scatter plot showed that there were no major deviations from the assumptions of normality, linearity and homoscedasticity.

Table 7.8: *Regression Analyses-1: Indirect Parameters vs Energy Consumption_ Model Summary*

Model	R	R^2	Adjusted R^2	Sig.
1	.782	.612	.539	.0005

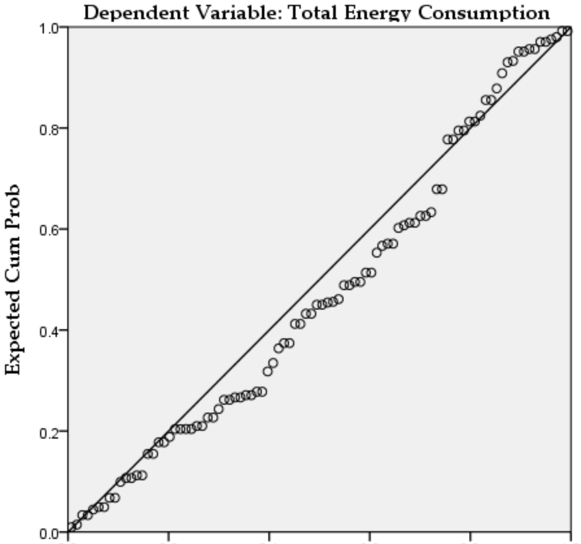

Figure 7.34: *Regression Analyses-1:Normal P-P Plot of Regression Standardised Residual*

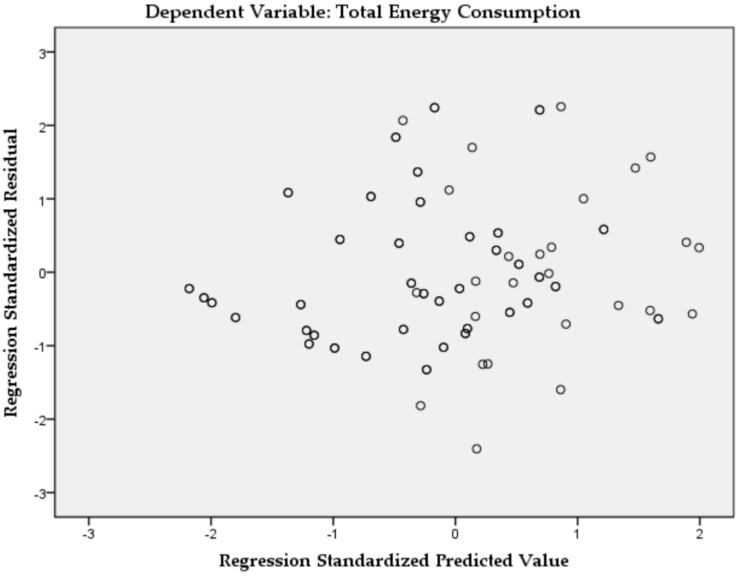

Figure 7.35: *Regression Analyses-1: Scatterplot*

To find out the most dominant indirect parameters (i.e., which of the independent variables contributed the most to the prediction of the dependent variable), the standardised coefficient (Beta) value for all of the independent variables were checked from the coefficients chart of the regression analyses output with associated statistical significance. It was found from the results that apartment size, total occupants, monthly income, cross-ventilation, frequency of opening bedroom doors, frequency of opening bedroom windows and mosquito nets reached the statistical significance, which suggested that these parameters each made a unique contribution in predicting the dependent variable in the model. That is, these were likely to be the most dominant indirect parameters in determining the energy-use intensity of the households in the case study areas.

Table 7.9: *Beta value of the Significant Independent Variables (Indirect Parameters)*

#	Parameters	Standardised Coefficients (Beta)	Sig.
1	Frequency of opening bedroom windows	.290	p < .001
2	Apartment size	.269	p = .004
3	Cross-ventilation	.236	p < .001
4	Mosquito nets	.203	p < .001
5	Monthly income	.197	p = .001
6	Total occupants	.184	p = .039

#	Parameters	Standardised Coefficients (Beta)	Sig.
7	Frequency of opening bedroom doors	.164	p = .013

Further analysis was conducted to find out the level of influence of the significant indirect parameters. To do this, the Beta values of the significant indirect parameters were compared. It was seen from the results that frequency of opening bedroom windows had the largest Beta value, followed by apartment size, cross-ventilation, having mosquito nets, monthly income, total occupants and frequency of opening bedroom doors. The frequency of opening bedroom windows made the largest unique contribution in explaining the total energy consumption when the contribution of all other variables was controlled in the model. This result indicated that the operational practices of the occupants, such as opening windows and doors, particularly in bedrooms (i.e., allowing more ventilation) had the strongest impact on the energy-consumption intensity of the households. This was followed by the income and occupant number.

The urban and building design and construction-related parameters had no significant unique contribution in explaining energy consumption when assessed along with all other indirect parameters. From an energy-consumption point of view, the result suggested that if the indoor ventilation could be improved, household energy consumption would be effectively reduced.

The second regression analysis was conducted with all the direct parameters or the appliances used in the case study apartments, to find out which appliances account for the major share of the total energy consumption. The appliances investigated for the regression analyses were total fans, total ACs, total heaters, total lights, total refrigerators, total freezers, total TVs, total computers, total rechargeable items, total number of appliances and the possession of a geyser, washing machine, electric oven, microwave oven, toaster, sandwich maker, juicer, iron, hair dryer, rice cooker, cordless telephone, vacuum cleaner, home theatre, printer and IPS.

A statistically significant model ($p < .001$) with $R^2 = .571$ was derived from the second standard regression analysis with the direct parameters as independent variables, which meant that the model could explain 57.1% of the variance in the dependent variable (total energy consumption). The normal probability plot (P-P) of the regression standardised residual and the scatter plot (see Figures 7.36 and 7.37) showed that there were no major deviations from the assumptions of normality, linearity and homoscedasticity.

Table 7.10: *Regression Analyses-2: Direct Parameters vs Energy consumption_ Model Summary*

Model	R	R^2	Adjusted R^2	Sig.
2	.756	.571	.536	$p < .001$

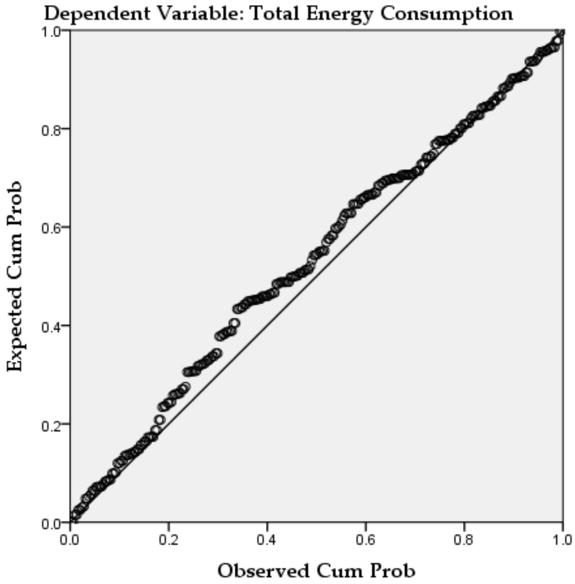

Figure 7.36: *Regression Analyses-2: Normal P-P Plot of Regression Standardised Residual*

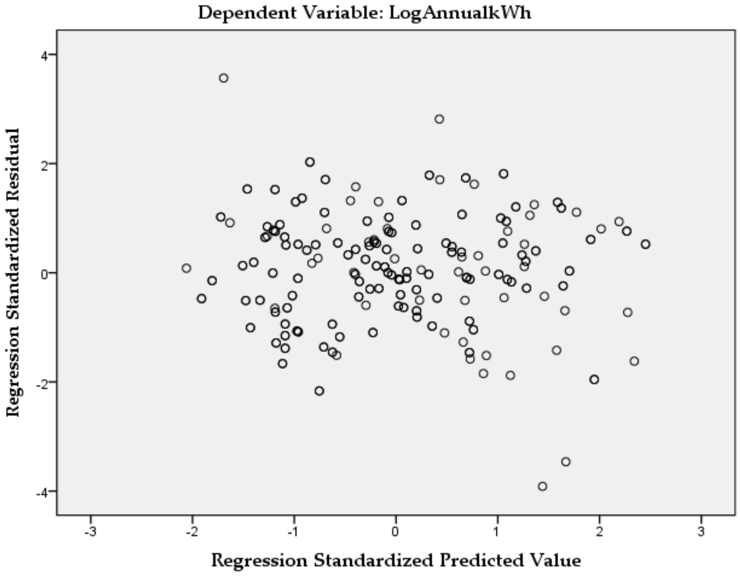

Figure 7.37: *Regression Analyses-2: Scatterplot*

To find out which direct parameters (appliances) contributed most to the prediction of the dependent variable (total electricity consumption), standardised coefficient (Beta) values were checked with associated statistical significance for all. It was found from the table that the total number of ACs, rechargeable items, computers and the ownership of freezer, washing machine, electric oven, microwave oven, hair dryer and home theatre reached the statistical significance, which suggested that these parameters made unique contributions in predicting the dependent variable. That is, owning these appliances was likely to contribute strongly to the energy-use intensity of the households in the case study areas.

Table 7.11*: Beta Value of the Significant Independent Variables (Direct Parameters)*

#	Parameters	Standardised Coefficients (Beta)	Sig.
1	Total ACs	.495	p < .001
2	Total rechargeable items	.251	p < .001
3	Freezer ownership	.209	p < .001
4	Hair Dryer ownership	.184	p = .015
5	Home Theatre ownership	.176	p < .001
6	Electric Oven ownership	.141	p = .015
7	Washing Machine ownership	.140	p = .004
8	Microwave oven ownership	.113	p = .047
9	Total computers	.088	p = .049

Further analyses with the Beta value of the significant direct parameters were compared. It was seen from the results that the total number of AC units had the largest Beta value, followed by total rechargeable items, ownership of freezer, hair dryer, home theatre, electric oven, washing machine and microwave oven and the total number of computers. This meant that the total number of AC units made the largest unique contribution in explaining the total energy consumption when the contribution of all other variables was controlled in the model. The result clearly suggested that possession of AC units was the most influential factor in determining the energy use intensity of the studied households. This finding is not unusual, given the fact that AC units require a large amount of energy to run and they are expensive to buy; therefore, they are owned by wealthier households, who tend to consume more energy. However, from an energy-consumption point of view, this study also suggested that reducing the use of AC by enhancing thermal comfort through appropriate design decisions would result in reduced energy consumption.

It is certain that owning an AC increases the household's total energy consumption significantly; however, it is difficult to infer from any statistical analyses the extent or percentage of total energy consumption that is due only to AC use. First, households do not run AC throughout the year and second, the households with AC were likely to use a variety of other energy-intense appliances. The extent of AC use and the extent to which this use could be reduced were investigated in this study through simulation studies, as discussed in the next stage of this research (see Chapter 8).

7.7 SUMMARY FINDINGS AND DISCUSSION

7.7.1 Summary Findings: Existing Contexts

The following table summarises the existing contexts of different household parameters in the case study areas.

Table 7.12: *Summary Chart with Key Findings: Existing Contexts of the Household Parameters*

#	Household Parameters	Key Findings: Existing Contexts
1	Average number of occupants per household	4.84
2	Home-stay maid	Present in 52.1% of the households.
3	Average occupants' number (excluding maids)	4.15
4	Male-female ratio	51/49
5	Occupancy pattern	Households are never fully vacant throughout the day, whether it is a working day or a holiday.
6	Average apartment size	Single-unit apartment: 2,535 ft^2 (225.5 m^2). Double-unit apartment: 1387 ft^2 (128.9 m^2).
7	Average unit area per person	546 ft^2 (50.8 m^2)
8	Average number of floors	5.37
9	Dwelling-unit density	8.19/building
10	External wall	5″ (125 mm) or 10″ (250mm) solid bricks.
11	Roof	RCC slab with cement finish
12	Floor finish	Tiles.
13	Carpet	Not common.
14	Roof garden	Present in 25% of the buildings.
15	Dominant window type	Sliding with an aluminium frame.
16	External glass door	In 38.5% of the households.
17	Window operation	Infrequent—70% of the households do not open the bedroom windows frequently.
18	Ceiling fan	Present in 100% of the households (usually in every room).
19	Average number of ceiling fans per household	6.43, majority (70.9%) have 4–6 fans.
20	Average use of a ceiling fan	On a working day in summer: 7.55 hours On a weekend in summer: 8.55 hours Average use of a bedroom fan (9.9 hours on a working day) is nearly double the average use of a common space's fan (4.42 hours, working day)
21	AC ownership	Present in 70.5% of the buildings.

#	Household Parameters	Key Findings: Existing Contexts
22	Average number of AC units per household	2.36—the majority (62%) have 1–2 AC units.
23	AC installation	Majority (84.2%) of the cases in the master bedroom.
24	AC type	Window or split. No central AC systems.
25	Average use of an AC	On a working day in summer: 5.9 hours On a weekend in summer: 6 hours
26	Heaters	Not common. Present only in 14% of the households.
27	Average number of lights per household	19.5
28	Common types of lights	Energy bulbs (CFL, 20–25 Watt) and tube lights (fluorescent, 40 Watt). 92% of households had more than one type of bulb.
29	Cold appliances	Refrigerator: Present in 100% of the households Freezer: Present in 58.5% of the households Majority (61.3%) had more than one cold appliance.
30	Age of cold appliances	More than 50% of cold appliances older than 5 years.
31	Wet appliances	Washing machine, dryer & geyser: Not very common.
32	Cooking appliances	Juicer-blender and microwave oven the most common.
33	Brown goods	TV: The most common appliance—nearly every household has a TV. CRT and LCD TVs are the most common. Average use 6.25 hours/day.
34	Standby power	Occupants generally unaware about standby power consumption.
35	Energy-efficient appliances	Not common (excluding artificial lights) .
36	Electricity consumption (kWh) per household (in 2013)	Annual Average (all households): 6,570 kWh Annual Average (without AC): 4,381 kWh Annual Average (with AC): 7,649 kWh Lowest daily average: 13.9 kWh in January Highest daily average: 21.3 kWh in July
37	Electricity consumption (kWh) per unit area	Single-unit apartment: 41.47 kWh/m^2 Double-unit apartment: 42.08 kWh/m^2

7.7.2 Summary Findings: Household Parameters vs Energy Consumption

Among the household-characteristic-related parameters, income and the total number of occupants had a significant positive relationship with the total energy consumption. Income had stronger relationship than the number of occupants.

Among the building parameters, the size of the apartment, whether it was developer-built or owner-built, apartment floor level, external wall construction, window type, presence of glass doors and presence of mosquito nets had significant correlation with the total energy consumption. Of these parameters, developer-built or owner-built, external wall construction and type of windows were negatively correlated and the others were positively correlated. The interpretation of these results is that if the building was built by the owner and had a thicker external wall (250 mm instead of 125 mm) and if the windows were shutter type instead of sliding, the energy consumption of the households decreased. If the size and floor level of the apartment increased and glass doors and mosquito nets were present, the energy consumption increased. Apartment size and the presence of glass doors had considerably stronger relationship than other parameters.

Among the indoor ventilation and operational parameters, the overall cross-ventilation condition and the frequency of opening balcony doors, bedroom doors and windows, as well as opening windows in summer, were significantly related with the total energy consumption. Of these, cross-ventilation and opening windows in summer were positively correlated and the frequency of opening balcony doors, bedroom doors and windows were negatively correlated. The interpretation of these results was that if the cross-ventilation condition inside was poor and the windows were not opened in summer, the energy consumption increased. If the balcony doors, bedroom doors and windows were opened more frequently, total energy consumption decreased. The frequency of opening bedroom doors and windows had a stronger relationship than the other parameters.

As expected, all thermal comfort-achieving appliances, such as fans, AC and heaters, as well as artificial lights, showed a positive correlation with the total energy consumption, which means that increasing the number and use of these appliances increased the total energy consumption. The ownership of an AC had the strongest correlation, followed by the number of AC units and artificial lights.

Among the domestic appliances, all cold appliances and wet appliances, microwave oven, toaster, sandwich maker, rice cooker, number and use of TVs, home theatre, iron, vacuum cleaner, hair dryer, total number of rechargeable items and appliances and ownership of IPS had a significant positive correlation with the total energy consumption. The ownership and capacity of freezers, as well as the number of TVs, had the strongest relationship compared to other significantly correlated domestic appliances.

Among all indirect parameters, frequency of opening bedroom windows, apartment size, cross-ventilation, the presence of mosquito nets, monthly income, total number of occupants and frequency of opening bedroom doors had the strongest impact on the total energy consumption. The result suggested that the operational practices of opening windows and doors, particularly in bedrooms, and the income of the households were the most influential indirect parameters in determining the total energy consumption of the households within the given contexts. Building design and construction type were weaker determinants of the energy consumption within the given contexts.

Among all direct parameters or appliances, total number of AC units, rechargeable items and computers and the ownership of freezer, hair dryer, home theatre, electric oven, washing machine and microwave oven had the strongest impact on the total energy consumption. The result suggested that owning these appliances influenced the energy use intensity most. However, given the findings that not all households owned the above appliances, the result may indicate the fact that the households with higher income owned these appliances and hence, had higher energy consumption. This further emphasises the importance of increasing awareness of the households about the energy consequences of different appliances as well as promoting energy-efficient appliances, to maximise the reduction in energy consumption in the residential developments.

7.7.3 Discussion

This study has identified several household parameters and existing practices that could be altered and improved to obtain substantial energy conservation. One of the major findings was the consistent and significant correlation between the frequency of opening doors and windows and overall cross-ventilation and the total energy consumption. This indicates quite strongly that a lack of ventilation leads to higher energy consumption. This finding is further confirmation of the findings of the microclimatic study, which also showed much higher indoor air temperatures when the doors and windows were closed. While improving cross-ventilation and heat release from inside the buildings will reduce the households' consumption of cooling energy, how that will be achieved is a major challenge, considering Dhaka's socio-cultural and socio-economic contexts. The extent to which this energy reduction can be achieved also needs to be identified.

In addition to cross-ventilation, household income and the number of occupants of the household were stronger determinants of the total energy consumption than the building design and construction. Considering the general unawareness of Dhaka households about energy-efficient appliances, as well as the energy consequences of certain practices, this finding also suggests that increasing the awareness of households and promoting energy-efficient appliances could result in a significant reduction in energy consumption. In addition, it is the wealthier households of the city that consume more energy and they can afford to buy energy-efficient appliances.

AC, along with the cold appliances (refrigerator and freezer), were the dominant appliances in determining the energy use intensity of a household. Therefore, promoting energy efficiency in these appliances should provide significant results in reducing energy consumption. Since AC is used mostly in the master bedroom and bedroom-2, these two rooms need extra attention from a design and construction point of view to achieve thermal comfort. Achieving thermal comfort during the hot-wet months is likely to maximise the reduction of consumption of cooling energy. However, since the average cooling requirement accounts for about 24% of the total energy consumption and more than 70% of the households' consumption is due to other appliances, without reducing consumption from other appliances, energy reduction maximisation is not possible. To reduce energy consumption from other appliances, the introduction and promotion of energy-efficient appliances is important. So far, energy-efficient appliances (apart from energy-efficient artificial lights) have not yet penetrated the market and are not popular among households.

Every studied household had ceiling fans, artificial lights and TVs. More than half of the households had a microwave oven, juicer-blender, iron, IPS and a number of rechargeable items. Therefore, along with AC and cold appliances, replacing these appliances with energy-efficient ones should be targeted first, along with an awareness campaign to increase the occupants' willingness regarding energy-efficient appliances and energy-saving behaviour, such as turning off the switch after watching TV.

7.8 CONCLUSION

This chapter has presented the existing contexts of different energy-influencing household parameters along with the household energy consumption pattern and intensity in typical residential developments in Dhaka. In addition, the relationship between different parameters and energy consumption has been presented. Several existing contexts and parameters have been identified as being capable of reducing the current energy consumption level; however, whether these changes would result in reductions in energy consumption and to what extent the reductions could occur were tested through simulation studies, the results of which are presented in Chapter 8.

Part III: Results (Simulation Studies) and Conclusion

Chapter 8: Results: Exploring Possibilities for Energy Independence

Chapter 9: Conclusion and Recommendations

8 RESULTS: EXPLORING POSSIBILITIES FOR ENERGY INDEPENDENCE

8.1 INTRODUCTION

This chapter presents the final stage of the research to answer the three RQs of this study:

i) What are the ways to reduce existing household energy (electricity) consumption in typical planned residential developments in Dhaka?
ii) To what extent can the existing energy consumption of the households in typical planned residential developments be reduced?
iii) Is it possible to achieve energy independence through roof-mounted solar PVs after reducing the level of energy consumption?

8.2 METHODS

As discussed in Section 4.4.4, building simulation was used to answer the RQs and the IESVE (Version 2015.2.2.0) program was used for the studies. The procedures followed for the simulation studies were divided into four parts: selection of the case study apartment; reproduction of the case study apartment; calibration of the model; and data generation and analysis.

8.2.1 Selection of the Case Study Apartment

One of the 18 case study apartments that were investigated during the microclimatic contexts study was selected to conduct the simulation studies. The case study apartment used for the simulation studies was situated in DOHS Baridhara. The main reasons for selecting this apartment were that it was representative of a typical apartment in a typical developer's building and the willingness of the owner to provide the detailed information regarding the input data needed for the simulation. It had an indoor data logger installed along with an outdoor logger, the measurements of which could be used for calibration purposes.

The case study apartment was a typical Type B double-unit apartment (see Section 5.3.5) situated at 3rd-floor level with two front facades (see Section 5.3.2) at the north and west (see Figures 8.1 and 8.2). This study focused on buildings with Type B double-unit apartments, as these were the most common (see Section 5.3.5). In addition, a Type B apartment unit adjacent to the access roads has the most exposure to direct solar radiation and hence, the highest consumption of cooling energy. It is important to note that not only were the building characteristics of the case study apartment typical of the apartments in this study, the apartment's total energy consumption (7,369 kWh) was similar to the average energy consumption of the studied households with AC (7,649 kWh) (see Section 7.5).

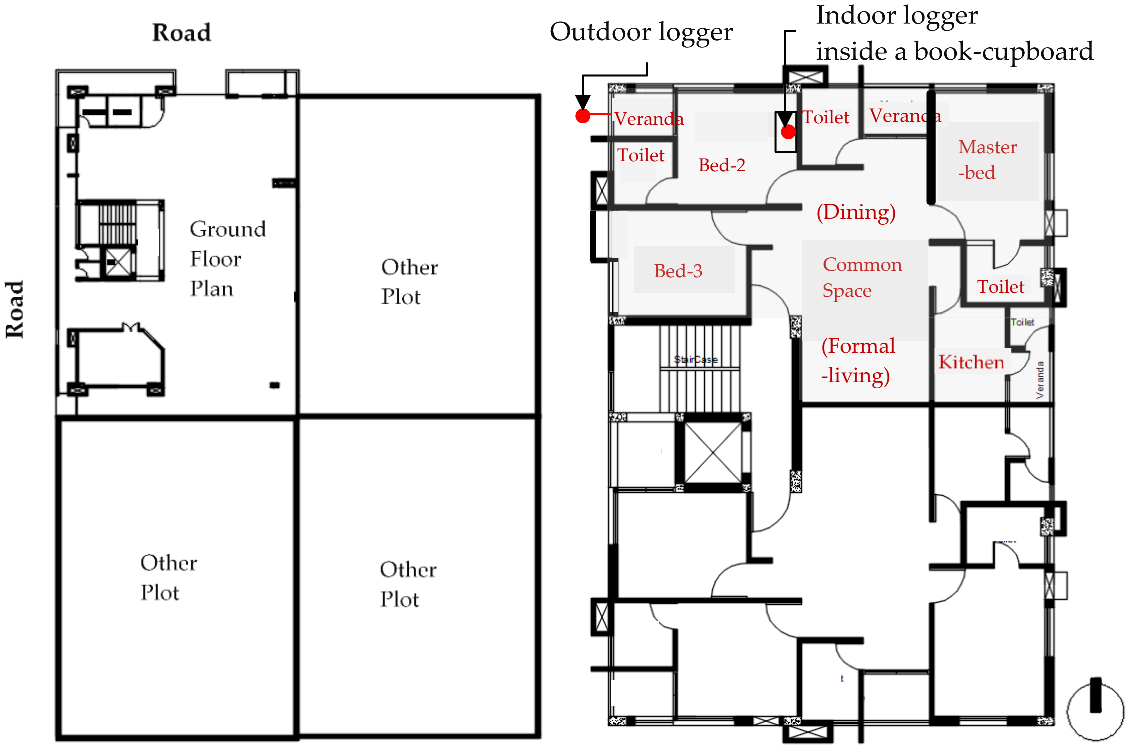

Figure 8.1: *Ground Floor Plan and Unit-plan of the Case Study Apartment*

Figure 8.2: *The Case Study Apartment and the Outdoor Logger*

8.2.2 Reproduction of the Case Study Apartment

Two types of input data were collected to reproduce the case study building in the simulation program: basic data, which were definite and included factors such as orientation, dimensions of the external and internal walls, glazing areas, construction materials and appliance ownership; and tentative data, which were not definite and included factors such as occupancy pattern, window operation and appliances use hours. Most of the basic data (collected from the architectural drawings, site survey and the questionnaire survey) and some of the tentative data (through personal communications) were collected during the field studies. Further detailed information regarding factors such as window operation and appliance use were collected afterwards through several phone calls. Once all the necessary input data were collected, the case study apartment, along with its surrounding built-environmental contexts, was reproduced in IESVE (Figures 8.3 and 8.4).

Figure 8.3: *The Simulated and the Actual Building*

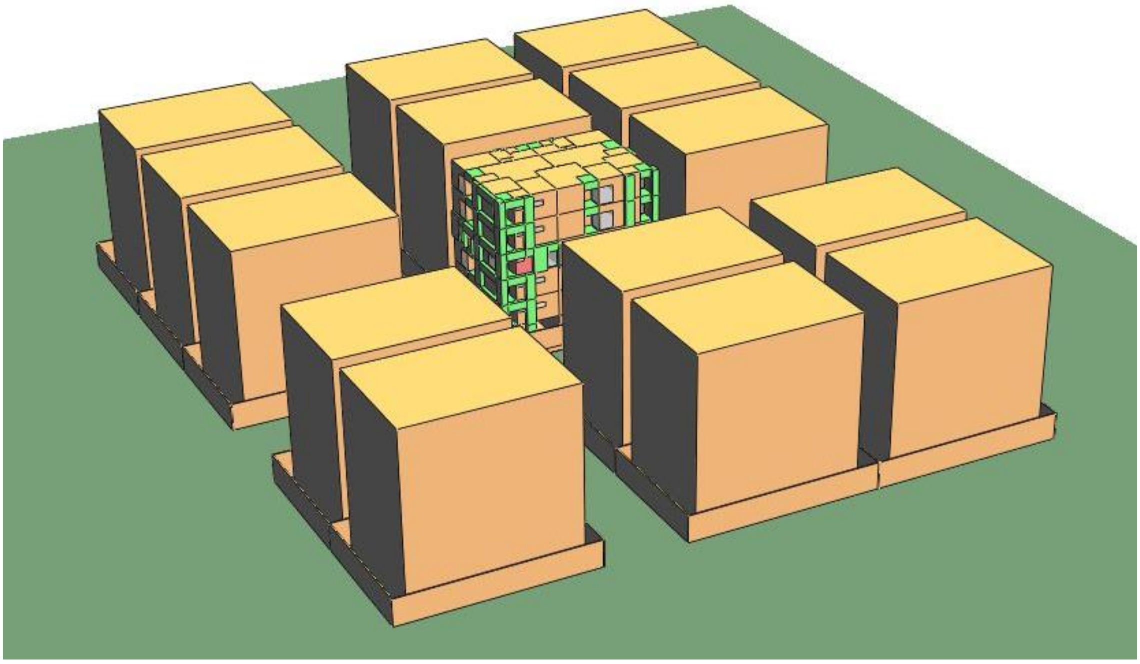

Figure 8.4: *The Case Study Building with the Surroundings in Simulation*

Table 8.1: *Basic Input Data for the Reproduction of the Case Study Apartment*[17]

#	Item	Description
	General	
1	Total number of occupants	Four. In general, at least one person stay at home throughout the day.
2	Apartment size	1365 ft^2 (126.88 m^2)
	Construction	
3	External walls	10″ (250 mm) solid brick wall, plastered on both sides and painted. U value (W/m^2 K): 2.0514. Few walls such as the ones between rooms and verandas are 5″ (125 mm) solid brick wall, plastered and painted. U value (W/m^{2}K): 2.9529.
4	Window glazing	0.24″ (6 mm), single-glaze reflective glass with aluminium framing. U value (W/m^2 K): 5.5599
5	External glass door to the veranda[18] from the bed-2	0.24″ (6 mm), single-glaze reflective glass with aluminium framing. U value (W/m^2 K): 5.2520
6	External glass door to the veranda from the common space	0.24″ (6 mm), single-glaze reflective glass with aluminium framing. U value (W/m^2 K): 5.1742

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[17] *Simulation input such as occupancy schedules, doors and windows operation and appliances use profiles can be found in the supplied IESVE files in CD.*

[18] *In Dhaka, balconies are commonly referred to as verandas.*

#	Item	Description
7	Internal ceiling and floor	5″ (125 mm) reinforced concrete slab with clay tile for flooring and plaster for ceiling. U value (W/m² K): 3.1757
8	Internal room walls	5″ (125 mm) solid brick wall, plastered on both sides and painted. U value (W/m² K): 2.0148
9	Toilet walls	5″ (125 mm) solid brick wall, clay tile finish on the toilet side and plastered on the other side. U value (W/m² K): 1.8622
10	Toilet ceiling and floor	5″ (125 mm) reinforced concrete slab with clay tile for flooring and plaster for ceiling. U value (W/m² K): 3.1267
11	Doors	Main entry door: 1.8″ (45 mm) thick wooden door, U value (W/m² K): 1.8454 All other doors: 1.5″ (37.5 mm) thick particle board door, U value (W/m² K): 2.5602
12	Book-cupboard wall	1″ (25 mm) thick particle board attached to 5″ (125 mm) solid brick wall, plastered. U value (W/m² K): 2.0148
13	Book-cupboard floor and roof	0.75″ (18.5 mm) thick particle board attached to clay tile and reinforced concrete slab. U value (W/m² K): 2.3168
14	Book-cupboard door	0.24″ (6 mm) thick clear float glass. U value (W/m² K): 3.7888
	Appliances	
15	AC	Total no: 3. In the master-bed, bed-2 and common space. No rating. Coefficient of performance: 1.42 KW/KW
16	Ceiling fan	Total no: 5 (70—75 Watt). 3 in the bedrooms and 2 in the common space
17	Artificial light	Total no: 15 (680 Watt). Two incandescent bulbs (100 Watt), two CFL bulbs (20 Watt) and 11 fluorescent bulbs (40 Watt)
18	Refrigerator (600Ltr)	Total no: 1. No rating (130 Watt)
19	TV	Total no: 2 (255 Watt).
20	Computer	Total no: 2. One desktop (100 Watt) and one laptop (130 Watt)
21	Washing machine	Total no: 1 (1300 Watt)
22	Miscellaneous	IPS (800 Watt), micro-oven (940 Watt), kitchen exhaust fan (45 Watt), iron and other kitchen appliances such as oven, sandwich-maker, toaster(4600 Watt), mobile charger and WIFI router (12 Watt)

8.2.3 Calibration of the Model

The success or reliability of a simulation study is dependent largely on the degree of replication of the real-world contexts achieved in the virtual model (Groat & Wang, 2013). Therefore, it is very important to calibrate the model before conducting any investigations with the simulated model. As stated in the international performance measurement and verification protocol (International Performance Measurement & Verification Protocol Committee, 2002),

> Calibration is achieved by verifying that the simulation model reasonably predicts the energy use of the facility by comparing model results to a set of calibration data. (p. 33)

In this study, the model was calibrated twice by comparing the simulation results: i) with the measured indoor air temperature data (from 1 September to 10 October 2013) and ii) with the monthly electricity consumption data (for 2013). Two separate weather files were used to calibrate the model. First, an hourly weather file for the study year (2013) was created from the 3-hourly weather data collected from the Bangladesh meteorological department. For the calibration with the measured indoor air temperature, the air-temperature of the created hourly weather file (from 1 September to 10 October 2013) was replaced with the measured outdoor air temperature since the micro-climatic study found that the air-temperature varies according to different orientations. For the calibration with the monthly electricity consumption data, the hourly weather file created from the 3-hourly weather data was used.

Previous studies have shown that first models often vary beyond the acceptable calibration range (American Society of Heating, Refrigerating and Air-conditioning Engineers, 1999; Haberl & Bou-Saada, 1998; Pedrini, Westphal & Lamberts, 2002) and this study was no exception to that. When inconsistencies occur, the usual procedure is to adjust the input data until the model matches with the measured data within the acceptable range (Heo, Choudhary & Augenbroe, 2012; Pan, Huang & Wu, 2007; Raftery, Keane & O'Donnell, 2011; Raftery, Keane & Costa, 2011; Reddy, Maor & Panjapornpon; 2007a, 2007b; Soebarto, 1997). Note that for the safety reason, the indoor logger was placed in a book-cupboard in the case study apartment, which is likely to bias the temperature when compared with the simulation results. To obtain accurate results, the book-cupboard itself was also modelled in the IESVE simulation. For the calibration with the measured indoor air temperature, adjustments were made mainly to the window and door operation schedules. The final use schedules better reflected the actual apartment use (see Appendix F.4: Calibrated Base-cases supplied in CD).

To evaluate how well the model has replicated the real-world situation, calculating the coefficient of variance of the root-mean-square error (CV (RMSE)) between the simulated data and measured data is most commonly used (International Performance Measurement & Verification Protocol Committee, 2002; Soebarto, 1997; Freney, Soebarto & Williamson, 2013; Pedrini et al., 2002). The equations to calculate the CV (RMSE) are as follows (Soebarto, 1997):

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (\hat{y}_i - y_i)^2}{n}} \qquad (1)$$

and

$$\text{CV (RMSE)} = \text{RMSE} / \bar{y} \times 100 \qquad (2)$$

In the above equations, $\hat{y}_i$ is the predicted value at hour i and y_i is the measured value at the same hour; n is the number of hours during the comparison period; and $\bar{y}$ is the average of the measured values for all hours of the period.

According to International Performance Measurement & Verification Protocol Committee (2002), calibrations based on monthly utility data can achieve ± 20% CV (RMSE) and those based on hourly data can achieve ± 10% to ± 20%. The prescribed acceptable range for CV (RMSE) is up to 20 % (American Society of Heating, Refrigerating and Air-conditioning Engineers in Pedrini et al., 2002; Habrel & Bou-Saada, 1998); therefore, a model that achieves at least 20% CV (RMSE) is generally considered acceptable. In this study, the calibration of the model with the measured hourly indoor air temperature achieved 1.37% CV (RMSE), which is much lower than the accepted range; hence, the accuracy of the model was considered very good, as it replicated the indoor thermal contexts of the case study apartment very well (see Appendix F.1 for detail CV(RMSE) calculation) . The model was further calibrated with the monthly electricity consumption of the case study apartment. The same procedures were followed. However, this time, the adjustments for the calibration were made with the AC use temperature and frequency. The calibration of the model with the monthly electricity consumption achieved 7.42% CV (RMSE), which was also better than the acceptable range (see Appendix F.2 for detail CV (RMSE) calculation).

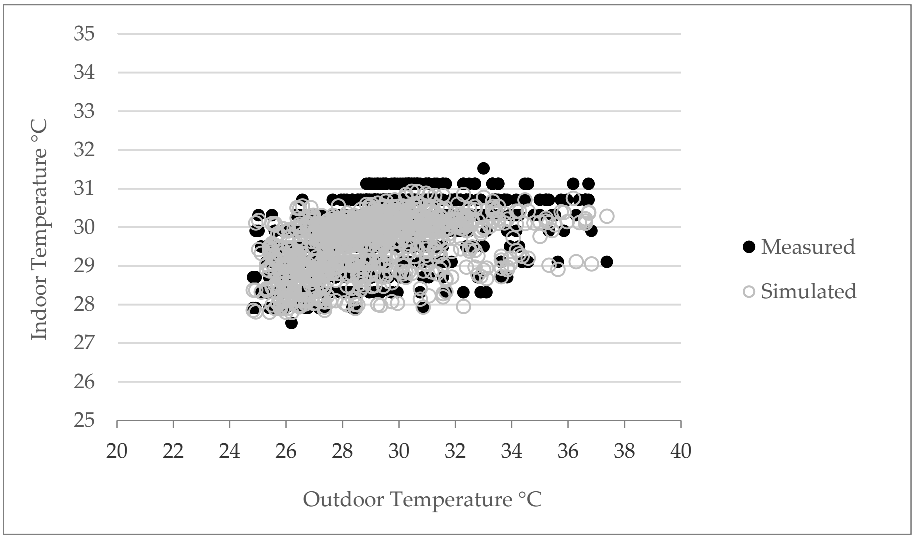

Figure 8.5: *Hourly Measured and Simulated Indoor Air Temperature (1 Sept.–10 Oct. 2013)*

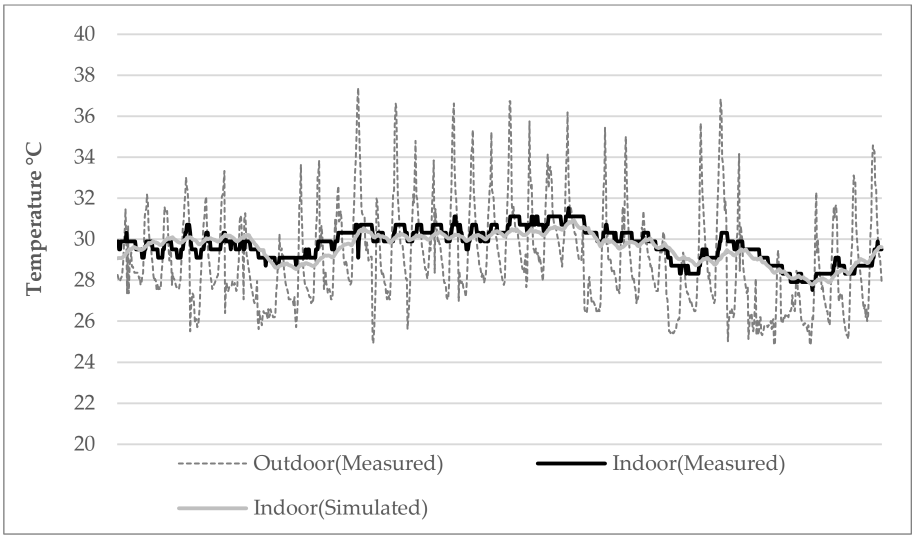

Figure 8.6: *Hourly Outdoor and Measured and Simulated Indoor Air Temperature (1 Sept.–10 Oct. 2013)*

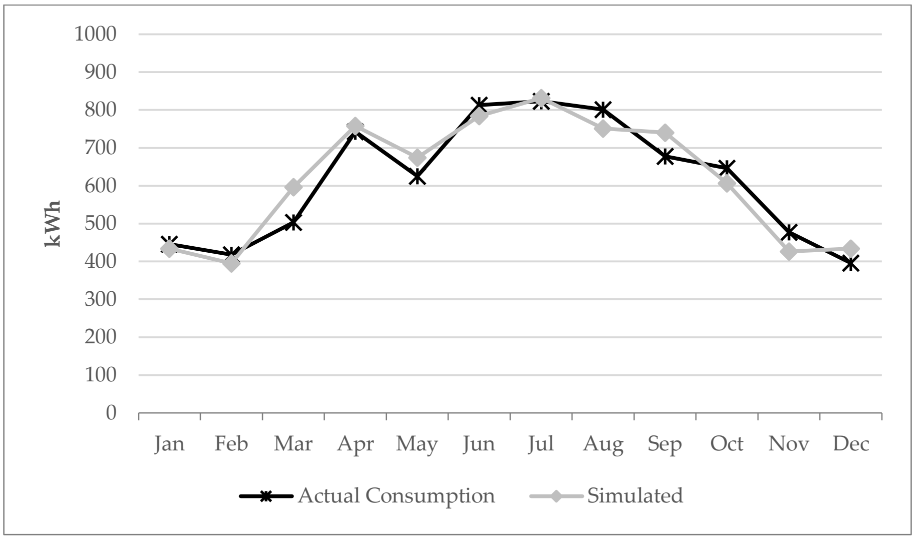

Figure 8.7: *Monthly Electricity Consumption for 2013 (Actual Consumption and Simulated)*

8.2.4 Data Generation and Analyses

Once the model was calibrated, simulations were run to generate data for conducting the simulation studies. Generated data were then analysed mainly through data comparison employing data visualisations or graphical representations methods with the help of Excel plots. Any simulation study essentially makes logical assumptions about the real world contexts. Further details of the analyses procedures as well as the assumptions made during the simulation studies are provided with the relevant sections.

For all the simulation studies, an hourly weather file for a typical meteorological year (TMY) in EPW format was used. The weather file was obtained from EnergyPlus (US Department of Energy, 2016). This research acknowledges that ideally, the weather file should be varied according to different orientations, as the microclimatic contexts study identified variations in air temperature due to different orientations; however, this was beyond the scope of this research, as the field study collected data for 40 days and a weather file for different orientations for a year was not available.

8.3 RESULTS

The following sections present the results of the analyses of the simulation studies, organised in three sections. The first section presents the results regarding the ways to reduce household energy consumption; the second section presents the results regarding the extent to which the existing consumption level could be reduced; and the third section presents the results regarding the possibilities of achieving energy independence.

8.3.1 Ways to Reduce Existing Energy Consumption

To find out ways to reduce the existing household energy consumption in typical residential developments, the effect of different parameters on energy consumption was investigated and the best practice for each of the parameters was identified. The calibrated apartment was used for all studies with input data adjusted for the context; for example, the shading from surrounding buildings for different floor levels. First, the urban parameters such as the orientation and effective CR were investigated followed by the building parameters such as external wall, window glazing, shading devices and WWR, window operation and most commonly used domestic appliances, which included ceiling fans, AC, artificial lights, refrigerator, freezer and TV.

To conduct these investigations, the case study apartment with its original input data such as the number of occupants, occupancy schedule, construction materials, internal heat gains, ceiling fans, AC, lights and other appliances' use frequencies were used. It was deemed appropriate to use the same profiles of the case study apartment, as the main goal of this step was to compare the difference in energy consumption due to different scenarios, to identify the impact and the best practices for different parameters.

The general procedures followed for the investigations were as follow: i) the parameters of the case study apartment were changed in simulation one at a time and the resultant energy consumption for that change was recorded; ii) the remaining parameters were kept constant while changing one parameter; and iii) the recorded results for different existing practices or possible alternatives of a parameter were then compared through Excel plots to identify the best practice within the given contexts.

8.3.1.1 Orientation

To find out the effect of different building orientations on energy consumption, in total eight orientations were investigated: north, east, south, west, north-east, south-east, south-west and north-west. Although, four cardinal orientations (north, east, south and west) are the most common in the typical developments, four orientations oblique to the cardinal orientations (north-east, south-east, south-west and north-west) were also investigated.

The most typical urban context is that the buildings are surrounded by buildings of the same height on three sides and the fourth side is the access road (see Section 5.2.1). Since the case-study apartment was on a corner plot, it was surrounded by two same height buildings and the other two sides were next to two access roads. For investigating the sole effect of different orientations within the given urban practice, the most typical urban context was considered, that is, in the simulation, the case study apartment was surrounded by same height buildings on three sides and the orientation of the north front façade was considered as the orientation of the case study apartment (see Figures 8.1 and 8.8). The orientation of the case study apartment was then changed in the simulation program and the associated energy consumption was recorded. The results obtained through simulation for each of the orientations were then plotted in Excel and compared. All other parameters of the case study apartment were kept constant while changing the orientations in the simulation.

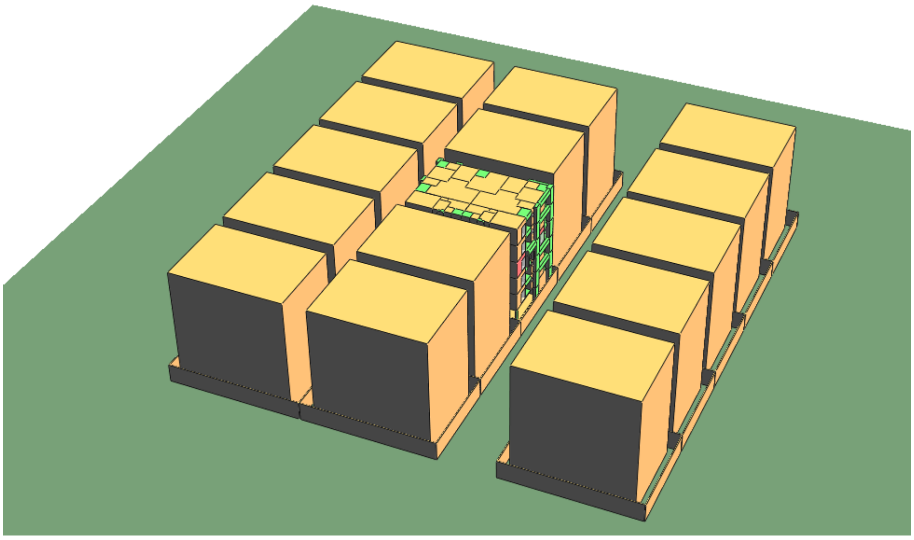

Figure 8.8: *Surrounding Built-environment of the Case-study Apartment for Orientation Studies*

Results were obtained for the five floor levels of the building[19]. The results showed that within the given urban practice at all floor levels, the case study apartment would have the maximum energy consumption when it was oriented south-west and the minimum energy consumption when oriented towards the north (see Figures 8.9–8.13). When the four cardinal orientations such as north, east, south and west were considered, the results showed that at the lower floor levels (up to 3rd floor), the maximum energy consumption occurred when the case study apartment was south-oriented. At the 4th and 5th floor, the east and west orientation required higher energy consumption than the south. The consumption variation pattern was the same at all floor levels for the four oblique orientations; that is, the maximum energy

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[19] *A typical apartment building is six storeys, with apartments from the 1st to 5th floor level (see Section 5.3.3).*

consumption was required when the case study apartment was oriented towards the south-west, followed by the south-east, north-west and north-east. These results suggested that within the given urban practices, at lower levels, south-oriented buildings would have higher consumption of cooling energy and at the upper levels, west-oriented buildings would have higher consumption of cooling energy than east and south. Buildings with a north orientation would always have the lowest consumption of cooling energy.

The average consumption of the five floor levels were compared, to find out which orientation, on average, would result in the best energy consumption. The north was identified as the best orientation, followed by the north-east, north-west, south-east, east, west, south and south-west (see Figure 8.14). The results suggested that excluding the north and south-west, the obliquely oriented buildings would be better than the cardinally oriented buildings such as the south, west and east.

Further study found that on average, the case study apartment would consume 2%, 1.7%, 1.7%, 1.4%, 1.3%, 1.1% and 0.7% more energy respectively, if it was oriented towards the south-west, south, west, east, south-east, north-west and north-east instead of oriented towards the north, within the given contexts (see Figure 8.15). In addition, for all orientations, the upper floors were found to have higher energy consumption than the lower floors, which is not unusual as the upper floors receive the highest amount of direct solar radiation (see Figure 8.16). It should be noted that the micro-climatic study found a slight decrease in outdoor air-temperature at upper floors for south orientation. This indicates that the energy consumption at upper floors of a south-oriented building may be slightly lower than the lower floors; however, the energy simulation found slightly increased energy consumption with increased height irrespective of orientation. This was likely due to the unavailability of orientation specific weather file as mentioned in Sec 8.2.4. However, since the difference is minimal, if this limitation leads to any error, it is likely to be minor.

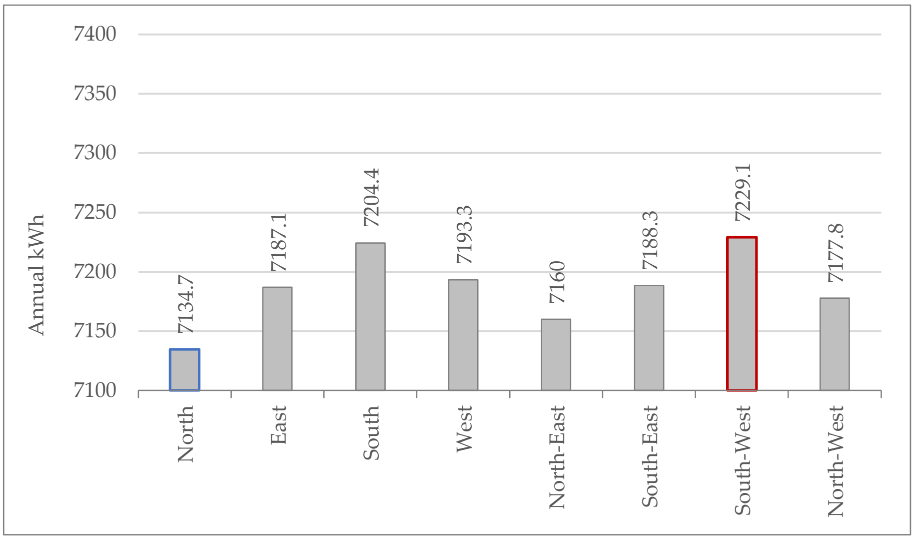

Figure 8.9: *Impact of Orientation at 1st-floor Level*

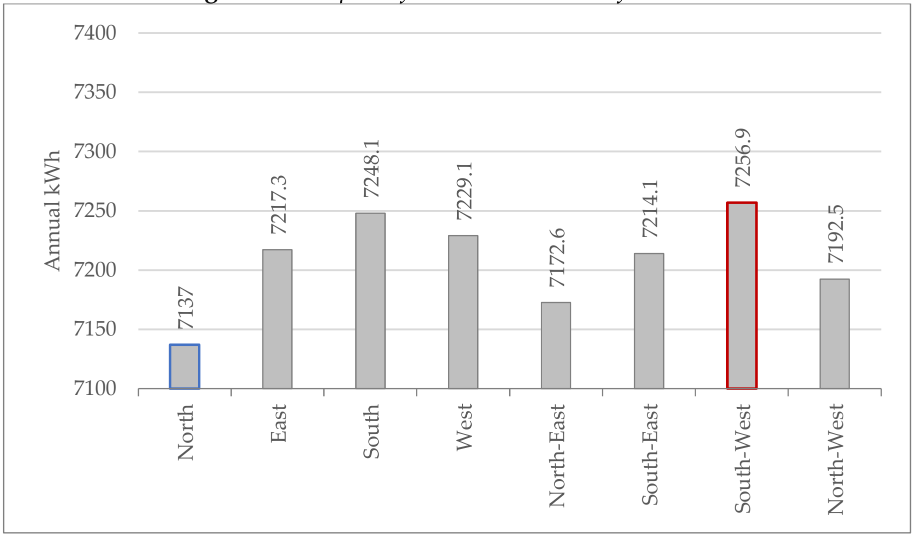

Figure 8.10: *Impact of Orientation at 2nd-floor Level*

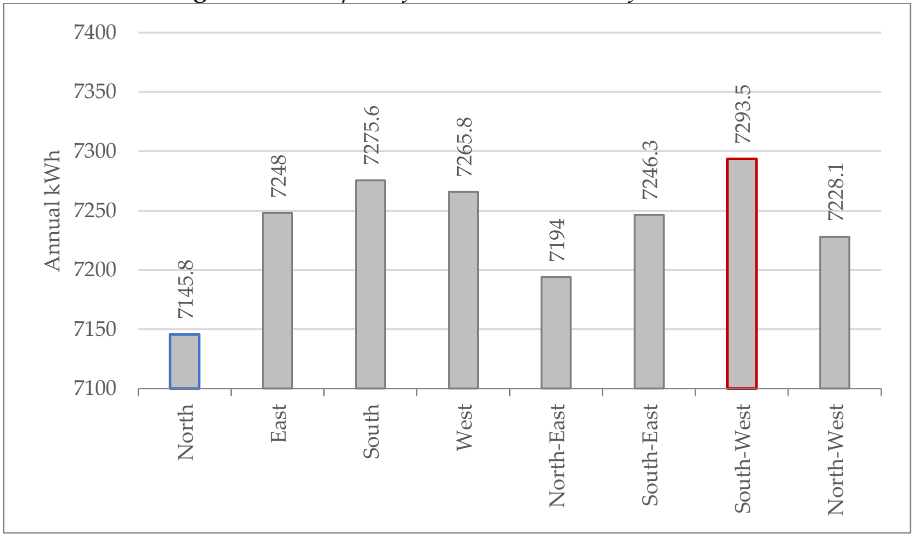

Figure 8.11: *Impact of Orientation at 3rd-floor Level*

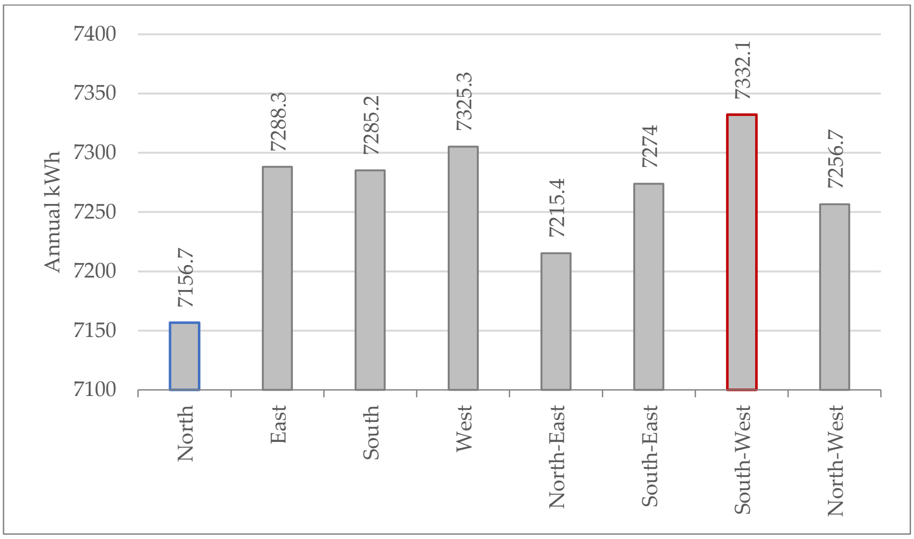

Figure 8.12:*Impact of Orientation at 4th-floor Level*

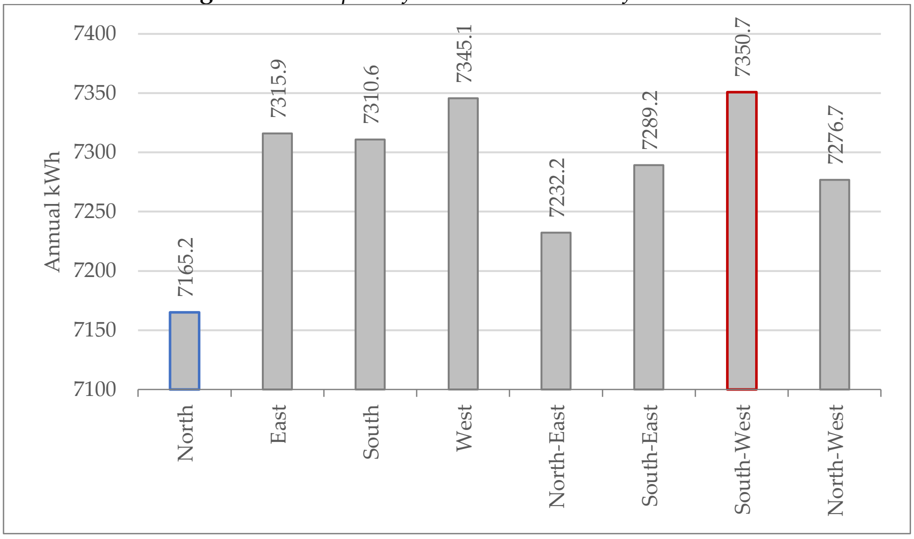

Figure 8.13: *Impact of Orientation at 5th-floor Level*

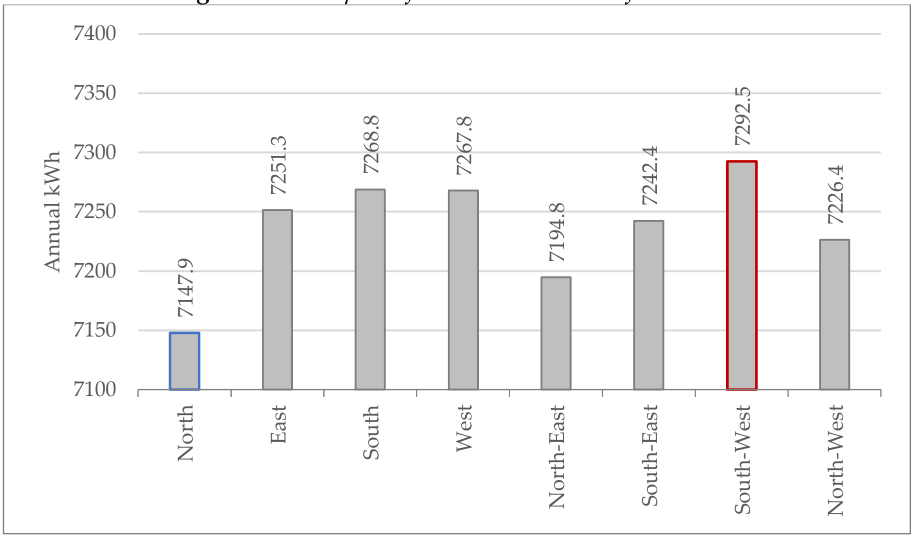

Figure 8.14: *Impact of Orientation: Average of all Floors*

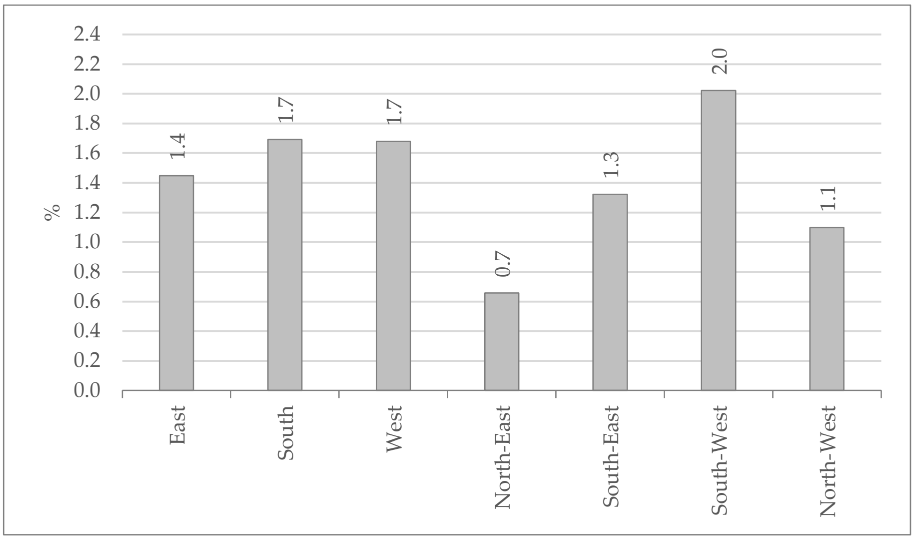

Figure 8.15: *Percentage Increase of Energy Consumption with North*

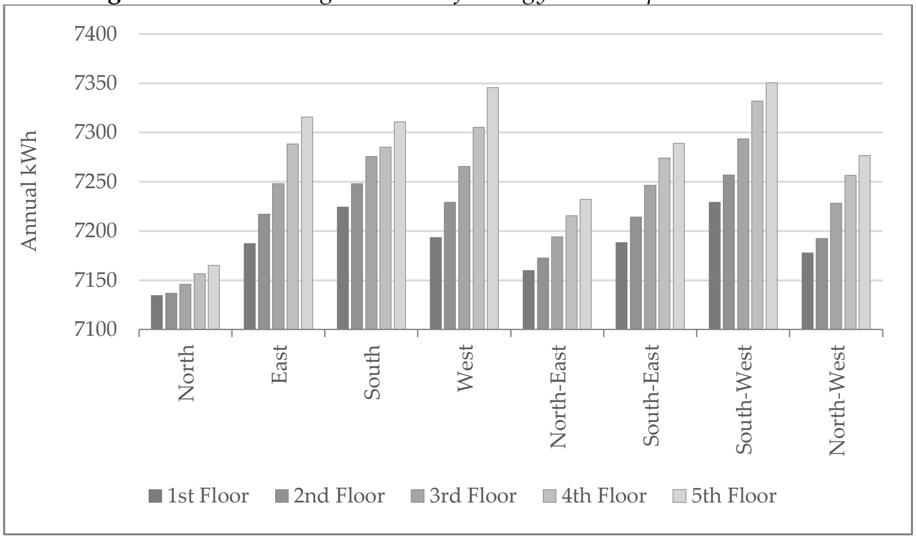

Figure 8.16: *Energy Consumption at Different Floor Levels for all Orientations*

Based on the findings, it can be said that within the given urban practices, a north-oriented building would have the lowest consumption of cooling energy and a south-west-oriented building would have the highest, compared to any other orientation when all other parameters were the same. If only the four cardinal orientations were considered, excluding north, the three other orientations did not vary meaningfully from each other from an energy-consumption point of view. Although the south orientation had a slightly higher energy consumption than east and west, the difference was so minimal, particularly between south and west, that it could be considered as no difference. These results were in line with what was assumed, based on the microclimatic findings that north-oriented building would have the lowest consumption of cooling energy and south-oriented building would have the highest, within the given urban contexts. The results also showed that within the given urban practices, the south was not the best orientation from an energy-consumption point of view. According to the findings of the existing contexts study, less than 30% of the total plots had a north orientation (see Section 5.2.3). Therefore, to maximise energy consumption reduction in typical residential developments in Dhaka, more plots should be north oriented although the maximum consumption difference was 2%.

8.3.1.2 Effective Canyon Ratio

Investigations were made to find out the impact of the effective CR on energy consumption for different orientations. Considering the typical building-to-building distance at the front and the maximum height of a six-storey building in typical residential developments (see Section 5.3.3), the effective CR in front of the buildings were 1.33 at 1st-floor level, 1.08 at 2nd-floor level, 0.83 at 3rd-floor level, 0.58 at 4th-floor level and 0.33 at 5th-floor level. To find out the impact of the effective CR (that is, the shadow effect of the opposite building) for different orientations, the width of the access road and the height of the opposite building were varied in the simulation program to obtain different CRs and the resultant energy consumption for a particular ratio. All other parameters of the case study apartment were kept constant while changing the CR in simulation.

The results showed that for a north orientation, energy consumption decreased with the increase of CR up to 1.8 in a slightly curvilinear way; however, the decrease was very slight. The results also showed that increasing CR above 1.8 did not result in a noticeable change for this orientation (see Figure 8.17). However, for east and west orientations, changing the CR resulted in noticeable curvilinear changes in consumption; that is, consumption decreased steeply up to 1.2 CR and after that it decreased more slowly up to 2.2 CR. Above 2.2 CR, the consumption remained nearly same, without noticeable changes (see Figures 8.18 and 8.20). For a south orientation, consumption decreased gradually and linearly with the increase of CR up to 2.8 CR. After that, increasing the CR did not affect the consumption (see Figure 8.19).

The impact of CR was found to have similar pattern for other four oblique orientations: north-east, south-east, south-west and north-west (see Figures 8.21–8.24). For all four instances, the consumption was found to decrease in a slightly curvilinear fashion up to 2.1 CR; however, above 2.1 CR, the consumption reduction was negligible.

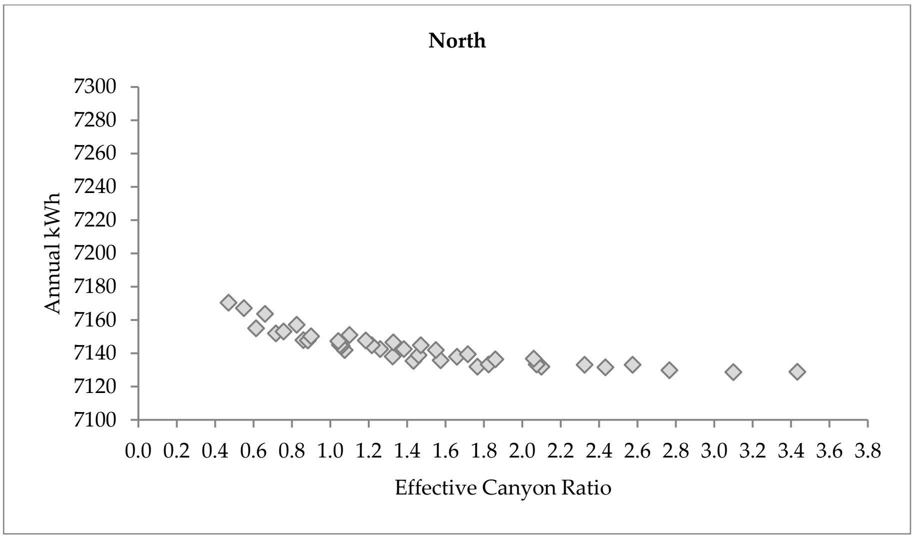

Figure 8.17: *Impact of Effective CR at North Orientation*

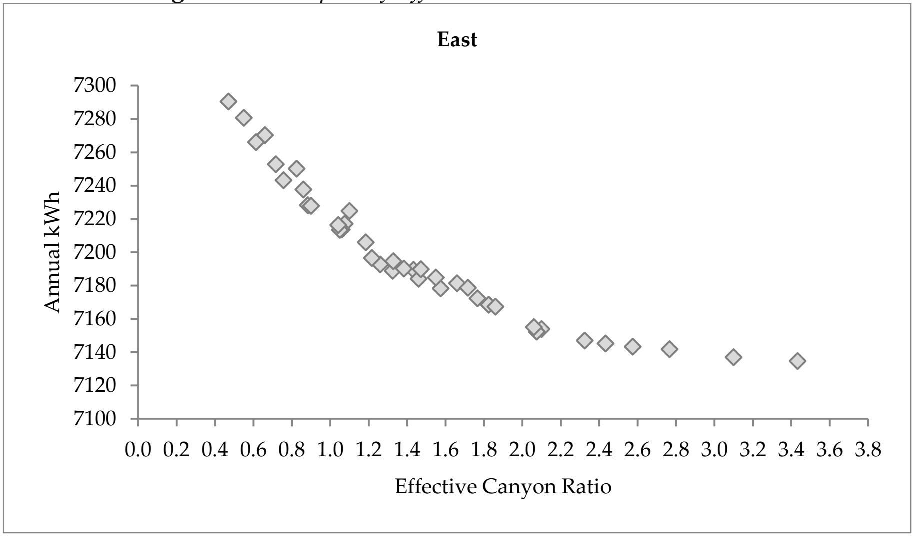

Figure 8.18: *Impact of Effective CR at East Orientation*

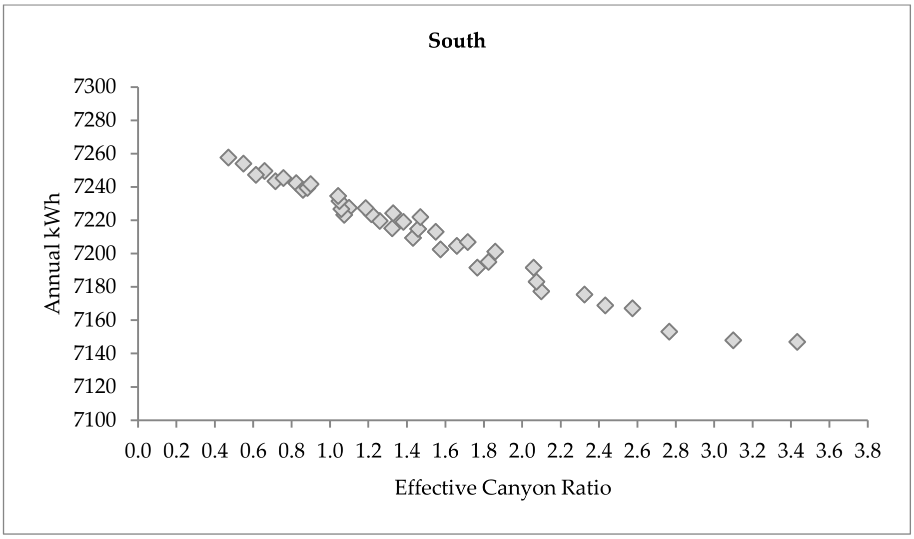

***Figure 8.19**: Impact of Effective CR at South Orientation*

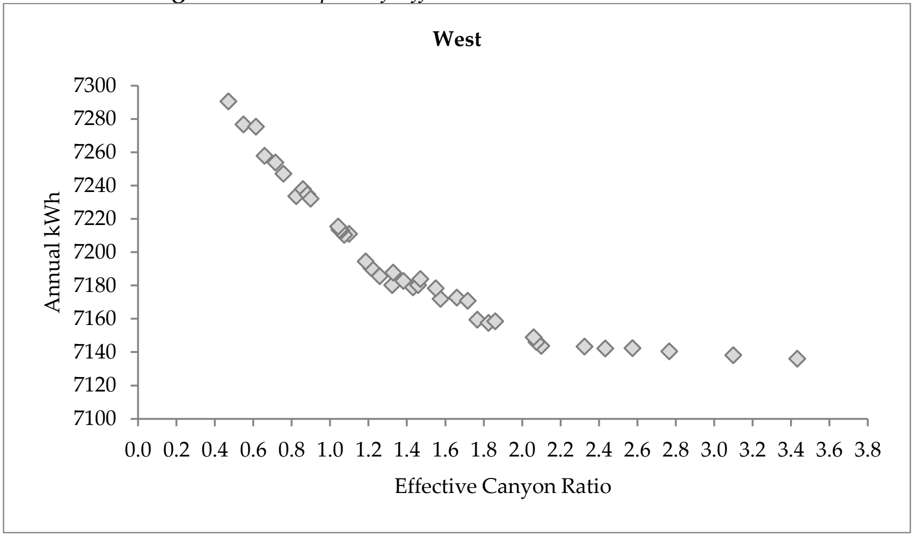

***Figure 8.20:** Impact of Effective CR at West Orientation*

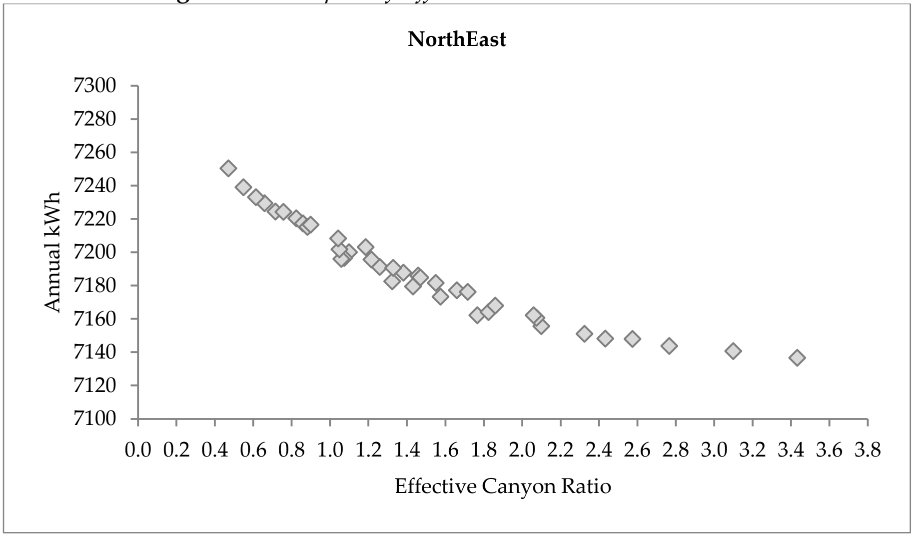

***Figure 8.21:** Impact of Effective CR at North-east Orientation*

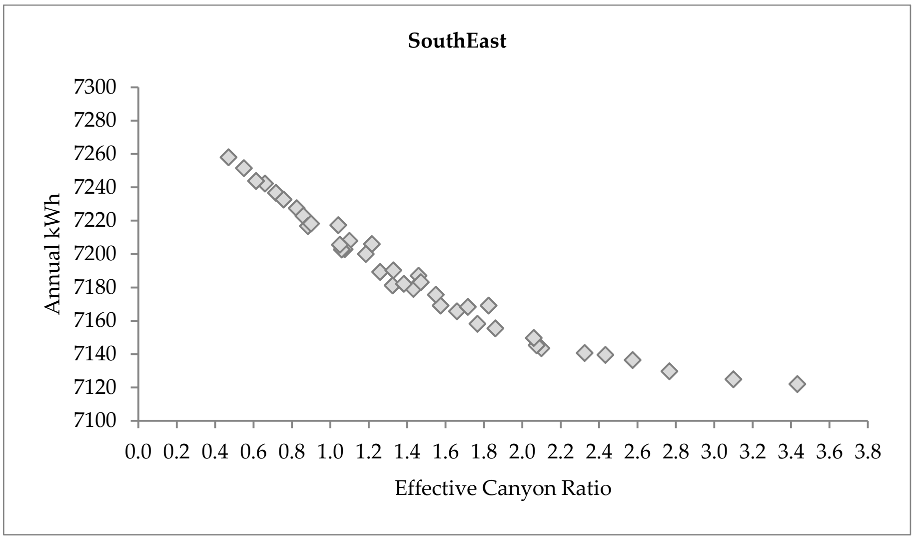

Figure 8.22: *Impact of Effective CR at South-east Orientation*

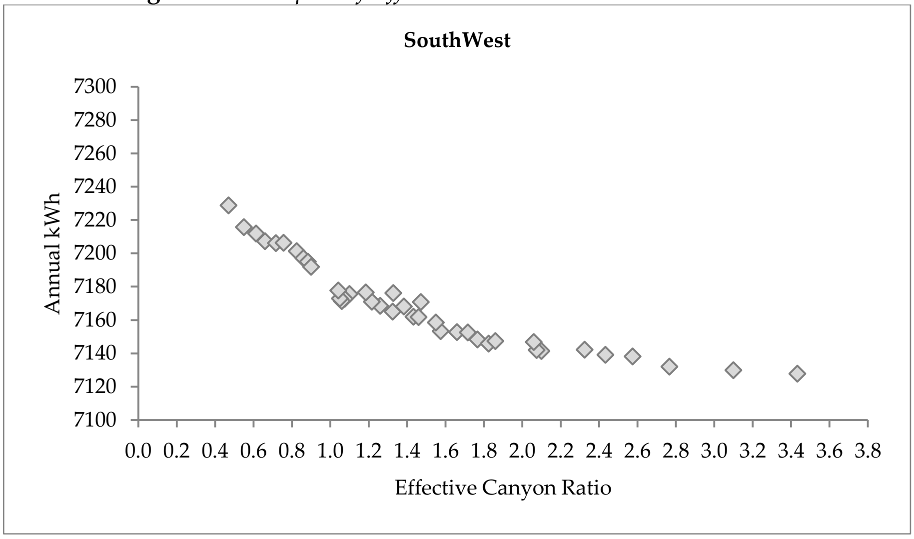

Figure 8.23: *Impact of Effective CR at South-west Orientation*

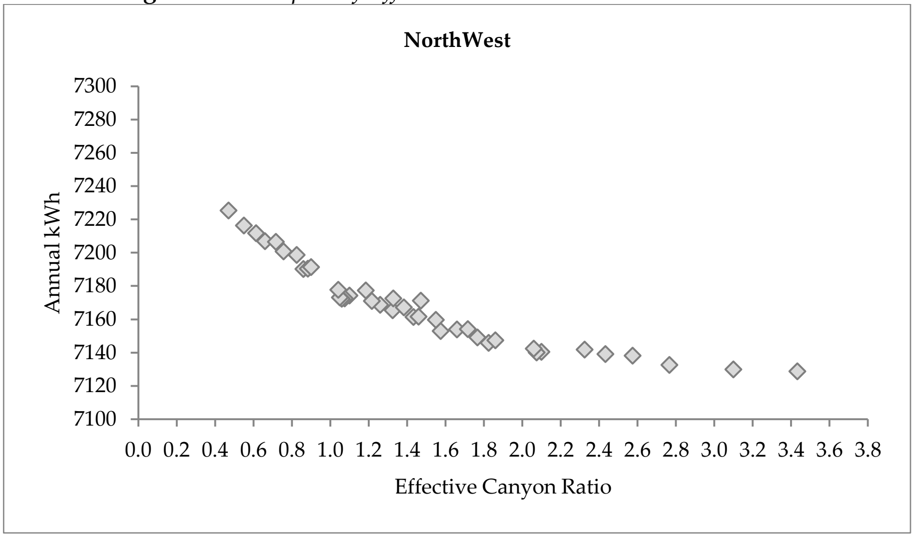

Figure 8.24: *Impact of Effective CR at North-west Orientation*

Based on these findings, it can be said that the impact of CR varied noticeably among the cardinal orientations while the pattern remained the same among the oblique orientations. The results suggested that the shadow of the opposite building hardly influenced the consumption of a north-oriented building, but it noticeably affected the consumption of east- and west-oriented buildings. Therefore, the shadow benefit of the opposite building was maximum for an east- or west-oriented building within the given contexts. The height of the opposite building had to be significantly higher for a south-oriented building to receive enough shadow benefit. Therefore, it can be said that in general for all orientations excluding the south, if the effective CR in front of an apartment was at least 2 or more, local shading would not be needed, as the opposite building would provide enough shadow; however, for the south orientation the CR would need to be 2.8 or more. An effective CR 2 means that the height of the opposite building from the point of measurement is twice the horizontal distance of the building. Since the maximum effective CR in typical developments is 1.33, this implies that to maximise energy reduction, local shading would be needed for all orientations.

8.3.1.3 External Wall Construction

Investigations on the effect of external wall constructions were conducted in two steps. In the first step, different brick wall constructions such as solid and cavity brick walls with different thicknesses were tested and in the second step, different concrete block wall constructions were tested. The most common types of external wall construction for typical residential buildings in Dhaka are with 5″ (125 mm) and 10″ (250 mm) solid bricks, plastered and painted on both sides. Some constructions have 3.75″ (90 mm) solid concrete blocks (see Section 5.3.11). This study also tested other thicknesses and combinations of wall construction, which were either previously available but now extinct, such as 20″ (500 mm) brick walls, or were newly available, such as concrete hollow block. In total, nine types of brick constructions were tested: 5″ (125 mm), 8″ (200 mm), 10″ (250 mm), 13″ (325 mm), 15″ (375 mm) and 20″ (500 mm) solid brick wall, plastered and painted on both sides, as well as three combinations of brick cavity walls: 5″ (125 mm) x 3″ airgap (75 mm) x 5″ (125 mm); 10″ (250 mm) x 3″ airgap (75 mm) x 5″ (125 mm); and 10″ (250 mm) x 3″ airgap (75 mm) x 10″(250 mm).

In the second step, 10 types of concrete wall constructions were tested: 3″ (75 mm), 3.75″ (90 mm), 5″ (125 mm), 5.75″ (140 mm), 7.75″ (190 mm) and 9.75″ (240 mm) solid concrete block; 5.75″ (140 mm) and 7.75″ (190 mm) concrete hollow block plastered and painted on both sides; and two combinations of concrete block cavity walls: 4.1″ (107 mm) x 3″ airgap (107 mm) x 4.1″ (107 mm) and 9.75″ (240 mm) x 3″ airgap (75 mm) x 4.1″ (107 mm).

The results showed that among all types of brick wall constructions, the cavity wall with 10″ (250 mm) brick at both outer and inner leaf was the best and 5″ (125 mm) solid brick wall is the worst from an energy-consumption point of view (see Figure 8.25). Among all types of concrete wall constructions, the cavity wall with 9.75″ (240 mm) concrete block at outer leaf and 4.1″ (107 mm) at inner leaf was the best and 3.75″ (75 mm) solid concrete block was the worst. The results also showed that in general, brick walls were slightly better than the concrete block walls with similar thickness. The cavity walls, whether made of brick or concrete, were better than the solid ones (see Figure 8.26). In addition, the results showed that increasing the thickness of the brick wall decreased the total energy consumption noticeably and increasing the thickness of the concrete block wall decreased the total energy consumption slightly. Apart from this, concrete hollow blocks were better than solid block of the same thickness.

Further study found that the case study apartment would consume 3%, 2.5%, 1.7%, 1.1%, 1%, 0.7%, 0.4% and 0.2% more energy respectively in the case of using 125 mm, 200 mm, 250 mm, 325 mm, cavity wall (125x125), 375 mm, cavity wall (250x125), and 500 mm brick wall instead of cavity wall (250x250) (see Figure 8.27). Similarly, the case study apartment would consume 3%, 2.9%, 2.8%, 2.8%, 2.3%, 2.2%, 1.7%, 1.3% and 0.8% more energy respectively in the case of using 75 mm, 90 mm, 125 mm, 140 mm, 190 mm, 140 mm-hollow, 240 mm, 190 mm-hollow and cavity wall

(107x107) made of concrete block instead of concrete cavity wall (240x107) (see Figure 8.28).

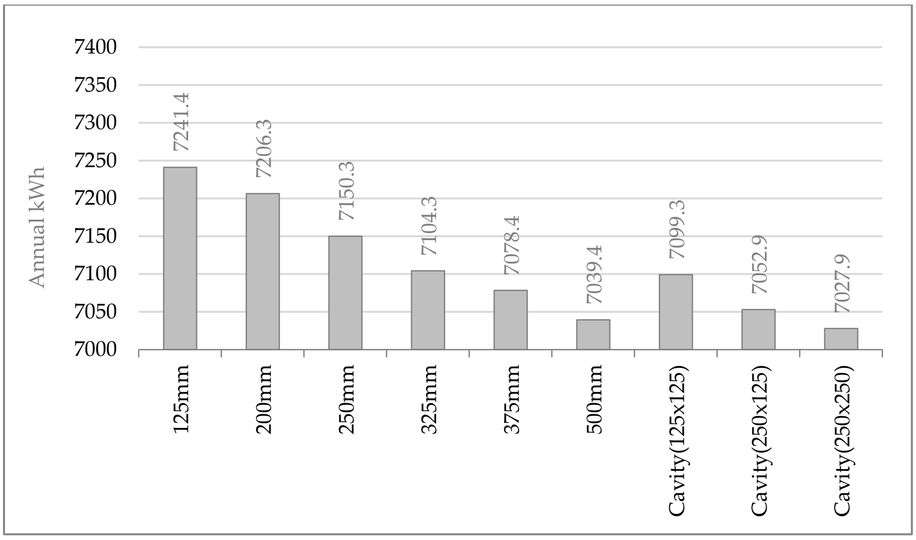

Figure 8.25: *Impact of Different Brick Wall Constructions*

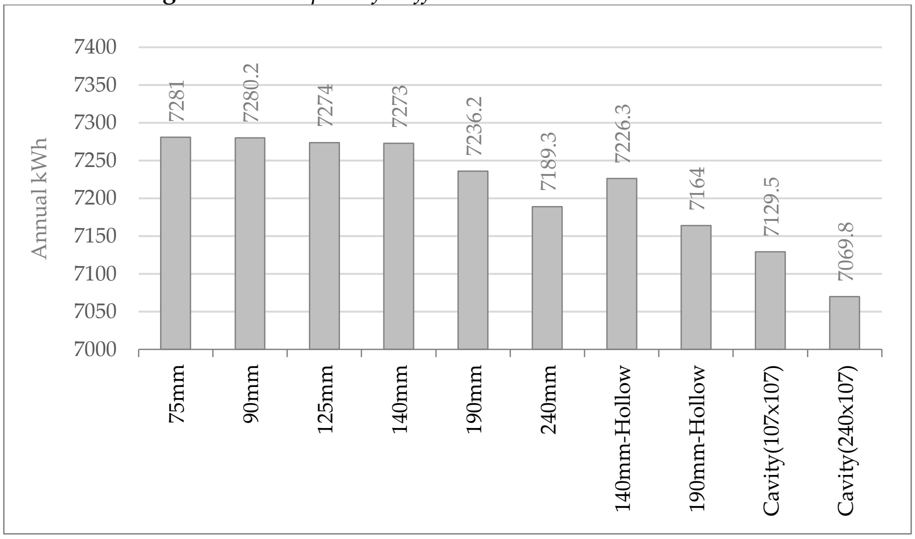

Figure 8.26: *Impact of Different Concrete Wall Constructions*

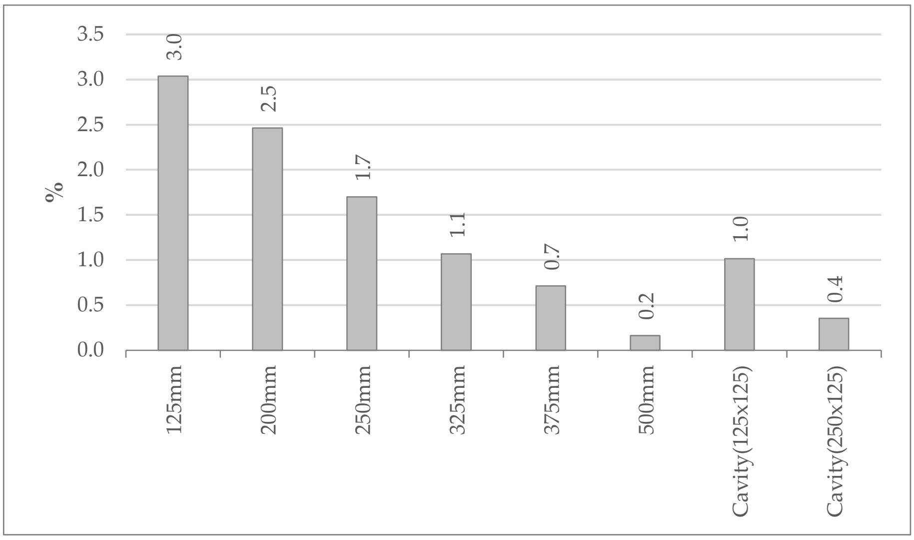

Figure 8.27: *Additional Consumption due to Other Brick Walls Instead of Brick Cavity Wall (250x250)*

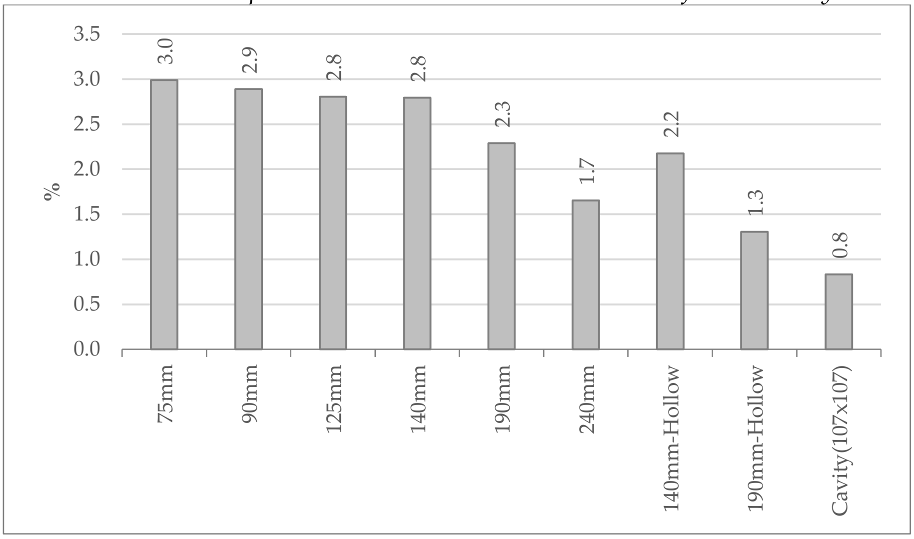

Figure 8.28: *Additional Consumption due to Other Concrete Walls Instead of Cavity Wall (240x107)*

Based on the findings, it can be said that the cavity walls were better from an energy-consumption point of view than the solid walls, and the brick walls were better than the concrete walls. The results also suggested that the thicker the wall, the lower the total energy consumption. Although cavity walls provided the best performance, the difference was minimal compared with the solid wall with the same thickness, excluding the airgap. Given the fact that cavity walls consume more space and more resources, it seems that using thicker solid walls instead of cavity walls would be the best option in the given contexts. In addition, thick walls could be provided only in spaces that are more frequently occupied and use AC, such as the master bedroom.

Other less-occupied spaces, such as the formal living and dining areas, could have walls with a lower thickness.

8.3.1.4 Window Glazing

Investigations were made in two steps to find out the impact of different window glazing types on energy consumption. In the first step, different types of glass (clear, tinted and reflective) with varying thicknesses were tested and in the second step, the effects of different combinations of double-glazing were tested to find out what type of glass would be best within the given contexts. The most common types of window glazing used in Dhaka's residential buildings are 5–6 mm clear float, tinted or reflective single-glazed windows (see Section 5.3.9). Some buildings have started to use double-glazing recently with clear float glass.

The results showed that for single-glazed windows, the reflective glass type was best for any thickness, followed by the tinted and clear glass (see Figure 8.29). Energy consumption could be reduced up to 1.1% if reflective glass was used instead of clear glass and up to 0.7% if tinted glass was used. The results also showed that for reflective and tinted glass types, increasing glass thickness did not provide any benefit; rather, it increased the energy consumption slightly. Conversely, increasing the thickness of clear float glass decreased the energy consumption.

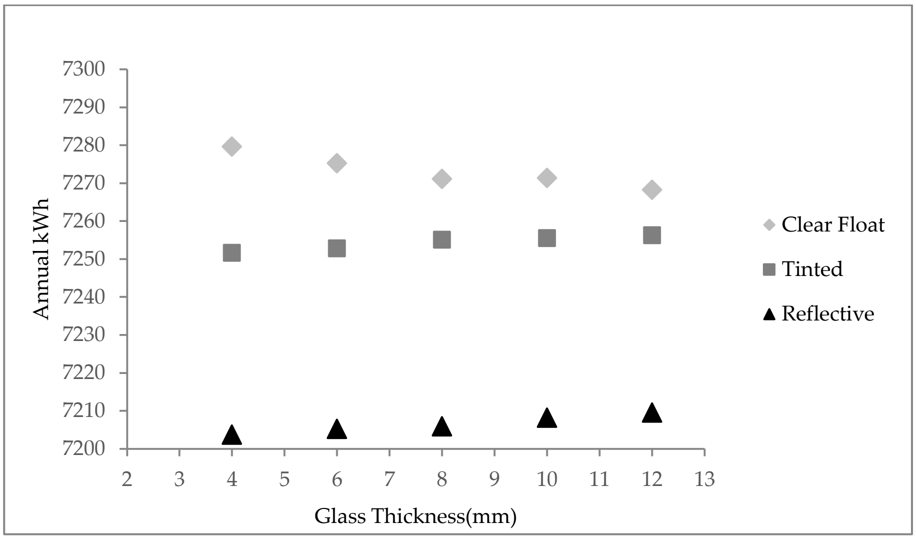

Figure 8.29: *Impact of Different Window Glass Types: Single Glazed*

Further investigations were conducted to find out the difference in energy consumption due to single- and double-glazed windows. For double-glazed windows, the glass type variation was made for the outer pane and the inner pane was always clear float glass (4 mm) with an airgap of 6 mm. The results showed that energy consumption was reduced if double-glazed windows were used instead of single-glazed windows for both clear and reflective glass types; however, the difference was minimal for tinted glass (see Figures 8.30–8.32). Further analysis found that the total consumption could be reduced up to 0.9% (on average, 0.78%) if a double-glazed window with clear float glass was used instead of a clear float single-glazed window. Consumption could be reduced up to 0.6% (on average, 0.55%) in the case of reflective glass. The results suggested that double-glazing with tinted glass did not provide any extra benefit over single-glazed tinted glass, but double-glazing with clear float glass made a maximum difference compared to single glazing (see Figure 8.33).

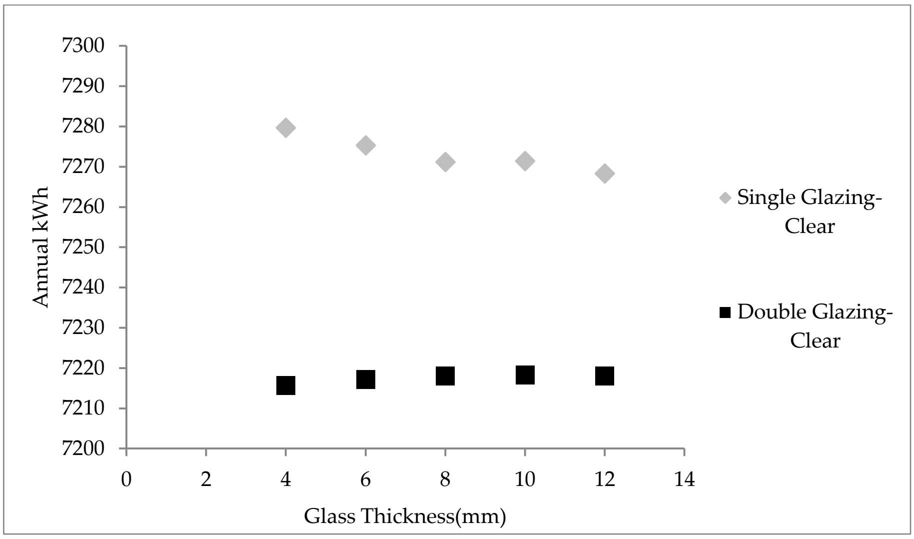

Figure 8.30: *Impact of Single- and Double-glazed Windows with Clear Float Glass*

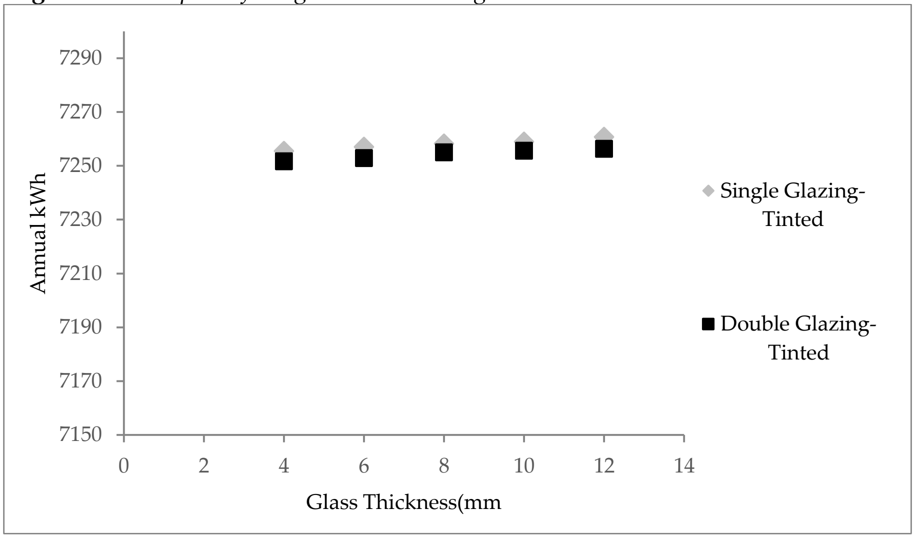

Figure 8.31: *Impact of Single- and Double-glazed Windows with Tinted Glass*

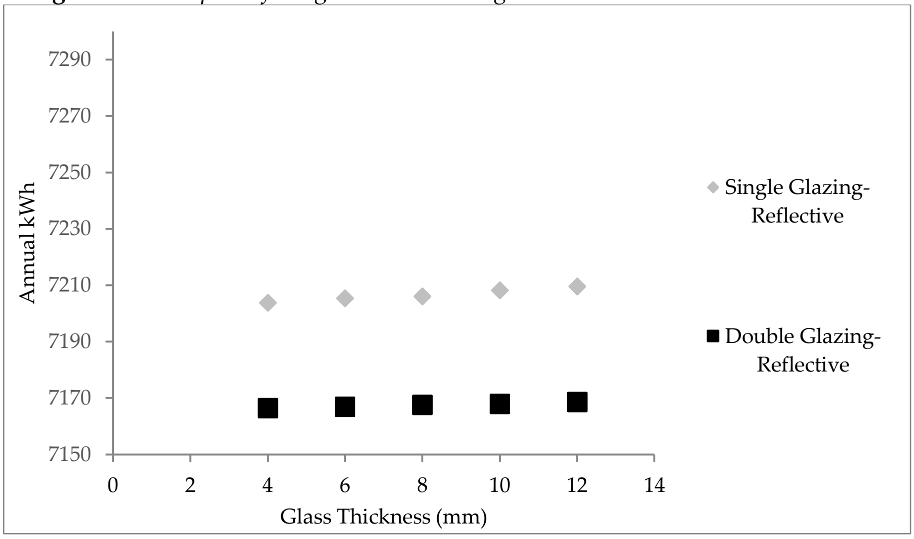

Figure 8.32: *Impact of Single- and Double-glazed Windows with Reflective Glass*

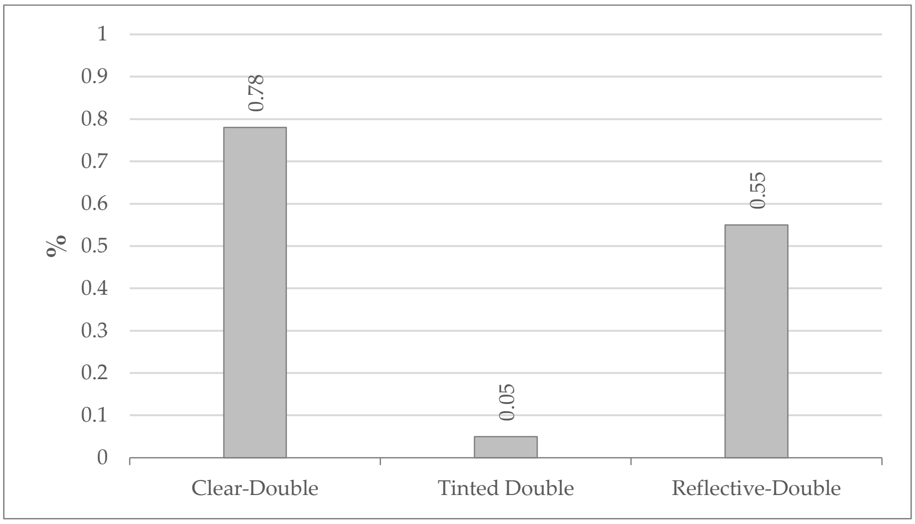

Figure 8.33: *Consumption Reduction due to Double Glazing Instead of Single Glazing*

Investigations were made to find out the impact of different combinations of double-glazed windows. To identify the differences, the airgap between the outer and inner pane, as well as the thickness of the outer pane glass, were varied. The results showed that for all instances, double-glazed windows with a reflective outer pane was best, followed by the clear float and tinted outer pane. Further analysis showed that increasing the airgap between the panes did not make any difference for reflective glass; however, increasing the airgap thickness worsened the energy consumption in the case of both clear float and tinted glass (see Figure 8.34). In addition, varying the outer pane glass thickness did not result in any noticeable difference for all glass types (see Figure 8.35). Further analysis showed that if all other energy-influencing parameters remained constant, then the consumption of the case study apartment would be 1.5% less with double-glazed windows (4x4) than with single-glazed windows with clear float glass (4 mm).

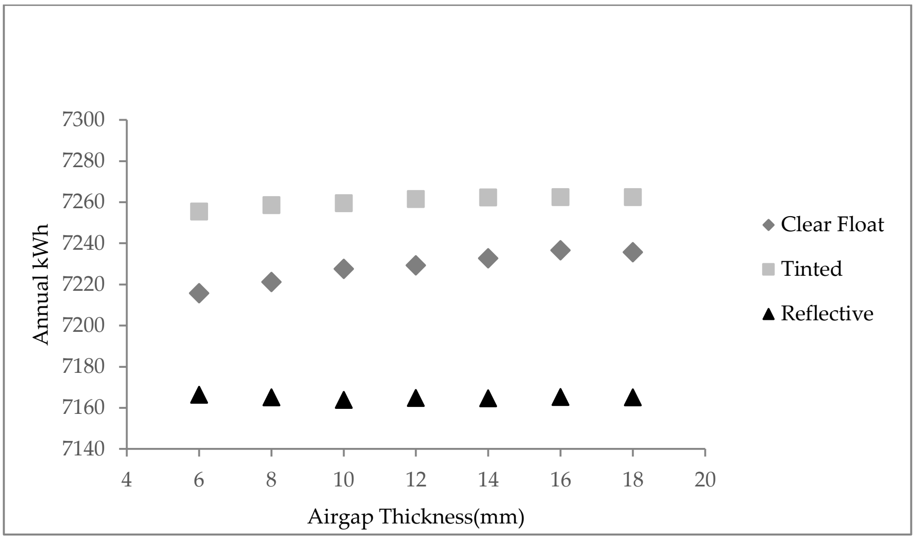

***Figure 8.34:** Impact of Different Double-glazings with Varying Airgap Thickness (4 mm Outerpane)*

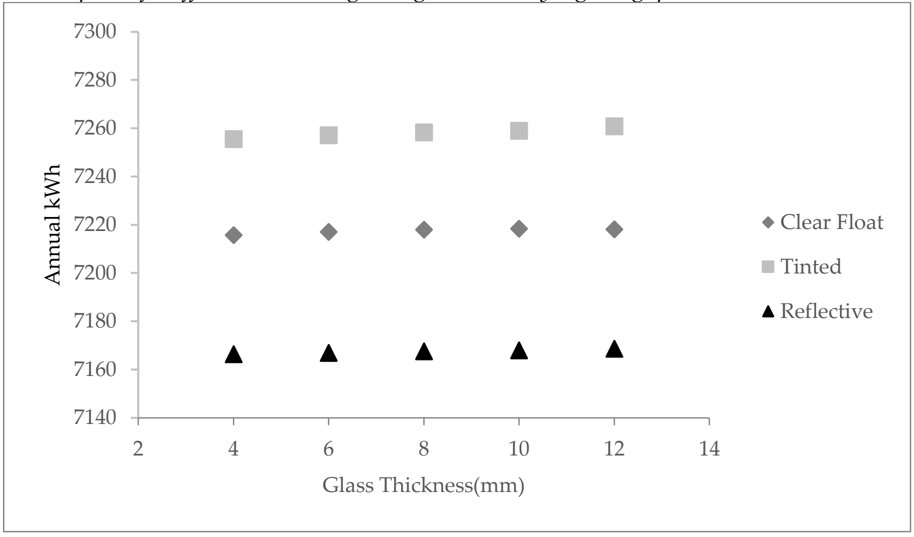

***Figure 8.35:** Impact of Different Double-glazings with Varying Glass Thickness (6 mm Airgap)*

Based on these findings, it can be said that in Dhaka's contexts for single-glazed windows, reflective glass was best, followed by tinted and clear float glass. For double-glazed windows, an outer pane with reflective glass was best, followed by clear float and tinted glass. In addition, double-glazed windows were better than single-glazed windows; however, increasing the airgap between the panes and glass thickness were found to have no impact or a deteriorating impact (for clear float). Double-glazed windows with minimum glass thickness (4 mm) and airgap (6 mm) seemed to be the best choice for residential windows in Dhaka. As it was found in the buildings contexts study, the majority of residential buildings in Dhaka have either clear float or tinted single glazing (see Section 5.3.9), replacing them with reflective glass would result in substantial reduction of energy consumption; however, to maximise the reduction, double-glazed windows would provide the best result. Considering the fact that double-glazing is significantly more expensive than single glazing, it seems more appropriate to use the double-glazed windows for the bedrooms that are more frequently occupied and use AC. Other less-frequently occupied spaces could have single-glazed reflective glass.

It is important to note that although the use of reflective glass instead of clear glass would reduce the consumption of cooling energy, it may increase the daytime lighting consumption. Investigating the impact of different glass types on daytime lighting use was beyond the scope of this research, due to the unavailability of information—it was not possible to set the lighting schedule in the simulation based on daylight luminance. Instead, the schedule was set based on the data collected from the occupants of the case study apartment, who provided information on lighting use in hours, such as total hours of use of each light in the apartment. Therefore, this research acknowledges that further research into daytime artificial lighting is needed.

8.3.1.5 Shading Devices

To find out the impact of different shading device types on energy consumption within the given urban contexts, four types of device were tested: horizontal, vertical, L-shape and egg-crate. Investigations were made to find out what type and ratio of shading devices were best for each of the orientations. The effective CR in front of the case study apartment in the simulation was considered 0.325, which was the ratio for the top-floor apartment. The lowest possible CR within the given contexts was considered for the shading device studies, as the shadow impact of the opposite building was least for this floor. To find out the impact of different devices, the ratio between the shading device depth and the height or width of the opening was considered (see Figure 8.36).

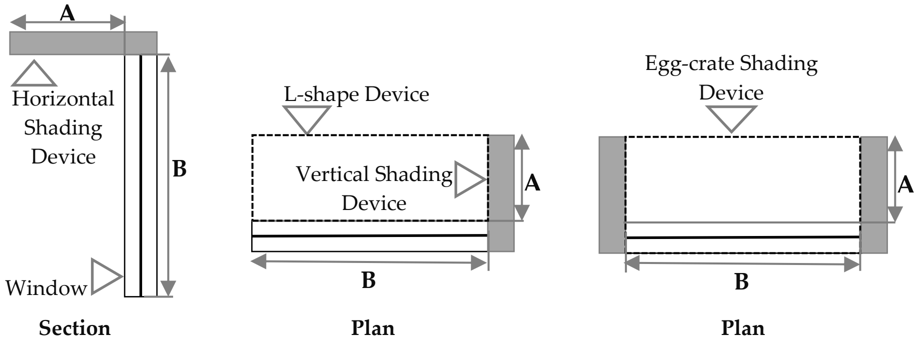

Figure 8.36: *Shading Device Ratio: A/B; A = Device Depth, B = Window Height or Width*

The results showed that for all orientations, an egg-crate shading device provided the best result and the vertical devices did not make noticeable improvement within the given contexts (see Figures 8.37–8.44). The results also showed that the total energy consumption decreased as the device ratio increased; however, above a 0.6 device ratio, the consumption reduction was small for all orientations. For a north-oriented window, none of the devices made a significant improvement and for east- and west-oriented windows, both horizontal and egg-crate shading devices made a nearly equal contribution towards the reduction in energy consumption.

Further analysis found that an egg-crate shading device (with a device ratio of .6 and above) could reduce the total energy consumption up to 0.19% (on average, 0.15%) for a north-oriented window, up to 0.54% (on average, 0.39%) for an east-oriented window, up to 0.66% (on average, 0.51%) for a south-oriented window, up to 0.58% (on average, 0.4%) for a west-oriented window, up to 0.37% (on average, 0.28%) for a north-east-oriented window, up to 0.71% (on average, 0.52%) for a south-east-oriented window, up to 0.79% (on average, 0.6%) for a south-west-oriented window and up to 0.56% (on average, 0.41%) for a north-west-oriented window, compared to a window without any shading devices within the given urban contexts (see Figure 8.45).

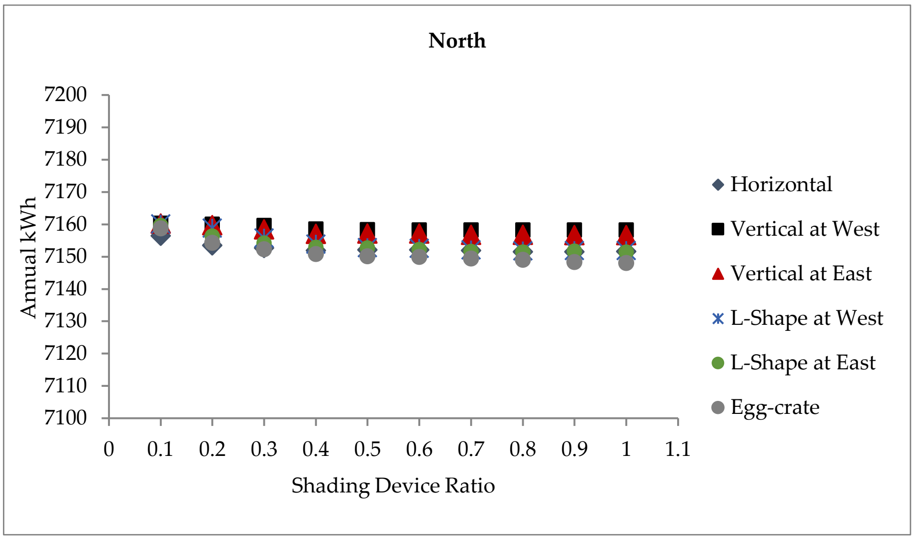

Figure 8.37: *Impact of Shading Device at North Orientation*

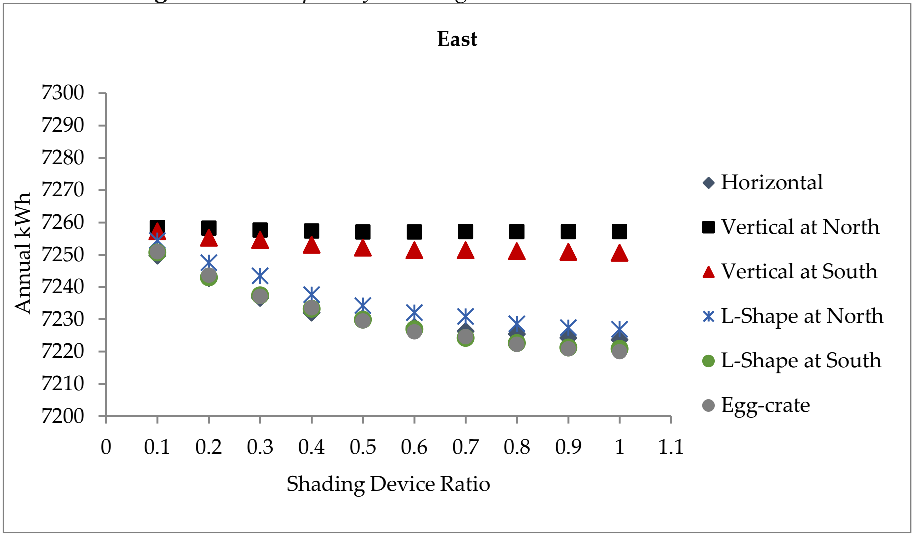

Figure 8.38: *Impact of Shading Device at East Orientation*

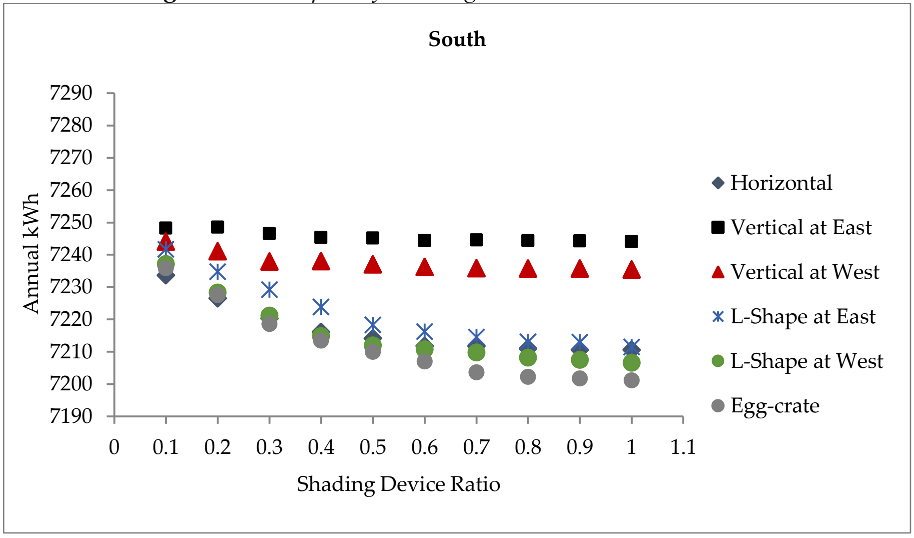

Figure 8.39: *Impact of Shading Device at South Orientation*

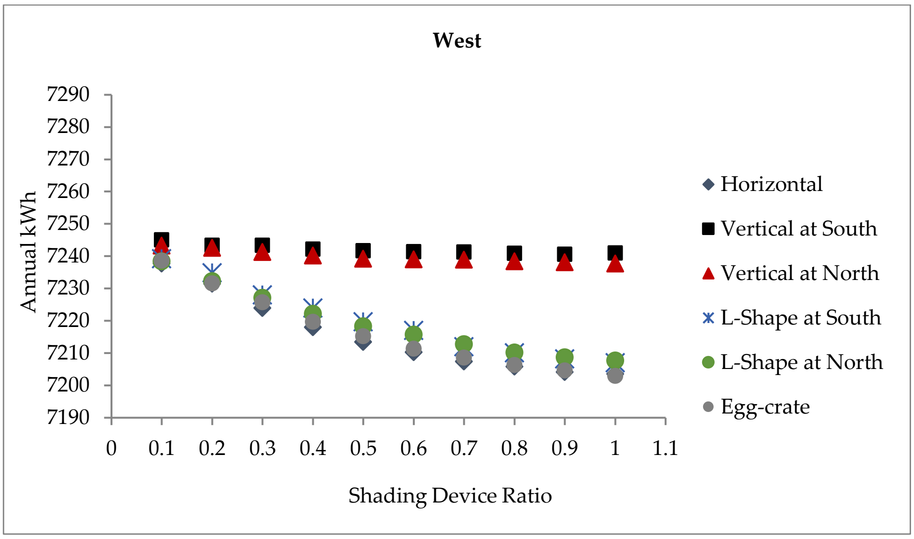

Figure 8.40: *Impact of Shading Device at West Orientation*

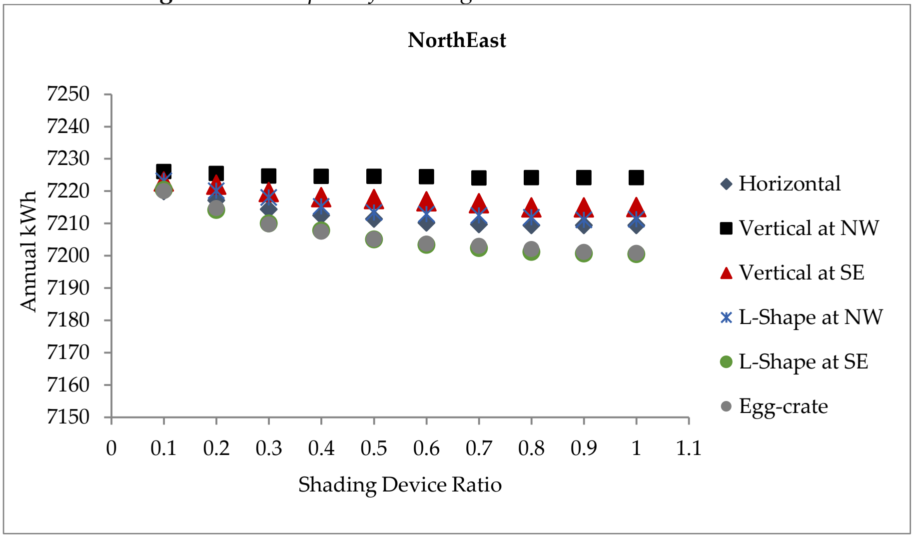

Figure 8.41*: Impact of Shading Device at North-east Orientation*

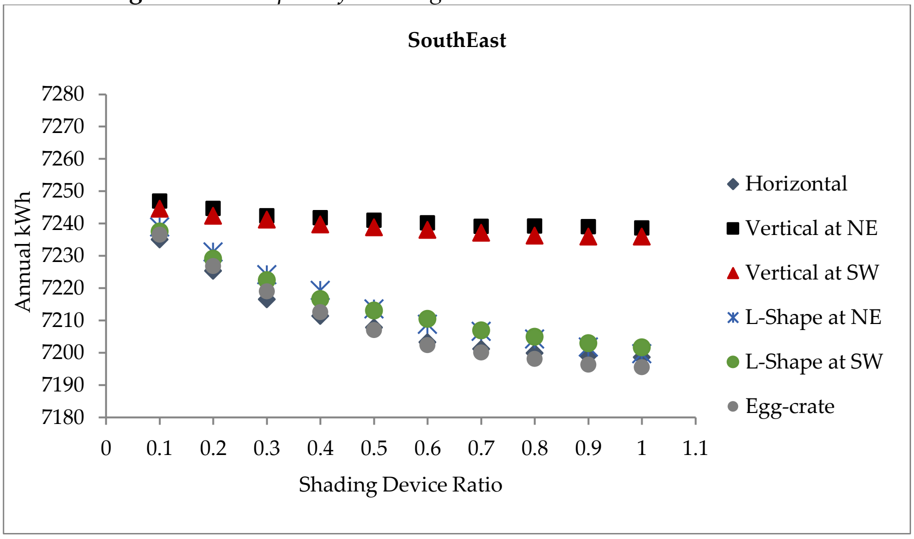

Figure 8.42: *Impact of Shading Device at South-east Orientation*

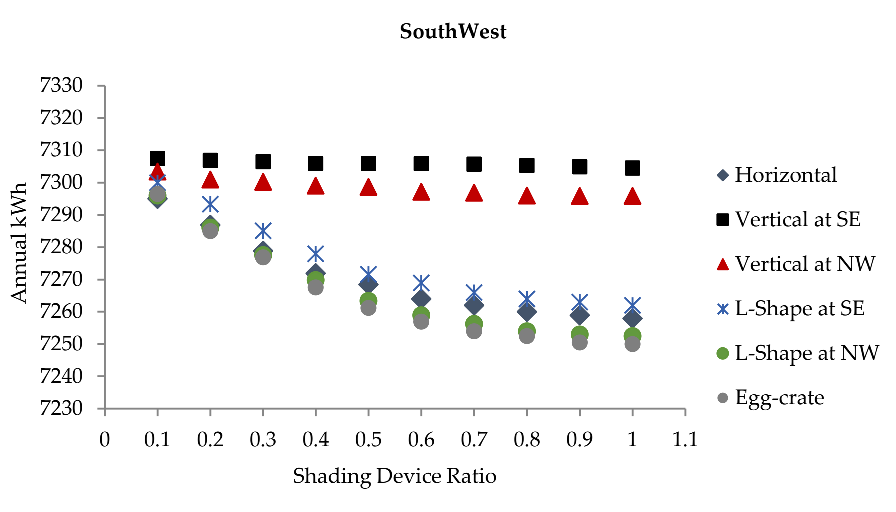

Figure 8.43: *Impact of Shading Device at South-west Orientation*

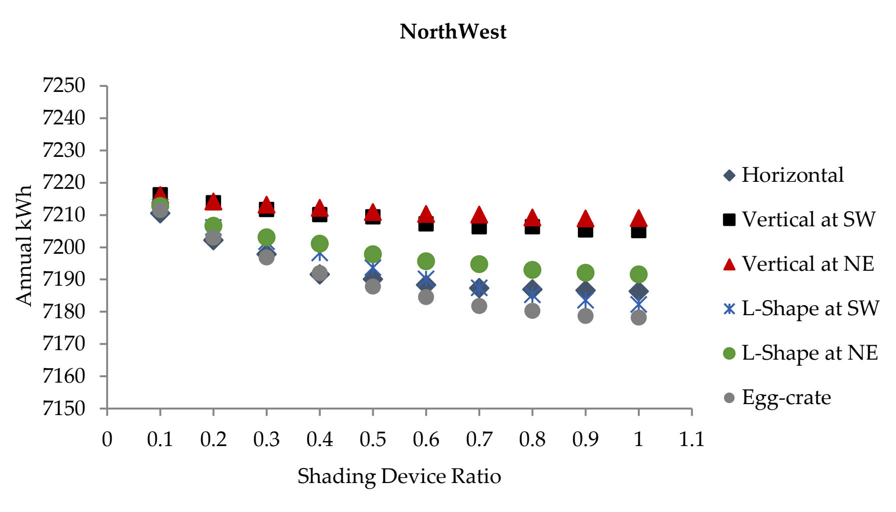

Figure 8.44: *Impact of Shading Device at North-west Orientation*

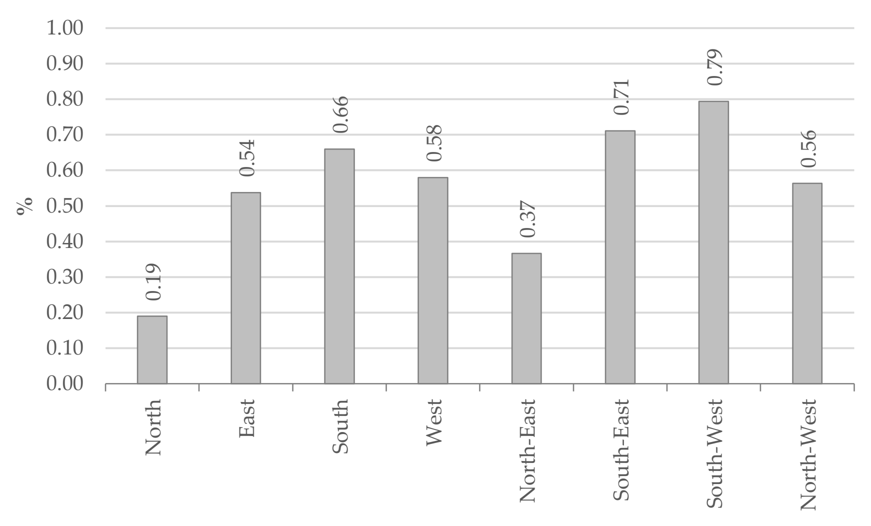

Figure 8.45: *Consumption Reduction due to Egg-crate Shading Device Compared to No Shading*

Based on the findings, it can be said that shading devices were more effective on any south-oriented windows than on north-oriented ones, which is not unusual as the north orientations face less direct solar radiation than the south. Obliquely oriented windows gained more advantages from the shading devices than the cardinal orientations did (see Figure 8.45). The results of this study also showed that while the egg-crate shading devices provided the best result for all orientations, horizontal shading devices performed equally for east-, west- and south-east oriented windows within the given urban contexts. The building contexts study found that the majority of the buildings in typical developments did not have proper shading devices and when they did, they were not based on an informed decision (see Section 5.3.10). Hence, to maximise the reduction in cooling energy consumption, egg-crate devices in general, or horizontal shading devices in the case of east, west or south-east orientation, with a minimum 0.6 device ratio should be provided, particularly on east-, west- and south-oriented windows.

8.3.1.6 Window-to-wall Ratio

Investigations were conducted to find out the effect of window surface area or window size on energy consumption, as it was found in the building contexts study that recent market pressure is on providing more glass surfaces, particularly on the front façade (see Section 5.3.9). To find out the effect of increased glazed surfaces, the ratio between the window surface and external wall surface of the front façade was used.

The results showed that with the increase of glass surface areas, total energy consumption increased in a slight curvilinear fashion regardless of the types of glass used, such as clear float, tinted and reflective (see Figure 8.46). The total energy consumption remained nearly the same up to the 0.2 ratio, which means that energy consumption did not vary until the window areas exceeded 20% of the total external wall surfaces. The results also showed that the energy consumption started to increase gradually after the 0.2 ratio, kept increasing up to the 1.0 ratio, and increased more steeply at higher ratios. The results suggested that increasing the window area above the 0.2 ratio had a negative impact on total energy consumption and the impact is higher with clear float and tinted glass. In the case of clear float glass, the energy consumption of the case study apartment was 1.6% and 5.8% more respectively when the window surface area was at a 0.5 and 1.0 ratio, instead of a 0.2 ratio. With tinted glass, the increase was 1.4% and 5.5% respectively and with reflected glass, it was 1.2% and 4.9 % (see Figure 8.47).

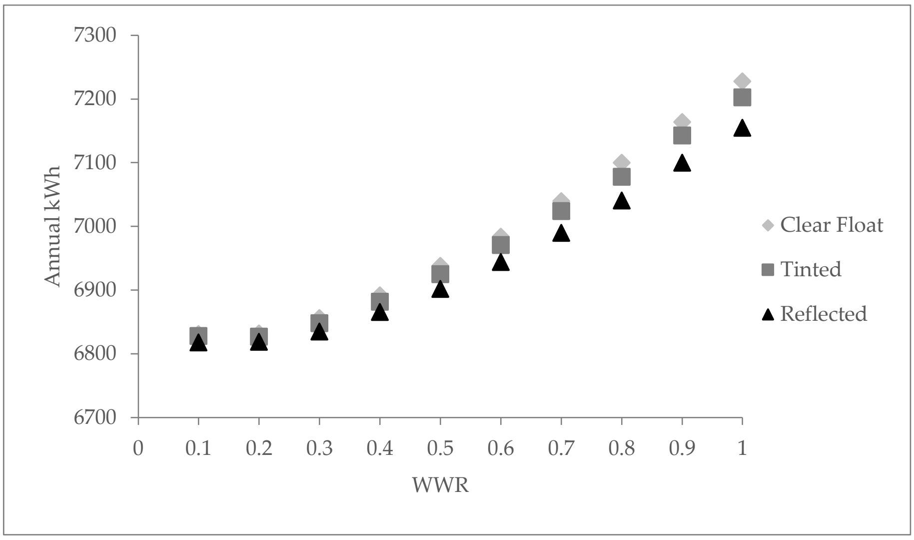

Figure 8.46: *Impact of WWR*

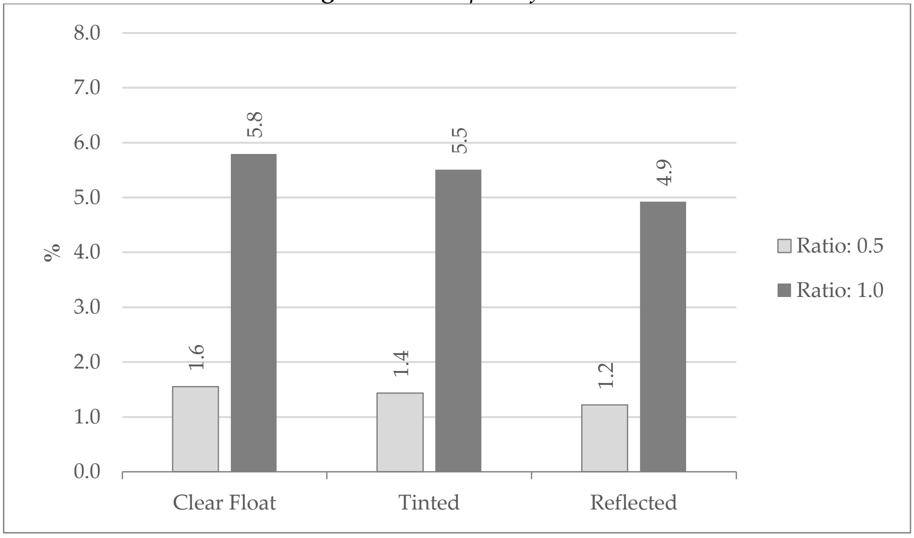

Figure 8.47: *Additional Consumption due to Glass Surface with 0.5 and 1.0 ratio instead of 0.2 ratio*

Based on the findings, it can be said that in Dhaka's contexts, the best WWR from the energy-consumption point of view was 0.2; however, the existing contexts study found that on average, the window sizes for the master bedroom and bedroom-2 were 38. ft^2/11.6 m^2 (see Table 5.6, Section 5.4.3), which is on average about 31% of the external wall surfaces (120 ft^2/11.15 m^2). Decreasing the window size has an effect on indoor daylight, which may result in further consumption of energy for artificial lighting. As this study has shown that the total energy consumption did not increase significantly up to the 0.3 glass ratio, it seems more appropriate to continue with the existing window size practices. As the recent trend of providing more glass surfaces on the front façade has a negative effect on the total energy consumption, the glass surface should be limited to no more than 30% of the external wall surfaces, particularly in rooms where AC is used more frequently, such as the master bedroom.

8.3.1.7 Window Operation

Investigations were conducted to find out the effect of different window-operation patterns or ventilation on energy consumption. In the IESVE program, window operation can be modelled by setting up opening schedules in 'MacroFlo'. The window operations were tested based on the condition that when the indoor air temperature went above 32°C, windows would be closed and AC would be turned on. The threshold air temperature was set at 32°C as this is the upper limit of the comfort temperature for Dhaka (Mallick, 1996) and it was found during the calibration of the case study apartment that the AC is used at higher temperature. Six window-operating patterns were tested: i) windows closed for 24 hours; ii) windows open all day (7:00am–7:00pm); iii) windows open all night (7:00pm–7:00am); iv) windows open in the evening (6:00pm–12:00am); v) windows open all day and evening, excluding night (8:00am–12:00am); and vi) windows open for 24 hours.

The results showed that energy consumption could vary noticeably according to different window-operating patterns. Energy consumption was reduced significantly if the windows were open all night (7:00pm–7:00am) but closed during the day and significantly higher if the windows were closed at night but open during the day (7:00am–7:00pm), regardless of the orientation of the building (see Figures 8.48–8.55). According to the findings, it was better to keep the windows closed 24 hours instead of opening them during the day but closing them at night. The results also showed that keeping the windows open even for a short time in the evening could reduce the total energy consumption significantly. The results suggested that keeping the windows closed at night had the most detrimental impact on total energy consumption. These results supported the assumptions made based on the findings of the microclimatic contexts study, that to reduce energy consumption in the studied households, night-time ventilation needed to be enhanced (see Table 6.3).

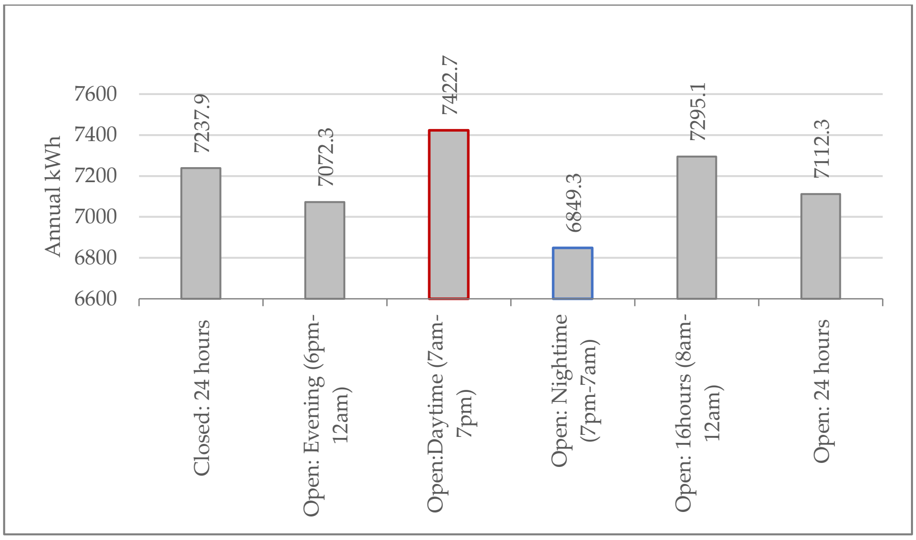

Figure 8.48: *Impact of Different Window Operation: North Orientation*

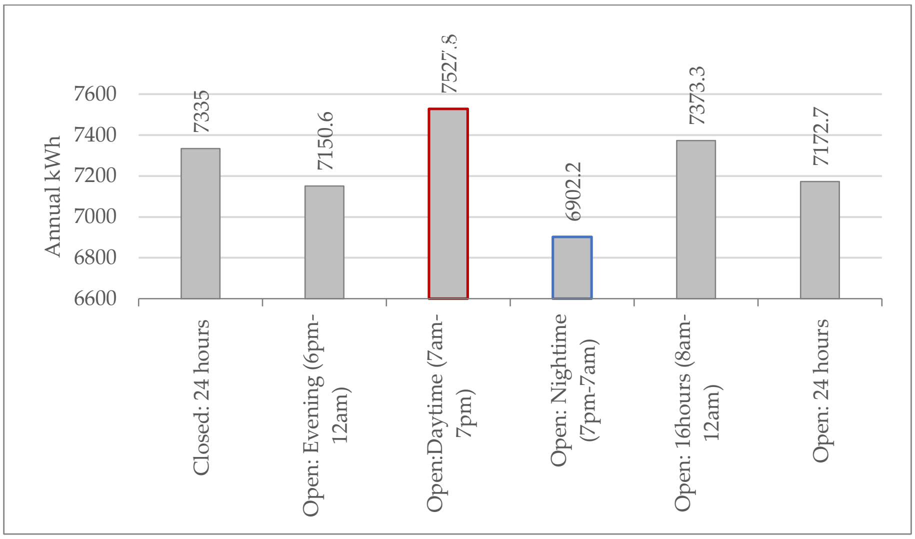

Figure 8.49: *Impact of Different Window Operation: East Orientation*

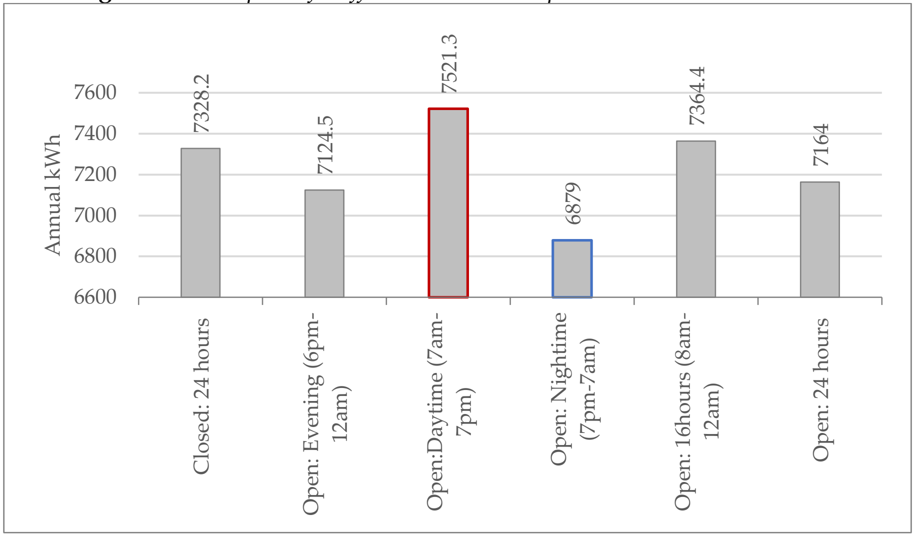

Figure 8.50: *Impact of Different Window Operation: South Orientation*

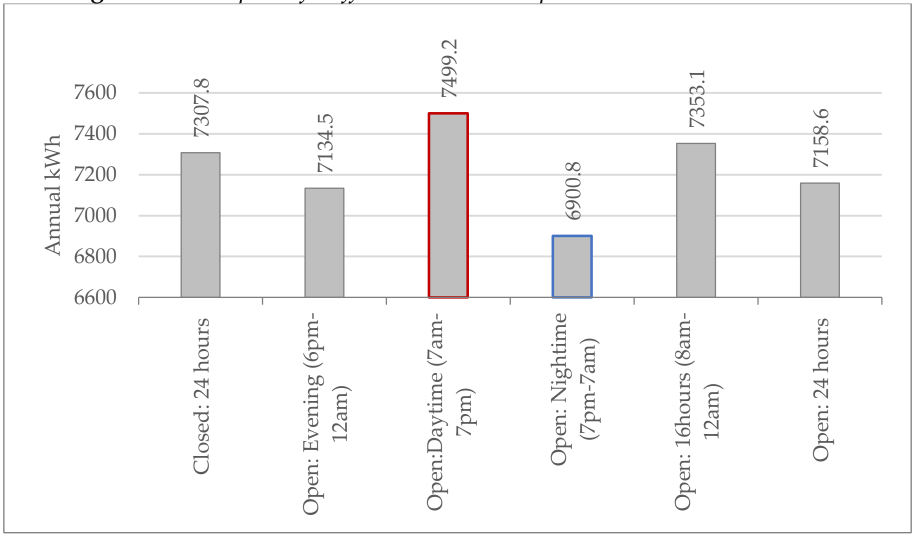

Figure 8.51*: Impact of Different Window Operation: West Orientation*

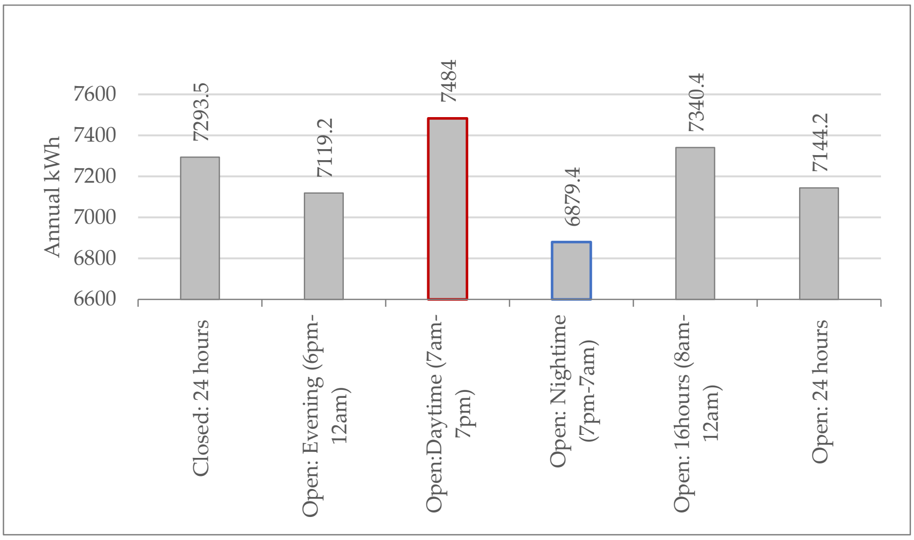

Figure 8.52: *Impact of Different Window Operation: North-east Orientation*

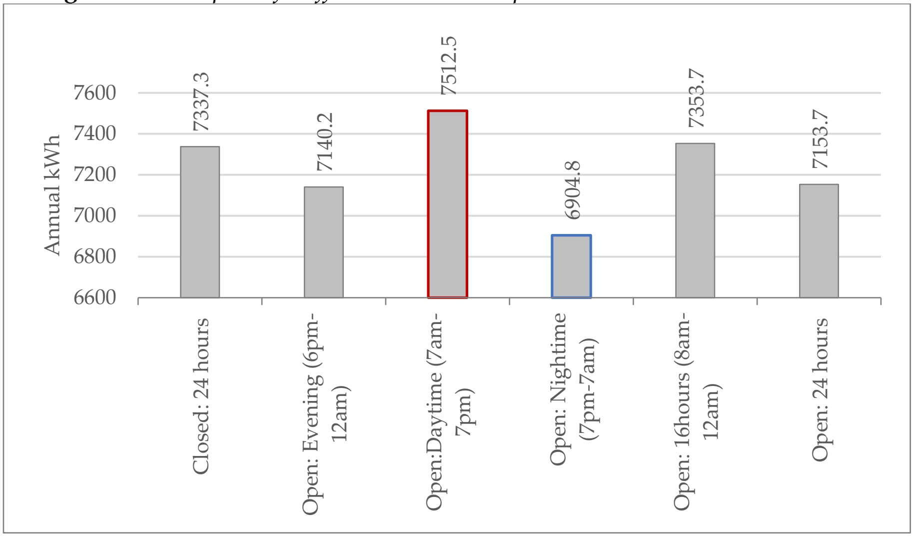

Figure 8.53: *Impact of Different Window Operation: South-east Orientation*

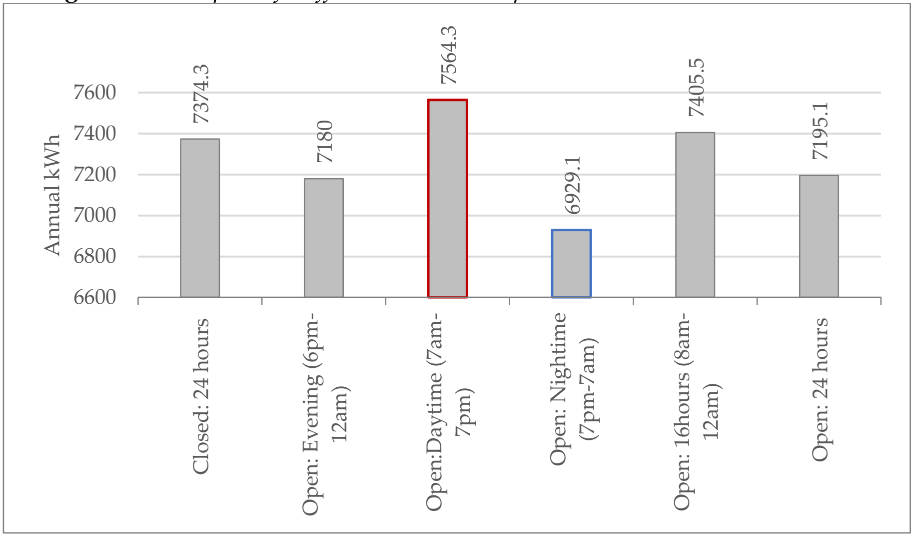

Figure 8.54: *Impact of Different Window Operation: South-west Orientation*

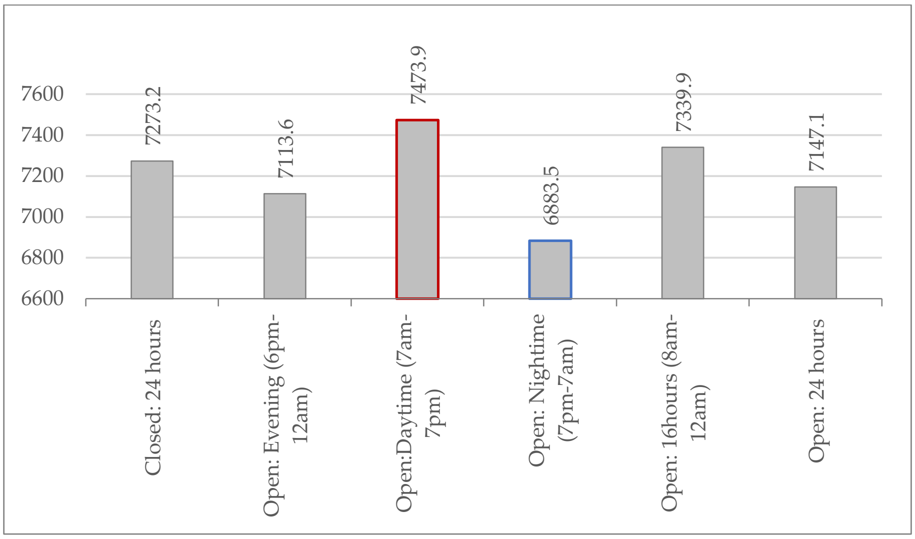

Figure 8.55: *Impact of Different Window Operation: North-west Orientation*

Further investigations were conducted to find out the difference in consumption between the worst-case and best-case scenarios; that is, how much the energy consumption increased if the case study apartment had the windows open during day and closed at night, instead of the reverse. The study found that when the windows were open during the day and closed at night, energy consumption increased by 8.4%, 9.1%, 9.3%, 8.7%, 8.8%, 8.8%, 9.2% and 8.6% respectively for north, east, south, west, north-east, south-east, south-west and north-west orientations (see Figure 8.55).

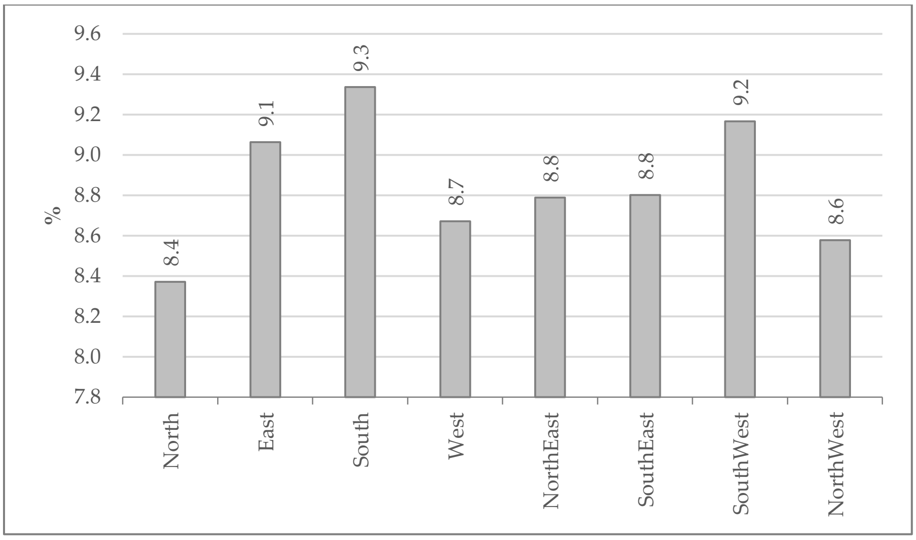

Figure 8.56: *Additional Consumption in the case of Windows Being Open During the Day but Closed at Night, Compared to Closed During the Day but Open at Night*

Based on the findings it can be said that regardless of the orientation, to maximise the reduction of energy consumption of typical residential developments, the best practice is to keep the windows open at night and closed during the day. Given that the windows in these areas are not opened very often, particularly in bedrooms because of issues such as privacy, security, dust, noise and AC use (see Section 7.4.3), the biggest challenge is how to achieve night-time ventilation. Innovative ventilation strategies would be needed to maximise the reduction of energy consumption, perhaps including the revival of traditional ventilators appropriate to the current urban contexts and lifestyle.

8.3.1.8 Appliances

Investigations were conducted to find out the impact of different appliances; that is, to what extent the energy consumption of the case study apartment could be reduced if the major appliances were upgraded to energy-efficient ones. The appliances investigated in this study were ceiling fans, AC, artificial lights, refrigerator and TV, since these were the most common and frequently used appliances in the household contexts study (see Section 7.4.6).

The study found that the total energy consumption of the case study apartment could be reduced by 3.13% (224 kWh) and 5.41% (388 kWh) respectively if the existing ceiling fans (75 watts) were replaced with five-star (50 watt) and super-efficient (35 watt) ceiling fans, without changing the urban and building contexts (see Figure 8.57).

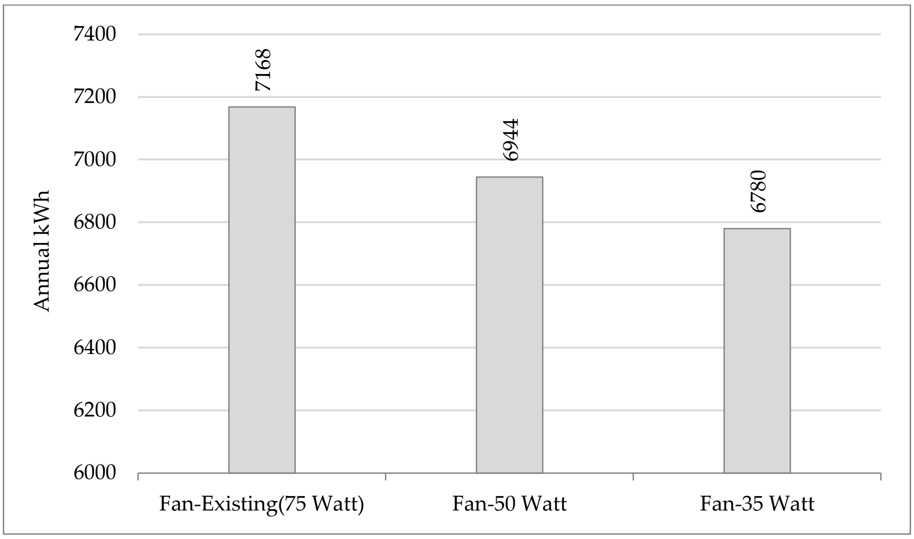

Figure 8.57: *Impact of Energy-efficient Ceiling Fans*

Investigations regarding energy-efficient AC found that the total energy consumption of the case study apartment could be reduced by 5.3% (378 kWh), 6.2% (442 kWh) and 6.8% (490 kWh) if the existing AC units[20] were replaced with one-star units (COP = 2.5 kW/kW), three-star units (COP = 3.1 kW/kW) and five-star units (COP = 3.3 kW/kW) AC respectively (see Figure 8.58).

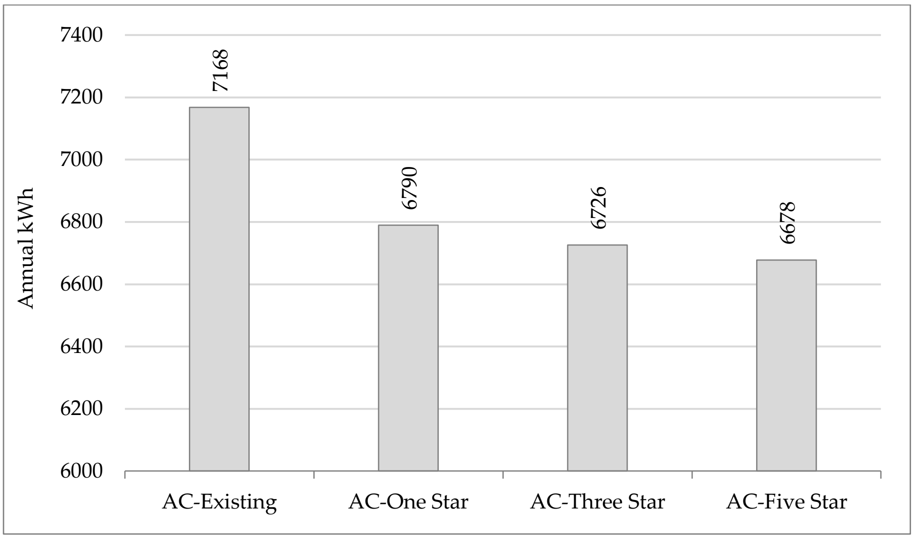

Figure 8.58: *Impact of Energy-efficient AC*

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[20] *The Coefficient of Performance (COP) of the existing AC units has been considered as 1.42 kW/kW.*

Investigations regarding artificial lights found that replacing the existing artificial lights (a mix of fluorescent tube and CFL, 30 watt (avg.)/bulb) with energy-efficient LED bulbs (10 watts) would result in a 5.7 %(410 kWh) reduction in the total energy consumption.

Investigations regarding refrigerators found that if the existing non-energy-efficient refrigerator (600 Ltr, 130 watt) in the case study apartment was replaced with a two-star refrigerator (about 75 Watt) or a five-star refrigerator (about 55 Watt), the total energy consumption could be reduced by 5.5% (394 kWh) and 9.7% (692 kWh) respectively. Lastly, investigations regarding energy-efficient TV found that replacing the existing CRT TV (255 watt) in the case study apartment with a LCD TV (125 Watt) would result in 2.42% (173.4 kWh) reduction of the total energy consumption.

Further study was conducted to find out the extent to which the energy consumption of the case study apartment could be reduced if all the appliances were replaced with the most energy-efficient ones. The results showed that replacing all of the above appliances could result in a 39.76% (2850 kWh) reduction of the total energy consumption of the case study apartment. The results also showed that the most energy could be saved by changing the refrigerator, followed by AC, lights, fans and TV (see Figure 8.59).

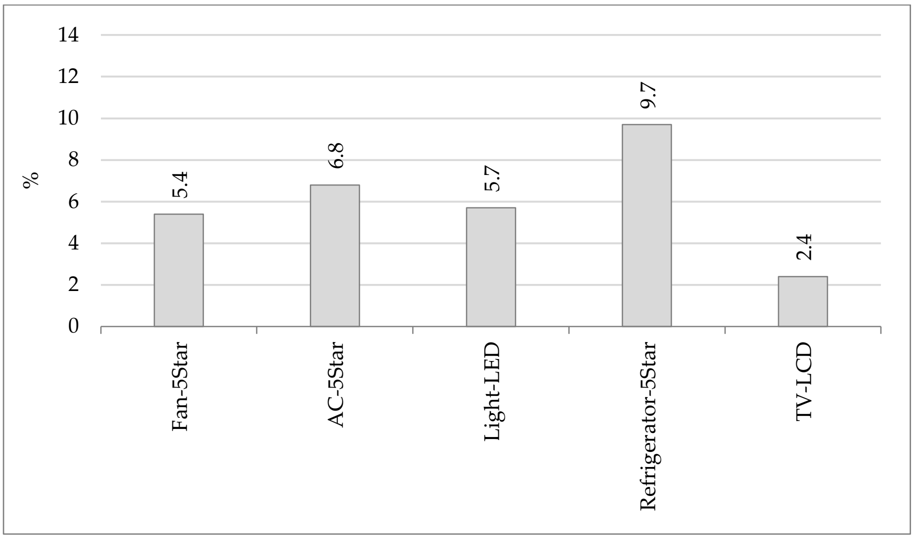

Figure 8.59: *Consumption Reduction Percentage due to Energy-efficient Appliances*

Based on the findings of this study, it can be said that a substantial amount of current household energy consumption could be reduced by replacing the existing major appliances with energy-efficient appliances. The results suggested that the reduction in energy consumption that could be achieved through upgrading the major appliances was much larger than the reduction that could be achieved through adjusting urban, building and operational practices. Therefore, to achieve maximum reduction of energy consumption, energy-efficient appliances must be introduced. As described in Chapter 7, energy-efficient appliances (excluding CFL bulbs) are not common in Dhaka and there is no general public awareness regarding using energy-efficient appliances. A public awareness campaign and increased availability of energy-efficient appliances in the market would be needed to ensure success in reducing the total energy consumption in residential areas.

8.3.2 Extent of Reduction in Energy Consumption

To find out the extent to which the existing household consumption level of typical residential developments could be reduced, investigations were made in two steps. First, the annual electricity consumption of a representative apartment in a 'business as usual' (BaU) scenario was predicted, based on the findings of the existing contexts studies presented in Chapters 5, 6 and 7. In the second step, annual consumption in a scenario of all best practices was predicted and was deducted from the BaU scenario to ascertain the extent to which the consumption had been reduced.

To predict the consumption in case of the BaU scenario, the building and apartment layout as well as the dimension of the windows and glass doors of the case study apartment were used, as it was representative of the type of apartments in this study. Similarly, for the input data regarding number of occupants and occupancy schedule, the profile of the case study apartment was used, as occupants number of the case study apartment (4) and the average occupants number of the studied households were similar (4.8, see Table 7.12). For the input data regarding construction materials, such as external walls, internal walls, ceilings, floors and windows, the most common practices were considered as found in the existing building contexts study. For window operation, the most common practices and for major appliances (Ceiling fan, AC, light, refrigerator, freezer and TV) and their use frequencies, the averages of the studied households in the household contexts study were used. Once the input data were set, the simulation was run to obtain the energy consumption for the representative apartment in the BaU scenario. The input data were then changed to the best practices and the simulation was run to obtain the reduced energy consumption, which was then deducted from the BaU case to identify the extent of reduction in consumption.

It is important to note that the investigations in this phase were conducted with north- and south-oriented buildings, since the north orientation was found to have the lowest consumption among all orientations and according to current development practices, having buildings with north orientation also means an equal number of south-oriented buildings. Therefore, to achieve overall energy independence, both north- and south-oriented buildings need to be energy independent.

The energy consumption of the major appliances in the BaU scenario, such as the usual consumption of a ceiling fan or 24” CRT TV in Dhaka, were based on the consumption calculator provided on DESCO's website, as well as the website of the largest household electric appliance retailer in Bangladesh, Singer Bangladesh Ltd (DESCO, 2016b; Singer Bangladesh, 2016). For the energy consumption of other appliances such as computer, iron and microwave oven, the consumption profile of the case study apartment was considered, partly because of the unavailability of detailed information for the average households regarding these appliances and partly because the case study apartment did not show any major deviation from the average household consumption. The following table shows the input data used for each of the major parameters to predict the consumption in the BaU scenario, as well as the best practice considered against the existing practices.

Table 8.2: *Input Data for the BaU Scenario and the Best-practices Scenario*

#	Item	BaU Scenario	Best Practice Scenario
1	External wall construction	10" (250 mm) solid brick wall, plastered & painted on both sides (see Section 5.3.11). U value (W/m² K): 2.0514.	20" (500 mm) solid brick wall in master bedroom & bedroom-2 (U value (W/m² K): 1.2354) and 10" (250 mm) solid brick wall in other areas, plastered & painted on both sides (see Section 8.3.1.3).
2	Window glazing	6 mm clear float glass with aluminium frame (see Section 5.3.9). U value (W/m² K): 5.599	Double-glazing for master bedroom & bedroom-2 (4 mm reflective glass x 6 mm airgap x 4 mm clear float) (U value (W/m² K): 3.4859) and 6 mm single-glaze reflective glass with aluminium frame for other rooms (U value (W/m² K): 5.599). See Section 8.3.1.4.
3	Glass door to verandas	6 mm clear float glass with aluminium frame. U value (W/m² K): 5.252	Double-glazing with aluminium frame for bedroom-2 veranda door (U value (W/m² K): 3.2503). 6 mm single-glaze reflective glass with aluminium frame for common space veranda door (U value (W/m² K): 5.1742).
4	Shading device	No shading device (see Section 5.3.10).	Egg-crate device with 0.6 ratio (see Section 8.3.1.5).
5	Window operation	In non-AC rooms, open during the evening, 6:00pm–10:00pm. In AC-rooms,	Open all night: 7:00pm–7:00am (see Section 8.3.1.7). In AC-rooms, windows were assumed

#	Item	BaU Scenario	Best Practice Scenario
		windows are closed all-day (see Section 7.4.3).	to be closed above 31°C from July-Sept. and above 32°C for the rest of the year during the operation period. It was assumed that AC was used above those temperatures and the windows were closed.
6	Ceiling fans	75 watt/fan: 3 in bedroom, 2 in common space, avg. use: 10 hrs/bedroom fan, 4.25 hrs/common-space fan (see Section 7.4.4). In the non-AC-rooms, fans were assumed in operation above 26°C from July-Sept. and above 28°C for the rest of the year. In the AC-rooms, fans were assumed on between 26° and 31°C from July-Sept. and between 28° and 32°C[21] for the rest of the year. It was assumed that the fans were turned-off when the AC was in operation.	35 watt/fan: 3 in bedroom, 2 in common space (see Section 8.3.1.8). Avg. use: 10 hrs/bedroom fan, 4.25 hrs/common-space fan. The same operation profiles as the BaU scenario.
7	AC	No rating (COP = 1.42), 1 in master bedroom and 1 in bedroom-2, avg. use: 6.25 hrs/AC (see Section 7.4.4). ACs were assumed in operation above 31°C from July-Sept. and above 32°C for the rest of the year.	Five-star (COP = 3.3), 1 in master bedroom and 1 in bedroom-2, Avg. Use: 6.25 hrs/AC (see Section 8.3.1.8). The same operation profiles as the BaU scenario.
8	Lights	30 watt (mix of fluorescent tube and CFL bulb), 15 no, avg. use: 3 hrs/bulb (see Section 7.4.5).	10 watt (LED), 15 no., avg. use: 3 hrs/bulb (see Section 8.3.1.8).
9	TV	200 watt (CRT), avg. use: 5.25 hrs/day (see Section 7.4.6).	125 watt (LCD), avg. use: 5.25 hrs/day (see Section 8.3.1.8).

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[21] *The comfort range for Dhaka is 24–32°C (Mallick, 1994), with 28°C as the neutral temperature (Shajahan, 2012). During the model calibration it was found that ceiling fans were used at the lower to neutral comfort temperatures and the ACs were used at the upper limits of comfort temperatures. In addition, it was found that both ceiling fans and ACs were used at 1-2° C lower temperatures during the monsoon period (July-Sept.) compared to the rest of the year. Hence, the threshold temperatures for using the fans and ACs were set based on the findings during the calibration.*

#	Item	BaU Scenario	Best Practice Scenario
10	Refrigerator	No rating (110 Watt), 428 Ltr (see Section 7.3.6).	Five star (55 Watt), 428 Ltr (see Section 8.3.1.8).
11	Freezer	No rating (100 Watt), 333 Ltr (see Section 7.3.6).	Five star (55 Watt), 333 Ltr (see Section 8.3.1.8).

8.3.2.1 Consumption in Business-as-usual Scenario

To find out the average energy consumption of a household in a typical building for the BaU case, the energy consumption of the representative apartment was obtained for all five floor levels and then averaged. The study found that if the current practices continued, the annual average consumption of a typical household in a north-oriented building would be 7,500 kWh and in a south-oriented building it would be 7,676 kWh (see Figure 8.60). It is important to note that to consider the worst-case scenario, the building was considered with the highest possible household density, that is, 10 double units per building. Therefore, the consumption showed per floor in Figure 8.60 is the average consumption of two households on that floor. In addition, the 5th- or top-floor roof of the building was considered as shaded, since it was assumed that roof-mounted solar PVs would be elevated and would act as a double roof for the building.

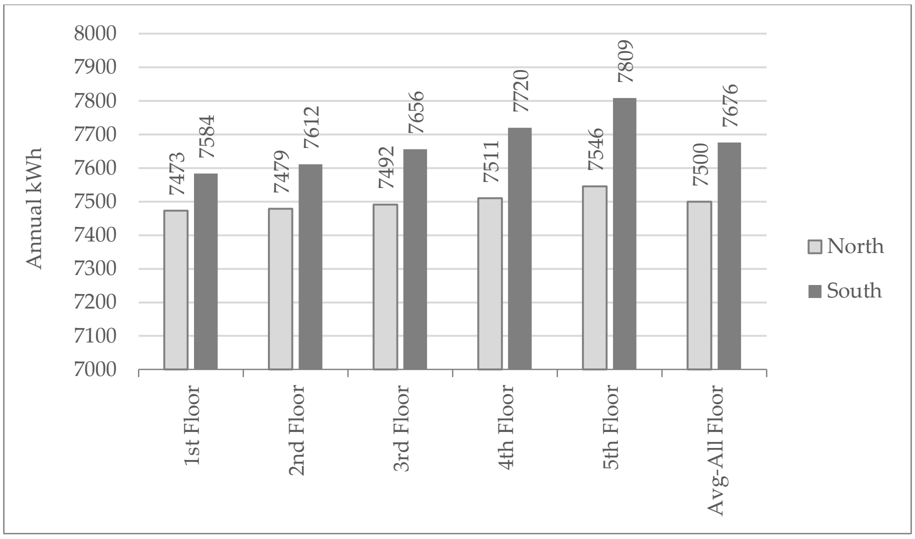

Figure 8.60: *Average Consumption of a Typical Household at Different Floors in the BaU Scenario*

8.3.2.2 Energy Consumption after Reduction through Using Best Practices

In the next step, investigations were conducted to find out the extent to which consumption could be reduced with the use of best practices. To investigate the best practices, the apartment at the front at 3rd floor level was used, as the average consumption of all households at all levels was similar to the average consumption of the 3rd floor level households. In addition, the apartment at the front represents the worst case scenario. The energy consumption of the north-oriented household at the 3rd floor level in BaU scenario was 7,517 kWh and the consumption of the south-oriented household was 7,776 kWh.

Replacing the existing external wall and window glazing practices with the best practices, as well as providing shading devices, could reduce energy consumption by 1.2% (89 kWh), 2.2% (164 kWh) and 0.2% (15.6 kWh) respectively for the household in the north-oriented building and by 1.7% (136 kWh), 3% (233 kWh) and 1.3% (97.5 kWh) for the household in the south-oriented building. In addition, if the windows were kept open all night, a further 3.7 % reduction in energy consumption could be achieved for both orientations (277.8 kWh and 288.7 kWh). The results showed that the best building and operational practices could reduce average energy consumption by 7.3% (546.5 kWh) for the north-oriented building (7,517 kWh to 6,970 kWh) and by 9.7% (755 kWh) for the south-oriented building (7,776 kWh to 7,021 kWh). The best building and operational practices had more impact in reducing total energy consumption for a south-oriented building than for a north-oriented building. This was not unexpected, as best building practices reduce the heat-gain impact due to solar radiation and the south face receives direct solar radiation throughout the day while the north face has limited solar exposure. Further study showed that with appropriate building and operational practices, the energy consumption gap between a south- and a north-oriented household could be reduced from 3.5% (259.8 kWh) to 0.7% (51.3 kWh).

Further investigations with the appliances found that replacing the existing fans, AC units, lights, TVs and refrigerators with the most energy-efficient appliances could reduce the total consumption by 3.1% (235 kWh), 5.5% (415 kWh), 8.4% (635 kWh), 4% (297.5 kWh) and 11.7% (876 kWh) respectively for the household in the north-oriented building and by 2.6% (201.6 kWh), 6.1% (475.6 kWh), 8.2% (635 kWh), 3.8% (297.5 kWh) and 11.3% (876 kWh) for the household in the south-oriented building. In total, replacing the existing appliances with energy-efficient appliance could reduce the energy consumption by 32.7% (2458.9 kWh) for the north-oriented household (7,517 kWh to 5,058 kWh) and 31.1% (2485.8 kWh) for a south-oriented building (7,776 kWh to 5,291 kWh).

Further analysis with all best practices, including building, operational and appliances, showed that together they could reduce the energy consumption by 39.98% (3005.4 kWh) for the household in the north-oriented building (7,517 kWh to 4,511.7 kWh) and 41.67% (3240.8 kWh) for the household in the south-oriented building (7,776 kWh to 4,536 kWh) (see Figure 8.61). Among all building and operational practices, ensuring night ventilation, or opening the windows at night, had the maximum result for both north-oriented and south-oriented buildings. Among all the appliances, replacing the refrigerator with an energy-efficient model had the most effect on reduction of energy consumption (see Figure 8.62).

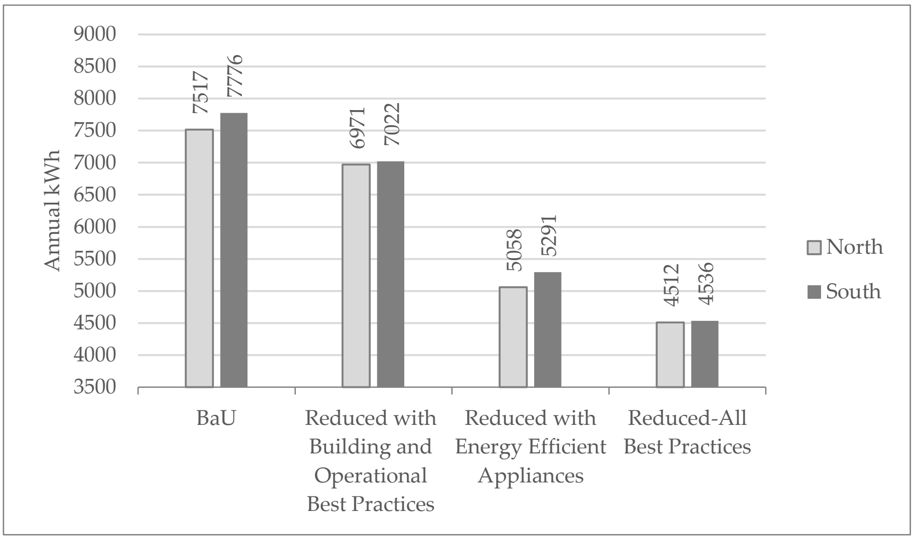

Figure 8.61: *Average Consumption of a Household in BaU and Reduced Scenarios*

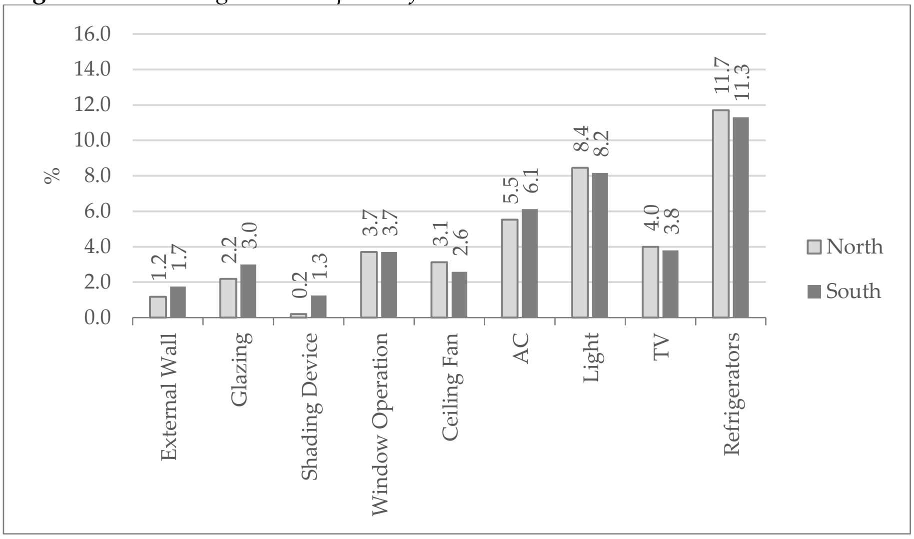

Figure 8.62: *Consumption Reduction after Applying Best Practices for Different Parameters*

Based on the findings of this study, it can be said that the existing energy consumption level of typical residential developments in Dhaka could be reduced substantially if the existing practices could be changed to the best practices identified through this study. The results have shown that while building and operational best practices do contribute towards the reduction of total energy consumption, the contribution amount is much less than the reduction possible through the use of energy-efficient appliances. Therefore, to maximise the reduction in energy consumption, households must shift towards using energy-efficient appliances along with the best urban, building and operational practices.

8.3.3 Energy Independence

In the last step of the simulation studies, investigations were conducted to find out if energy independence would be achievable through roof-mounted solar PVs. To find out this, the total annual energy demand of a whole building after reduction based on the findings of the previous step was deducted from the total electricity generation possible through roof-mounted PVs from the available roof areas. The investigations were made for both north- and south-oriented buildings.

To estimate the whole building-energy demand, the reduced consumption of the household as presented in the previous section was multiplied by 10, which was the highest possible number of households per building. The whole building-energy demand was therefore 45,120 kWh per year for a north-oriented building and 45,360 kWh per year for a south-oriented building.

Two most commonly used PV types, monocrystalline silicon and polycrystalline silicon, were investigated in the IESVE program to find out the maximum electricity generation possible though roof-mounted PVs. Other types of PV such as amorphous silicon and thin film were excluded from the investigation as due to more space requirement they are not suitable for roof installation. The monocrystalline PVs usually have higher efficiency (15-20%) compared to the polycrystalline PVs (13-16%) as well as monocrystalline tends to perform slightly better than the polycrystalline in higher temperatures (Maehlum, 2015; Solar Choice, 2016; SunPower, 2016).

To estimate the PV generation, the PVs were considered facing south, with a 23° tilt[22] from horizontal, mounted without any shading. Minimum PV efficiency was considered for both the PV types, that is, 15% for the monocrystalline and 13% for the

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[22] *23° is the local latitude and is most commonly practised while installing solar PVs in Dhaka (S. A. Chowdhury et al., 2011)*

polycrystalline. The roof area available for PV installation on the base building was 2,623 ft^2 (244.3 m^2).The results showed that with the available roof area, monocrystalline silicon could produce 49,873 kWh per year and polycrystalline silicon could produce 43,224 kWh electricity per year.

Considering the total annual demand of the whole building (45,120 kWh for north orientation and 45,360 kWh for south orientation), it was clear that while the monocrystalline PV with available roof area could generate more than enough electricity to achieve energy independence in the worst-case scenario, the polycrystalline PV type could not. In fact, further analyses showed that with monocrystalline PV, the electricity demand of the north-oriented building could be met with 90.5% (221.1m^2) and the south-oriented building with 91.1% (222.6m^2) of the available roof area. Further studies were conducted with higher efficiency (14%) polycrystalline panels. The results showed that with 14% panel efficiency, polycrystalline silicon could produce 46,548 kWh electricity per year, which is enough to achieve energy independence in the worst-case scenario for both north- and south-oriented buildings on annual basis. While annual totals looked promising, more detailed analysis is required to investigate the viability of the proposal.

Further investigations were conducted with monthly PV generation and electricity demand. This was to find out if enough PV generation is possible during the monsoon months (June–Sept.) since the electricity demand is higher at that period (due to higher use of AC) but the sky is overcast and less PV generation should be anticipated. To find out this, monthly total energy demand of the buildings were deducted from the monthly total PV generation and was plotted on Excel. The results showed that while the PVs (both types) would generate excess electricity than demand from January to April (Jan.–May with monocrystalline) and November to December (Oct.–Dec. with monocrystalline), they could not generate sufficient electricity from May/June to September/October (see Figure 8.63). Hence, it was clear that while the total annual demand of a building could be met by the roof-mounted PVs (with 15%

efficient monocrystalline and 14% efficient polycrystalline), they could not generate sufficient electricity to meet the demand during the monsoon months.

Further investigations were conducted with maximum efficient PVs, that is, 20% efficiency for monocrystalline and 16% for polycrystalline (Maehlum, 2015). This was to find out if with maximum efficient PVs, energy demand during the monsoon months could be met with available roof area (244.3 m^2). Monthly PV generations with 20% efficient monocrystalline and 16% efficient polycrystalline were simulated using IESVE. For the investigation, monthly PV generations were deducted from the monthly energy demand and was plotted in Excel. The results showed that with monocrystalline PVs, it would be possible to meet the electricity demand of both north- and south-oriented buildings during the monsoon months. However, with polycrystalline, it would not be possible to meet the electricity demand from June–September (see Figure 8.64).

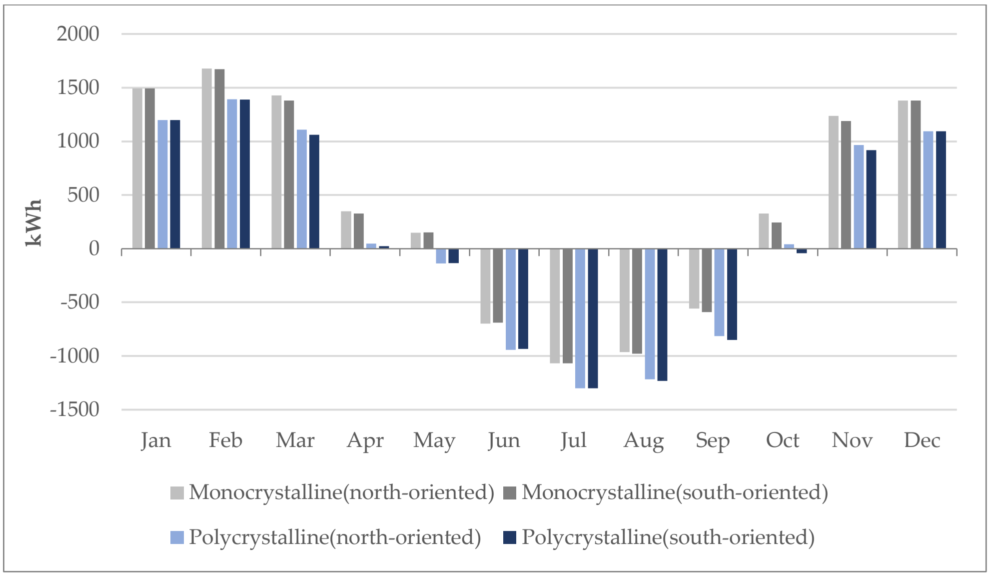

Figure 8.63: *Monthly Gap between Simulated PV Generation and Whole-building Electricity Demand for North- and South-Oriented Buildings with Monocrystalline(15%) and Polycrystalline(14%) PV*

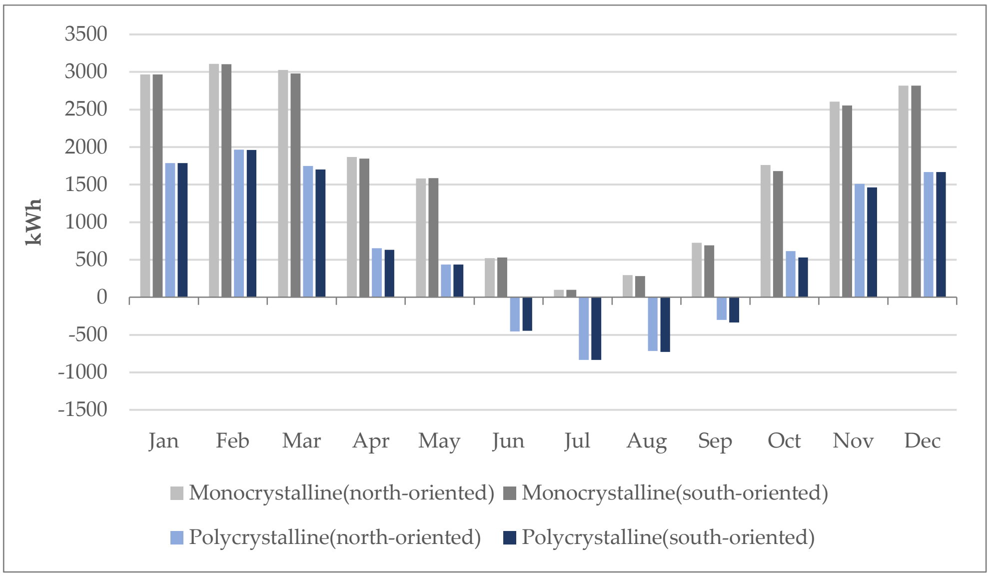

Figure 8.64: *Monthly Gap between Simulated PV Generation and Whole-building Electricity Demand with Maximum Efficient Monocrystalline(20%) and Polycrystalline(16%) PV*

It was clear from the results that to achieve energy independence throughout the year without grid-connection through roof-mounted solar PVs, the buildings actually would need to be plus-energy on annual basis or in other words, would need to produce substantially higher energy than total annual demand. Total annual PV generation as estimated through IESVE showed that with 20% panel efficiency and available roof area, monocrystalline PVs would generate 66,498 kWh per year, which as an example, would require to install a total 152 panels of 327 Watt capacity (SunPower, 2016). The total PV generation would be 47.4% (21,378 kWh) more than the total annual demand of the north-oriented building and 46.6% (21,138 kWh) more than the total annual demand of the south-oriented building.

Further investigations were conducted with daily hourly energy demand and PV generation. To conduct this, the hourly energy demand was deducted from the hourly PV generation (with 20%-efficient monocrystalline). The results showed that on daily basis, there would be times when there would be energy demand but insufficient or no PV generation (see Figure 8.65). It is not unusual as the major energy demand as well as the peak energy demand is likely to occur in the evening with artificial lighting on but there would be no PV generation at that time. This means that the excess electricity produced during daytime need to be stored in the batteries to be consumed in the evening and night.

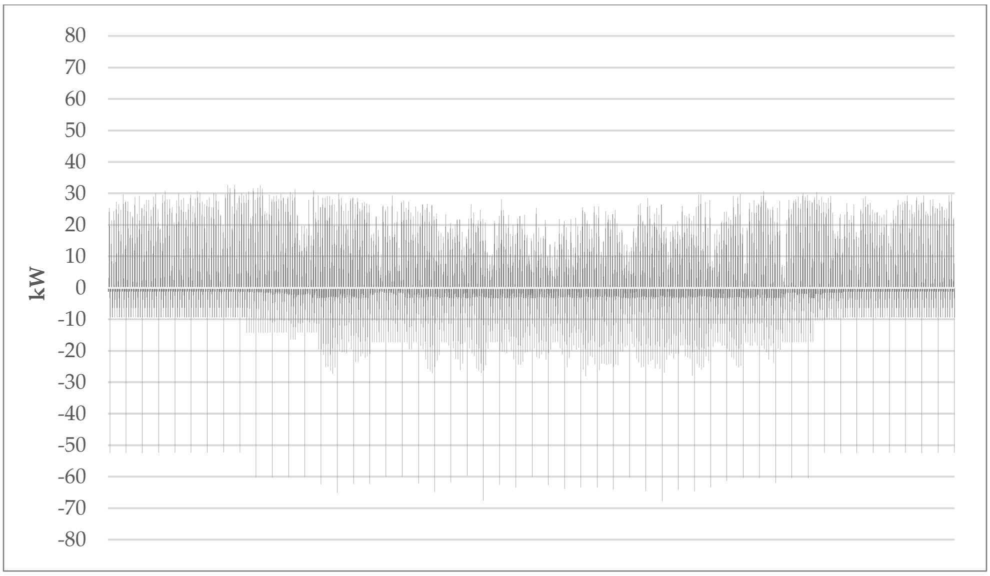

Figure 8.65: *Hourly Gap between Simulated PV Generation and Whole-building Electricity Demand*

To estimate the battery storage required, average daily demand during evenings from June to August (when there would be insufficient PV generation) was calculated. The result showed that the average daily evening/night-time demand for the whole building during these months would be 111.43 kWh or, 11.1 kWh per household. Therefore, to meet the energy demand at dark, battery storage per household would need to be at least 11.1 kWh.

The day peak load demand was also identified from the simulation results. The results showed that for both north- and south-oriented buildings, the maximum peak-energy demand occurred on 11 June at 18:30 pm and the peak demand was 67.6 kW or 6.8 kW per household for both the buildings. Hence, from the results, it can be said that to meet the energy demand of the households during the periods with insufficient or no PV generation, each household would need to have at least 11.1 kWh of battery storage with 6.8 kW peak output. As an example, based on these findings, each household would need to be equipped with two Tesla Powerwall batteries (6.4 kWh Model, maximum output 3.3 kW) (Tesla, 2016).

Based on the findings of this study, it can be said that after reducing the existing energy consumption level to the maximum, energy independence could be achieved in the buildings in typical residential developments in Dhaka through roof-mounted solar PVs. However, sufficient battery storage would be needed to supply electricity in the evening when there would be no PV generation. Furthermore, to achieve complete energy independence throughout the year, buildings would be needed to produce more than 45% electricity than total annual energy demand as shown in Figure 8.64. This excess electricity produced during the non-monsoon months could be supplied to other areas of the city or used for other purposes.

While it is understood that the success of energy-independence would be dependent on the battery storage options as well as cost-effectiveness of the PVs, investigating these aspects were beyond the scope of this research. Hence, this research strongly recommends further research regarding these topics.

8.4 SUMMARY FINDINGS AND DISCUSSION

The summary findings of the simulation studies are presented next, followed by a discussion that includes the outcomes regarding the ways to reduce the existing energy consumption of typical residential developments, the extent to which the energy consumption could be reduced and the ways to achieve energy independence in typical residential development contexts in Dhaka.

8.4.1 Summary Findings: Ways to Reduce Existing Energy Consumption

To find out the ways to reduce existing household energy consumption, the impact of various energy-influencing parameters at different levels such as urban, building, operational and household appliances was investigated through simulation studies using a calibrated apartment model. Based on the findings, the best practice for each of the parameters was identified for the given contexts.

At the urban level, the orientation of the buildings and the effective canyon ratio (CR) in front of the buildings were investigated. The study found that among all possible orientations within the existing urban practices, north was the best and south-west was the worst from the energy-consumption point of view; any north-related orientation, such as north-east, was better than any south-related orientation, such as south-east. Excluding north, the other three cardinal orientations (east, south and west) did not vary much from each other. Therefore, to maximise the reduction of energy consumption in typical developments, more buildings should face north.

The study regarding CR found that in general, if the effective CR in front of an apartment was at least 2 or more, the shadow of the opposite building was sufficient for shading and additional shading devices would not be required for any orientation apart from south. For the south orientation, the CR would need to be 2.8 or more. However, the maximum CR within the given practices is 1.33; therefore, to maximise the reduction in energy consumption, additional shading devices would be needed for the windows.

At the building level, external wall construction, window glazing, shading devices and window size were investigated. The study found that in general, brick walls performed better than concrete block walls and cavity walls were better than solid walls. Thicker walls performed better than thinner walls. A cavity wall with 250x250 mm brick performed the best, but was only marginally better than a solid wall with 500 mm thickness.

In the case of single-glazed windows, reflective glass performed better than clear float and tinted glass. Increasing the thickness of reflective glass negatively affected the total energy consumption; therefore, reflective glass with 4 mm or 6 mm thickness was the best in the case of single-glazed windows. Double-glazed windows performed better than single-glazed windows. Increasing the thickness of glass or the airgap negatively affected the consumption. Therefore, double-glazing with the minimum thickness of glass and airgap provided the best result in Dhaka's contexts. The best-performing double-glazing was a 4 mm thick reflective outer pane x 6 mm airgap x 4 mm clear float inner pane. According to the findings of this study, to achieve the maximum reduction of energy consumption, double-glazed windows with a reflective outer pane should be used.

The investigation regarding different shading devices found that the egg-crate shading device provided the best result for all orientations; however, horizontal shading devices also performed equally well on east-, west- and south-east oriented windows. Shading devices did not improve the energy consumption condition noticeably for north-oriented windows. Although, shading devices with a higher device ratio performed best, they did not improve the situation noticeably after the 0.6 device ratio.

With regard to the area of glazed surfaces, the study found that the total energy consumption did not vary until the glass surface area reached 20% of the total external wall surface area. Consumption started to increase once the glass surface ratio exceeded 20% and increased more steeply at a higher ratio than at a lower ratio. Therefore, according to the findings of this study, the reduction in energy consumption could be maximised if the glass surface was no more than 20% of the total external wall surface areas.

Investigations regarding window operation found that different patterns of window operation could significantly affect the total energy consumption of the households. The maximum reduction in energy consumption could be achieved if the windows were kept open at night and closed during the day; that is, if night-time ventilation was maximised. Opening the windows even for a shorter period in the evening could noticeably reduce the total energy consumption. Having the windows open during the day had a negative impact on total energy consumption. According to the findings, the best practice was to keep the windows closed during the day and open at night.

Investigations regarding major household appliances found that a significant amount of energy consumption could be reduced by changing the existing non-energy-efficient appliances for energy-efficient appliances. Within the given contexts, the maximum reduction in energy consumption could be achieved by replacing older refrigerators with energy-efficient refrigerators. Therefore, to maximise the reduction in energy consumption, households should shift towards energy-efficient appliances, particularly refrigerators.

8.4.2 Summary Findings: Extent of Reduction in Energy Consumption

The study found that if the existing building and operational practices could be replaced with the best practices, then the existing energy consumption could be reduced by 7.3% for a north-oriented building and 9.7% for a south-oriented building. If the existing major appliances could be replaced with appliances with maximum energy efficiency, the total consumption could be reduced by more than 31%. In total, if all of the best practices could be applied at all levels, then the existing energy consumption could be reduced by 39.98% for a north-oriented building and 41.67% for a south-oriented building. The study also found that from energy-consumption point of view, the best building and operational practices had more impact on a south-oriented building than on a north-oriented building. Therefore, south-oriented buildings would need to adopt best building practices to maximise the reduction in energy consumption. If best building practices were adopted, the consumption gap between north- and south-oriented buildings decreased.

8.4.3 Summary Findings: Energy Independence

The ultimate aim of this research was to find out whether energy independence was possible for the buildings in typical residential developments in Dhaka. The study has found that after reducing the existing energy consumption by adopting best practices, it would be possible to achieve energy independence through the use of roof-mounted solar PVs and battery storage for each apartment.

8.4.4 Discussion

This study has identified several key existing practices in typical residential developments of Dhaka that could be altered to achieve substantial reductions in energy consumption. Several of the findings of the simulation studies confirmed the assumptions made based on the findings of the existing contexts study. Examples of this include the findings that north-oriented buildings were found to consume the lowest amount of energy (south-oriented buildings were found to consume more because of cooling); the upper floors of a building were found to consume more energy than the lower floors; enhancing night ventilation could reduce the total energy consumption; and cold appliances, such as the refrigerator and freezer, account for a large amount of the total consumption.

Although north-oriented buildings were found to have the lowest energy consumption, within the given urban development practices, having more buildings with a north orientation would mean having an equal number of south-oriented buildings. Therefore, the existing urban layout practices need rethinking to maximise the reduction in energy consumption and hence, create more-sustainable developments. Possible alternative urban layouts were not investigated in this study as this was beyond the scope of this research.

While the existing practice is to construct external walls with 125 mm or 250 mm solid brick, a cavity wall as well as a thicker external wall (500 mm) was found to reduce the level of energy consumption. However, given the existing contexts of urban land and resource scarcity, it does not seem appropriate to apply thick walls for all rooms and spaces of an apartment. Constructing thick walls only for the energy-intense rooms, such as the master bedroom and bedroom-2, seems more appropriate in the contexts of Dhaka. In addition, as the production process for brick is responsible for huge carbon emissions, its use should be optimised.

Double-glazed windows were the best from an energy-consumption point of view, rather than the existing practice of single glazing. As double-glazed windows are more expensive than single-glazed windows and their thermal performance is not significantly higher than a single-glazed window, it seems appropriate to use double-glazed windows only for energy-intense rooms such as the master bedroom. Whether the windows are double glazed or single glazed, using reflective glass would maximise the reduction in energy consumption. The best glass surface ratio was found to be 0.2, or 20% of the total external wall area rather than the existing common practice of having 30% glass area. Reducing the window glass area may have an implication for the daylight condition, increasing the total artificial lighting consumption. As energy consumption did not increase significantly up to a 0.3 glass ratio, it seems more appropriate to continue with the current practice but to avoid the recent trend towards increasing the glass surface area.

One of the major findings of this study was the effect of night-time ventilation on total energy consumption. Given the existing contexts of Dhaka city, ensuring night-time ventilation could be one of the greatest challenges, since for various reasons (e.g., privacy, security, dust and AC use) many households are reluctant to open the windows, particularly at night and in the bedrooms. Therefore, within the given built-environmental and social contexts, ensuring night-time ventilation would require innovative design approaches or applications, possibly including the revival of traditional ventilators modified to suit the current urban contexts.

Replacing the current major appliances with energy-efficient appliances was found to have the maximum impact on the reduction of energy consumption. Therefore, every effort should be made to encourage the use of energy-efficient appliances. As energy-efficient appliances are more expensive and few households are aware of them, as well as the fact that these appliances are not yet available in the markets of Dhaka, incentives as well as awareness campaigns will be required for success in this area. However, if the old appliances are not replaced with energy-efficient appliances, meaningful reduction of energy consumption cannot be achieved.

This study also found that after reducing the existing energy consumption to the maximum by the above means, it would be possible to achieve energy independence with the available roof area and monocrystalline PV (20% efficiency). However, battery storage would be needed to meet the demand when there is no or insufficient PV generation.

Table 8.3: *Summary Chart with Key Findings: Simulation Studies*

Answers to RQ 1: Ways to Reduce Existing Energy Consumption

#	Item	Prevailing Practices	Best Practice According to Simulation Findings	Recommended Practice Considering Dhaka's Contexts
1	Orientation	North (28.7%), south (29%), east (18.9%), west (18.7%), others (4.8%).	North	North
2	Effective CR	Max. 1.33 at 1st-floor level, min. 0.325 at 5th-floor level.	For effective CR 2 & above, local shading is not needed for all orientations apart from south. For south, CR has to be 2.8 or above.	Local shading is needed for all orientations, as the maximum CR is 1.33.
3	External wall	125 mm & 250 mm solid brick wall.	Cavity wall.	500 mm solid brick wall for master bedroom & bedroom-2. 125/250 mm solid brick wall in other spaces.
4	Glazing type	Single glaze, 5–6 mm clear float (56), tinted (29) and reflective (15%) glass.	Double-glazing: 4 mm(reflective outer pane) x 6 mm airgap x 4 mm (clear float inner pane).	Double-glazing with reflective glass for master bedroom and bedroom-2, single glazing with reflective glass in other spaces.
5	Shading Devices	None or 10-20” (0.25–0.5 m) deep recessed	Egg-crate shading device with 1.0 device ratio for all	Egg-crate shading device with 0.6 device ratio for all

Answers to RQ 1: Ways to Reduce Existing Energy Consumption

#	Item	Prevailing Practices	Best Practice According to Simulation Findings	Recommended Practice Considering Dhaka's Contexts
		windows or horizontal shading.	orientations, horizontal shading device with 1.0 device ratio for east, west & south-east orientation.	orientations, or horizontal shading device with 0.6 device ratio for east, west & south-east orientation.
6	Window size	30% of total external wall surface, with current trend of increasing glass areas to 100% in some cases.	20% of the external wall surface.	30% of the external wall surface.
7	Window operation	Sometimes used. In general, windows not kept open, particularly at night & in bedrooms.	Open at night and closed during day.	Open at night and closed during day.
8	Appliances	Non-energy-efficient appliances used. No general awareness about energy-efficient appliances & efficient appliances not available in the market.	Maximum use of energy-efficient appliances.	Maximum use of energy-efficient appliances.

Answers to RQ 2: Extent of Reduction in Energy Consumption

#	Item	Key Findings
1	Reduction in energy consumption through use of best building & operational practices.	7.3% reduction in total energy consumption for north-oriented building & 9.7% for south-oriented building.
2	Reduction in energy consumption through use of energy-efficient appliances.	More than 31% reduction for both north- and south-oriented buildings.
3	Reduction in energy consumption through use of all best practices.	39.98% reduction for north-oriented buildings and 41.67% reduction for south-oriented buildings.

Answers to RQ 3: Achievement of Energy Independence

#	Item	Key Findings
1	Energy independence through the use of roof-mounted solar PVs.	• It is possible to achieve energy independence with available roof area and monocrystalline PV with 20% efficiency. However, sufficient battery storage (67.6 kW) is needed to meet the peak-energy demand.

8.5 CONCLUSION

The final outcomes of this research, derived through simulation studies, have been presented in this chapter. The study has identified the energy impact of several key practices in typical residential developments in Dhaka that could be altered to achieve substantial reductions in energy requirements and even energy independence.

9 CONCLUSION AND RECOMMENDATIONS

9.1 INTRODUCTION

This chapter presents the conclusions of this research, which aimed to investigate the possibilities for energy independence in residential developments in the contexts of Dhaka, with a particular focus on typical planned residential developments that accommodate the higher- and higher-middle-income section of the city and hence, are more energy intense. As presented in Section 1.4, three RQs were designed to address this aim. Considering the research outcomes as presented in Chapter 8, this research concludes that it would be possible to achieve energy independence for typical planned residential developments in Dhaka through the use of roof-mounted solar PVs if efficiency measures were adopted at all levels, ranging from urban design to the use of energy-efficient appliances. Further, not only the future developments but also the existing ones could become energy independent with minor retrofitting and replacement of existing appliances. To obtain the outcomes of this research, six objectives were set, along with extensive literature reviews. The key findings of these are discussed in the next section.

9.2 KEY FINDINGS

It was evident from the literature review (see Chapters 1 and 3) that one of the central challenges of 21st-century development is energy. The attainment of sustainable development is largely dependent on the way this energy challenge is addressed, particularly by buildings. Not only do buildings need to be highly energy efficient but also the source of the energy has to be emission-free. This is particularly true for developing countries, in which a large number of new buildings are upcoming. Achieving optimum energy efficiency in buildings can be difficult, as the energy consumption of buildings is affected by a large number of parameters acting at different levels such as urban, building and occupants. Further, as the influence of these parameters varies under different conditions, such as local climate and construction practices, context-specific efficiency strategies are required. Hence, the literature review suggested that to achieve optimum energy efficiency in buildings, context-specific efficiency measures would need to be identified through in-depth research and a common standard and definition would need to be set for energy-efficient buildings. New building types such as 'zero-energy' and 'plus-energy' are considered one of the best solutions to the energy challenges of the building sector.

While the literature strongly suggested that energy efficiency in buildings is one of the key strategies for tackling the energy issues, many developing countries such as Bangladesh still do not have a building energy code. Moreover, although a large number of new developments are under construction, there are no directions or requirements to consider factors of the local climate during the design phase, to minimise the UHI effect or maximise the benefits of the prevailing wind. Despite the negative impact of fossil fuels and their depletion, Bangladesh continues to invest significantly in fossil-fuel-based power plants and has planned to meet 50% of future power generation with coal-powered energy. The deployment of renewable energy sources is primarily rural based and overall progress in the share of renewable energy is insignificant. In addition, there are several energy-wasting practices, such as system loss and the use of inefficient IPSs. As presented in Chapter 2, to reduce the future energy demand and GHG emissions of Bangladesh, actions that enhance the development of energy plans that prohibit energy-wasting practices, prioritise energy-efficiency achievements and focus on the wider deployment of renewable energy sources, particularly at the building level, are needed. Given the development and energy contexts of Bangladesh, focusing on making buildings energy independent seems to be the best way to address all the challenges.

The urban and building contexts study as presented in Chapter 5 explored the dominant urban and building design practices in typical residential developments in Dhaka. The study found that the developments were highly homogeneous and did not vary according to different development authorities. It was found that the south orientation is the most preferred orientation and the majority of the plots were either facing south or north along with a grid road network. Each plot contained one multi-storey, multi-unit apartment building with maximum ground coverage and with very little green space. The buildings were closely spaced with narrow canyons in between. There were usually two apartment units per floor and there was an increasing preference for larger glazed areas. The building regulations were not research based and the existing practices were driven mainly by social, economic and political forces, without much consideration for the environment or for energy performance. Many of the existing practices were found to be rather counterproductive and were causing unnecessary energy consumption, such as increasing the number of smaller-sized plots that are likely to increase the UHI intensity and the absence of shading devices on the windows or larger glazed areas on the south façade. There were many reasons behind the absence of energy-efficient practices, such as the high profit-making motivation, which means there is little interest in spending extra money on passive-design strategies. Additionally, as the energy effects of the prevailing practices are unknown and there is no building energy code, the professionals are not equipped to make energy-efficient decisions. This study infers that if the inefficient practices could be removed, a significant energy saving would be possible.

The microclimatic contexts study (presented in Chapter 6) revealed that the most preferred orientation (south) of typical developments is actually the warmest; that is, it may require more cooling energy than any other orientation. In addition, the upper floors are warmer than the lower floors. The indoors have a higher average temperature than the outdoors and are considerably warmer at night, indicating the lack of heat release at night. The UHI effect was found to be present with varying intensity for different orientations. The maximum intensity was found to occur after approximately six hours after sunset, at midnight. In addition, Cool Islands were present in the setback areas where the canyons were deep and narrow. The results imply that since residential energy consumption occurs mainly at night, a significant energy reduction could be achieved by mitigating the UHI effect as well as ensuring night-time heat release. In addition, the findings indicated that the common belief of the south being the best orientation in terms of thermal comfort may not be true within the given physical contexts of typical residential developments.

The findings of the household contexts study (presented in Chapter 7) identified several practices that could be altered to achieve significant energy saving. For example, good cross-ventilation was found to correlate significantly with less energy consumption; however, occupants were reluctant to keep the windows open in general. Most of the households were never completely vacant during the day. Ceiling fans, artificial lights, refrigerator and TV were the most common appliances, and most owned an AC unit and more than one cold appliance, such as refrigerator and freezer. Wet appliances were not common. The master bedroom and bedroom-2 were the most energy-intense rooms of the households, as cooling appliances were used in these rooms the most. The energy consumption of the households was highest during the hot-wet season, indicating higher use of AC during this season; however, the consumption of cooling energy accounted for only 24% of the total energy consumption; more than 70% of consumption was due to other appliances. Although larger apartments had a higher total energy consumption, the average consumption per unit area was nearly same for the smaller and larger apartments. It was found that the occupant-related parameters were more significant in affecting energy consumption than the building parameters. The cold appliances, such as refrigerator, freezer and ACs, were been identified as having the most effect on increasing the energy consumption. Energy-efficient appliances were not common and a general lack of awareness energy-efficient behaviour or appliances was evident. The study inferred that improving the comfort condition of the master bedroom and bedroom-2, particularly during the hot-wet season, as well as the deployment of energy-efficient appliances and increasing the awareness of the occupants, could result in significant energy saving at the household level.

The simulation studies (presented in Chapter 8) explored the energy impact of the different urban, building and operational practices as well as of the commonly used appliances. The simulations further confirmed many of the assumptions made based on the findings of the existing contexts studies. It was found that the north is the best orientation in terms of energy consumption and local shading is not needed if the adjacent CR is more than 2.0 for all orientations except the south. In addition, maximum energy savings could be achieved through the use of brick cavity walls with 500 mm thickness, double-glazed windows with a 4 mm reflective outer pane and 4 mm clear float inner pane with a 6 mm airgap, egg-crate shading devices, and restricting the total glazed area to no more than 30% of a wall. Further, keeping the windows open at night and closed during the day could reduce the consumption of cooling energy significantly. Finally, the greatest reduction in energy consumption could be achieved by replacing the refrigerators with energy-efficient ones.

The results showed that replacing the detrimental practices with the best practices at all levels could result in at least a 39% total energy saving. Overall energy independence could be achieved through the use of roof-mounted solar PVs after these energy conservation measures where applied together with a switch to using energy-efficient appliances. Further, the results indicated that not only the future developments but also the existing buildings could achieve energy independence with minor retrofitting and replacement of the existing appliances.

9.3 CONTRIBUTION TO KNOWLEDGE

This research for the first time attempted to find out the energy consequences of the different urban, building and household practices in typical planned residential developments in Dhaka. While doing this, it has explored and documented the prevailing practices along with the energy consumption pattern and intensity of the households in the researched developments. The results of this research can be considered the foundation for future research in the area of energy-efficient developments. In addition, this research has explored the consequences of such developments on the microclimate and has highlighted the need for climatic considerations during the urban planning and design stage, to obtain maximum energy efficiency. The research has shown that it is possible to shift the existing developments from being an energy consumer to being an energy generator and hence, to become energy independent. The results of this research will assist professionals and policy makers in making more-informed and appropriate decisions.

9.4 LIMITATIONS OF THE RESEARCH

While the overall aim of this research has been attained, it is important to note several limitations. Due to budget constraints, a limited number of data loggers were used to identify the microclimatic consequences of the current development practices. Should data be collected at more buildings the data may give different results. In addition, the findings of the microclimatic study were based on record during September and October; hence, the seasonal variation is not known and a year-long average could be different from what has been found in this study.

For the household contexts study, the responses were collected according to the availability and accessibility of participants and were not truly random; therefore, there could be a sample bias. Due to information unavailability, the research could not incorporate the effect of the use of reflective glass on daytime lighting use in predicting the energy demand after applying all best practices; hence, the demand predicted may be slightly lower than it would be if this effect had been incorporated. To conduct the simulation studies in case of BaU and best-practice scenarios, several assumptions regarding input data such as occupancy schedule, threshold temperature for ceiling fan and AC use and, use of several appliances were taken from the case-study apartment. Hence, the predicted results may be different if other households' occupancy assumptions are adopted.

Another important limitation of this research is that it could not incorporate orientation-specific weather files due to the unavailability of year-long weather data. Hence, for the simulation studies, the energy plus weather file was used for all orientations, which may have provided lower consumption results for the south orientations. Finally, the research has identified the energy impact of different urban and building design practices; however, it could not quantify the energy consequences of the UHI effect, due to the unavailability of appropriate weather files.

9.5 CHALLENGES TO OVERCOME

While it is essential that a large number of similar research projects should be conducted on reducing the demand for energy and the GHG emissions of Bangladesh, several serious challenges will need to be overcome. First, there is a general lack of useful weather data. The weather data provided by the national meteorological department are 3-hourly, whereas a simulation program requires hourly weather data. In addition, correct solar radiation data are not available at the national meteorological department and there is no other local organisation that can provide weather data to the public. Therefore, this research highlights the need for appropriate weather data for future research.

9.6 FURTHER RESEARCH RECOMMENDATIONS

From the outcomes of this research, the following further research needs have been identified:

- This research was conducted based on the existing urban layout and identified the best practices within the given urban practices. Time constraints did not allow the investigation of different urban layouts, which could have led to further investigation regarding future energy-efficient developments that incorporated natural ventilation strategies through computational fluid dynamics.
- Further research is needed for buildings constructed by following new building construction rules.
- Further research is needed for other plot size and types, such as 3 Katha, 7.5 Katha, 10 Katha and corner plots, as well as other types of residential developments, such as spontaneous developments and high-rises.
- Further microclimatic research is needed, incorporating wind flow, RH and solar radiation.
- Further extensive UHI investigation is needed, considering the whole year, as well as the energy consequences of the UHI effect and appropriate mitigation strategies.
- Further investigations are needed regarding indoor ventilation strategies and night-time ventilation.
- Further qualitative research is needed to explore occupants' behavioural parameters regarding the use of different appliances and to identify appropriate strategies to motivate and educate the occupants in energy-saving behaviour.
- Further research is needed that incorporates the daytime use of lighting and location-specific weather files.
- Further research is needed to explore the possibilities of other types of renewable energies, such as organic wastes and wind energy, along with ways to execute the integration of renewable energies.

- Further in-depth qualitative research is needed to explore the socio-economic aspects of such developments.
- Further research is needed on technical aspects of such developments such as battery storage and grid-connection options.
- Finally, as the overall energy demand of these residential developments will rise along with the economic progress of Bangladesh, regular research on the upgrading of renewable energy generation, as well as efficiency measures, should be considered.

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Appendices

Appendix A.1: Paper 1

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INVESTIGATING URBAN HEAT ISLAND TO DERIVE ALTERNATIVE OPTIONS FOR ENERGY EFFICIENT RESIDENTIAL DEVELOMENTS, CASE STUDY: DHAKA, BANGLADESH

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Fig 1: DOHS Baridhara, one of the typical residential areas of Dhaka

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Research summary

This study proposes urban design recommendations for future residential developments of Dhaka, a fast growing city with a tropical climate in a developing country. The aim of the research was to derive alternative urban design recommendations based on first hand quantitative data, which can lead to more energy-efficient and comfortable residential developments. The preliminary assumptions were that the current forms of residential developments in Dhaka contributed to the urban heat island (UHI), leading to increased cooling demand. This study conducted a UHI investigation in one of the typical residential areas of the city in 2013, and found that on average the air temperature of the case study area was .8°C higher than a nearby weather station during the study period and every 1°C temperature increase during the hot seasons caused 5.1% more energy consumption due to cooling purposes in the study area in that particular year. The study also found that some moderate changes in current planning could considerably reduce energy consumption from such developments in the future. Implementation of the recommendations not only will reduce the economic burden of a developing country from generating more energy but will also inflict less demand on already depleting global energy resources.

Keywords: UHI, Residential Development, Energy-efficiency, Developing City.

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1. Introduction

Urban heat island (UHI) is the phenomenon where the air temperature of an urban area is higher than its surrounding non-urban areas. The phenomenon is well studied and the studies have found that the formation and intensity of an UHI is largely dependent on the morphology of an urban area which can significantly influence the energy use of that urban area. (Ahmed, 1996; Santamouris et al., 2001; Williamson and Erell, 2001; Eliasson, 2000; Pearlmutter et al., 1999; Arnfield, 1990; Ahmed, 2003). UHI generally is unwanted for low and mid latitude cities as this can considerably increase the cooling energy demand (Taha, 1997). Every 1°C temperature increase can increase the energy consumption by 5% (Wong et al., 2009) and cooling load can be reduced by 5-10% just by altering urban morphology(Wong et al., 2011).

Dhaka, the capital of Bangladesh is situated at 23.24°N, 91.23°E and is one of the fastest growing megacities of the 21st century. It has been estimated that by 2020, more than 20 million people will be living in Dhaka making it the second largest megacity in the world (Roy, 2009). Consequently, numerous new urban projects are being developed and will be developed in near future to meet the increasing urbanization demand. From the capital development authority of Dhaka (RAJUK)'s website, it is found that at present 33 new projects of nearly 4606ha land are being developed in and around the city. These are mainly residential projects with unique characteristics where a big piece of land is divided into small plots with road layouts predominantly along the east-west axis that are perpendicular to the prevailing wind direction (Field Survey). Since this type of residential developments are likely to be continued for many more years to come, it is timely to find out the UHI intensity and pattern in such developments to know the level of impacts they are having on energy consumption.

This paper presents the findings of a study which investigated the UHI intensity and pattern of a typical existing residential area in Dhaka. The objectives of the study were to find out (i) if an UHI is present in the study area, (ii) if present, the intensity and pattern of the UHI and, (iii) the possible impact of UHI on the energy consumption of the area.

2. The Physical Contexts of the Case Study Area

DOHS Baridhara, a typically planned residential area of nearly 90 acres, located at the northern part of Dhaka, was chosen for this study. It is one of the newer additions of the city yet has been mostly built and therefore is suitable for a UHI study.

There are 567 plots in total in the study area. Except few irregular ones, each plot is rectangular in shape of 3600Sft (335m^2).The width of the only primary road is 40' (12.19m) laid along the N-S axis and the width of the 16 secondary roads is 30' (9.14m) of which 14 are along the E-W axis and 2 are along the N-S axis. Entrance to the plots is either from south or north for 95% of the cases. Maximum height of any building in the area is about 62'(19m) and the minimum setback distances from the boundary line of a plot are, from the side = 3.4'(1.25m), from the front =5'(1.5m) and from the back= 6'(2m). Building materials are fairly similar for all with brick walls covered by cement plaster within a Reinforced Cement Concrete structure. All the road surfaces are made of asphalt and the sidewalks are made of ceramic brick. One of the main sources of anthropogenic heat along with motorized vehicles is the air-conditioner, which is either wall or window mounted and is usually installed at the sides or back of a building.

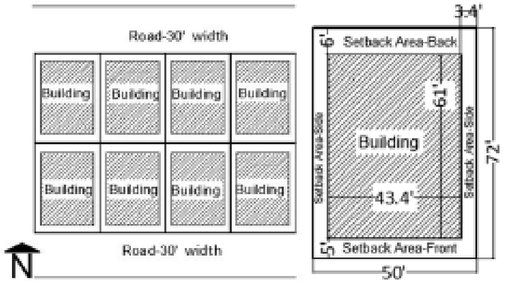

Fig 1: Example of plot layouts and blowup of a plot

3. Methodology

The study collected data on air temperature and monthly electricity consumption of the area along with a physical survey. Data were then analysed and compared with the data from a nearby meteorological station (Met), which has been considered as the non-urban area for this study. Finally, based on the findings, recommendations were made.

Primary data on air temperature were collected from 18 outdoor points and 12 indoor points. Outdoor air temperature data were collected from six different locations and the indoor temperatures were collected from four locations at three levels (3m, 9m and 15m above ground level). However, for this study, only the outdoor temperature at 3m level is considered. Outdoor temperature data were collected by HOBO U23-001 data loggers. Data were collected for 40 days from 1st September to 10th October 2013 and the monthly electricity bill of 70 apartment units for 2013 were collected through a questionnaire survey.

There are five types of urban canyons (UC) present in the case study area. UC type-1 is formed by the N-S axis primary road, UC type-2 is formed by the E-W axis secondary roads, UC type-3 is formed by the N-S axis secondary roads, UC type-4 is formed by the side setback roads, UC type-4 is formed by the side setback areas and UC type-5 is formed by the back setback areas between buildings. Loggers were installed in UC type-1, 2, 4 and 5 as 90% of the study area is comprised of these four types of canyons. For UC type- 1 and 2, two loggers were installed from two oppositely oriented canyon walls. This provided an opportunity to measure the impact of different orientations on the adjacent air temperature. Whereas, since the UC type- 4 and 5 are very narrow, loggers were installed from only one canyon wall.

Table 1: Installed Loggers ID and Details

Logger ID	UC Type	Canyon Axis	Canyon Ratio (H/W)	Canyon Wall's Orientation
DL1	UC-1	N-S	1.32	East
DL2	UC-1	N-S	1.32	West
DL3	UC-2	E-W	1.55	North
DL4	UC-2	E-W	1.55	South
DL5	UC-3	N-S	8.87	Setback area
DL6	UC-4	E-W	5.16	Setback area

Fig 2: Loggers ID and locations

4. Data Analyses and Findings

Data were analysed in 3 stages to address the three objectives of this study, which are presented below.

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4.1. Finding the Presence of UHI

Daily average air temperature of each day for all locations along with the Met data during the study period were plotted and compared. The result shows that a UHI is present in the area intensity of which varies according to different orientations (Fig 3-4). The south-oriented logger recorded the highest average temperature followed by the east-oriented one, the setback area and west oriented ones, and lastly, the north-oriented one. On average, the south-oriented logger showed nearly 1°C higher average air temperature compared to the met station data. Also, the south-oriented logger showed more than .5°C higher air temperature compared to all other locations except the east-oriented one.

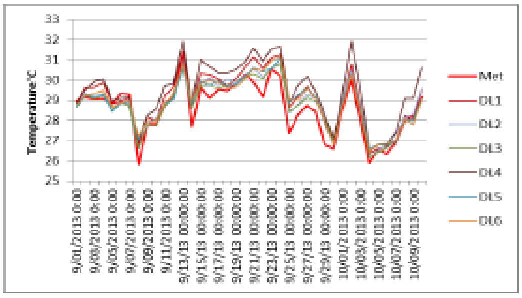

Fig 3: Average air temperature for each day

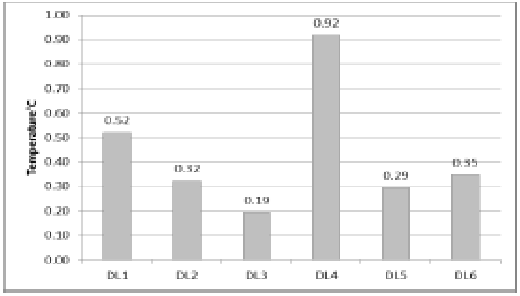

Fig 4: UHI intensity for different orientations

However, it should also be noted that the actual UHI intensity may be higher than what was found if the Met station were in a true rural setting. Although the Met station is surrounded by large open spaces and greens, it is still in the middle of the city. Also, the study was conducted during September-October months, which are mostly cloudy and the cloud possibly have masked the actual intensity. It is safe to assume that the UHI intensity is much higher during the hot-dry season from March-May when the sky is clear.

4.2. UHI Intensity & Pattern

UHI has distinct characteristics, which is more profound during night times and on clearer days with still air. Analyses were conducted to find out how these factors affect the UHI intensity and pattern of the case study area. Daily 3-hourly temperature data for all six locations and the Met were plotted and compared (Fig 5-8).

Figures show that the UHI intensity was more profound during night times especially near the end of the September when the days were clearer.

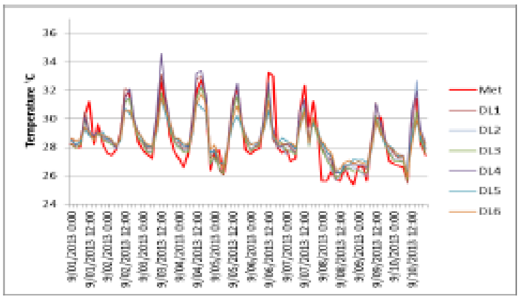

Fig 5: Daily 3-hourly air temperature(1-10Sept'13)

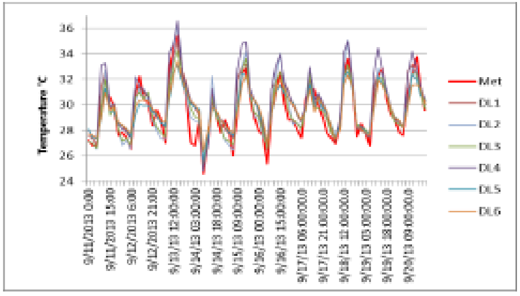

Fig 6: Daily 3-hourly air temperature(11-20Sept'13)

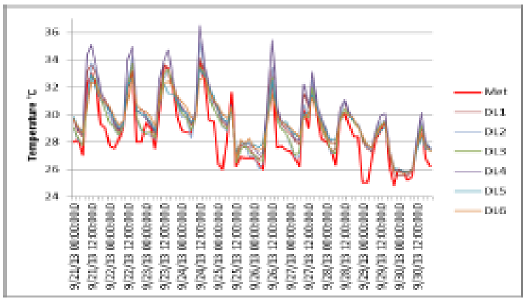

Fig 7: Daily 3-hourly air temperature(21-30Sept'13)

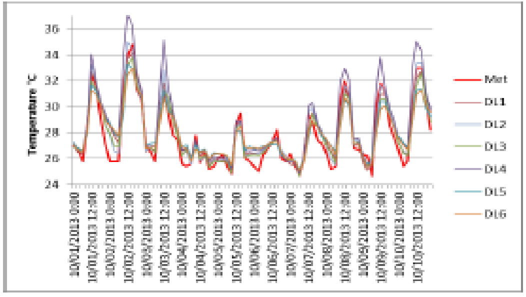

Fig 8: Daily 3-hourly air temperature(1-10 Oct'13)

Further analyses were conducted to see how the UHI intensity changes from daytime to night-time according to different orientations and canyon ratios. UHI intensity for daytime (6:00am-6:00pm) and night time (6:00pm-6:00am) were calculated and then plotted with the Met data and compared (Fig 9). The result shows the presence of an urban cool island in one of the setback areas although much lower in intensity. The result also shows a much higher night time average temperature in the setback areas despite of its orientation and its being shaded most of the time during day. This may indicate the inability of trapped warm air to escape due to low sky view factor in the narrow setback areas. On the other hand, the south-oriented logger consistently showed higher temperature both at day and night.

Further analyses were conducted to see the differences in UHI pattern and intensity between clearer and cloudy days. The result shows that whether it is a clearer day or cloudy, a positive UHI is present for all the locations (Fig 10) although the intensity between clearer and cloudy days fluctuates sharply for the south-oriented logger.

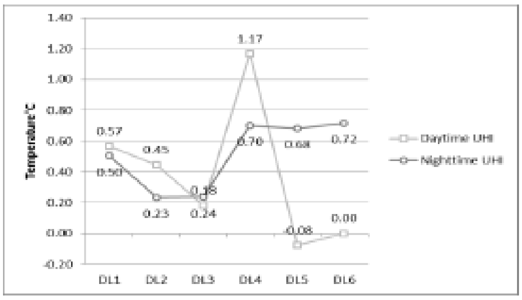

Fig 9: Daytime and nighttime UHI intensity pattern

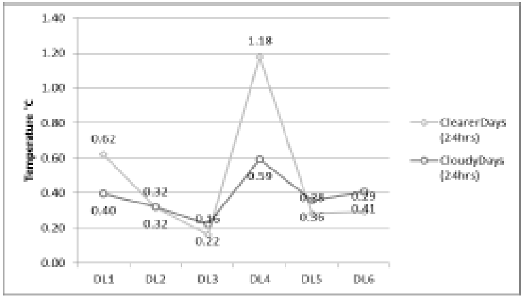

Fig 10: Clearer and cloudy days UHI intensity

However, further analyses particularly focussing on daytime and night time temperature differences revealed interesting UHI pattern. The result shows that three of the locations that were shaded during daytime experienced daytime cool islands in both clearer and cloudy days (Fig 11-12).

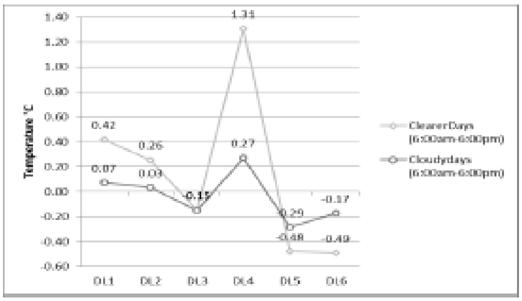

Fig 11: Clearer and cloudy days: Daytime UHI

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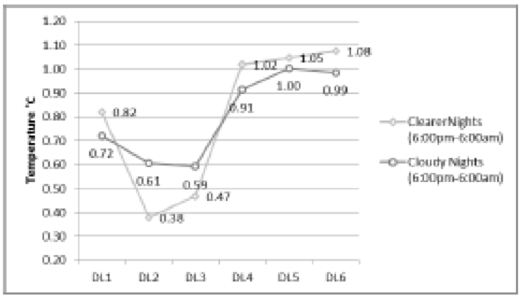

Fig 42: Clearer and cloudy days: Nightime UHI

4.3. Impact of UHI on Energy Consumption

Average monthly electricity consumption data of the study area shows that, in 2013, the maximum energy consumption reached in August and the minimum energy consumption was in February. The average annual electricity consumption per household was 8125.24 kWh. The result shows that the monthly electricity consumption pattern of the case study area strongly agrees with the seasonal variations of Dhaka city. Three distinct climatic seasons are present in the city known as cool-dry season (Dec-Feb), hot-dry season (March-May) and, hot-wet season (Jun-Nov). It can be seen from Fig 14 that the lowest consumption was during the cool-dry period and the maximum consumption was during the hot-wet period. Since AC is not likely to be required during the cool-dry period, it is almost certain that the extra energy was consumed for cooling purposes during the hot-dry and hot-wet periods.

On average, 30% more energy was consumed in hot-dry period and nearly 38% more energy was consumed in hot-wet period in comparison to cool-dry period in 2013. Also, 11.5% more energy was consumed in hot-humid period compared to the hot-dry period. This result signifies the important role relative humidity (RH) also plays along with air temperature on energy consumption. Taking the average energy consumption during cool-dry period as baseline, it can be said that nearly 30% of annual energy consumption of a household was due to cooling purposes in 2013.

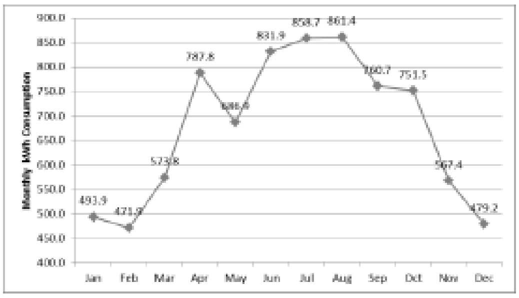

Fig 13: Average monthly electricity consumption

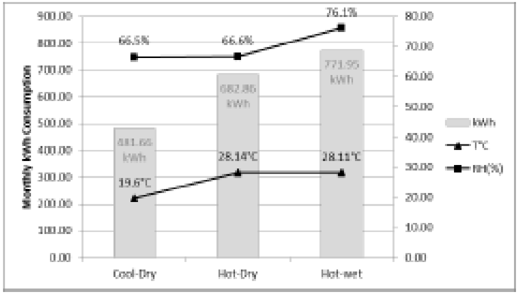

Fig 14: Average air temperature, RH and kWh consumption in different seasons

A regression analysis between the monthly average air temperature and the monthly average kWh consumptions was done to find out the relationship between air temperature and energy consumption. A significant positive correlation of R^2=.75 was found, which confirms that an increase in air temperature does increase the electricity consumption.

However, since energy consumption increases with cooling demand increases, a regression analysis was conducted excluding the cool-dry months but including RH in order to reasonably quantify the impact of UHI on cooling demand. This analysis result showed a significant positive correlation with adjusted R^2=.71 and with the coefficients values from the analyses, following statistical equation was drawn, kWh= (37.99*Temperature)+(5.28*RH)-771

This equation can be interpreted as, if the RH remained same then for every 1°C of temperature increases, extra 37.99 kWh consumption occurred per month during the hot seasons due to cooling purposes. In other words, every 1°C temperature increase resulted in 5.1% more cooling demand in 2013 in the case study area. The average UHI intensity for the whole case study area during the study period was found .8°C.

5. Examining the Current Practices

In the current development practices, the buildings are either oriented on north or south along E-W axis road. Based on the findings and from the energy consumption point of view, this type of layout seems to be the worst possible one as not only a south-oriented building experience very hot air during daytime but also it does not cool down easily at night. It is known from the experience that the main reasons for laying E-W axis roads are to take the advantage of prevailing wind direction from the south and to ensure as many buildings as possible to have the south orientation. However, in reality, this is creating opposite results for two reasons. 1) Previous studies have shown that for an E-W axis road, a canyon ratio of more than .25:1 creates an almost calm situation in the corridor (Ahmed, 1996) and the existing canyon ratio in the study area is 1.55. Therefore, the south-oriented buildings actually cannot take any advantage of the prevailing wind direction. 2) On the other hand, 50% buildings in the area are north-oriented, which are absolutely at the opposite side of the prevailing wind direction. In addition, the setback rules are creating deep and narrow canyons between buildings not only making it difficult to release trapped heated air soonest but also provides very little space for greenery. Overall, the area is full of hard surfaces with ineffective open spaces for any use.

6. Design Recommendations

Based on the findings, this study provides following design recommendations for future residential developments. If followed, it is expected that the energy consumption from future developments will be reduced significantly.

- Roads should be along the N-S axis with buildings facing the East or West to reduce the chance of overheating from direct radiation and also to take the advantage of prevailing wind direction by using the roads as breezeways to remove the excess heats.
- The canyon ratio for such a road should be no more than 2:1 as a previous study and a shadow analysis showed that this is the minimum ratio to get a shadowed corridor throughout the year (Ahmed, 1996).
- However, if the new developments are for lower density, roads along the E-W axis can be considered but the canyon ratio should not be more than .25:1 to allow wind flow.
- Side setbacks between buildings should be omitted as such narrow canyons become heat source at night. The buildings instead can share a common wall or common stair case.
- The saved setback areas from side can be used to increase the back setbacks between buildings which can become a continuous green corridor to be used by public. In the proposed new layout, the same density and floor-area ratio as the current ones would be maintained.

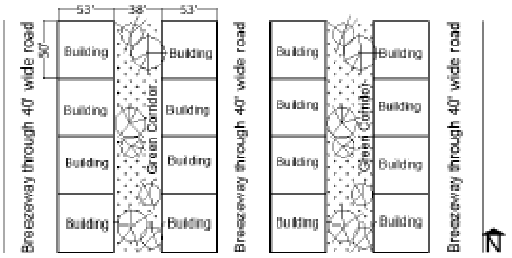

Fig 15: Proposed layout

7. Conclusions

This study showed that some moderate and achievable changes in current practices can reduce energy consumption by the future residential developments. However, the study also stresses on the importance of more in-depth research in the field so that the information needed to achieve energy efficient developments will be available to designers.

7. Acknowledgments

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Appendix A.2: Paper 2

Potentiality of energy-plus urban developments in developing countries. Case study: Dhaka, Bangladesh

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ABSTRACT: Our world is going through an unprecedented energy crisis. The increasing global energy demand combined with declining energy resources have resulted in such crisis. Moreover, energy sector is also claimed to be one of the major contributors of climate change as 65% of world's green house gas (GHG) emission is energy related. A huge share of this energy is consumed by the cities and buildings. Reducing energy consumption by the building sector as well as shifting to green energy sources have become one of the prime agendas to address both the issues of climate change and energy security. Several alternative buildings and neighbourhoods have been emerged in developed countries to address this issue. Unfortunately, even after the successful existence of such alternatives for more than a decade, to date these have not yet been very successful to create a market demand. This paper argues that developing countries are rather in a favourable position due to some particular contexts for being successful in the wider deployment of these alternatives. This paper, through an in-depth literature review and personal experiences of the author as an architect and a Dhaka city dweller, examines and presents the potentiality of energy-plus urban developments in the unique context of Dhaka, the capital of Bangladesh.

Conference theme: Buildings and energy
Keywords: Energy-plus urban developments, developing countries, Dhaka

INTRODUCTION

Our world is going through an unprecedented energy crisis. Increasing global energy demand in contrast to the depleting fossil fuels or main energy resources have resulted in such crisis. Moreover, world's energy sector alone accounts for sixty five percent of total green house gas (GHG) emission and this is claimed to have a significant negative impact such as global warming and climate change on environment (Lund 2009; Evan et. al. 2009; UNEP 2007). The overall instability of the energy sector is being manifested through fuel price rise, global political conflict, economic instability and increased competition for an access to finite fossil fuel resources (Williams 2012). As a consequence, the energy security of developed countries is being threatened while the energy scarcity of developing ones is being exacerbated.

Global energy demand is increasing at an exceptional rate mainly due to the rapid growth in population and urbanization in developing countries. It has been projected that the world's population will increase from slightly above 7 billion in 2012 to 9-10 billion in 2050 and the majority of them will be living in Asian developing countries (WB 2011; USCB 2012; UN 2010; Ferrey & Cabraal 2006). Not only the population is growing at a faster rate but also a rapid urbanization is taking place in developing countries as a result of significant rural-urban migrations. It is estimated that 93% of urban growth will be occurring in developing countries and 80% of them will be in Asia (UN 2005; UNFPA 2007). At present, nearly1.6 billion people predominantly in developing countries are yet to have an access to electricity (Energypedia 2012; IEA 2010). The existing population without energy access along with the future ones will therefore put pressure on energy resources in the coming years, with major energy demand in fact coming from cities and buildings in developing countries.

Since buildings are one of the major consumers of energy and are thus responsible for 30-40% of world's total GHG emission, several alternative buildings and settlements have emerged in developed countries to reduce the energy consumption and GHG emission by buildings (UNEP 2007; Harvey 2006). It has been estimated that to reach the desired target of GHG emission reduction, buildings in developed countries need to reduce energy consumption by sixty percent by 2050 (WBCSD 2007). Alternative buildings that are commonly known as passive, low-energy, zero-net energy and energy-plus buildings not only consume lesser energy than a traditional one but some of them are also able to generate energy on their own by building integrated or mounted micro-generators such as photovoltaic, wind turbine etc. (Williams 2012; Disch 2009). The energy generated by such buildings is from renewable energy sources such as sun, wind, bio-mass or geothermal and therefore is GHG emission free (Williams 2012; Droege 2009). Unfortunately, despite of having the existence of several such successful exemplar buildings for more than a decade now and the high potential of these alternatives to supply clean energy and reduce GHG emission from building sector, to date these alternatives have not yet been very successful in creating a market demand for them in developed countries (Williams 2012).

This paper argues that several contexts such as energy scarcity, daily power blackout and managing emergency power supply during blackout that are particular to a developing country can in fact be considered as advantages for being successful in the wider deployment of alternative buildings in developing countries. In addition to these contexts, majority of future energy demand will be from the developing countries since more than two-thirds of the future megacities are emerging in that part of the world. Therefore, more effort should be dedicated to initiate developments that accommodate energy-generating buildings, especially energy-plus buildings, in developing countries. Successful deployment of such developments in developing countries can play two major roles; 1) it can significantly contribute to meet the energy demand of these countries, which is an absolute necessity for them to get rid of energy poverty and, 2) It can greatly reduce the future GHG emission from these countries beforehand. This paper through an in-depth literature review and personal experiences of the author as an architect and a Dhaka city dweller examines and presents the potentiality of energy-plus urban developments in the unique context of Dhaka, the capital city of a South Asian developing country named Bangladesh.

1. ENERGY-PLUS BUILDING AND URBAN DEVELOPMENT

A building or a group of buildings can be called "energy-plus" if it can generate surplus energy than it consumes through building integrated or mounted micro generators such as photovoltaic, wind turbine etc. from renewable energy sources (Williams 2012; Disch 2009). An energy-plus building was first developed in the last decade of 20th century as a response to emerging energy crisis. Such building can potentially address two central energy issues- increase energy security by reducing dependency on fossil fuels and reduce GHG emission from building sector.

Buildings consume energy in five major stages, namely, manufacturing of the material, transportation of the materials to site, actual construction, operation and demolition. Of all the stages, operational stage alone accounts for 80% of total energy consumption by a traditional building during its lifetime (Williams 2012; Evan et.al.2009). The operational stage of a building consumes energy for lighting, heating, cooling and other activities like cooking, cleaning etc. The energy consumed during operational stage can potentially be supplied by building integrated or mounted renewable energy technologies. However, the amount of energy a traditional building consumes probably cannot be fully supported by building mounted or integrated technologies if the buildings do not consider energy efficiency. Only with increased efficiency and reduced consumption can renewable energy technologies be useful. This in fact is the basic idea based on which energy-plus buildings have been developed. Following the same definition of an energy-plus building therefore an urban development can be called energy-plus if it can (or if the components of an urban development such as buildings, street lights, and traffic lights) can generate surplus energy than it consumes. Nonetheless, the success of an energy-plus urban development will largely depend on to what extent the most important component of the development – buildings- can generate surplus energy.

The first energy-plus building was constructed only in 1994 in Frieburg, Germany by the German architect Rolf Disch. The first building he constructed was his domicile known as 'Heliotrope". The design of the building was inspired by the heliotrope plants, such as sunflower, which turns with the course of the sun. The cylindrical, three-storied structure of the heliotrope building including a sun sail made of photovoltaic on the roof also rotates to track the sun. The energy generated by the building is entirely renewable, emissions free and CO_2 neutral. The second Heliotrope was built in Offenburg, Germany as a visitor's centre and showroom and the third Heliotrope was built in Hilpolstein, Bavaria to be used as a technical dental laboratory (Disch 2009).

After the success of the Heliotropes, Rolf Disch applied the concept for the first solar settlement on earth with positive energy balance. The settlement accommodates 59 plus-energy houses and a commercial centre named 'Sunship' in Vauban quarter of Freiburg, Germany. Until today, this is the largest energy-plus settlement development that is built. Energy-plus buildings follow two basic principles. They are,

1) Reducing energy demand through low-energy building techniques, such as, passive solar building design, insulation, careful site selection and placement and,

2) Generating energy through building integrated or mounted micro generators from renewable energy sources mainly by exploiting solar energies through solar PV module and heat trap.

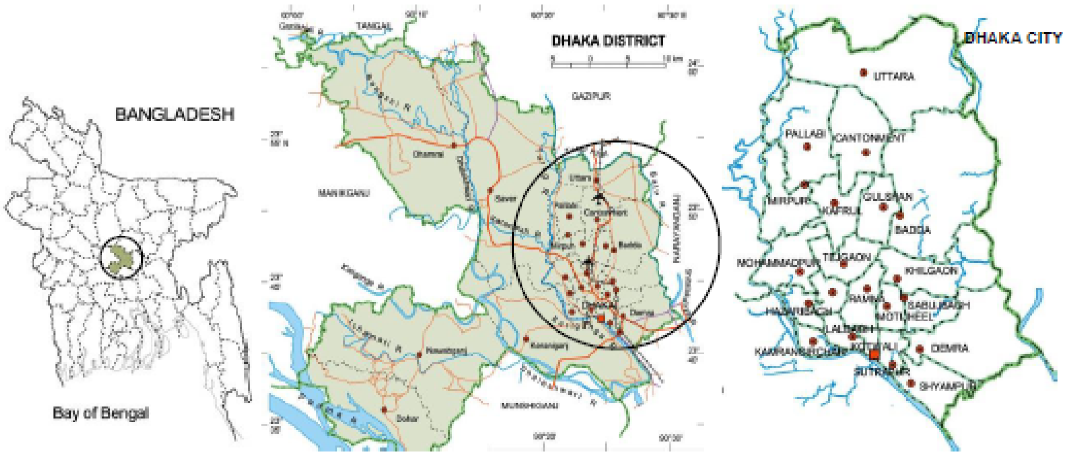
Following these two basic principles, heliotropes and the buildings in Freiburg generate 4 to 6 times more energy depending on the time of the year (Disch 2009).

2. THE CASE STUDY: DHAKA

Dhaka, the capital of Bangladesh, is located centrally and lies between East Longitudes 90°20′ and 90°30′ and between North Latitudes 23°40′ and 23°55′. The tropic of cancer is through the southern part of the city. The total area of the city is 1,460 square kilometres (BBS 2011; BBS 2010). Topographically, the city is on a flat land, which is surrounded by low-lying regions and three rivers. Historically, it played an important role on the formation of the city as it could grew mostly towards the north (Ahmed 2006; Islam 1996; Chowdhury et. al. 1991).

The city has experienced several ups and downs in growth before its being born as the capital city of a newly independent country in 1971 after a bloody war with former West Pakistan now known as Pakistan (Ahmed 2006; Islam 1996). However, after gaining the sudden status of a capital city, the city is only experiencing growth (Ahmed 2006). A tremendous growth in urbanization took place and the population suddenly increased from 718,766 in 1971 to 2,068,353 in 1974 (BBS 1997; Chowdhury et.al. 1991). Within a decade one million new populations were added to the city within an area of about 510 sq. km (Islam 1996). Dhaka was the only city on earth that experienced a population growth at an annual rate of 6.9% during the period 1974-2000(UN 1999). The rapid growth in population of the city was described as 'exceptional' by the United Nations (UN 1999). The city began to expand in all directions to meet the needs of the newly independent country's capital and the wetlands and low-lying areas within the city and the fringe areas started to disappear quickly (RAJUK 2012).

The current population of Dhaka mega city is slightly over 15 million and still is growing due to rural urban migration at one of the highest annual rates (4.2%) in the world (CIA 2012; Wikipedia 2012; UN 2001). Only 28% of the country's current population lives in urban areas; however, it has been projected that by 2050 this figure will increase to 58.75% (CIA 2012). Dhaka will be inhabited by more than 20 million people in 2015 making it the second largest megacity on earth (Williams 2012; UN 2001).



Source: (Ahmed 2006)

Figure 01: Showing Dhaka city map and location

2.1. Urban Context of Dhaka city

Since the city expanded unexpectedly after the liberation war, the Government or development authority could not keep pace with the urbanization rate. To address the new pace of urbanization a new master plan was proposed in 1993. The goal of the plan was to provide a long-term strategy for the greater Dhaka development for a period of 20 years from 1995 to 2015(RAJUK 2012; DMDP 1993). This plan is known as Dhaka Metropolitan Development Plan (DMDP) 1995-2015. The target population was 15 million; however, the city already has crossed the estimated projection of 15 million three years earlier. Inability of the development authority to meet the development demand has resulted in a numerous informal and spontaneous developments in Dhaka city. Evidently, Dhaka city represents a mixed character of formal and informal developments.

Formal developments are essentially undertaken by the formal public and private sectors and both sectors usually follow the same development formula or patterns. The most common type of development by the public sector is land development for housing or township projects along with infrastructural developments such as road networks and utilities. The developed land is then divided into plots and is allocated to citizens to build their residential or commercial buildings by following the building codes and regulations. The common features of such developments are; straight and nearly gridiron pattern road networks, wide roads and same sized symmetric regular shaped rectangular plots. Although during the Pakistan period, sizes of the plots varied mostly between 7500sft (697sqm apx.) to 15000sft (1395sqm apx.), a huge demand on serviced land has resulted in reduced plot sizes in post-independence period. Currently, the plots are around 2250sft (209sqm apx.), 3750sft (348sqm apx.) or sometimes 7500sft (RAJUK 2012; REHAB 2010; Parveen 2006).

For land development, the private sector follows the same pattern of the public sector; however, in addition to land development, the private sector also develops individual apartment buildings in negotiation with the landowner. The most common form of negotiation is 60-40 or 50-50 share depending on the location of the land, where, developers build the apartments and give 40- 50% of the apartments to the landowner and sell the rest of the apartments to buyers. In addition to developing individual apartment buildings, some large-scale developers also build housing complexes with high-rise apartment buildings of 15-20 stories (REHAB 2010; Parveen 2006).

To cater the new population and to shift the pressure from central Dhaka city, numerous development projects & townships around Dhaka are being constructed both by public and private sector following the above-mentioned principles. Currently, the largest township of the country is being developed by the Government at the eastern side of Dhaka city with 25,000 residential plots and 62,000 apartments on 6150 acres of land with four more to come in the future (RAJUK 2012).

On the other side, independent and individual landowners develop informal settlements. These developments are usually adjacent to the established formal developments with the common features include narrow streets with a serpentine character, irregular, inconsistent and asymmetric shapes and size of building plots. The main reason for such characters is that initially these were the fringe areas and lands were bought according to the affordability of a landowner when the area was under developed and cheap; however, eventually with the expansion of the city, these areas have become an integrated part of the city. Streets are narrow and serpentine in nature because landowners mutually left some of their lands to make an access form the main road network of the city to the plot. The landowner usually develops buildings in informal developments over a long period of time with the help of local contractors and in general without consulting a professional such as architect or builder. Usually these are the high-density areas (Parveen 2006).

2.2. Dhaka's urban context and energy consequences

What are the impacts of current urban development pattern and construction practices on energy consumption? Several studies have indicated that Dhaka city buildings have an unsustainable and inefficient energy consumption pattern (Ahsan 2009; Ahmed 1996). The main reason for this is, the present planning and building laws mainly focuses on the density and development control related issues and not on the energy consequences of urban and building development practices. To date, Bangladesh is one of the very few countries that do not have any energy codes for the buildings even though the cities are highly dense. There are no regulations for the building envelope, materials or energy performance of a building. As a result, real estate developers are not obliged to follow passive design principles and to avoid additional costs; they usually construct 125 mm thick external walls instead of 250 mm walls, which have serious consequences on indoor thermal comfort and results in increased use of energy intensive active means such as air conditioners (Ahsan 2009).

The present setback rules are related to a particular plot dimension without regard to any urban module or blocks thus resulting in an uneven building line, which often obstructs the natural airflow. In addition, the setbacks are narrow and do not allow ample daylight into the interior spaces of a building, therefore is resulting in the use of artificial lighting even in daytime. Significant variation in temperatures has been recorded in different parts of the city by several studies, which is suggestive of the growing problem of overheating due to Dhaka's inexorable urban growth (Ahmed 1995, Ahmed 1987).

Studies have also shown significantly higher temperature in city area than the surrounding vicinity (Ahmed 1995). The situation became worse during post-independence period as the reduced plot sizes resulted in increased hard surface areas. Overheating of the city is becoming a growing concern as it has direct link to energy consumption. Studies have indicated that higher consumption of electricity during summer months is possibly due to the urban climatic factor on the energy need (Ahmed 1995).

It is therefore evident that there is a high potential for reducing energy consumption from existing and future buildings and urban developments if necessary steps are taken, which will then provide the base for successful renewable energy deployment. This is important as the country is struggling with poor energy system and extreme energy scarcity with one of the lowest per capita energy consumption of 220 kWh/ year (Energypedia 2012; Islam 2006). Only 47% of total Bangladeshi population has access to modern energy and a huge gap of 2000MW exists between electricity demand and supply, which is seriously hindering the economic development of the country (MPEMR 2012; Munim et.al. 2010).

2.3. Energy context of Dhaka city

Dhaka city consumes nearly one-fifth of total commercial energy produced daily. Peak electricity demand of the city is 2000MW; however, the city is supplied with only about 1000-1200 MW (Kabir et.al. 2009). Power outage or load shedding is the most common everyday phenomenon experienced by Dhaka city dwellers. During hot summer months when the gap between demand and supply is the highest, the load shedding situation becomes worse and some parts of the city, mainly in fringe areas, experience 8-12 hours of daily power outages. Probably Dhaka city suffers most due to the interrupted and unreliable energy supply, as all major administrative, commercial, institutional or industrial activities of the country are Dhaka centric.

This poor energy condition is seriously hindering daily activities of the city and causing huge economic loss as unreliable and interrupted energy supply reduces the lifespan of energy driven appliances and machines such as, computers, refrigerators or televisions as well as it hampers the production of many small-scale industries that cannot afford alternative power supply through personal generators.

Every household of the city manages their own emergency power supply during power outages through different methods depending on the affordability. The most common power sources are, candle, kerosene lamp, lantern, Instant Power Supply (IPS) by batteries, and diesel or gas run generators. However, the need of emergency power supplies not only hampers the daily activities of the city but also imposes additional costs to avail them. In addition, it threatens the health and well being of people as candle, kerosene lamp and generators produces toxic fumes, which cause air pollution. In addition, generators create noise pollution and the disposal of IPS batteries imposes environmental risk.

To handle the increasing energy demand of the city, which is increasing at an annual rate of 10%, the Government has imposed several embargos (MPEMR 2012). For example, electricity connection to new residential buildings was suspended for two years from 2009-2011, where trading times of the markets and shops have been reduced etc. Any new apartment building in Dhaka city, which will consume more than 2MWof electricity per year, is now required to install solar photovoltaic (PV) panels to manage some part of their energy demand. The embargo; however, has caused a significant recession in real estate business in last two years. Also, hospitals, schools and large institute buildings are advised to manage some of their electricity demands from solar powers (MPEMR 2012).

Apparently, rather than some policy implementation, no real actions have been taken to meet the immediate energy need of the city. It has been recommended in a study that deploying solar PV on available bright rooftops of the city can potentially fill up the gap between peak energy demand and supply of the city in a short period of time (Kabir et. al. 2009).

3. POTENTIALITY OF ENERGY-PLUS URBAN DEVELOPMENTS IN THE CONTEXT OF DHAKA

As it has been mentioned earlier that even after having a number of successful examples of energy generating buildings and settlements in reality and despite of their high potentiality in addressing the issues of GHG emission and fossil fuel depletion, energy-plus developments have not been very successful in creating a market demand at their place of origin. It has been confirmed by a study that the reason is not technical in fact there is no technical limitation for deploying such developments (Williams 2012). The main reasons are rather non-technical and as identified by some studies are (Williams 2012; Jardine and Ault 2008),

1) Need to compromise with six quality of life dimensions such as comfort, convenience, privacy, personal freedom, affordability and, safety and security.
2) More active involvement of the consumer in energy management.
3) Higher initial costs with no added market value.
4) Lack of priority in energy saving.
5) People's perception of such projects as aesthetically less attractive therefore less market value.
6) Well supported conventional energy system and very strong energy lobbies to dismiss the entry of any new competitor.

The study suggested that the people's perception of quality of life is rather biased and are valued against what they are already accustomed to as a passive consumer of energy and are unable to assess as an active consumer of energy (Williams 2012). Further, the dramatic reduction of new building constructions due to economic recession in developed countries also has played a significant role against the wider deployment of energy-plus developments. These projects were initiated mainly to address and encourage the future building stocks but now the opportunity has become limited. Therefore, the scale of constructions needed to gain the momentum for creating a market demand as well as to develop the skill and expertise for wider deployment of such developments are absent in developed countries (Williams 2012).
On the other hand, the contexts in developing countries are completely opposite. If we consider the case of Dhaka we see that a huge number of new constructions and urban developments are going to take place in coming years. More than five million new population needs to be accommodated in Dhaka by 2020, which can provide the necessary momentum to create a market demand for energy-plus urban developments in Dhaka city.

In addition, the barriers such as compromised living quality or more involvement in energy management are very unlikely to become an issue for Dhaka city dwellers. The main reason is people in Dhaka city already live in a substandard living condition with interrupted and insufficient energy supply due to extreme energy scarcity. Also, they are involved with personal energy management because of the need of managing emergency power supply during power outages. Therefore, a little improvement in energy supply in fact will improve the living quality significantly and compromising with living qualities such as comfort, convenience etc. is much more acceptable than no energy or lack of energy. Besides, the existing energy system of the country is poor and state owned therefore energy lobbies are not as strong as in developed countries and policy making is easier.

However, higher costs can also be a potential barrier in the context of Dhaka, but the advantage is the Government is in a better position to offer more economic incentives since CO_2 trade is an option for developing countries. Moreover, energy-plus urban developments will reduce the need for investments in new energy plants thus will save a significant amount of money, which can be directed towards promoting energy-plus urban developments in Dhaka city. In addition, access to climate change fund or other similar funds will be much easier for financing such developments.

The geographic location of Dhaka city also offers excellent potentials for energy-plus developments. Energy-plus buildings are highly solar energy dependent and aim at maximizing the use of solar energy for surplus electricity generation. According to Ar. Rolf Disch, the architect of the first energy-plus house in the world, 'The solar era has begun. The era of fossil and nuclear fuels is a thing of the past' (Disch 2009:11). Therefore, solar potential of a particular location is important for achieving the best result or to what extent surplus energy can be produced. Dhaka, being located on the tropic of cancer offers high Global Horizontal Irradiance (GHI) value equivalent to 4.2 kWh/m2/day (Kabir et. al 2009). Also, the daily average sunshine hour is 5-7 hours and sunshine is available for 300 days/year (Ahmed, 1996). A study revealed that geophysical factors like geographical location, GHI, sunshine duration are fully supportive to large-scale photovoltaic (PV) application in Dhaka city and the current available bright roof tops of Dhaka city alone can generate nearly 1000MW of electricity through standalone solar PV, which is half of the peak energy demand of the city (Kabir et al 2009).

Solar PV has been deployed in nearly one million rural households of Bangladesh commonly known as solar home system (SHS) to meet the very basic energy needs (IDCOL 2007). Except the PV module, the country produces all the necessary supporting accessories needed for PV deployment, such as battery, wire, inverters etc. Two PV industries are currently under construction near Dhaka city, which will allow the country to produce its own PV modules. Therefore, the technical knowhow to install and generate energy through standalone PV modules is already available in Bangladesh, which offers an additional advantage for initiating energy-plus buildings and urban developments in Dhaka city (REIN 2007).

In addition to solar energy, energy-plus buildings and settlements also utilize waste to generate surplus energy. In Dhaka, an average household produces 7 kg of organic waste daily, which is mainly due to the absence of processed food and consumption of raw foods, such as undressed chicken, meat, fish or vegetables. Therefore, a high potential for generating energy through organic wastes is also present.

In general, Dhaka city buildings are not as energy intensive as the buildings in developed countries due to the limited use of modern energy-driven thermal control appliances such as air conditioner or heater. Yet again, the buildings are highly suspected for inefficient energy consumption for the tight setback rules, the absence of energy code, highly dense built environment that does not allow ample daylight and airflow inside buildings and for not following passive design options. Therefore, the already low energy demand can significantly be reduced further if energy efficiency measures are applied both at urban and building level. It can be expected that the energy generated through solar, waste and other methods afterwards will potentially be able to surplus the reduced energy demand.

Theoretically, Dhaka city is better prepared than any other developed countries to embrace and initiate energy-plus urban developments and possess higher potentiality for being successful in wider deployment of such developments.

4. CHALLENGES

Although Dhaka city may offer considerably higher potentials for successful deployment of energy-plus developments over developed countries; several challenges will need to be addressed to achieve real success. In contrary to the situation in developed countries, the primary challenge for energy-plus urban developments in Dhaka will be technical rather than social, economical or political.

One of the major challenges will be the application of energy efficiency measures since energy-plus buildings require more stringent standards for maximizing energy saving to generate surplus energy, which may only be achieved through the construction of complex and highly technical energy efficiency measures such as high-tech façade, rotating solar sail or window glazing etc. Such expensive and highly technical measures may not be suitable to apply in the context of a developing city like Dhaka where the construction of a building in majority of cases is completely based on manual labor under the supervision of a half educated contractor therefore inexpensive. Less technical efficiency measures that are suitable for a developing country therefore need to be developed. However, since the buildings in Dhaka city are much less energy intensive compared to the ones in developed countries, buildings with less technical and less stringent efficiency standards may still generate surplus energy.

The only energy-plus settlement available to date is the solar settlement in Freiberg, which is a suburban moderate density settlement. To generate surplus energy by any building in a settlement, maximum exploitation of solar energy is needed therefore the distance between buildings is important as shadow casting of one building on another is not desirable. This principle in low density developments where the buildings are two-three storied high can be followed easily; however, this will impose a serious challenge for a high density multistorey development, which is the case of Dhaka city.

Moreover, the solar settlement in Freiberg is located in cold climate of Germany where the buildings are primarily focused on preventing heat loss in contrast to the climatic context of Dhaka where the focus is on cooling rather than heating. A contradictory situation may arise from deployment of solar technologies in Dhaka as to generate energy from solar PV; buildings need to receive as much solar radiation as possible, which will result in increased temperature inside the building and requirement for further cooling. Achieving thermal comfort while maximizing energy generation from solar PV will be a great challenge for a successful implementation of energy-plus urban developments in Dhaka city.

Therefore, the success of energy-plus urban developments in Dhaka city will largely depend on the way it is being implemented in a densely populated hot-humid area.

CONCLUSION

An energy-plus development can be considered as a highly promising approach in addressing three major energy challenges – depletion of fossil fuel resources, GHG emission from energy sector and increased energy demand. However, predetermined notion about quality of life, strong conventional energy lobby, higher costs, and recent recessions in new building constructions are obstructing the market penetration and wider deployment of such developments in developed world. It is now time to look towards developing countries for deployment of such developments since these are the countries where the majority of megacities are emerging and hence the majority of future energy demand is surfacing.

The context of Dhaka city presented and examined in this paper has shown that the apparent backward contexts such as energy scarcity, daily blackouts or poor energy system that prevail in this city in fact offer higher potentiality for being successful in embracing and wider deployment of this new type of urban development if technical challenges are addressed properly. This possibility can start a whole new era since not only this can be a potential way to meet the future energy demand in developing countries, it also offers a solution with minimal negative impact on the environment. Therefore, much effort should be dedicated to, and more in-depth researches should be conducted for deploying and promoting energy-plus urban developments not only in Dhaka but also in other developing countries as a step forward towards a more socially just energy poverty free and environment friendly world.

ACKNOWLEDGEMENT

This paper is based on the initial literature review, which I conducted to develop the research proposal for my PhD research. I would like to acknowledge the guidance of my principal supervisor Associate Professor Veronica I Soebarto and Co-supervisor Dr. David Ness for shaping my PhD research focus. Special thanks to my principal supervisor for her diligence in checking and correcting the research proposal based on which this paper is written.

I also would like to acknowledge Australian Government for granting me the "Endeavour Postgraduate Research Award 2012", which has enabled me to commence my PhD research at The University of Adelaide. Finally, I'd like to express my gratitude to Bangladesh University of Engineering & Technology for granting me the study leave to pursue my PhD research.

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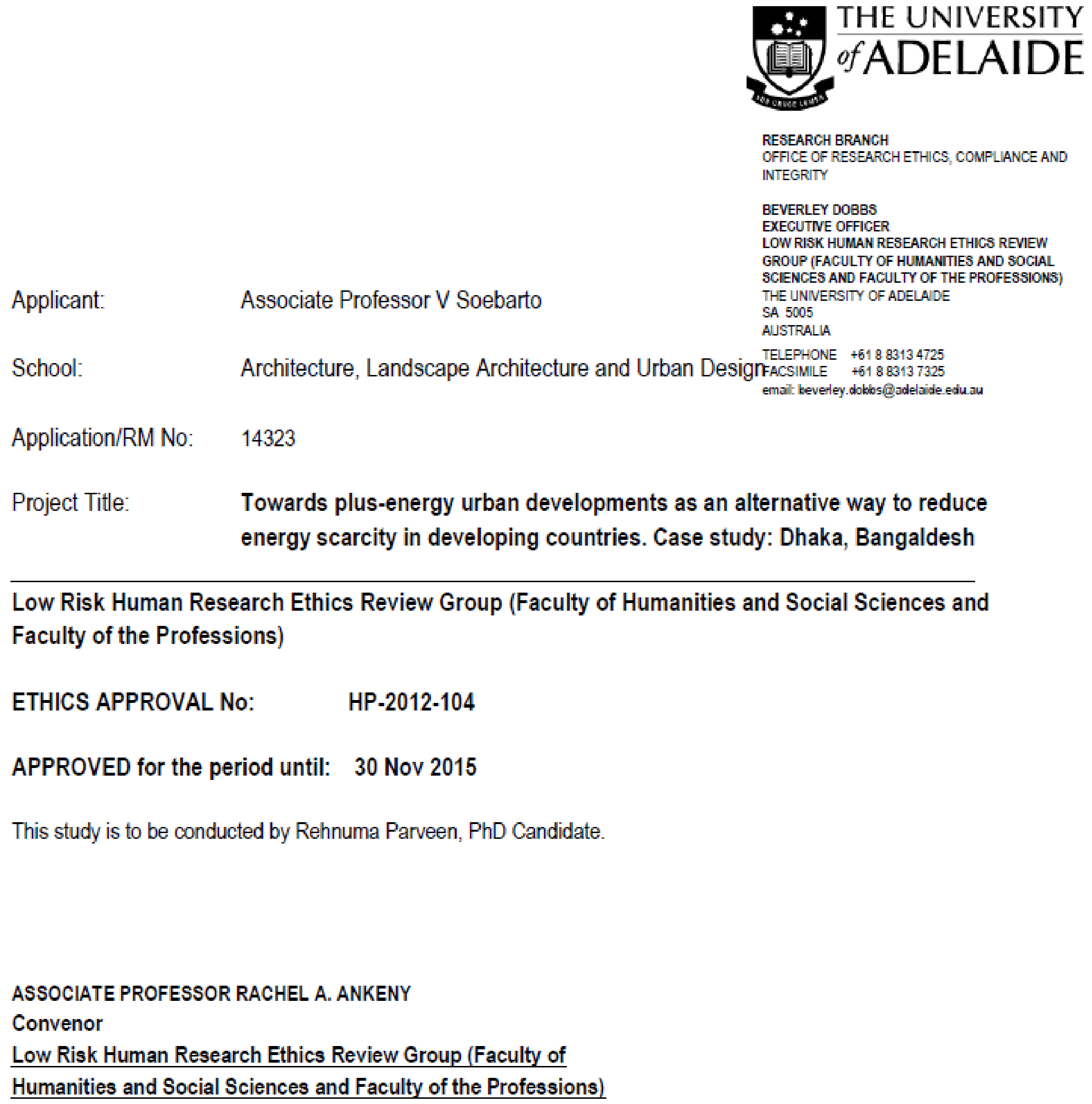
Appendix B.1: Ethics Approval Letters



THE UNIVERSITY of ADELAIDE

RESEARCH BRANCH
OFFICE OF RESEARCH ETHICS, COMPLIANCE AND INTEGRITY

BEVERLEY DOBBS
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LOW RISK HUMAN RESEARCH ETHICS REVIEW GROUP (FACULTY OF HUMANITIES AND SOCIAL SCIENCES AND FACULTY OF THE PROFESSIONS)
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email: beverley.dobbs@adelaide.edu.au

Applicant:	Associate Professor V Soebarto
School:	Architecture, Landscape Architecture and Urban Design
Application/RM No:	14323
Project Title:	**Towards plus-energy urban developments as an alternative way to reduce energy scarcity in developing countries. Case study: Dhaka, Bangaldesh**

Low Risk Human Research Ethics Review Group (Faculty of Humanities and Social Sciences and Faculty of the Professions)

ETHICS APPROVAL No: HP-2012-104

APPROVED for the period until: 30 Nov 2015

This study is to be conducted by Rehnuma Parveen, PhD Candidate.

ASSOCIATE PROFESSOR RACHEL A. ANKENY
Convenor
Low Risk Human Research Ethics Review Group (Faculty of Humanities and Social Sciences and Faculty of the Professions)

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4 December 2012

Associate Professor V Soebarto
School of Architecture, Landscape Architecture and Urban Design

Dear Associate Professor Soebarto

ETHICS APPROVAL No: **HP-2012-104**
PROJECT TITLE: **Towards plus-energy urban developments as an alternative way to reduce energy scarcity in developing countries. Case study: Dhaka, Bangaldesh**

I write to advise that the Low Risk Human Research Ethics Review Group (Faculty of Humanities and Social Sciences and Faculty of the Professions) has approved the above project. The ethics expiry date for this project is **30 Nov 2015**.

Ethics approval is granted for three years subject to satisfactory annual progress and completion reporting. The form titled *Project Status Report* is to be used when reporting annual progress and project completion and can be downloaded at http://www.adelaide.edu.au/ethics/human/guidelines/reporting. On expiry, ethics approval may be extended for a further period.

Participants in the study are to be given a copy of the Information Sheet and the signed Consent Form to retain. It is also a condition of approval that you **immediately report** anything which might warrant review of ethical approval including:

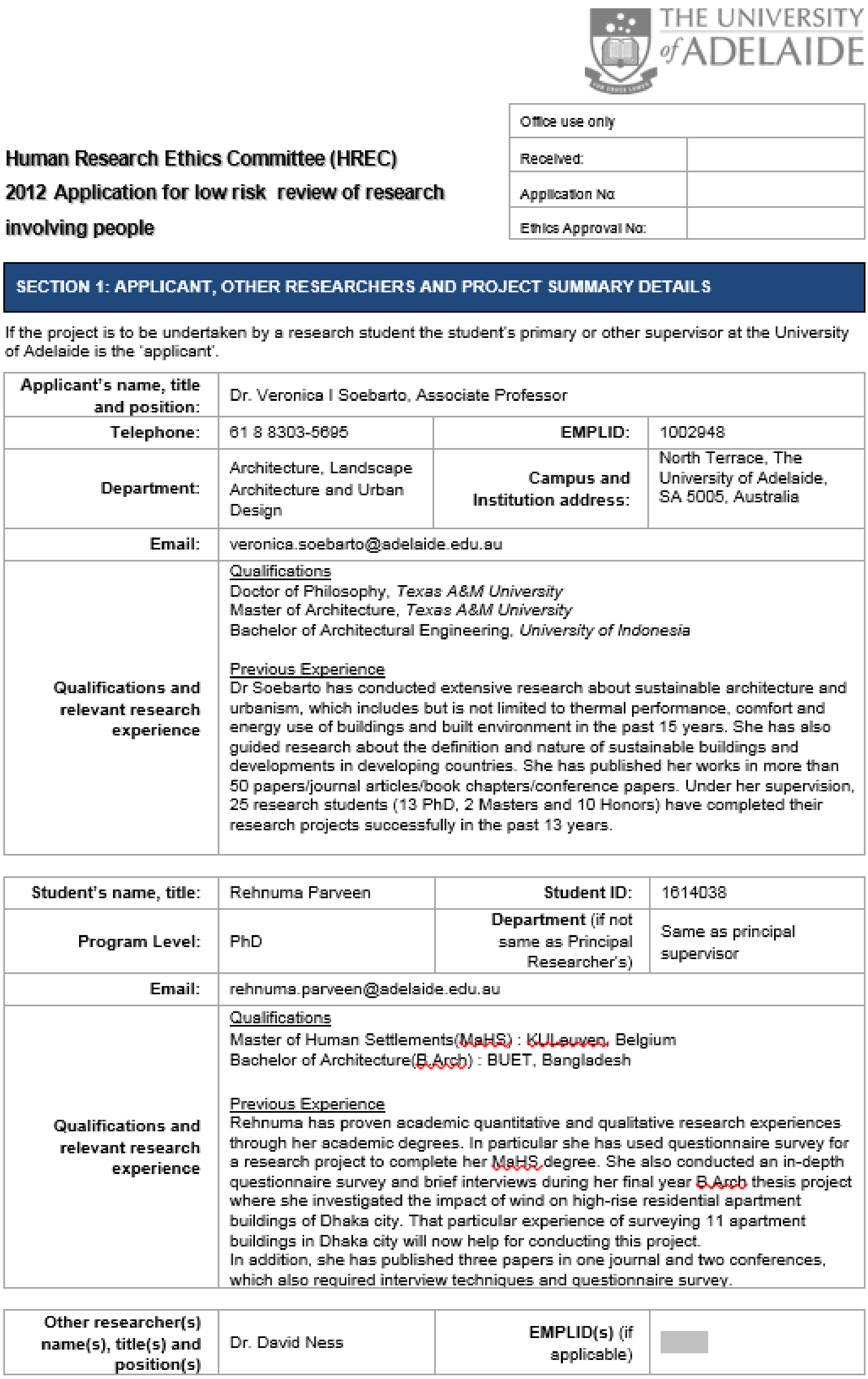
- serious or unexpected adverse effects on participants,
- previously unforseen events which might affect continued ethical acceptability of the project,
- proposed changes to the protocol; and
- the project is discontinued before the expected date of completion.

Please refer to the following ethics approval document for any additional conditions that may apply to this project.

Yours sincerely

ASSOCIATE PROFESSOR RACHEL A. ANKENY
Convenor
Low Risk Human Research Ethics Review Group (Faculty of Humanities and Social Sciences and Faculty of the Professions)

Appendix B.2: Ethics Application Form



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Office use only	
Received:	
Application No:	
Ethics Approval No:	

Human Research Ethics Committee (HREC)
2012 Application for low risk review of research involving people

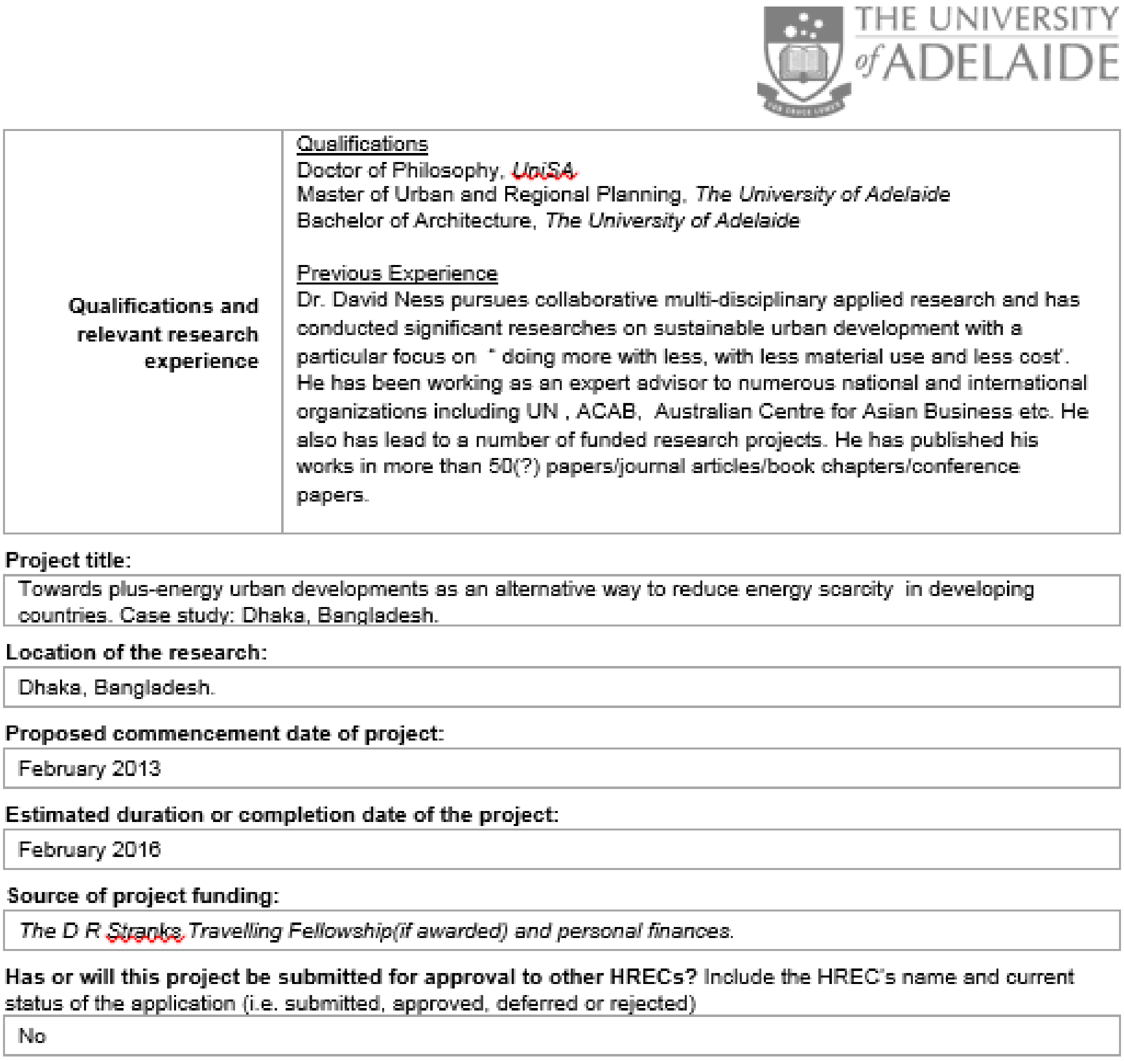
SECTION 1: APPLICANT, OTHER RESEARCHERS AND PROJECT SUMMARY DETAILS

If the project is to be undertaken by a research student the student's primary or other supervisor at the University of Adelaide is the 'applicant'.

Applicant's name, title and position:	Dr. Veronica I Soebarto, Associate Professor		
Telephone:	61 8 8303-5695	**EMPLID:**	1002948
Department:	Architecture, Landscape Architecture and Urban Design	**Campus and Institution address:**	North Terrace, The University of Adelaide, SA 5005, Australia
Email:	veronica.soebarto@adelaide.edu.au		
Qualifications and relevant research experience	<u>Qualifications</u> Doctor of Philosophy, *Texas A&M University* Master of Architecture, *Texas A&M University* Bachelor of Architectural Engineering, *University of Indonesia* <u>Previous Experience</u> Dr Soebarto has conducted extensive research about sustainable architecture and urbanism, which includes but is not limited to thermal performance, comfort and energy use of buildings and built environment in the past 15 years. She has also guided research about the definition and nature of sustainable buildings and developments in developing countries. She has published her works in more than 50 papers/journal articles/book chapters/conference papers. Under her supervision, 25 research students (13 PhD, 2 Masters and 10 Honors) have completed their research projects successfully in the past 13 years.		

Student's name, title:	Rehnuma Parveen	**Student ID:**	1614038
Program Level:	PhD	**Department** (if not same as Principal Researcher's)	Same as principal supervisor
Email:	rehnuma.parveen@adelaide.edu.au		
Qualifications and relevant research experience	<u>Qualifications</u> Master of Human Settlements(MaHS) : KULeuven, Belgium Bachelor of Architecture(B.Arch) : BUET, Bangladesh <u>Previous Experience</u> Rehnuma has proven academic quantitative and qualitative research experiences through her academic degrees. In particular she has used questionnaire survey for a research project to complete her MaHS degree. She also conducted an in-depth questionnaire survey and brief interviews during her final year B.Arch thesis project where she investigated the impact of wind on high-rise residential apartment buildings of Dhaka city. That particular experience of surveying 11 apartment buildings in Dhaka city will now help for conducting this project. In addition, she has published three papers in one journal and two conferences, which also required interview techniques and questionnaire survey.		

Other researcher(s) name(s), title(s) and position(s)	Dr. David Ness	**EMPLID(s)** (if applicable)	



THE UNIVERSITY *of* ADELAIDE

Qualifications and relevant research experience	Qualifications Doctor of Philosophy, *UniSA* Master of Urban and Regional Planning, *The University of Adelaide* Bachelor of Architecture, *The University of Adelaide* Previous Experience Dr. David Ness pursues collaborative multi-disciplinary applied research and has conducted significant researches on sustainable urban development with a particular focus on " doing more with less, with less material use and less cost'. He has been working as an expert advisor to numerous national and international organizations including UN , ACAB, Australian Centre for Asian Business etc. He also has lead to a number of funded research projects. He has published his works in more than 50(?) papers/journal articles/book chapters/conference papers.

Project title:

Towards plus-energy urban developments as an alternative way to reduce energy scarcity in developing countries. Case study: Dhaka, Bangladesh.

Location of the research:

Dhaka, Bangladesh.

Proposed commencement date of project:

February 2013

Estimated duration or completion date of the project:

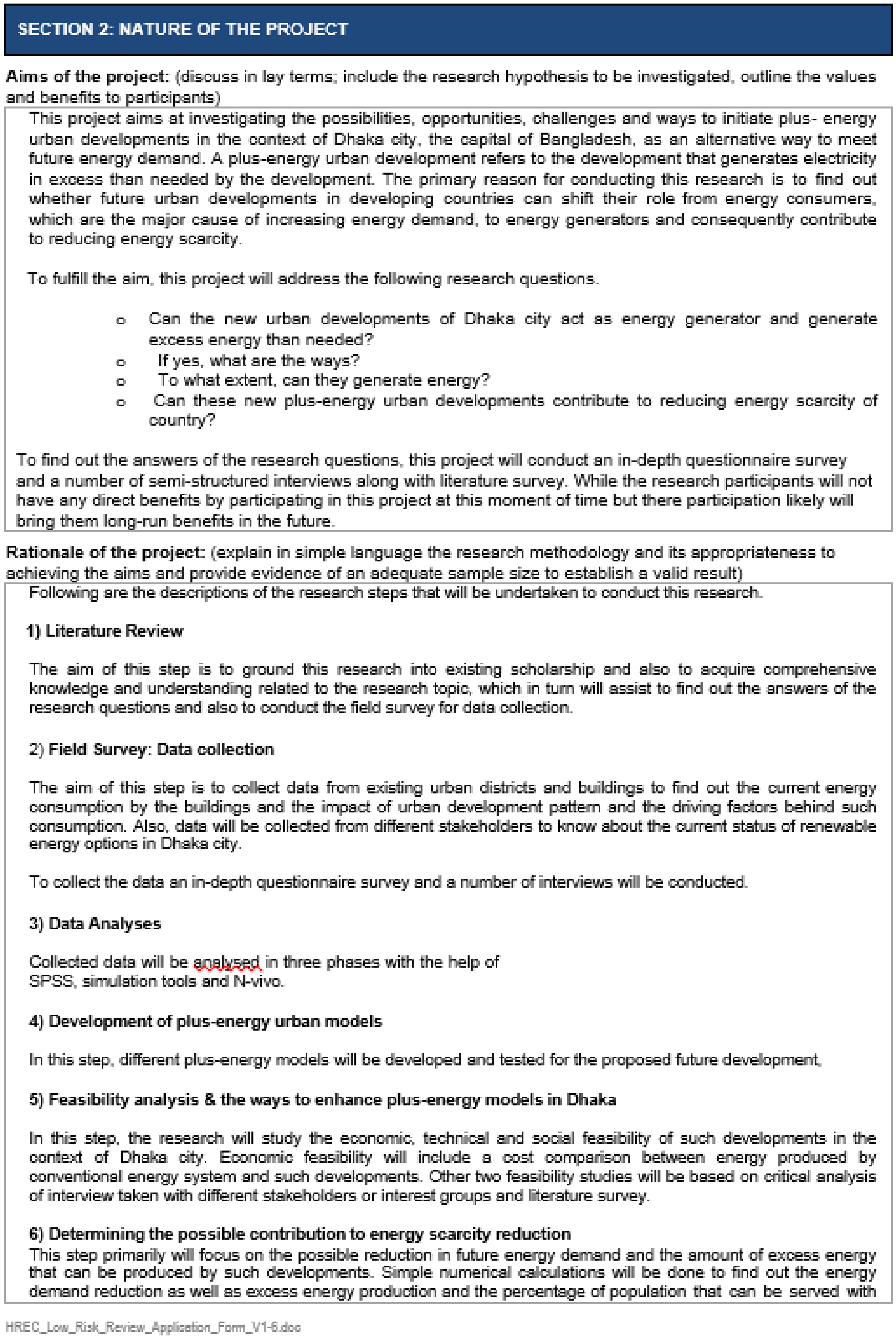
February 2016

Source of project funding:

The D R Stranks Travelling Fellowship(if awarded) and personal finances.

Has or will this project be submitted for approval to other HRECs? Include the HREC's name and current status of the application (i.e. submitted, approved, deferred or rejected)

No



SECTION 2: NATURE OF THE PROJECT

Aims of the project: (discuss in lay terms; include the research hypothesis to be investigated, outline the values and benefits to participants)

This project aims at investigating the possibilities, opportunities, challenges and ways to initiate plus- energy urban developments in the context of Dhaka city, the capital of Bangladesh, as an alternative way to meet future energy demand. A plus-energy urban development refers to the development that generates electricity in excess than needed by the development. The primary reason for conducting this research is to find out whether future urban developments in developing countries can shift their role from energy consumers, which are the major cause of increasing energy demand, to energy generators and consequently contribute to reducing energy scarcity.

To fulfill the aim, this project will address the following research questions.

- Can the new urban developments of Dhaka city act as energy generator and generate excess energy than needed?
- If yes, what are the ways?
- To what extent, can they generate energy?
- Can these new plus-energy urban developments contribute to reducing energy scarcity of country?

To find out the answers of the research questions, this project will conduct an in-depth questionnaire survey and a number of semi-structured interviews along with literature survey. While the research participants will not have any direct benefits by participating in this project at this moment of time but there participation likely will bring them long-run benefits in the future.

Rationale of the project: (explain in simple language the research methodology and its appropriateness to achieving the aims and provide evidence of an adequate sample size to establish a valid result)

Following are the descriptions of the research steps that will be undertaken to conduct this research.

1) Literature Review

The aim of this step is to ground this research into existing scholarship and also to acquire comprehensive knowledge and understanding related to the research topic, which in turn will assist to find out the answers of the research questions and also to conduct the field survey for data collection.

2) **Field Survey: Data collection**

The aim of this step is to collect data from existing urban districts and buildings to find out the current energy consumption by the buildings and the impact of urban development pattern and the driving factors behind such consumption. Also, data will be collected from different stakeholders to know about the current status of renewable energy options in Dhaka city.

To collect the data an in-depth questionnaire survey and a number of interviews will be conducted.

3) Data Analyses

Collected data will be analysed in three phases with the help of
SPSS, simulation tools and N-vivo.

4) Development of plus-energy urban models

In this step, different plus-energy models will be developed and tested for the proposed future development,

5) Feasibility analysis & the ways to enhance plus-energy models in Dhaka

In this step, the research will study the economic, technical and social feasibility of such developments in the context of Dhaka city. Economic feasibility will include a cost comparison between energy produced by conventional energy system and such developments. Other two feasibility studies will be based on critical analysis of interview taken with different stakeholders or interest groups and literature survey.

6) Determining the possible contribution to energy scarcity reduction

This step primarily will focus on the possible reduction in future energy demand and the amount of excess energy that can be produced by such developments. Simple numerical calculations will be done to find out the energy demand reduction as well as excess energy production and the percentage of population that can be served with that. Also, possible CO2 trade and the economic gain from such projects will be calculated. Finally, this step also will try to find out if the poorer section of the urban areas can gain access to the excess energies produced by such developments.

Background to the project: (discuss any previous research of relevance and include references)

One of the most significant challenges in our modern world is certainly the 'energy crisis', which is mainly due to the depletion of fossil fuel resources and a huge increase in energy demand. The crisis is resulting in fuel price rise, political conflict and hard competition for getting an access to finite fossil fuel resources (William, 2012). Moreover, energy sector is responsible for 65% of world's total green house gas (GHG) emission, which has a significant negative impact on environment (WBCSD, 2009; William, 2012). The overall situation in one hand is threatening the energy security of developed countries and on the other; it is exacerbating the energy poverty of developing ones. Energy is important for social and economic well-being of people as inadequate energy service has a direct relationship with many poverty indicators such as infant mortality, illiteracy, life expectancy or total fertility rate, which is quite evident in all developing countries that suffer from energy poverty (Dufo et.al, 2008; UPOSC, 2002). Therefore, world's energy sector is facing a unique dilemma where significantly more energy generation is needed especially in developing countries to eliminate energy scarcity but the energy resources are declining and more energy generation is associated with more negative impact on environment due to GHG emission by burning fossil fuels(Lund, 2010; Ferrey & Cabraal, 2006).

t seems that developing countries are going to pay the greatest toll as the majority of future energy demand will be from these countries. The problem is, however, these are countries that are not in a competitive position due to weaker economy to have access to fuel resources. Nearly 1.6 billion of people, mainly in South Asian and Sub-Saharan developing countries, still have no access to electricity (Energypedia, 2012; IEA, 2010). It has also been projected that the world's population will increase from slightly above 7 billion in 2012 to 9-10 billion in 2050 and the majority of them will be living in Asian countries (WB, 2011; USCB, 2012; UN, 2010; Ferrey & Cabraal, 2006). The existing population without energy access along with the new ones will therefore put pressure on energy resources in the coming years, with major energy demand in fact coming from cities and buildings in developing countries. Not only the population is growing at a faster rate but also a rapid urbanization is taking place in developing countries as a result of significant rural-urban migrations. It is estimated that 93% of urban growth will be occurring in developing countries and 80% of them will be in Asia (UN, 2005; UNFPA 2007). Since urbanization and electrification goes hand in hand and the new urbanites will seek for better standard of living, the situation altogether will result in more energy demand.

The burning question is: how can adequate energy be provided to the sheer number of future population and urban development in developing countries without leaving significant negative impact on environment? Are there any alternatives?

After the first oil crisis in 1973, when the OPEC cartel was formed to manipulate the oil price to maximize group revenue, renewable energies were developed as an alternative to fossil fuels (Williams, 2012; Ferrey & Cabraal, 2006). Renewable energies generate energy by harnessing the sun, wind, biomass, hydro, tidal and ocean waves and geothermal. The greatest advantages of renewable energy are: (1) it does not emit green house gas (GHG)[1] while producing energy and (2) the energy sources are free and abundant to all (Lund, 2010; Ferrey & Cabraal, 2006). Renewable energy technologies can be deployed in a large scale (e.g. an energy plant) or in a small scale (e.g. a micro generator in buildings). In fact, deploying renewable energy technology in buildings is becoming increasingly popular due to some advantages over large-scale power plants as the buildings can provide the necessary infrastructural support and the energy produced can be consumed on spot, therefore, eliminates the need for long distance transmission (Droege, 2009).

Utilizing the possibilities of renewable energies, a couple of alternative building and urban development models that can generate energy have emerged in developed countries in recent past. These models are commonly known as zero-energy and plus-energy models (Williams, 2012). A zero-energy model refers to a building or development that can generate the energy needed while a plus-energy model refers to a building or development that can generate excess energy than needed (Disch, 2009). The main two basic principles followed in these alternative models are,

1) Reducing energy demand by applying energy efficiency measures, and

2) Meeting the reduced energy demand by generating energy from green or renewable energy sources while in the plus-energy model; there will be excess energy after the demand is met.

This research hypothesises that since the major future energy demand will be from buildings and cities of developing countries, the plus-energy development can be a highly potential alternative way to meet the energy demand in these countries. Not only will this possibility eliminate the need of establishing new power plants to feed new developments, it will also offer an opportunity to produce additional green energy supply to be used elsewhere. This research also hypothesises that, only addressing the buildings independently will not be sufficient as the energy consumed by buildings is highly dependent on the urban settings it is situated in (Ahmed, 1995). Therefore, a plus-energy approach in developing countries should address the buildings collectively along with its urban settings in an integrated way.

The plus-energy models and concepts have been developed and implemented in developed countries mainly to address the issue of GHG emission reduction by these countries. In developing countries, the motivations are different; they are an answer to the ongoing energy scarcity and the need for coping with further development in a sustainable way without leaving a negative impact on environment. Further research is therefore needed in order to find out the challenges, opportunities, and ways of initiating plus-energy urban developments that are particular to the need of a developing country. To date, no record of such developments or research in this area in developing countries can be found. Since different developing countries will have different challenges, especially since energy generation through renewable options are highly dependent on the geographic location of a country and most of the developing countries have different climatic conditions than the models are originally generated, these issues need to be investigated as well to find out how such technologies can be transferred effectively to developing countries. Also, until now, plus-energy developments mainly focuses on individual buildings or small scale housing premises, but, this research intends to find out an urban solution along with its buildings, therefore, the urban issues for plus-energy developments also need to be addressed.

Bangladesh, one of the energy starving developing countries on earth, is the subject of this research. The research will be carried out in the context of Dhaka, the capital city of Bangladesh and the hometown of the researcher. The city is experiencing an acute energy scarcity and one of the highest urbanization growth rates in the world, which will make it the second largest megacity on earth by 2015 (Williams, 2012; UN,2001).

Have there been any preliminary studies, if Yes, provide the project title and HREC approval number(s):

No

Outline the study plan and design, giving a detailed description of all planned interactions between researchers and participants. *Attach copies of surveys, interview or focus group schedules, questions, and topics to be covered.*

This project intends to conduct an in-depth questionnaire survey and a number of semi-structured interviews from different stakeholder groups to collect data from research participants.

There will be no or minimal interactions between the researcher and participants during questionnaire survey phase. However, significant interaction is needed during semi-structured interview phase where the researcher will be conversing and recording the participants.

If research is to be conducted overseas; outline any local legislation, regulations, permissions or customs that need to be addressed before the research can commence. Outline the steps taken to ensure that this area has been adequately addressed in your proposal? ***Attach*** *authorizing correspondence, approval documentation to the application.*

None

SECTION 3: PARTICIPANTS AND RECRUITMENT

Who are the participants in this project? Include the source, number and age of all participants and outline how this sample will allow the aims of the project to be achieved.

This project will have two types of participants.

1) Participants for questionnaire survey
   Source: Occupants of randomly selected apartment buildings in formally developed townships by public sector in Dhaka city.
   Number: 300 (apx)
   Age: 18+
2) Participants for semi-structured interview
   Interview will be conducted among six different groups of stakeholders such as: Architects, Real Estate Developers, Solar Photovoltaic Entrepreneur, Waste Concern, Government Official and Consumer of Solar PV.
   Source: Participants from Architect, Real Estate Developers and Solar Photovoltaic entrepreneur stakeholder groups will be selected from professional directory. For participants from Waste Concern Group and Government Officials, higher authority of the organizations will be contacted. Consumer of Solar PV will be selected randomly.
   Number: 3 to 5 for all stake holders except Waste Concern and Government Officials from which one participant will be interviewed.
   Age: 30+

HREC_Low_Risk_Review_Application_Form_V1-6.doc

Outline the participant selection and exclusion criteria (include how and by whom the screening will be conducted):

Participant Selection:
For Questionnaire Survey: Random
For Semi-structured Interview: For professionals, at least with 10 years of work experiences. For consumers of Solar PV, head of the family member.
Selection will be done by the researcher. For, Architects, Real Estate Developers and Solar PV entrepreneurs, participants with 10 years work experience will be selected randomly from professional directory. For Waste Concern and Government official, Higher authority of the organizations will be contacted to select a participant. Consumer of Solar PV will be selected randomly.

How will participants be recruited? Explain each of the following areas in detail:

- *How you will recruit volunteers onto the study. How will people be approached and asked if they are willing to participate? How and by whom will personal information including names and contact details be accessed?*
- *What materials will be used? (Attach any advertisements, flyers, emails, Facebook pages, other.)*

For Questionnaire survey: survey form will be distributed randomly.
For interviews, an invitation letter will be sent initially to prospective participants.

Outline the specific tasks that participants will be asked to undertake including approximate time involved?

For Questionnaire survey, participants will have to answer and/or choose from multiple answers of a question. Total time for this work should not be more than 30 minutes.
For interviews, participants will be talking about their ideas, experiences and opinions about a given topic. Time will vary depending on the participant's willingness to talk.

If recruitment is to be conducted by a third party or another organisation, outline how this will be done?

N/A

Describe any possible risks to the health or safety of the researcher(s) when undertaking the research?
Note: where interviews are to be held in participants' homes as opposed to public places provide a rationale for why this is necessary and outline the personal safety protocol for the researchers involved:

This is a low-risk research project therefore no significant risk is present to the researcher's health or safety. The only possible risk can be interviewing the consumer of solar PV as the interview will possibly take place at home. However, if this is the case, the researcher will not go alone for conducting this interview.

SECTION 4: ETHICAL CONSIDERATIONS

Provide a detailed description of all potential risks and benefits to participants (including physical, emotional, social or legal) and steps to address these risks:

None

Is there a protocol that will be followed in the event of any adverse events? Note: an adverse event can include situations where participants may decide to withdraw themselves or their information during/after an interview or focus group. *Attach a copy of the protocol to the application.*

N/A

Will participants receive any reimbursement of out of pocket expenses, or financial or other rewards as a result of participation? What is the amount or nature of the reward and the justification for this?

No

Will a written Information Sheet be provided to all participants? Explain how and when? *Attach this document to the application.*

Yes.
For questionnaire survey, the information sheet will be included with the survey form.
For semi-structured interviews, the information sheet will be provided beforehand with invitation letter and consent form.

How and when will written consent be obtained? *Attach this document to the application.*

For questionnaire survey, if the participants return the form answered, it will be considered as the consent has been given.
For interview participants, an invitation letter to participate in the project along with the information sheet and consent form will be provided to the possible participants at least two weeks earlier. Based on the consent given, a suitable time and location for interview will be fixed. It is expected that most of the interviews will be conducted at daylight at offices or public places.

For participants not fluent in English or who have difficulty understanding English, what arrangements will be made to ensure comprehension of the Information Sheet and Consent Form?

Questionnaire survey form will be provided with native language. Semi-structured interviews will be conducted in native language(Bengali) as both the researcher and participants speak the same language.

SECTION 5: PROTECTION OF PRIVACY AND CONFIDENTIALITY OF INFORMATION

Which of the following statements apply to the research:

☒ **Complete anonymity of participants?** (i.e. researchers will not know the identity of participants as the participants are part of a random sample and are required to return responses with no form of personal identification)

☐ **Non-identified samples or data?** (i.e. an irreversible process whereby identifiers are removed from data and replaced by a code, with no record retained of how the code relates to the identifiers. It is then impossible to identify the individual to whom the sample of information relates)

☒ **Re-identifiable samples or data?** (i.e. a reversible process in which the identifiers are removed and replaced by a code. Those handling the data subsequently do so using the code. If necessary, it is possible to link the code to the original identifiers and identify the individual to whom the sample or information relates)

☐ **Participants have the option of being identified in any publication arising from the research?**

☐ **Participants are referred to by a pseudonym in any publication arising from the research?**

☐ **Other methods of protecting the privacy of participants?** *(please describe below)*

Will researchers be taking photographs or recordings of participants using audio tape, film/video, or other electronic medium and how are these to be used?

Yes. Interviews will be recorded with a digital voice recorder. The researcher herself will record while conducting the interviews.

How will the confidentiality of the data collected/disseminated, including the identity of participants, be assured? Where the sample size is very small, it may be impossible to guarantee anonymity/confidentiality of participant identity. Participants involved in such projects need to be clearly advised of this limitation in the *Information Sheet.*

Questionnaire survey will collect data that identifies participant's area of residences, but not name. Interviews will collect data that identifies participant's occupation, experiences and office along with the participant's name, which be removed after transcription. The researcher is aware that the small number of case studies may lead to interviewees being identified through association with other data. Inclusion of direct quotes will be done with great care.

SECTION 6: DATA ANALYSIS AND STORAGE

How is the information (data) to be analysed, and who will have access?

Questionnaire survey data will be analyzed with SPSS and Microsoft excel and in some cases with simulation tools.
Interview data will be transcribed and be analyzed with N-Vivo software.

Only the researchers will have access to these data.

Will participants receive feedback of findings prior to any publication (including access to transcripts of interviews or drafts of reports)?

Interview data will be transcribed and post-coded. It will be included as required in the thesis. Interview participants will receive a summary and interpretation of the interview before being included in thesis and any publication. All data may be used in academic papers.

Will the project outcomes be made publicly accessible at the end of the project and in what forms (e.g. journal article, book, conference paper, the Media)?

Yes, journal article, book, conference paper.

Outline the methods to be used for the storage, location, and access to, all records and materials (written or electronic) that have been used/collected during and after completion of the project.

The survey data will be stored in appropriate databases/spreadsheets at both the University of Adelaide and at the researcher's personal computer, with transfer storage via portable devices. Names will not be collected with surveys. The interview data will be recorded using a digital voice recorder. This data will be stored in its raw format and transcribed. It will be stored at the University of Adelaide and at the researcher's personal computer, with transfer storage via portable devices. All data will be de-identified as soon as it has been transcribed, with cross-referencing information not placed on portable devices, unless absolutely necessary. All of the above will be stored according to the Australian Code for Responsible Conduct of Research. The University of Adelaide ethics committee will be advised of the final storage intentions.

Outline the length of time that the records and materials will be retained by the University. (Note that the minimum period for retention of research data is 5 years from the date of any publication and varies depending on the specific type of research. For more information refer to Section 2.1 of the Australian Code for the Responsible Conduct of Research at http://www.nhmrc.gov.au/guidelines/publications/r39)

5 years.

SECTION 7: CONFLICT OF INTEREST OR OTHER ETHICAL ISSUES

Outline any 'conflict of interest' issues that may arise during the project?

N/A

Do the researchers expect to obtain any direct or indirect financial or other benefits from conducting this research? (Note that such benefits must be declared to the HREC and included in the *Information Sheet*.)

No

Outline any other ethical or relevant issues not discussed in this application:

N/A

SECTION 8: DECLARATION BY THE RESEARCHERS

Declaration by the researcher(s)

I/we have read the *National Statement on Ethical Conduct in Human Research (2007)*.

I/we, the researcher(s) agree to:

- start this research project only after obtaining final approval from the Human Research Ethics Committee (HREC)
- only carry out this research project where adequate funding and personnel is available to enable the project to be carried out according to good research practice and in an ethical manner
- notify the HREC in writing in the event of any adverse or unforeseen events; amendments; completion; discontinuation of the project or changes to research personnel
- provide an annual progress report to the HREC for the duration of the research project;

- apply for annual renewal (noting approval is only given for a period up to 12 months)
- provide the HREC with a final report
- agree to participate in an audit if requested by the HREC.

In addition, as the applicant, I:

- accept responsibility for the conduct of this research project according to the *National Statement on Ethical Conduct in Human Research (2007)*
- certify that all researchers and other personnel involved in this project are appropriately qualified and experienced or will undergo appropriate training and supervision to fulfil their role in this project
- will take responsibility for the confidential maintenance of the data as per the University's Responsible Conduct of Research Policy and as required by legislation.

Applicant's signature:		Name:	Associate Professor Dr. Veronica I Soebarto	Date:	
Researcher's signature:		Name:	Rehnuma Parveen	Date:	
Researcher's signature:		Name:	Dr. David Ness	Date:	
Researcher's signature:		Name:		Date:	

SECTION 9: CHECKLIST

The following documents are attached to this application:

Yes	No	N/A*	
☒	☐	☐	Participant Information Sheet
☐	☐	☒	Standard Consent Form for a participant in a research project
☐	☐	☒	Third Party to Participation Form required where participants are children under 18 years or a dependent adult
☒	☐	☐	Contacts and Independent Complaints Sheet
☒	☐	☐	Survey instrument/Questionnaire
☒	☐	☐	Procedure/protocol for interviews or focus groups including topics and questions
☐	☐	☒	Recruitment advertisement, flyers, recruitment letter
☐	☐	☒	Adverse event procedure/interview protocol
☐	☐	☒	Evidence of approval/rejection by other HRECs, including comments and requested alterations to the application
☐	☐	☒	Overseas research only: Evidence of permissions, approvals from overseas authorities etc

*Not applicable

Appendix D.1: Indoor and Outdoor Temperature at 9m and 15m Level

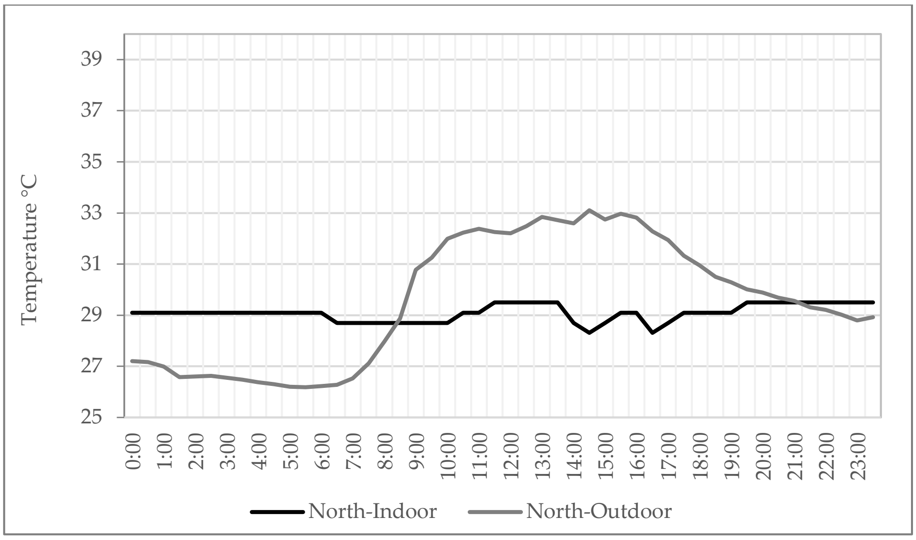


Figure A.1: North (9m)

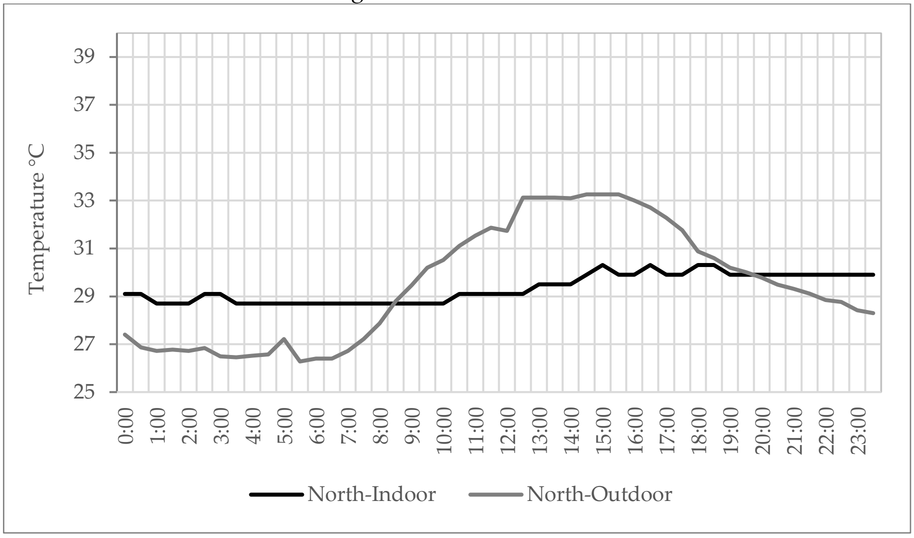


Figure A.2: North (15 m)

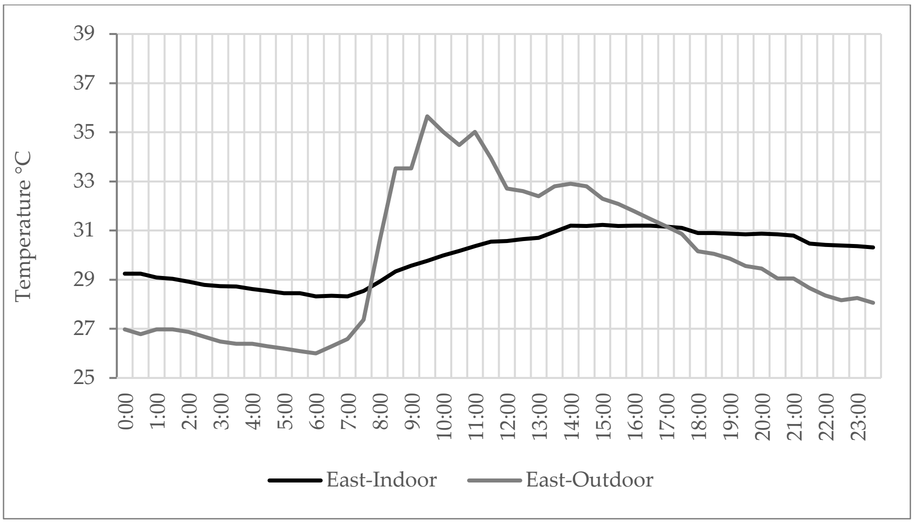


Figure A.3: East (9m)

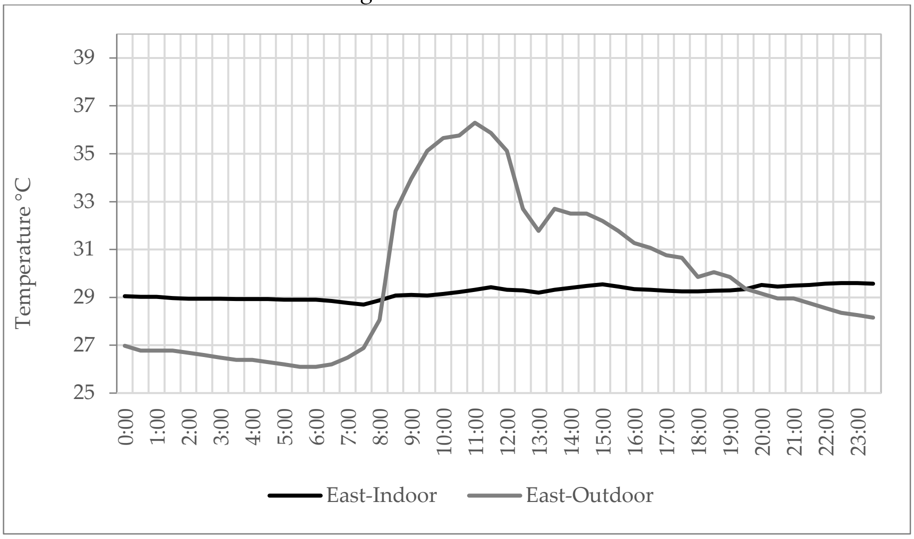


Figure A.4: East (15m)

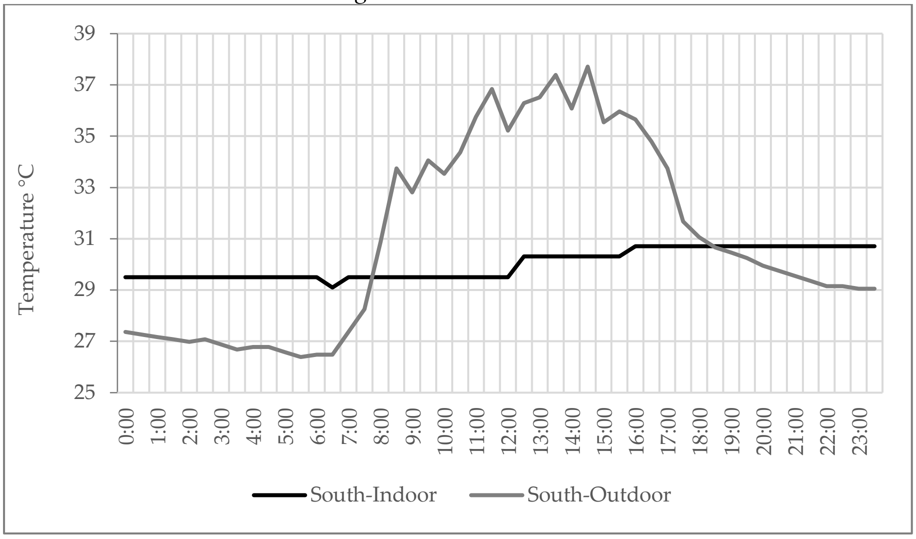


Figure A.5: South (9m)

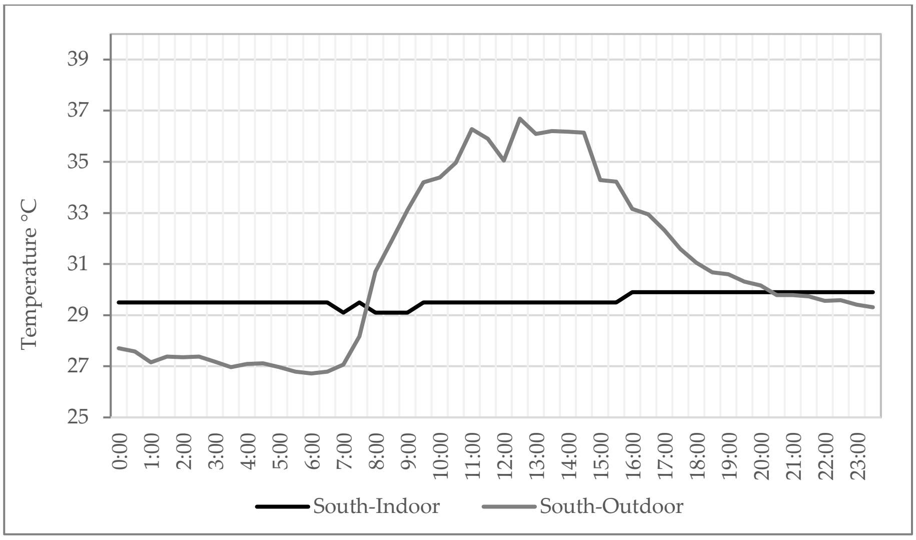


Figure A.6: South (15m)

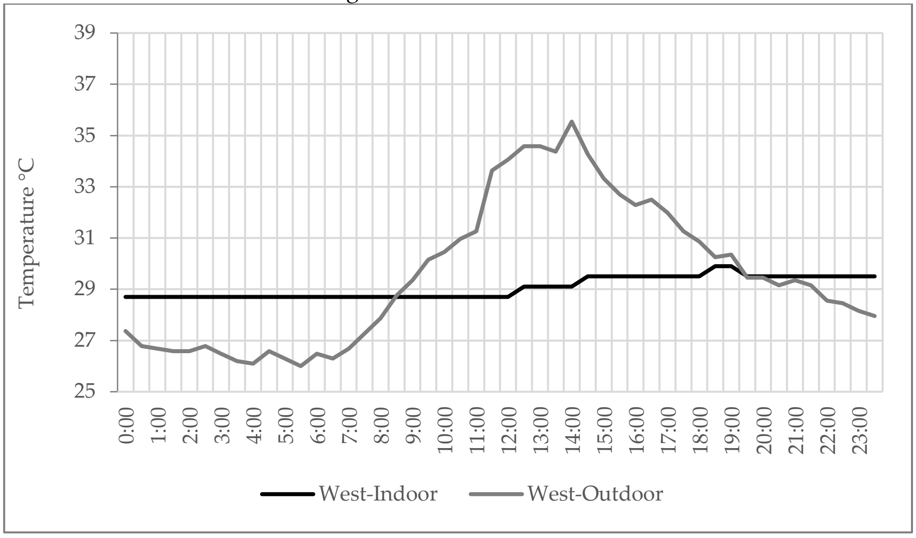


Figure A.7: West (9m)

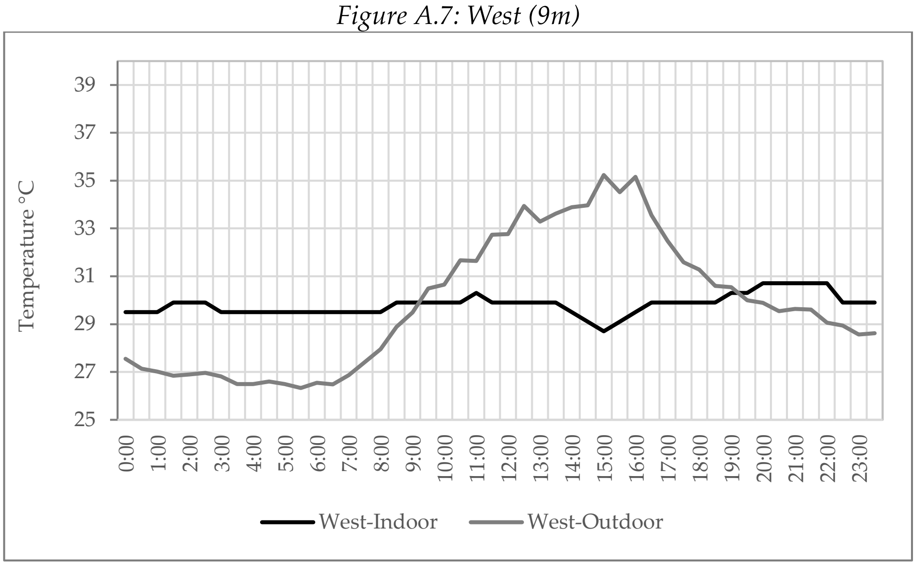


Figure A.8: West (15m)

Appendix D.2: UHI Study on Two More Clear Days

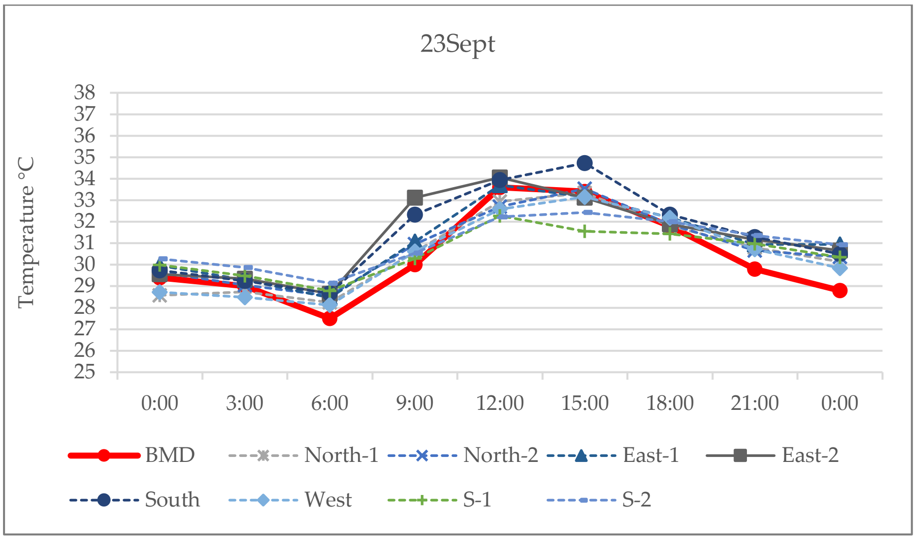


Figure A.9: UHI Study on another Clear Day (23 Sept. 2013)

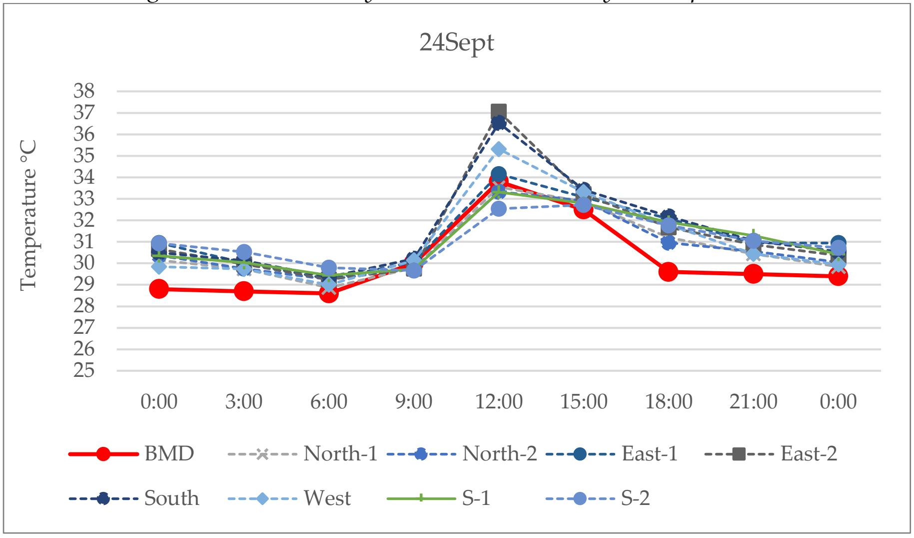
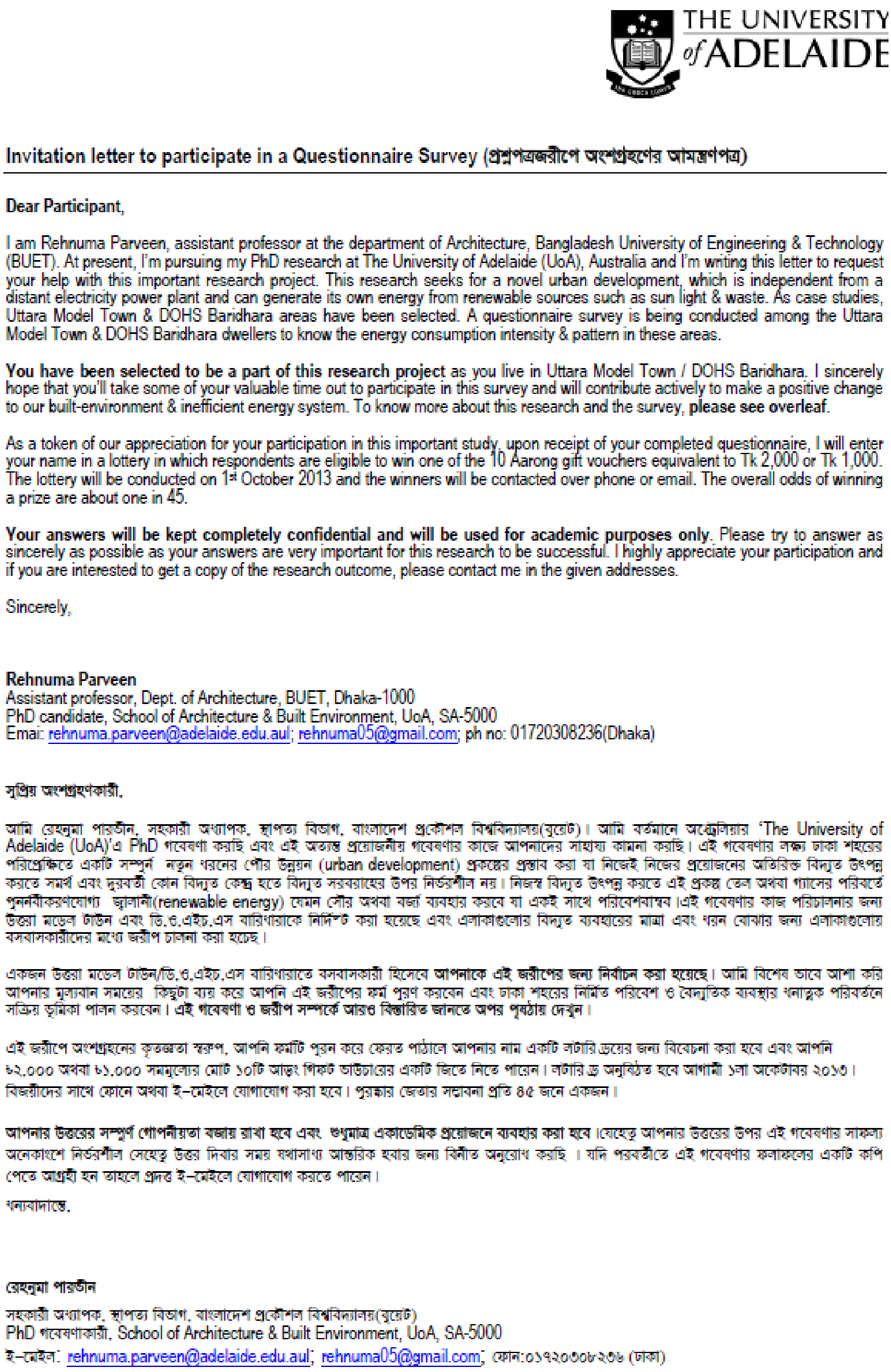


Figure A.10: UHI Study on another Clear Day-2 (24 Sept. 2013)

Appendix E.1: Participants' Information Sheet



THE UNIVERSITY of ADELAIDE

Invitation letter to participate in a Questionnaire Survey (প্রশ্নপত্রজরীপে অংশগ্রহণের আমন্ত্রণপত্র)

Dear Participant,

I am Rehnuma Parveen, assistant professor at the department of Architecture, Bangladesh University of Engineering & Technology (BUET). At present, I'm pursuing my PhD research at The University of Adelaide (UoA), Australia and I'm writing this letter to request your help with this important research project. This research seeks for a novel urban development, which is independent from a distant electricity power plant and can generate its own energy from renewable sources such as sun light & waste. As case studies, Uttara Model Town & DOHS Baridhara areas have been selected. A questionnaire survey is being conducted among the Uttara Model Town & DOHS Baridhara dwellers to know the energy consumption intensity & pattern in these areas.

You have been selected to be a part of this research project as you live in Uttara Model Town / DOHS Baridhara. I sincerely hope that you'll take some of your valuable time out to participate in this survey and will contribute actively to make a positive change to our built-environment & inefficient energy system. To know more about this research and the survey, **please see overleaf**.

As a token of our appreciation for your participation in this important study, upon receipt of your completed questionnaire, I will enter your name in a lottery in which respondents are eligible to win one of the 10 Aarong gift vouchers equivalent to Tk 2,000 or Tk 1,000. The lottery will be conducted on 1st October 2013 and the winners will be contacted over phone or email. The overall odds of winning a prize are about one in 45.

Your answers will be kept completely confidential and will be used for academic purposes only. Please try to answer as sincerely as possible as your answers are very important for this research to be successful. I highly appreciate your participation and if you are interested to get a copy of the research outcome, please contact me in the given addresses.

Sincerely,

Rehnuma Parveen
Assistant professor, Dept. of Architecture, BUET, Dhaka-1000
PhD candidate, School of Architecture & Built Environment, UoA, SA-5000
Emai: rehnuma.parveen@adelaide.edu.aul; rehnuma05@gmail.com; ph no: 01720308236(Dhaka)

সুপ্রিয় অংশগ্রহণকারী,

আমি রেহনুমা পারভীন, সহকারী অধ্যাপক, স্থাপত্য বিভাগ, বাংলাদেশ প্রকৌশল বিশ্ববিদ্যালয়(বুয়েট)। আমি বর্তমানে অস্ট্রেলিয়ার 'The University of Adelaide (UoA)'এ PhD গবেষণা করছি এবং এই অত্যন্ত প্রয়োজনীয় গবেষণার কাজে আপনাদের সাহায্য কামনা করছি। এই গবেষণার লক্ষ্য ঢাকা শহরের পরিপ্রেক্ষিতে একটি সম্পুর্ন নতুন ধরনের পৌর উন্নয়ন (urban development) প্রকল্পের প্রস্তাব করা যা নিজেই নিজের প্রয়োজনের অতিরিক্ত বিদ্যুত উৎপন্ন করতে সমর্থ এবং দুরবর্তী কোন বিদ্যুত কেন্দ্র হতে বিদ্যুত সরবরাহের উপর নির্ভরশীল নয়। নিজস্ব বিদ্যুত উৎপন্ন করতে এই প্রকল্প তেল অথবা গ্যাসের পরিবর্তে পুনর্নবীকরণযোগ্য জ্বালানী(renewable energy) যেমন সৌর অথবা বর্জ্য ব্যবহার করবে যা একই সাথে পরিবেশবান্ধব।এই গবেষণার কাজ পরিচালনার জন্য উত্তরা মডেল টাউন এবং ডি.ও.এইচ.এস বারিধারাকে নির্দিশ্ট করা হয়েছে এবং এলাকাগুলোর বিদ্যুত ব্যবহারের মাত্রা এবং ধরন বোঝার জন্য এলাকাগুলোর বসবাসকারীদের মধ্যে জরীপ চালনা করা হচ্ছে।

একজন উত্তরা মডেল টাউন/ডি.ও.এইচ.এস বারিধারাতে বসবাসকারী হিসেবে **আপনাকে এই জরীপের জন্য নির্বাচন করা হয়েছে**। আমি বিশেষ ভাবে আশা করি আপনার মুল্যবান সময়ের কিছুটা ব্যয় করে আপনি এই জরীপের ফর্ম পুরণ করবেন এবং ঢাকা শহরের নির্মিত পরিবেশ ও বৈদ্যুতিক ব্যবস্থার ধনাত্মক পরিবর্তনে সক্রিয় ভূমিকা পালন করবেন। **এই গবেষণা ও জরীপ সম্পর্কে আরও বিস্তারিত জানতে অপর পৃষ্ঠায় দেখুন।**

এই জরীপে অংশগ্রহনের কৃতজ্ঞতা স্বরুপ, আপনি ফর্মটি পুরন করে ফেরত পাঠালে আপনার নাম একটি লটারি ড্রয়ের জন্য বিবেচনা করা হবে এবং আপনি ৳২,০০০ অথবা ৳১,০০০ সমমুল্যের মোট ১০টি আড়ং গিফট ভাউচারের একটি জিতে নিতে পারেন। লটারি ড্র অনুষ্ঠিত হবে আগামী ১লা অক্টোবর ২০১৩। বিজয়ীদের সাথে ফোনে অথবা ই–মেইলে যোগাযোগ করা হবে। পুরস্কার জেতার সম্ভাবনা প্রতি ৪৫ জনে একজন।

আপনার উত্তরের সম্পূর্ণ গোপনীয়তা বজায় রাখা হবে এবং শুধুমাত্র একাডেমিক প্রয়োজনে ব্যবহার করা হবে।যেহেতু আপনার উত্তরের উপর এই গবেষণার সাফল্য অনেকাংশে নির্ভরশীল সেহেতু উত্তর দিবার সময় যথাসাধ্য আন্তরিক হবার জন্য বিনীত অনুরোধ করছি । যদি পরবর্তীতে এই গবেষণার ফলাফলের একটি কপি পেতে আগ্রহী হন তাহলে প্রদত্ত ই–মেইলে যোগাযোগ করতে পারেন।

ধন্যবাদান্তে,

রেহনুমা পারভীন

সহকারী অধ্যাপক, স্থাপত্য বিভাগ, বাংলাদেশ প্রকৌশল বিশ্ববিদ্যালয়(বুয়েট)
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Information sheet for the participants (অংশগ্রহণকরীদের জন্য তথ্যপত্র)

Research Title

"Towards plus-energy urban developments as an alternative way to reduce energy scarcity in developing countries. Case study: Dhaka, Bangladesh."

Purpose of the Questionnaire Survey (প্রশ্নপত্রজরীপের উদ্দেশ্য)

This survey aims at knowing the energy consumption level and pattern in the Uttara Model Town & DOHS Baridhara areas of the Dhaka city. Energy consumption by a household depends on widely varied issues such as the number of people live in the house, anthropogenic heat release due to cooking, running a generator or the number of cars on the adjacent streets, construction & materials of the building, the amount of time the windows & curtains are open etc. The questions in this form are designed to collect information about all possible subjects that have an impact on energy consumptions by a household.

এই জরীপের উদ্দেশ্য হলো উত্তরা মডেল টাউন ও ডি,ও,এইচ,এস বারিধারা এলাকার বাড়িগুলোর বিদ্যুত ব্যবহারের মাত্রা এবং ধরন সম্পর্কে তথ্য সংগ্রহ করা। একটি বাড়ির বিদ্যুত ব্যবহার বিবিধ বিষয়ের উপর নির্ভরশীল যেমন, বাসায় কতজন মানুষ থাকেন, তাপ উৎপাদনের বিভিন্ন উৎস যথা রান্নার সময়, জেনারেটর চালনা অথবা বাড়ির পাশের রাস্তায় গাড়ির সংখ্যা, বাড়ির নির্মাণ সামগ্রী, কতসময় জানালা এবং পর্দা খোলা থাকে ইত্যাদি ।এই ফর্মের প্রশ্নগুলো যেকোন একটি বাড়ির বিদ্যুত ব্যবহারে ভূমিকা রাখে এমন সম্ভাব্য সকল বিষয়ের উপর তথ্য সংগ্রহ করার কথা মাথায় রেখে তৈরী করা হয়েছে যার উপর ভিত্তি করে নতুন পৌর পরিকল্পনা প্রস্তাব করা যায়।

Tasks of the participants (অংশগ্রহণকরীদের কাজ)

The questions are arranged under five different sections. Participants will have to complete several tables & choose answers from multiple choices for majority of the questions. For the rest of the questions, participants will fill in the blank. For convenience, Bengali translation is provided with each question.

প্রশ্নগুলো পাঁচটি সেকশনে ভাগ করে সাজানো হয়েছে। অংশগ্রহণকরীদের কিছু ছক পূরণ করতে হবে এবং কিছু প্রশ্নের উত্তর মাল্টিপল উত্তর থেকে বেছে নিতে হবে। বাকী প্রশ্নগুলোর ক্ষেত্রে শূণ্যস্থান পূরণ করতে হবে। বোঝার সুবিধার্থে প্রতিটি প্রশ্নের বাংলা অনুবাদ দেওয়া হয়েছে।

How much time will it take? (কত সময় প্রয়োজন?)

Approximately 35-45 minutes. (৩৫–৪৫ মিনিটের মতো।)

Possible benefits from the study, to the participant and/or the community (অংশগ্রহণের ফলে সম্ভাব্য সুবিধা প্রাপ্তি)

- An opportunity for the participants to effect change by conveying the information related to energy consumption by his/her household. (বিদ্যুত ব্যবহার সম্পর্কিত তথ্য সরবরাহের মাধ্যমে অংশগ্রহণকরীগণ দেশের উন্নতি ও ধনাত্মক পরিবর্তনে সক্রিয় ভূমিকা রাখতে পারেন।)
- An opportunity for the participants to review their energy consumption level & pattern while sharing the information. (এই জরীপে অংশগ্রহণ অংশগ্রহণকরীদের জন্য বিদ্যুত বিষয়ক তথ্য সরবরাহের সময় নিজ বাসার বিদ্যুত ব্যবহারের মাত্রা এবং ধরন নিরীক্ষা করার একটি সুযোগ হিসেবে বিবেচিত হতে পারে।)

If the participants wish to withdraw from the study (যদি অংশগ্রহণকরীগণ জরীপ হতে নিজেকে প্রত্যাহার করতে চান)

Your participation is voluntary. You may withdraw from the survey whenever you desire by simply advising the researcher of your intention to do so. (আপনার অংশগ্রহণ সম্পূর্ণ ঐচ্ছিক। আপনি যেকোন সময় গবেষণাকারীকে জানিয়ে নিজেকে এই জরীপ থেকে প্রত্যাহার করে নিতে পারেন।)

Assurances of confidentiality (সরবরাহকৃত তথ্যের গোপনীয়তা)

All answers will be kept confidential & codes will be used to identify your data. You won't be identified with your data as you don't need to provide your name on the survey form. (সমস্ত তথ্যের গোপনীয়তা বজায় রাখা হবে এবং শুধুমাত্র একাডেমিক প্রয়োজনে ব্যবহার করা হবে। আপনার উত্তরের জন্য কোড ব্যবহার করা হবে। আপনার নাম প্রদান করার প্রয়োজন নাই বিধায় আপনার উত্তরের সাথে আপনাকে চিহ্নিত করা যাবে না।)

For any further information, please do not hesitate to contact us:

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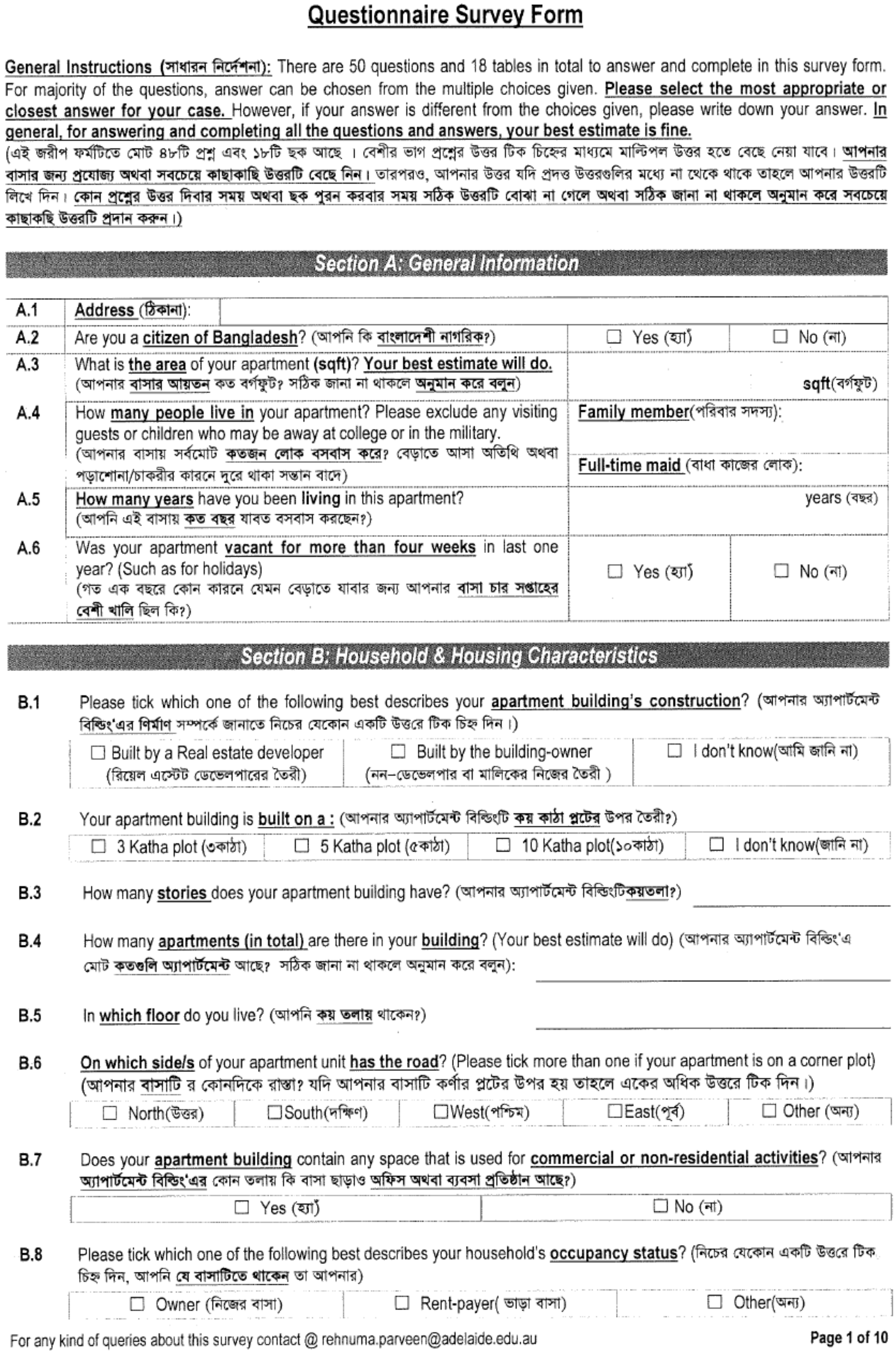
Appendix E.2: Questionnaire Survey Form



Questionnaire Survey Form

General Instructions (সাধারন নির্দেশনা): There are 50 questions and 18 tables in total to answer and complete in this survey form. For majority of the questions, answer can be chosen from the multiple choices given. **Please select the most appropriate or closest answer for your case.** However, if your answer is different from the choices given, please write down your answer. **In general, for answering and completing all the questions and answers, your best estimate is fine.**
(এই জরীপ ফর্মটিতে মোট ৪৮টি প্রশ্ন এবং ১৮টি ছক আছে । বেশীর ভাগ প্রশ্নের উত্তর টিক চিহ্নের মাধ্যমে মাল্টিপল উত্তর হতে বেছে নেয়া যাবে। **আপনার বাসার জন্য প্রযোজ্য অথবা সবচেয়ে কাছাকাছি উত্তরটি বেছে নিন।** তারপরও, আপনার উত্তর যদি প্রদত্ত উত্তরগুলির মধ্যে না থেকে থাকে তাহলে আপনার উত্তরটি লিখে দিন। **কোন প্রশ্নের উত্তর দিবার সময় অথবা ছক পুরন করবার সময় সঠিক উত্তরটি বোঝা না গেলে অথবা সঠিক জানা না থাকলে অনুমান করে সবচেয়ে কাছাকছি উত্তরটি প্রদান করুন।**)

Section A: General Information

A.1	**Address** (ঠিকানা):		
A.2	Are you a **citizen of Bangladesh**? (আপনি কি **বাংলাদেশী নাগরিক**?)	☐ Yes (হ্যাঁ)	☐ No (না)
A.3	What is **the area** of your apartment **(sqft)**? **Your best estimate will do.** (আপনার **বাসার আয়তন** কত বর্গফুট? সঠিক জানা না থাকলে **অনুমান করে বলুন**)	**sqft**(বর্গফুট)	
A.4	How **many people live in** your apartment? Please exclude any visiting guests or children who may be away at college or in the military. (আপনার বাসায় সর্বমোট **কতজন লোক বসবাস করে**? বেড়াতে আসা অতিথি অথবা পড়াশোনা/চাকরীর কারনে দুরে থাকা সন্তান বাদে)	**Family member**(পরিবার সদস্য): **Full-time maid** (বাধা কাজের লোক):	
A.5	**How many years** have you been **living** in this apartment? (আপনি এই বাসায় **কত বছর** যাবত বসবাস করছেন?)	years (বছর)	
A.6	Was your apartment **vacant for more than four weeks** in last one year? (Such as for holidays) (গত এক বছরে কোন কারনে যেমন বেড়াতে যাবার জন্য আপনার **বাসা চার সপ্তাহের বেশী খালি** ছিল কি?)	☐ Yes (হ্যাঁ)	☐ No (না)

Section B: Household & Housing Characteristics

B.1 Please tick which one of the following best describes your **apartment building's construction**? (আপনার অ্যাপার্টমেন্ট **বিল্ডিং'এর নির্মাণ** সম্পর্কে জানাতে নিচের যেকোন একটি উত্তরে টিক চিহ্ন দিন।)

☐ Built by a Real estate developer (রিয়েল এস্টেট ডেভেলপারের তৈরী)	☐ Built by the building-owner (নন–ডেভেলপার বা মালিকের নিজের তৈরী)	☐ I don't know(আমি জানি না)

B.2 Your apartment building is **built on a :** (আপনার অ্যাপার্টমেন্ট বিল্ডিংটি **কয় কাঠা প্লটের** উপর তৈরী?)

☐ 3 Katha plot (৩কাঠা)	☐ 5 Katha plot (৫কাঠা)	☐ 10 Katha plot(১০কাঠা)	☐ I don't know(জানি না)

B.3 How many **stories** does your apartment building have? (আপনার অ্যাপার্টমেন্ট বিল্ডিংটি**কয়তলা**?) ____________

B.4 How many **apartments (in total)** are there in your **building**? (Your best estimate will do) (আপনার অ্যাপার্টমেন্ট বিল্ডিং'এ মোট **কতগুলি অ্যাপার্টমেন্ট** আছে? সঠিক জানা না থাকলে অনুমান করে বলুন): ____________

B.5 In **which floor** do you live? (আপনি **কয় তলায়** থাকেন?) ____________

B.6 **On which side/s** of your apartment unit **has the road**? (Please tick more than one if your apartment is on a corner plot) (আপনার **বাসাটি** র কোনদিকে রাস্তা? যদি আপনার বাসাটি কর্ণার প্লটের উপর হয় তাহলে একের অধিক উত্তরে টিক দিন।)

☐ North(উত্তর)	☐South(দক্ষিণ)	☐West(পশ্চিম)	☐East(পূর্ব)	☐ Other (অন্য)

B.7 Does your **apartment building** contain any space that is used for **commercial or non-residential activities**? (আপনার **অ্যাপার্টমেন্ট বিল্ডিং'এর** কোন তলায় কি বাসা ছাড়াও **অফিস অথবা ব্যবসা প্রতিষ্ঠান আছে?**)

☐ Yes (হ্যাঁ)	☐ No (না)

B.8 Please tick which one of the following best describes your household's **occupancy status**? (নিচের যেকোন একটি উত্তরে টিক চিহ্ন দিন, আপনি **যে বাসাটিতে থাকেন** তা আপনার)

☐ Owner (নিজের বাসা)	☐ Rent-payer(ভাড়া বাসা)	☐ Other(অন্য)

For any kind of queries about this survey contact @ rehnuma.parveen@adelaide.edu.au

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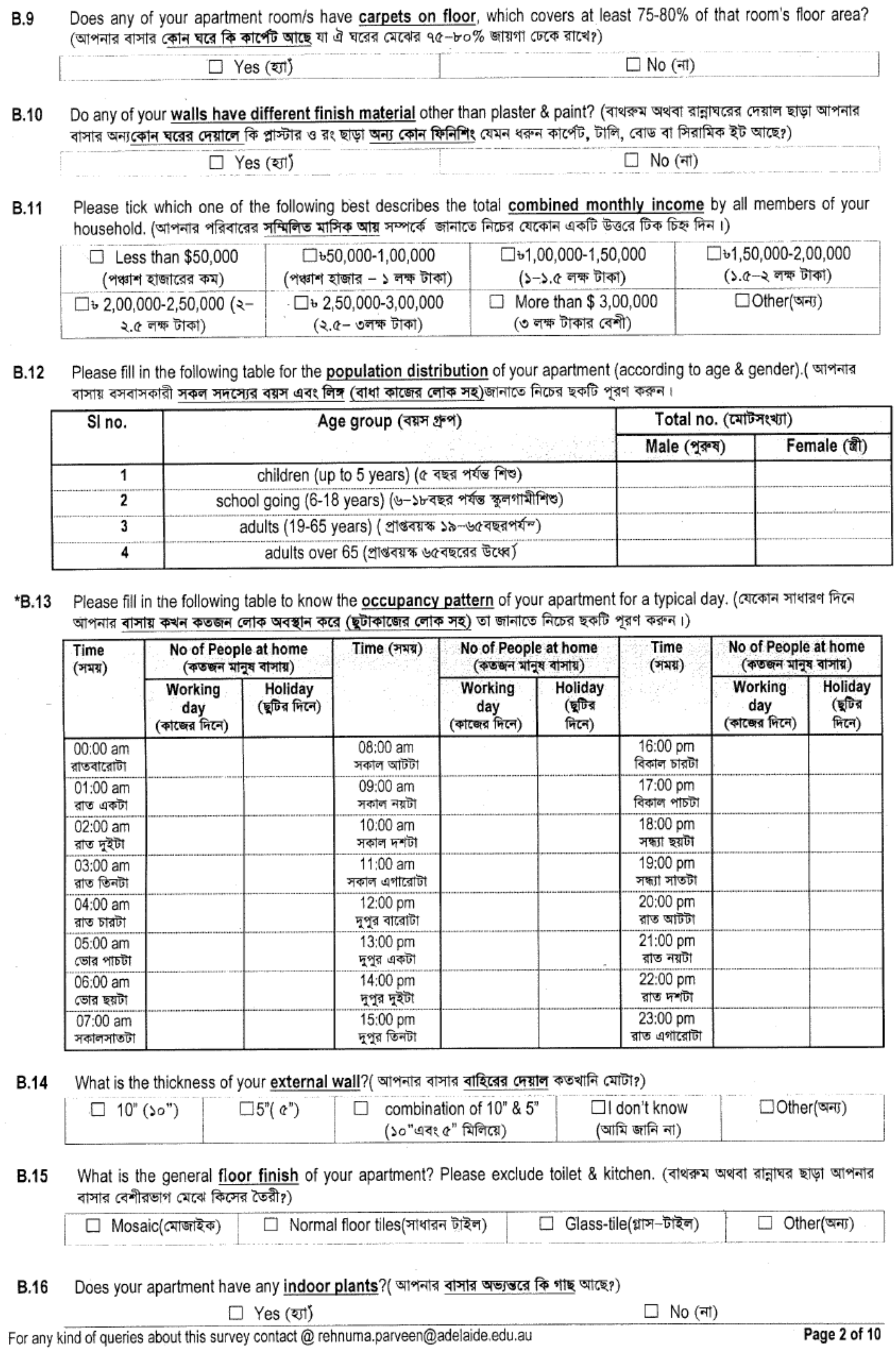

B.9 Does any of your apartment room/s have **carpets on floor**, which covers at least 75-80% of that room's floor area? (আপনার বাসার **কোন ঘরে কি কার্পেট আছে** যা ঐ ঘরের মেঝের ৭৫-৮০% জায়গা ঢেকে রাখে?)

☐ Yes (হ্যাঁ)	☐ No (না)

B.10 Do any of your **walls have different finish material** other than plaster & paint? (বাথরুম অথবা রান্নাঘরের দেয়াল ছাড়া আপনার বাসার অন্য**কোন ঘরের দেয়ালে** কি প্লাস্টার ও রং ছাড়া **অন্য কোন ফিনিশিং** যেমন ধরুন কার্পেট, টালি, বোড বা সিরামিক ইট আছে?)

☐ Yes (হ্যাঁ)	☐ No (না)

B.11 Please tick which one of the following best describes the total **combined monthly income** by all members of your household. (আপনার পরিবারের **সম্মিলিত মাসিক আয়** সম্পর্কে জানাতে নিচের যেকোন একটি উত্তরে টিক চিহ্ন দিন।)

☐ Less than $50,000 (পঞ্চাশ হাজারের কম)	☐৳50,000-1,00,000 (পঞ্চাশ হাজার – ১ লক্ষ টাকা)	☐৳1,00,000-1,50,000 (১-১.৫ লক্ষ টাকা)	☐৳1,50,000-2,00,000 (১.৫-২ লক্ষ টাকা)
☐৳ 2,00,000-2,50,000 (২-২.৫ লক্ষ টাকা)	☐৳ 2,50,000-3,00,000 (২.৫- ৩লক্ষ টাকা)	☐ More than $ 3,00,000 (৩ লক্ষ টাকার বেশী)	☐Other(অন্য)

B.12 Please fill in the following table for the **population distribution** of your apartment (according to age & gender).(আপনার বাসায় বসবাসকারী **সকল সদস্যের বয়স এবং লিঙ্গ (বাধা কাজের লোক সহ)**জানাতে নিচের ছকটি পূরণ করুন।

Sl no.	Age group (বয়স গ্রুপ)	Total no. (মোটসংখ্যা)	
		Male (পুরুষ)	Female (স্ত্রী)
1	children (up to 5 years) (৫ বছর পর্যন্ত শিশু)		
2	school going (6-18 years) (৬-১৮বছর পর্যন্ত স্কুলগামীশিশু)		
3	adults (19-65 years) (প্রাপ্তবয়স্ক ১৯-৬৫বছরপর্যন্ত)		
4	adults over 65 (প্রাপ্তবয়স্ক ৬৫বছরের উর্ধ্বে)		

***B.13** Please fill in the following table to know the **occupancy pattern** of your apartment for a typical day. (যেকোন সাধারণ দিনে আপনার **বাসায় কখন কতজন লোক অবস্থান করে (ছুটাকাজের লোক সহ)** তা জানাতে নিচের ছকটি পূরণ করুন।)

Time (সময়)	No of People at home (কতজন মানুষ বাসায়)		Time (সময়)	No of People at home (কতজন মানুষ বাসায়)		Time (সময়)	No of People at home (কতজন মানুষ বাসায়)	
	Working day (কাজের দিনে)	Holiday (ছুটির দিনে)		Working day (কাজের দিনে)	Holiday (ছুটির দিনে)		Working day (কাজের দিনে)	Holiday (ছুটির দিনে)
00:00 am রাতবারোটা			08:00 am সকাল আটটা			16:00 pm বিকাল চারটা		
01:00 am রাত একটা			09:00 am সকাল নয়টা			17:00 pm বিকাল পাচটা		
02:00 am রাত দুইটা			10:00 am সকাল দশটা			18:00 pm সন্ধ্যা ছয়টা		
03:00 am রাত তিনটা			11:00 am সকাল এগারোটা			19:00 pm সন্ধ্যা সাতটা		
04:00 am রাত চারটা			12:00 pm দুপুর বারোটা			20:00 pm রাত আটটা		
05:00 am ভোর পাচটা			13:00 pm দুপুর একটা			21:00 pm রাত নয়টা		
06:00 am ভোর ছয়টা			14:00 pm দুপুর দুইটা			22:00 pm রাত দশটা		
07:00 am সকালসাতটা			15:00 pm দুপুর তিনটা			23:00 pm রাত এগারোটা		

B.14 What is the thickness of your **external wall**?(আপনার বাসার **বাহিরের দেয়াল** কতখানি মোটা?)

☐ 10" (১০")	☐5"(৫")	☐ combination of 10" & 5" (১০"এবং ৫" মিলিয়ে)	☐I don't know (আমি জানি না)	☐Other(অন্য)

B.15 What is the general **floor finish** of your apartment? Please exclude toilet & kitchen. (বাথরুম অথবা রান্নাঘর ছাড়া আপনার বাসার বেশীরভাগ মেঝে কিসের তৈরী?)

☐ Mosaic(মোজাইক)	☐ Normal floor tiles(সাধারন টাইল)	☐ Glass-tile(গ্লাস-টাইল)	☐ Other(অন্য)

B.16 Does your apartment have any **indoor plants**?(আপনার **বাসার অভ্যন্তরে কি গাছ** আছে?)

☐ Yes (হ্যাঁ) ☐ No (না)

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B.17 Please tick which one of the following best describes the **roof construction** of your apartment building? (আপনার **অ্যাপার্টমেন্ট বিল্ডিং'এর ছাদের নির্মাণ** সম্পর্কে জানাতে নিচের যেকোন একটি উত্তরে টিক চিহ্ন দিন ।)

☐RCC slab (আর,সি,সি স্ল্যাব)	☐Hollow brick (হলো ব্রিক)	☐Other(অন্য)	☐ I don't know(জানি না)

B.18 Please tick which one of the following best describes the **roof-garden** of your apartment building?(আপনার বাসার **ছাদের বাগান** সম্পর্কে জানাতে নিচের যেকোন একটি উত্তরে টিক চিহ্ন দিন ।)

☐No roof-garden (ছাদে কোন গাছ নাই)	☐Almost all of the roof is covered(প্রায় পুরো ছাদে গাছ আছে)	☐Half of the roof is covered (প্রায় অর্ধেক ছাদে গাছ আছে)	☐Very little (অল্প কিছু অংশে গাছ আছে)

B.19 How would you rate the overall **cross-ventilation** of your apartment?(আপনার বাসায় **বাতাসের প্রবাহ বা ক্রস– ভেন্টিলেশনকে** অপনি কিভাবে মূল্যায়ন করবেন? নিচের উত্তর থেকে একটি বেছে নিন)

☐খুব খারাপ	☐খুব খারাপ আর মোটামুটির মাঝে	☐মোটামুটি	☐মোটামুটি আর খুব ভালোর মাঝে	☐খুব ভালো

B.20 Please fill up the table below to know how often you keep your **veranda doors open**? (আপনার **বারান্দার দরজাগুলো** সাধারনত **কতক্ষন খোলা** থাকে?)

Verandah doors (বারান্দার দরজা)	☐**Never (কক্ষনো নয়)**	☐**Very little (খুব কম)**	☐**Some time (মাঝে মাঝেই)**	☐**Quite often (প্রায়ই)**	☐**Always (সবসময়)**	☐**N/A (প্রযোজ্য নয়)**
Bedroom-1 veranda door	☐	☐	☐	☐	☐	☐
Bedroom-2 veranda door	☐	☐	☐	☐	☐	☐
Bedroom-3 veranda door	☐	☐	☐	☐	☐	☐
Bedroom-4 veranda door	☐	☐	☐	☐	☐	☐
Family living/Dining veranda door	☐	☐	☐	☐	☐	☐
Formal living veranda door	☐	☐	☐	☐	☐	☐

B.21 Are any of your **veranda doors made of glass**? (আপনার কোন **বারান্দার দরজা কি কাচের** তৈরী?)

☐Yes (হ্যাঁ)	☐ No (না)

- **If you've answered yes** to the above question, please mention **how many doors**? (যদি **উপরের প্রশ্নের উত্তর হ্যা** হয়ে থাকে তাহলে বলুন **কতগুলো** বারান্দার দরজা?) ____________________

B.22 Do you usually keep your bedroom **doors open during daytime**? (দিনের বেলায় আপনার **শোবার ঘরের দরজাগুলো** কি সাধারনত **খোলা থাকে**?)

☐Yes (হ্যাঁ)	☐ No (না)	☐ Other(অন্য হলে বলুন): __________

B.23 If you don't keep your windows open during summer days, **what are the reasons** for that? (গরমের দিনে আপনি যদি কখনোই আপনার **জানালা খোলা না রাখেন তার কারনগুলো** কি কি?)

☐Dust(ধুলা)	☐Privacy(গোপনীয়তা)	☐Noise(শব্দ)	☐Security(নিরাপত্তা)	☐AC (এসি)	☐Other(অন্য)

B.24 **Can air pass through** the door & window gaps even when they are closed? (আপনার ঘরের **দরজা–জানালা গুলো** বন্ধ করার পরও কি দরজা–জানালার ফাক দিয়ে বাতাস প্রবেশ করতে পারে?)

☐Yes (হ্যাঁ)	☐ No (না)	☐ I don't know(আমি জানি না)

B.25 Do you operate **any home-based business**?(আপনার বাসায় কি **এমন কোন কাজ চলে** যাতে সাধারন বাসার তুলনায় বেশী বিদ্যুত বাবহার হয়? যেমন ধরুন বাসায় বুটিকের কাজ, বেকারির জন্য কেক বানানো অথবা ছাত্র পড়ানো ।)

☐Yes (হ্যাঁ)	☐ No (না)

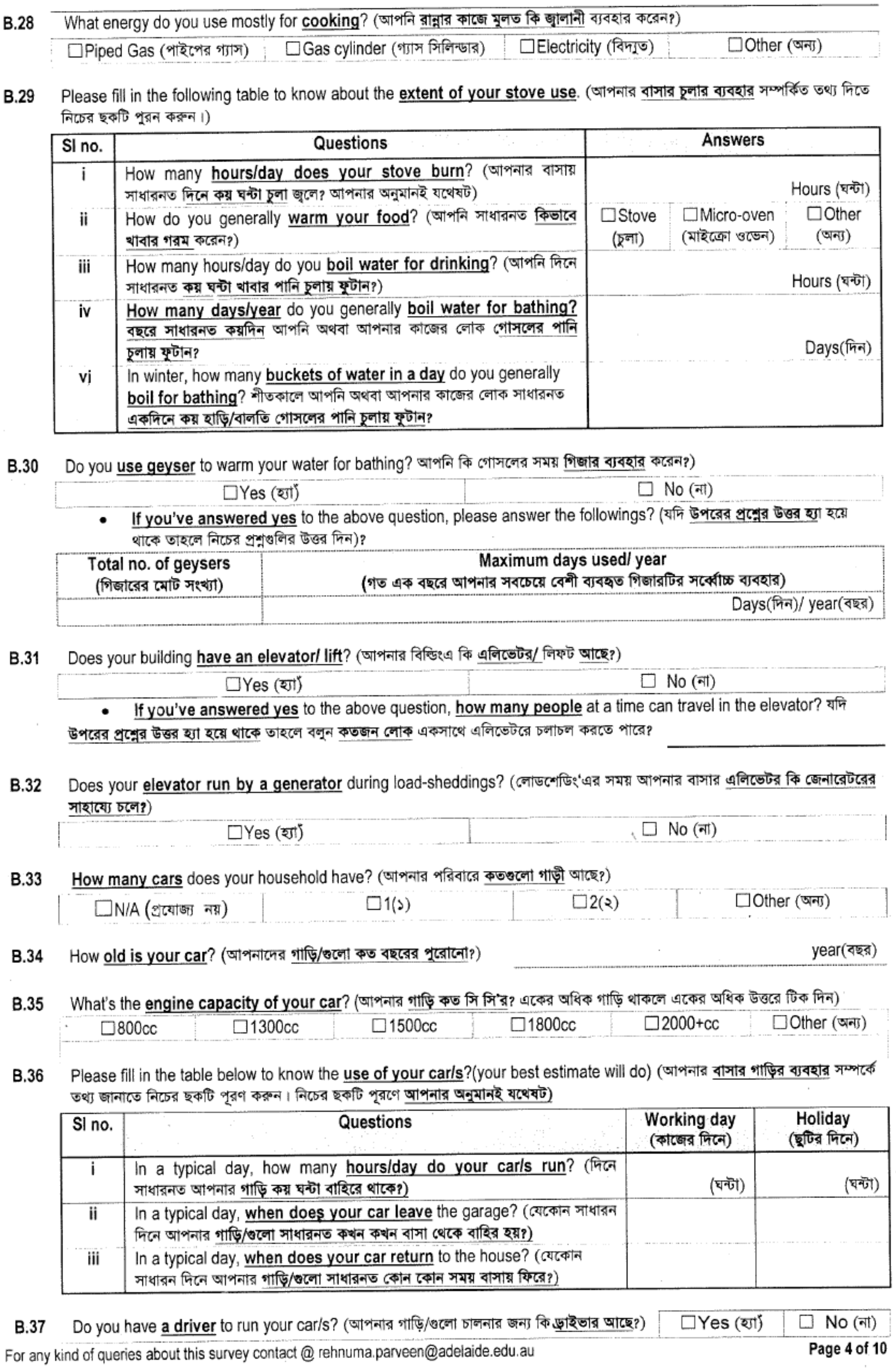
- **If you've answered yes** to the above question, please mention answer the following questions. (যদি **উপরের প্রশ্নের উত্তর হ্যা** হয়ে থাকে তাহলে তাহলে নিচের প্রশ্নগুলির উত্তর দিন)

Type of activity (কি ধরনের কাজ)	**Activity days/ week (সপ্তাহে কত দিন)**	**Hours of activity/day (দিনে কত ঘন্টা)**	**In which room (কোন রুমে)**
	Days(দিন)	Hours (ঘন্টা)	

B.26 How much **organic waste** does your household produce/ day? (আপনার বাসায় সাধারনত দিনে **কয় বালতি বর্জ্য** উৎপন্ন হয়?)

☐1 small bucket (এক ছোট বালতি)	☐1 medium bucket(এক মাঝারি বালতি)	☐1 large bucket (এক বড় বালতি)

B.27 **How many caretakers and guards** does your apartment building have? আপনার অ্যাপার্টমেন্ট বিল্ডিং'এ **কয়জন রক্ষনাবেক্ষনকারী ও দারোয়ান** আছে?



B.28 What energy do you use mostly for **cooking**? (আপনি **রান্নার কাজে মুলত কি জ্বালানী** ব্যবহার করেন?)

☐Piped Gas (পাইপের গ্যাস)	☐Gas cylinder (গ্যাস সিলিন্ডার)	☐Electricity (বিদ্যুত)	☐Other (অন্য)

B.29 Please fill in the following table to know about the **extent of your stove use**. (আপনার **বাসার চুলার ব্যবহার** সম্পর্কিত তথ্য দিতে নিচের ছকটি পুরন করুন।)

Sl no.	**Questions**	**Answers**		
i	How many **hours/day does your stove burn**? (আপনার বাসায় সাধারনত **দিনে কয় ঘন্টা চুলা** জ্বলে? আপনার অনুমানই যথেষট)			Hours (ঘন্টা)
ii	How do you generally **warm your food**? (আপনি সাধারনত **কিভাবে খাবার গরম** করেন?)	☐Stove (চুলা)	☐Micro-oven (মাইক্রো ওভেন)	☐Other (অন্য)
iii	How many hours/day do you **boil water for drinking**? (আপনি দিনে সাধারনত **কয় ঘন্টা খাবার পানি চুলায় ফুটান**?)			Hours (ঘন্টা)
iv	**How many days/year** do you generally **boil water for bathing? বছরে সাধারনত কয়দিন** আপনি অথবা আপনার কাজের লোক **গোসলের পানি চুলায় ফুটান**?			Days(দিন)
vi	In winter, how many **buckets of water in a day** do you generally **boil for bathing**? শীতকালে আপনি অথবা আপনার কাজের লোক সাধারনত **একদিনে কয় হাড়ি/বালতি গোসলের পানি চুলায় ফুটান**?			

B.30 Do you **use geyser** to warm your water for bathing? আপনি কি গোসলের সময় **গিজার ব্যবহার** করেন?)

☐Yes (হ্যা)	☐ No (না)

- **If you've answered yes** to the above question, please answer the followings? (যদি **উপরের প্রশ্নের উত্তর হ্যা** হয়ে থাকে তাহলে নিচের প্রশ্নগুলির উত্তর দিন)?

Total no. of geysers (গিজারের মোট সংখ্যা)	**Maximum days used/ year (গত এক বছরে আপনার সবচেয়ে বেশী ব্যবহৃত গিজারটির সর্ব্বোচ্চ ব্যবহার)**
	Days(দিন)/ year(বছর)

B.31 Does your building **have an elevator/ lift**? (আপনার বিল্ডিংএ কি **এলিভেটর/ লিফট আছে**?)

☐Yes (হ্যা)	☐ No (না)

- **If you've answered yes** to the above question, **how many people** at a time can travel in the elevator? যদি **উপরের প্রশ্নের উত্তর হ্যা হয়ে থাকে** তাহলে বলুন **কতজন লোক** একসাথে এলিভেটরে চলাচল করতে পারে? ____________

B.32 Does your **elevator run by a generator** during load-sheddings? (লোডশেডিং'এর সময় আপনার বাসার **এলিভেটর কি জেনারেটরের সাহায্যে চলে?**)

☐Yes (হ্যা)	☐ No (না)

B.33 **How many cars** does your household have? (আপনার পরিবারে **কতগুলো গাড়ী** আছে?)

☐N/A (প্রযোজ্য নয়)	☐1(১)	☐2(২)	☐Other (অন্য)

B.34 How **old is your car**? (আপনাদের **গাড়ি/গুলো কত বছরের পুরোনো**?) ____________ year(বছর)

B.35 What's the **engine capacity of your car**? (আপনার **গাড়ি কত সি সি'র**? একের অধিক গাড়ি থাকলে একের অধিক উত্তরে টিক দিন)

☐800cc	☐1300cc	☐1500cc	☐1800cc	☐2000+cc	☐Other (অন্য)

B.36 Please fill in the table below to know the **use of your car/s**?(your best estimate will do) (আপনার **বাসার গাড়ির ব্যবহার** সম্পর্কে তথ্য জানাতে নিচের ছকটি পূরণ করুন। নিচের ছকটি পূরণে **আপনার অনুমানই যথেষট)**

Sl no.	**Questions**	**Working day (কাজের দিনে)**	**Holiday (ছুটির দিনে)**
i	In a typical day, how many **hours/day do your car/s run**? (দিনে সাধারনত আপনার **গাড়ি কয় ঘন্টা বাহিরে থাকে?)**	(ঘন্টা)	(ঘন্টা)
ii	In a typical day, **when does your car leave** the garage? (যেকোন সাধারন দিনে আপনার **গাড়ি/গুলো সাধারনত কখন কখন বাসা থেকে বাহির হয়?)**		
iii	In a typical day, **when does your car return** to the house? (যেকোন সাধারন দিনে আপনার **গাড়ি/গুলো সাধারনত কোন কোন সময় বাসায় ফিরে?)**		

B.37 Do you have **a driver** to run your car/s? (আপনার গাড়ি/গুলো চালনার জন্য কি **ড্রাইভার আছে**?) ☐Yes (হ্যা) ☐ No (না)

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***B.38** Please fill in the table below for a detailed account of your **windows**. (আপনার বাসার বিভিন্ন ঘরের জানালা সম্পর্কে তথ্য দিতে নিচের ছকটি পুরণ করুন।)

Room Name (ঘরের নাম)	Window Type (এই ঘরে কি ধরনের জানালা আছে?)				Does this room have mosquito net? (এই ঘরের জানালায় কি মশার নেট আছে?)		In a typical hot day, how long do you keep this window open? (যেকোন গরমের দিনে এই ঘরের জানালা আপনি সাধারনত কত সময় খোলা রাখেন তা জানাতে প্রতি ঘরের পাশে নিচের যেকোন একটি উত্তরে টিক চিহ্ন দিন)					In a typical hot day, how long do you keep this curtain open? (যেকোন গরমের দিনে এই ঘরের পর্দা আপনি সাধারনত কত সময় খোলা রাখেন তা জানাতে প্রতি ঘরের পাশে নিচের যেকোন একটি উত্তরে টিক চিহ্ন দিন)				
	None (নাই)	Sliding (এলুমিনিয়াম স্লাইডিং)	Shutter-hinge (পাল্লা–কব্জা)	Other (অন্য)			Always (সবসময়)	Quite often (প্রায় সময়)	Some time (মাঝে মাঝেই)	Very little (খুব কম)	Never (কক্ষনো নয়)	Always (সবসময়)	Quite often (প্রায় সময়)	Some time (মাঝে মাঝেই)	Very little (খুব কম)	Never (কক্ষনো নয়)
Bedroom-1	☐	☐	☐	☐	☐Yes	☐No	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Dressing	☐	☐	☐	☐	☐Yes	☐No	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Bedroom- 2	☐	☐	☐	☐	☐Yes	☐No	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Bedroom-3	☐	☐	☐	☐	☐Yes	☐No	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Bedroom-4	☐	☐	☐	☐	☐Yes	☐No	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Family living	☐	☐	☐	☐	☐Yes	☐No	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Formal living	☐	☐	☐	☐	☐Yes	☐No	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Dining room	☐	☐	☐	☐	☐Yes	☐No	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Kitchen	☐	☐	☐	☐	☐Yes	☐No	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Servant's room	☐	☐	☐	☐	☐Yes	☐No	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Foyer/ Entry space	☐	☐	☐	☐	☐Yes	☐No	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐Yes	☐No	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

B.39 What **type of curtain** does your household have? (আপনার বাসার পর্দাগুলো কি কি ধরনের?)

☐Normal side curtain (সাধারন পাশে খোলা পর্দা	☐ Vertical blinds (ভার্টিকাল ব্লাইন্ড)	☐Horizontal blinds (হরাইজনটাল ব্লাইন্ড)	☐ Roll-up curtain (রোল আপ পর্দা বা বাঁশের চিক)	☐Other (অন্য)

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Section C: Energy Use _ Thermal Comfort & Artificial Lighting

*C.1 Please fill in the following table to know the **extent of fan use** in your apartment during hot summer months. **If you have two fans** in any room and one of them runs for 3 hours and the other one runs for 4 hours then for the use of fans for that room, **please write 3+4 hours.** (আপনার বাসার **গরমের দিনে ফ্যানের ব্যবহার** সম্পর্কে জানাতে নিচের ছকটি পুরন করুন। যদি কোন **ঘরে ২টি ফ্যান থাকে এবং তার একটি দিনে ৩ ঘন্টা এবং অন্যটি ৪ঘন্টা চলে তবে ঐঘরের জন্য ফ্যানের ব্যবহার ৩+৪ ঘন্টা লিখুন।**)

Room Name (ঘরের নাম)	**How many fans does this room have?** (এই ঘরে **কতগুলো ফ্যান** আছে? আপনার বাসার প্রতিটি ঘরের ফ্যানের জন্য নিচের ছক থেকে যেকোন **উত্তরে টিকচিহ্ন দিন**)				**What type of fan does this room have?** (এই ঘরে কি **ধরনের ফ্যান** আছে। আপনার বাসার প্রতিটি ঘরের ফ্যানের জন্য নিচের ছক থেকে যেকোন **উত্তরে টিকচিহ্ন দিন**)				**Maximum hours used/ day in a typical hot summer day.** (যেকোন গরমের দিনে প্রতিটি ঘরের জন্য আলাদা করে **ঐঘরের সব ফ্যানের সর্বোচ্চ ব্যবহার** নিচে লিখুন, **আপনার অনুমানই যথেষ্ট**)	
	None (নাই)	1(১)	2(২)	Other (অন্য)	Ceiling Fan (সিলিং ফ্যান)	Wall-mounted Fan (দেয়ালে ঝোলানো)	Pedestal Fan (পেডেস্টাল ফ্যান)	Table Fan (টেবিল ফ্যান)	Working day (কাজের দিনে) Hours/day (ঘন্টা/দিন)	Holiday (ছুটির দিনে) Hours/day (ঘন্টা/দিন)
Bedroom 1	☐	☐	☐	☐	☐	☐	☐	☐		
Dressing	☐	☐	☐	☐	☐	☐	☐	☐		
Bedroom 2	☐	☐	☐	☐	☐	☐	☐	☐		
Bedroom 3	☐	☐	☐	☐	☐	☐	☐	☐		
Bedroom 4	☐	☐	☐	☐	☐	☐	☐	☐		
Family living	☐	☐	☐	☐	☐	☐	☐	☐		
Formal living	☐	☐	☐	☐	☐	☐	☐	☐		
Dinning	☐	☐	☐	☐	☐	☐	☐	☐		
Kitchen	☐	☐	☐	☐	☐	☐	☐	☐		
Servant's room	☐	☐	☐	☐	☐	☐	☐	☐		
Foyer	☐	☐	☐	☐	☐	☐	☐	☐		
Other	☐	☐	☐	☐	☐	☐	☐	☐		

*C.2 Please fill in the following table to know the **extent of AC use** in your apartment during hot summer months. **If you have two ACs** in any room and one of them runs for 5 hours and the other one runs for 3 hours then for the use of ACs for that room, **please write 5+3 hours.** (আপনার বাসার **গরমের দিনে এসি ব্যবহার** সম্পর্কে জানাতে নিচের ছকটি পুরন করুন।যদি কোন **ঘরে ২টি এসি থাকে এবং তার একটি দিনে ৫ ঘন্টা এবং অন্যটি ৩ঘন্টা চলে তবে ঐঘরের জন্য ফ্যানের ব্যবহার ৫+৩ ঘন্টা লিখুন।**)

Room Name (ঘরের নাম)	**How many AC does this room have?** (এই ঘরে **কতগুলো এসি** আছে? আপনার বাসার প্রতিটি ঘরের এসির জন্য নিচের ছকে যেকোন একটি **উত্তরে টিকচিহ্ন দিন**)			**What type of AC does this room have?** (এই ঘরে কি **ধরনের এসি** আছে। আপনার বাসার প্রতিটি এসির জন্য নিচের ছকে যেকোন একটি **উত্তরে টিকচিহ্ন দিন**)			What's the **capacity of your AC's** (if known) (**আপনার এসি কত টনের?** আপনার বাসার প্রতিটি এসির জন্য নিচের ছকে যেকোন একটি উত্তরে টিকচিহ্ন দিন))				**How old is your AC?** (আপনার এই ঘরে র এসি'র বয়স কত?)	**Maximum hours used/ day in a typical hot summer day** (যেকোন গরমের দিনে প্রতিটি ঘরের জন্য আলাদা করে **ঐঘরের সব এসির সর্বোচ্চ ব্যবহার** নিচে লিখুন, **আপনার অনুমানই যথেষ্ট**)	
	None (নাই)	1(১)	2(২)	Window (উইন্ডো)	Split (স্প্লিট)	Other (অন্য)	1 ton (১ টন)	1.5 ton (দেড় টন)	2 ton (২ টন)	Other (অন্য)	year(বছর)	Working day (কাজের দিনে) Hours/day (ঘন্টা/দিন)	Holiday (ছুটির দিনে) Hours/day (ঘন্টা/দিন)
Bedroom 1	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐			
Bedroom 2	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐			
Bedroom 3	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐			
Bedroom 4	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐			
Family living	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐			
Formal living	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐			
Dinning	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐			
Foyer	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐			
Other	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐			

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C.3 At **what temperature** do you usually set **your AC**? (আপনার **এসি'র তাপমাত্রা** সাধারনত কত ডিগ্রীতে সেট করা থাকে?)

☐Below 24°C (২৪°সে.এর নীচে) ☐Above 24°C(২৪°সে.এর উপরে) ☐N/A (প্রযোজ্য নয়)

***C.4** Please fill in the following table to know about the **artificial lighting use** in your apartment. (Please include both fixed & portable bulbs)(আপনার বাসায় **বৈদ্যুতিক বাতি ব্যবহার** সম্পর্কে জানাতে নিচের ছকটি পূরণ করুন। স্থায়ী এবং বহনযোগ্য (যেমন টেবিল ল্যাম্প)উভয়ধরনের বাতিই গননায় ধরুন।)

Room Name (ঘরের নাম)	How many following bulbs do you have in each room? In a typical day, **how many hours / day are all the bulbs used in each room?** For example, if you have 2 energy bulbs in your bedroom & one of them is used for 3hours & the other one is used for 2hours then the total use of energy bulbs for that room will be 2+3 hours in total. **Your best estimate will do.** (আপনার বাসায় **প্রতিটি ঘরে কোন জাতীয় বাতি কতটি** আছে তার সর্বমোট সংখ্যা নিচে প্রতিটি ঘরের পাশে লিখুন। যেকোন সাধারন দিনে প্রতিটি ঘরের সবগুলো **বাতি সর্বোচ্চ কয় ঘন্টা জ্বলে**? যদি কোন **ঘরে ২টি এনার্জি বাল্ব থাকে এবং তার একটি দিনে ৩ ঘন্টা এবং অন্যটি ২ঘন্টা জ্বলে তবে ঐঘরের এনার্জি বাল্বের সর্বমোট ব্যবহার ২+৩ ঘন্টা** লিখুন । এভাবে প্রতিটি ঘরের জন্য আলাদা কওে ঐঘরের সব বাতির সর্বোচ্চ ব্যবহার লিখুন। **আপনার শ্রেষ্ঠ অনুমানই যথেষট**)									
	Incandescent-bulb (সাধারন হলুদ বাতি)		**Energy bulb** (এনার্জিবাল্ব)		**Tube light** (টিউব লাইট)		**Spot light** (স্পট লাইট)		**Other** (অন্য কোন ধরনের বাতি)	
	Total no. (মোট সংখ্যা)	**Hours/ day** মোট ব্যবহার (ঘন্টা/দিন)	Total no. (মোট সংখ্যা)	Hours/day মোট ব্যবহার (ঘন্টা/দিন)	Total no. (মোট সংখ্যা)	Hours/day মোট ব্যবহার (ঘন্টা/দিন)	Total no. (মোট সংখ্যা)	Hours/day মোট ব্যবহার (ঘন্টা/দিন)	Total no. (মোট সংখ্যা)	Hours/ day মোট ব্যবহার (ঘন্টা/দিন)
Bedroom 1										
Dressing										
Toilet 1										
Bedroom 2										
Toilet 2										
Bedroom 3										
Toilet 3										
Bedroom 4										
Toilet 4										
Family living										
Formal living										
Dinning										
Kitchen										
Servant's room										
Servant's toilet										
Foyer										
Other										

C.5 How long do the **lights of your stair case** usually remain on? (আপনার বিল্ডিং'এর **সিঁড়িঘরের বাতি** সাধারনত কতক্ষন জ্বলে?)

☐Whole night (সারা রাত) ☐Until 11 or12 at night (রাত এগারো বা বারোটা পর্যন্ত) ☐Other (অন্য)

C.6 How long do the **lights of your garage** usually remain on?(আপনার বিল্ডিং'এর গ্যারেজের**বাতি** সাধারনত কতক্ষন জ্বলে?)

☐Whole night (সারা রাত) ☐Until 11 or12 at night (রাত এগারো বা বারোটা পর্যন্ত) ☐Other (অন্য)

***C.7** We would like to know how much **electricity you actually consumed** in the past year. Please fill in the following table. (গত এক বছরে আপনার **বিদ্যুত ব্যবহার** এবং **বিল** জানাতে নিচের ছকটি পূরন করুন। সব মাসের বিল না থাকলে যে কয় মাসের বিল আছে তাই লিখুন।)

Electricity consumption (বিদ্যুত ব্যবহার)	**Jan'13**	**Feb'13**	**Mar'13**	**Apr'13**	**May'13**	**Jun'13**	**Jul'13**	**Aug' 12/13**	**Sep'12**	**Oct'12**	**Nov'12**	**Dec'12**
Unit(**KWH**)												
Bill (বিদ্যুতবিল,৳)												

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C.8 Do you use room **heaters** during winter?(আপনি কি **শীতকালে হিটার** ব্যবহার করেন?)

☐Yes (হ্যাঁ) ☐ No (না)

- **If you've answered yes** to the above question, please answer the followings? (**যদি উপরের প্রশ্নের উত্তর হ্যা** হয়ে থাকে তাহলে নিচের প্রশ্নগুলির উত্তর দিন)?

Total no. of heaters (হিটারের মোট সংখ্যা)	Maximum days used/year. (গত বছর আপনার সবচেয়ে বেশী ব্যবহৃত হিটারটি সর্ব্বোচ্চ কতদিন ব্যবহৃত?)	Maximum hours used in the coldest day of last winter (গতশীতে সবচেয়ে ঠান্ডার দিনে আপনার সবচেয়ে বেশী ব্যবহৃত হিটারটি সর্বোচ্চ কয়ঘন্টা ব্যবহৃত)
	Days(দিন)	ঘন্টা / দিন

Section D: Energy Use_ Others

D.1 Please fill in the following table for **Refrigerator, Deep freeze**, **Washing machine & dryer record.** (আপনার বাসার **ফ্রিজ, ডিপ ফ্রিজ, কাপড় ধোয়া ও শুকানোর যন্ত্র** সম্পর্কে জানাতে নিচের ছকটি পূরণ করুন।)

Item name (নাম)	How many of this Item do you have? (কতগুলো আছে? নিচের যেকোন একটি উত্তরে টিক চিহ্ন দিন)				What's the capacity of this item? (যন্ত্রটি কত বড়?)	How old is your item? (যন্ত্রটি কত পুরানো?)	Times used /week (সপ্তাহে কয়বার ব্যবহৃত হয়)
	None(নাই)	1(১)	2(২)	Other(অন্য)			
Refrigerator (ফ্রিজ)	☐	☐	☐	☐	Cft/ ltr	year(বছর)	--
Deep freeze (ডিপ ফ্রিজ)	☐	☐	☐	☐	Cft/ ltr	year(বছর)	--
Washing machine (কাপড় ধোয়া যন্ত্র)	☐	☐	☐	☐	kg(কেজি)	year(বছর)	
Dryer কাপড় (শুকানোর যন্ত্র)	☐	☐	☐	☐	kg(কেজি)	year(বছর)	

D.2 Please fill in the following table to know if you use the **following appliances** at your apartment? (আপনার বাসায় কি কি **বৈদ্যুতিক সরঞ্জামাদি ব্যবহার** হয় তা সম্পর্কে জানাতে নিচের ছকটি পুরন করুন।)

Sl no	Item name (নাম)	Do you use this item? (আপনি কি ইহা ব্যবহার করেন?)		Item name (নাম)	Do you use this item? (আপনি কি ইহা ব্যবহার করেন?)	
1	Electric stove (বৈদ্যুতিক চুলা)	☐Yes (হ্যাঁ)	☐ No (না)	Vacuum cleaner (ভ্যাকুয়াম ক্লিনার)	☐Yes (হ্যাঁ)	☐ No (না)
2	Electric Oven (ওভেন)	☐Yes (হ্যাঁ)	☐ No (না)	Hair Dryer (হেয়ার ড্রাইয়ার)	☐Yes (হ্যাঁ)	☐ No (না)
3	Micro oven (মাইক্রো-ওভেন)	☐Yes (হ্যাঁ)	☐ No (না)	Home-theatre (হোম থিয়েটার)	☐Yes (হ্যাঁ)	☐ No (না)
4	Dish washer (ডিশ ওয়াশার)	☐Yes (হ্যাঁ)	☐ No (না)	Projector (প্রজেক্টার)	☐Yes (হ্যাঁ)	☐ No(না)
5	Cordless Telephone (কর্ডলেস ফোন)	☐Yes (হ্যাঁ)	☐ No (না)	Rice cooker (রাইস কুকার)	☐Yes (হ্যাঁ)	☐ No (না)
6	Toaster (টোস্টার)	☐Yes (হ্যাঁ)	☐ No (না)	Printer (প্রিন্টার)	☐Yes (হ্যাঁ)	☐ No (না)
7	Sandwich maker (স্যান্ডউইচ মেকার)	☐Yes (হ্যাঁ)	☐ No (না)	Scanner (স্ক্যানার)	☐Yes (হ্যাঁ)	☐ No (না)
8	Juicer-mixer-grinder/blender (জুসার-ব্লেনডার)	☐Yes (হ্যাঁ)	☐ No (না)	Fax Machine (ফ্যাক্স মেশিন)	☐Yes (হ্যাঁ)	☐ No (না)
9	Iron(ইস্ত্রি)	☐Yes (হ্যাঁ)	☐ No (না)	Other(অন্য)	☐Yes (হ্যাঁ)	☐ No (না)

D.3 How many **mobile phones & tabs** do you charge everyday? (প্রতিদিন আপনার বাসায় **কতগুলো মোবাইল ফোন এবং ট্যাব রিচার্জ** হয়?) ____

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D.4 Do you also **switch-off the electric plug points** after using the following electric appliances? (আপনি নিচের সরঞ্জামাদিগুলো ব্যবহারের পর কি সাধারনত **বৈদ্যুতিক প্লাগ পয়েন্টের সুইচ বন্ধ করেন?**)

Item name (নাম)	☐Yes (হ্যাঁ)	☐ No, use remote control only (না, শুধু রিমোট কন্ট্রোল ব্যবহার করি)	Item name (নাম)	☐Yes (হ্যাঁ)	☐ No(না)
TV টিভি	☐	☐	Computer (কম্পিউটার)	☐	☐
AC (এসি)	☐	☐	Scanner/Printer (স্ক্যানার/ প্রিন্টার)	☐	☐
DVD player(ডিভিডি প্লেয়ার)	☐	☐	Micro oven (মাইক্রো–ওভেন)	☐	☐

D.5 Please fill in the following table to know about the use of your television **& personal computers**.(আপনার বাসার **টেলিভিশন ও কম্পিউটার ব্যবহার** সম্পর্কে জানাতে নিচের ছকটি পূরণ করুন।)

Sl no.	Item name (নাম)	How many of this item do you have? (কতগুলো আছে?)	Size of the screen/ monitor (মনিটর/স্ক্রিন কত বড়?)	How many hours/day do you use this item? (দিনে সর্বোচ্চ কত ঘন্টা ব্যবহৃত হয়)	In which room do you use this item? (কোন কোন ঘরে ব্যবহৃত হয়)
1	Traditional TV (সাধারন টিভি)		"(ইঞ্চি)	hours (ঘন্টা)	
2	LCD/LED TV (এল সি ডি টিভি)		"(ইঞ্চি)	hours (ঘন্টা)	
3	Flat screen TV (ফ্ল্যাট স্ক্রিন টিভি)		"(ইঞ্চি)	hours (ঘন্টা)	
4	Plasma TV (প্লাজমা টিভি)		"(ইঞ্চি)	hours (ঘন্টা)	
5	Computers (both desktop & laptop) (কম্পিউটার: ডেস্কটপ ও ল্যাপটপ উভয় মিলিয়ে)		"(ইঞ্চি)	hours (ঘন্টা)	

D.6 How often do you use your **kitchen hood/ exhaust fan**? Please tick an answer.(আপনি রান্নাঘরের **কিচেন হুড অথবা এক্সহস্ট ফ্যান** কখন কখন ব্যবহার করেন? নিচের যেকোন একটি উত্তরে টিক চিহ্ন দিন)

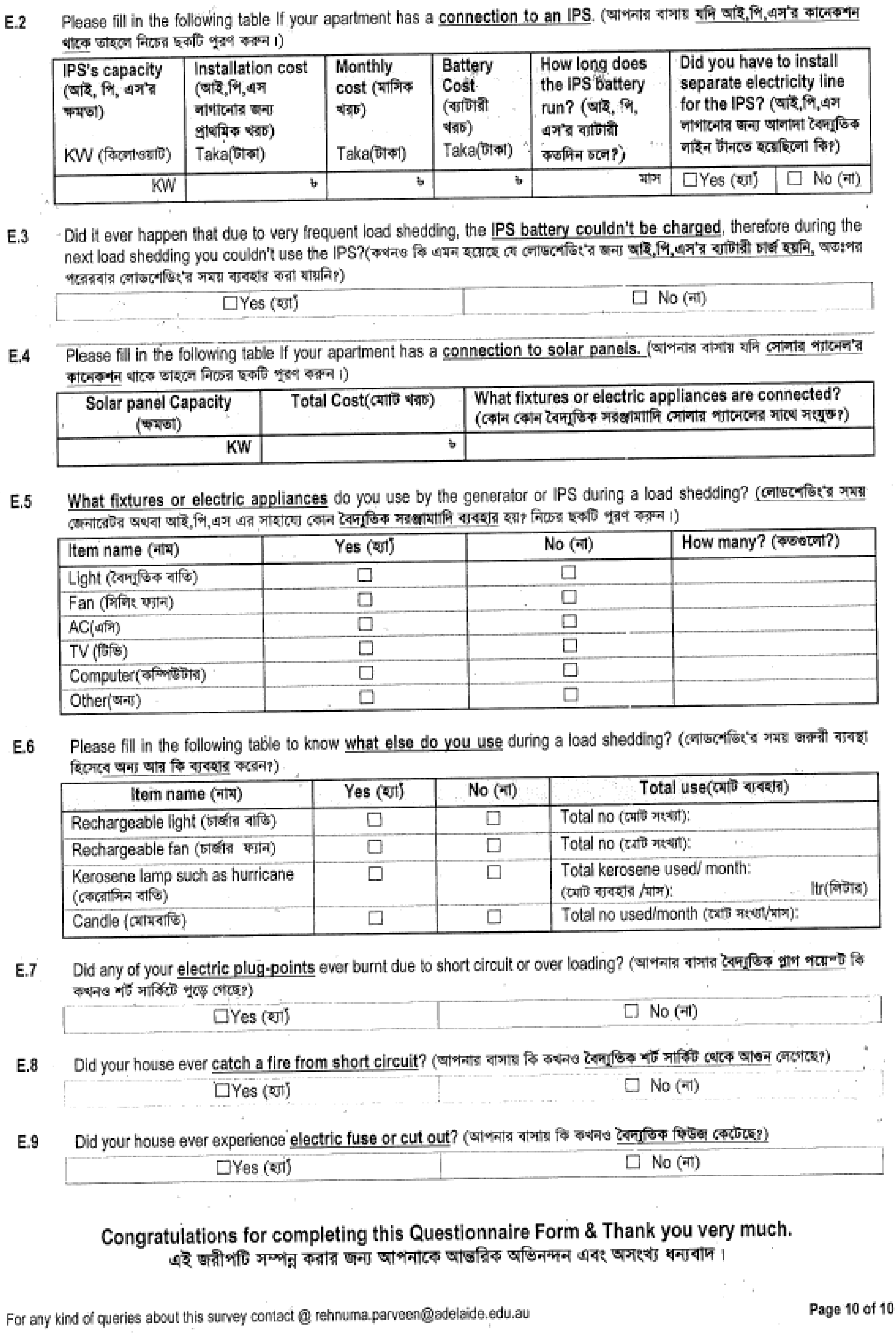
☐ Whenever the stove is on for any reason such as cooking or boiling water. (যখনই চুলা জ্বলে যেমন রান্না করা অথবা পানি গরম করা)	☐ Only during cooking. (সবসময় রান্না করার সময়)	☐ Some times during cooking (মাঝে মাঝে রান্নার সময়)	☐ Not at all (কক্ষনো নয়)

D.7 How many hours/day does the **water pump** of your building run to pump water? (if known) (যদি জানা থাকে তাহলে বলুন দিনে **কত ঘন্টা আপনার বিল্ডিং'র পানির পাম্প** চলে?) ________ hours (ঘন্টা)

Section E: Emergency Power Supply

E.1 Please fill in the following table If your apartment has a **connection to a generator**. (আপনার বাসায় **যদি জেনারেটর'র কানেকশন থাকে** তাহলে নিচের ছকটি পুরণ করুন।)

Generator's capacity (জেনারেটর'র ক্ষমতা) KV (কেভি)	Which fuel does your generator use? (জেনারেটরে কি জ্বালানী ব্যবহৃত হয়?)	How much fuel/ month does it consume? (প্রতি মাসে সাধারনত কত লিটার জ্বালানী ব্যবহৃত হয়?)	Monthly cost (মাসিক খরচ)		Does your generator support the elevator? (এলিভেটর কি লোডশেডিং'র সময় জেনারেটর'র সাহায্যে চলে?)
			For fuel (জ্বালানী বাবদ) Taka(টাকা)	For maintenance (রক্ষণাবেক্ষন বাবদ) Taka(টাকা)	
KV	☐ Diesel (ডিজেল)	ltr (লিটার)	৳	৳	
	☐ Petrol(পেট্রোল)				☐Yes (হ্যাঁ)
	☐ Gas (গ্যাস)				☐ No (না)
	☐ Other(অন্য)				



E.2 Please fill in the following table If your apartment has a connection to an IPS. (আপনার বাসায় যদি আই,পি,এস'র কানেকশন থাকে তাহলে নিচের ছকটি পুরণ করুন।)

IPS's capacity (আই, পি, এস'র ক্ষমতা) KW (কিলোওয়াট)	Installation cost (আই,পি,এস লাগানোর জন্য প্রাথমিক খরচ) Taka(টাকা)	Monthly cost (মাসিক খরচ) Taka(টাকা)	Battery Cost (ব্যাটারী খরচ) Taka(টাকা)	How long does the IPS battery run? (আই, পি, এস'র ব্যাটারী কতদিন চলে?)	Did you have to install separate electricity line for the IPS? (আই,পি,এস লাগানোর জন্য আলাদা বৈদ্যুতিক লাইন টানতে হয়েছিলো কি?)	
KW	৳	৳	৳	মাস	☐Yes (হ্যাঁ)	☐ No (না)

E.3 Did it ever happen that due to very frequent load shedding, the IPS battery couldn't be charged, therefore during the next load shedding you couldn't use the IPS?(কখনও কি এমন হয়েছে যে লোডশেডিং'র জন্য আই,পি,এস'র ব্যাটারী চার্জ হয়নি, অতঃপর পরেরবার লোডশেডিং'র সময় ব্যবহার করা যায়নি?)

☐Yes (হ্যাঁ)	☐ No (না)

E.4 Please fill in the following table If your apartment has a connection to solar panels. (আপনার বাসায় যদি সোলার প্যানেল'র কানেকশন থাকে তাহলে নিচের ছকটি পুরণ করুন।)

Solar panel Capacity (ক্ষমতা)	Total Cost(মোট খরচ)	What fixtures or electric appliances are connected? (কোন কোন বৈদ্যুতিক সরঞ্জামাদি সোলার প্যানেলের সাথে সংযুক্ত?)
KW	৳	

E.5 What fixtures or electric appliances do you use by the generator or IPS during a load shedding? (লোডশেডিং'র সময় জেনারেটর অথবা আই,পি,এস এর সাহায্যে কোন বৈদ্যুতিক সরঞ্জামাদি ব্যবহার হয়? নিচের ছকটি পুরণ করুন।)

Item name (নাম)	Yes (হ্যাঁ)	No (না)	How many? (কতগুলো?)
Light (বৈদ্যুতিক বাতি)	☐	☐	
Fan (সিলিং ফ্যান)	☐	☐	
AC(এসি)	☐	☐	
TV (টিভি)	☐	☐	
Computer(কম্পিউটার)	☐	☐	
Other(অন্য)	☐	☐	

E.6 Please fill in the following table to know what else do you use during a load shedding? (লোডশেডিং'র সময় জরুরী ব্যবস্থা হিসেবে অন্য আর কি ব্যবহার করেন?)

Item name (নাম)	Yes (হ্যাঁ)	No (না)	Total use(মোট ব্যবহার)
Rechargeable light (চার্জার বাতি)	☐	☐	Total no (মোট সংখ্যা):
Rechargeable fan (চার্জার ফ্যান)	☐	☐	Total no (মোট সংখ্যা):
Kerosene lamp such as hurricane (কেরোসিন বাতি)	☐	☐	Total kerosene used/ month: (মোট ব্যবহার /মাস): ltr(লিটার)
Candle (মোমবাতি)	☐	☐	Total no used/month (মোট সংখ্যা/মাস):

E.7 Did any of your electric plug-points ever burnt due to short circuit or over loading? (আপনার বাসার বৈদ্যুতিক প্লাগ পয়েন্ট কি কখনও শর্ট সার্কিটে পুড়ে গেছে?)

☐Yes (হ্যাঁ)	☐ No (না)

E.8 Did your house ever catch a fire from short circuit? (আপনার বাসায় কি কখনও বৈদ্যুতিক শর্ট সার্কিট থেকে আগুন লেগেছে?)

☐Yes (হ্যাঁ)	☐ No (না)

E.9 Did your house ever experience electric fuse or cut out? (আপনার বাসায় কি কখনও বৈদ্যুতিক ফিউজ কেটেছে?)

☐Yes (হ্যাঁ)	☐ No (না)

Congratulations for completing this Questionnaire Form & Thank you very much.
এই জরীপটি সম্পন্ন করার জন্য আপনাকে আন্তরিক অভিনন্দন এবং অসংখ্য ধন্যবাদ।

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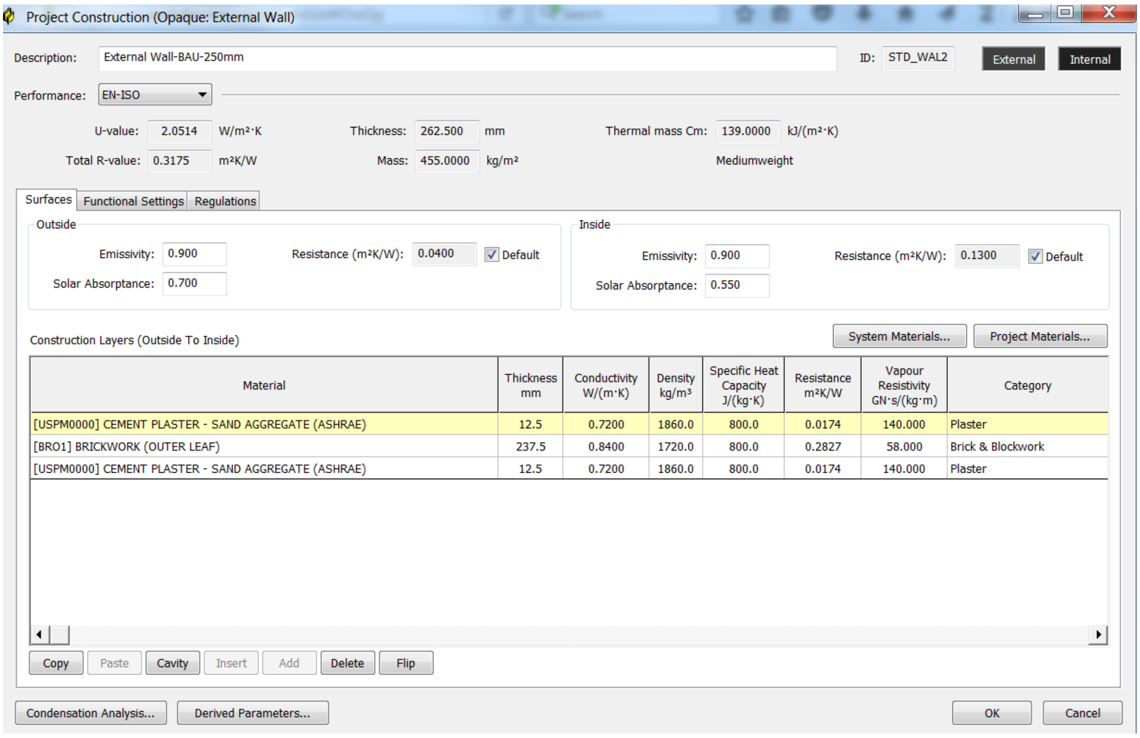
Appendix F.2: CV (RMSE) Calculation for kWh Calibration

#	Month	Actual Consumption	Simulated	Simulated- Actual	(Simulated- Actual)^2
1	**Jan**	446	433.9	-12.1	146.41
2	**Feb**	418	395.2	-22.8	519.84
3	**Mar**	503	596.7	93.7	8779.69
4	**Apr**	743	758.4	15.4	237.16
5	**May**	625	674.7	49.7	2470.09
6	**Jun**	813	784.7	-28.3	800.89
7	**Jul**	823	831.6	8.6	73.96
8	**Aug**	801	751.7	-49.3	2430.49
9	**Sep**	678	740.6	62.6	3918.76
10	**Oct**	646	606.9	-39.1	1528.81
11	**Nov**	477	426.2	-50.8	2580.64
12	**Dec**	396	433.9	37.9	1436.41
Total number (n)		12		Total Sum	24923.15
Average Measurement -->		614.0833333		Total Sum/n	2076.929167
				RMSE	45.57333833
				CV(RMSE)	7.421360564

Appendix F.3: Input Data (External Wall, Glazing and Window Operation)-BaU and Best Practice Scenario



Description: External Wall-BAU-250mm
ID: STD_WAL2
Performance: EN-ISO
U-value: 2.0514 W/m²·K
Thickness: 262.500 mm
Thermal mass Cm: 139.0000 kJ/(m²·K)
Total R-value: 0.3175 m²K/W
Mass: 455.0000 kg/m²
Mediumweight

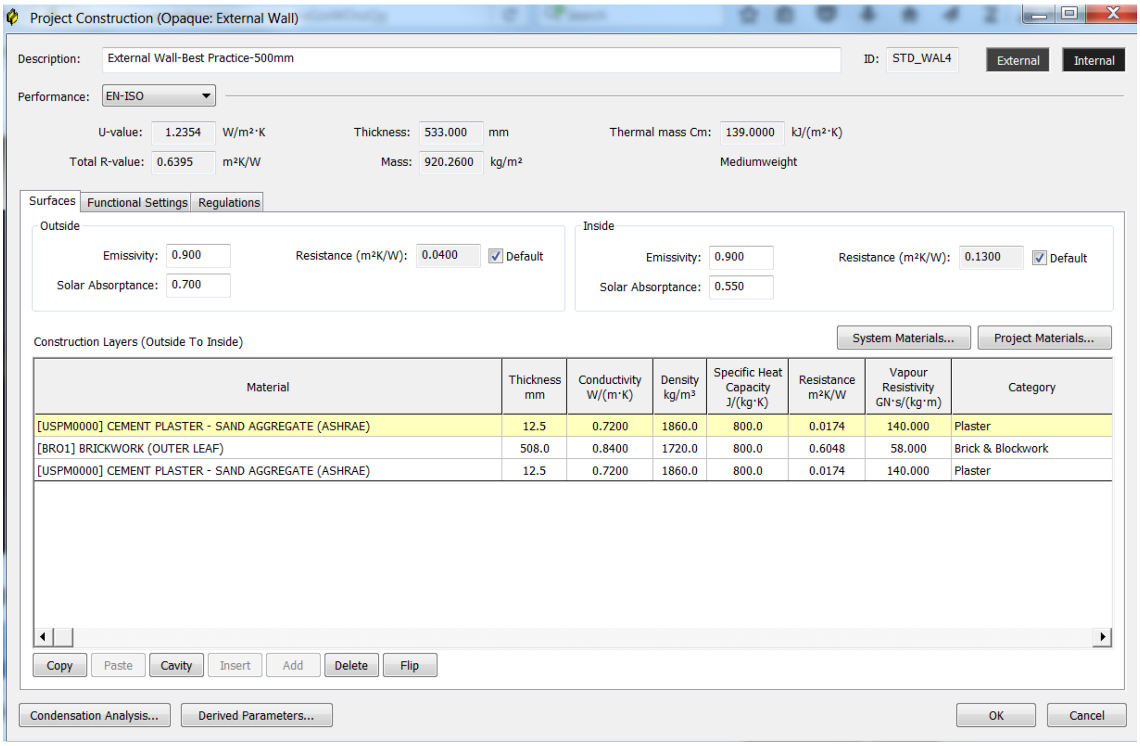
Outside
Emissivity: 0.900
Resistance (m²K/W): 0.0400 ☑ Default
Solar Absorptance: 0.700

Inside
Emissivity: 0.900
Resistance (m²K/W): 0.1300 ☑ Default
Solar Absorptance: 0.550

Construction Layers (Outside To Inside)

Material	Thickness mm	Conductivity W/(m·K)	Density kg/m³	Specific Heat Capacity J/(kg·K)	Resistance m²K/W	Vapour Resistivity GN·s/(kg·m)	Category
[USPM0000] CEMENT PLASTER - SAND AGGREGATE (ASHRAE)	12.5	0.7200	1860.0	800.0	0.0174	140.000	Plaster
[BRO1] BRICKWORK (OUTER LEAF)	237.5	0.8400	1720.0	800.0	0.2827	58.000	Brick & Blockwork
[USPM0000] CEMENT PLASTER - SAND AGGREGATE (ASHRAE)	12.5	0.7200	1860.0	800.0	0.0174	140.000	Plaster

Figure A.11: External Wall Construction Layer_ BaU Scenario



Description: External Wall-Best Practice-500mm
ID: STD_WAL4
Performance: EN-ISO

U-value: 1.2354 W/m²·K
Thickness: 533.000 mm
Thermal mass Cm: 139.0000 kJ/(m²·K)
Total R-value: 0.6395 m²K/W
Mass: 920.2600 kg/m²
Mediumweight

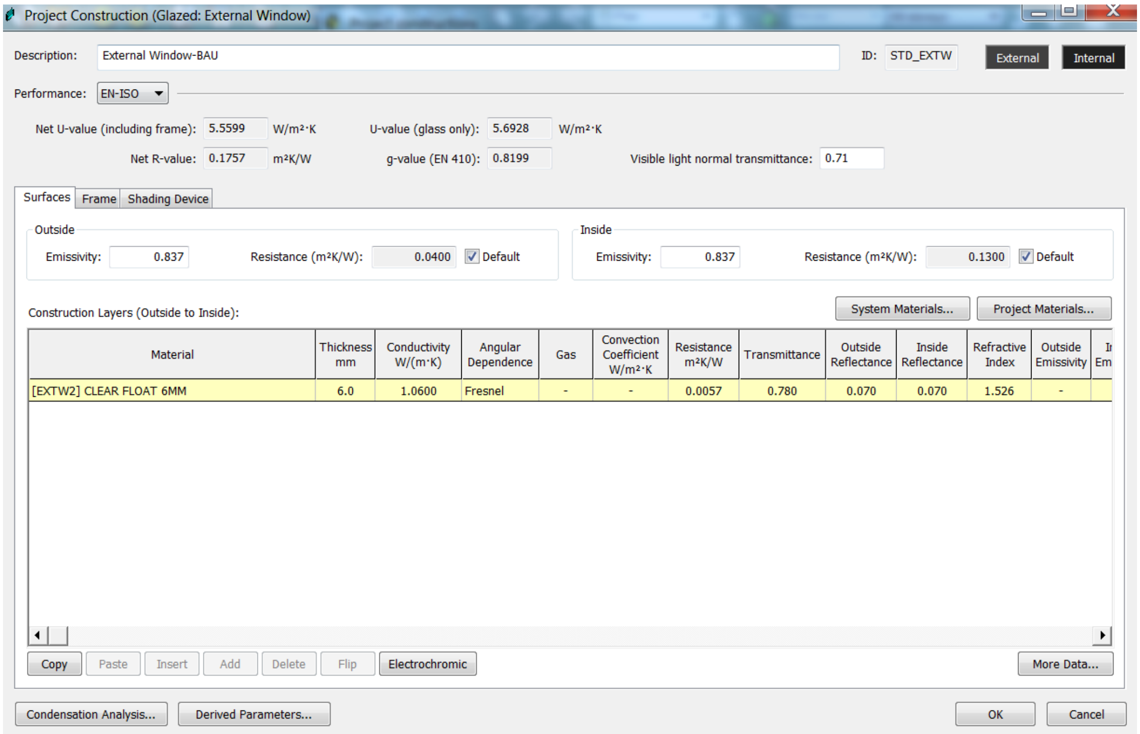
Outside
Emissivity: 0.900
Resistance (m²K/W): 0.0400 ☑ Default
Solar Absorptance: 0.700

Inside
Emissivity: 0.900
Resistance (m²K/W): 0.1300 ☑ Default
Solar Absorptance: 0.550

Construction Layers (Outside To Inside)

Material	Thickness mm	Conductivity W/(m·K)	Density kg/m³	Specific Heat Capacity J/(kg·K)	Resistance m²K/W	Vapour Resistivity GN·s/(kg·m)	Category
[USPM0000] CEMENT PLASTER - SAND AGGREGATE (ASHRAE)	12.5	0.7200	1860.0	800.0	0.0174	140.000	Plaster
[BRO1] BRICKWORK (OUTER LEAF)	508.0	0.8400	1720.0	800.0	0.6048	58.000	Brick & Blockwork
[USPM0000] CEMENT PLASTER - SAND AGGREGATE (ASHRAE)	12.5	0.7200	1860.0	800.0	0.0174	140.000	Plaster

Figure A.12: External Wall Construction Layer_ Best Practice Scenario



Description: External Window-BAU
ID: STD_EXTW
Performance: EN-ISO

Net U-value (including frame): 5.5599 W/m²·K
U-value (glass only): 5.6928 W/m²·K
Net R-value: 0.1757 m²K/W
g-value (EN 410): 0.8199
Visible light normal transmittance: 0.71

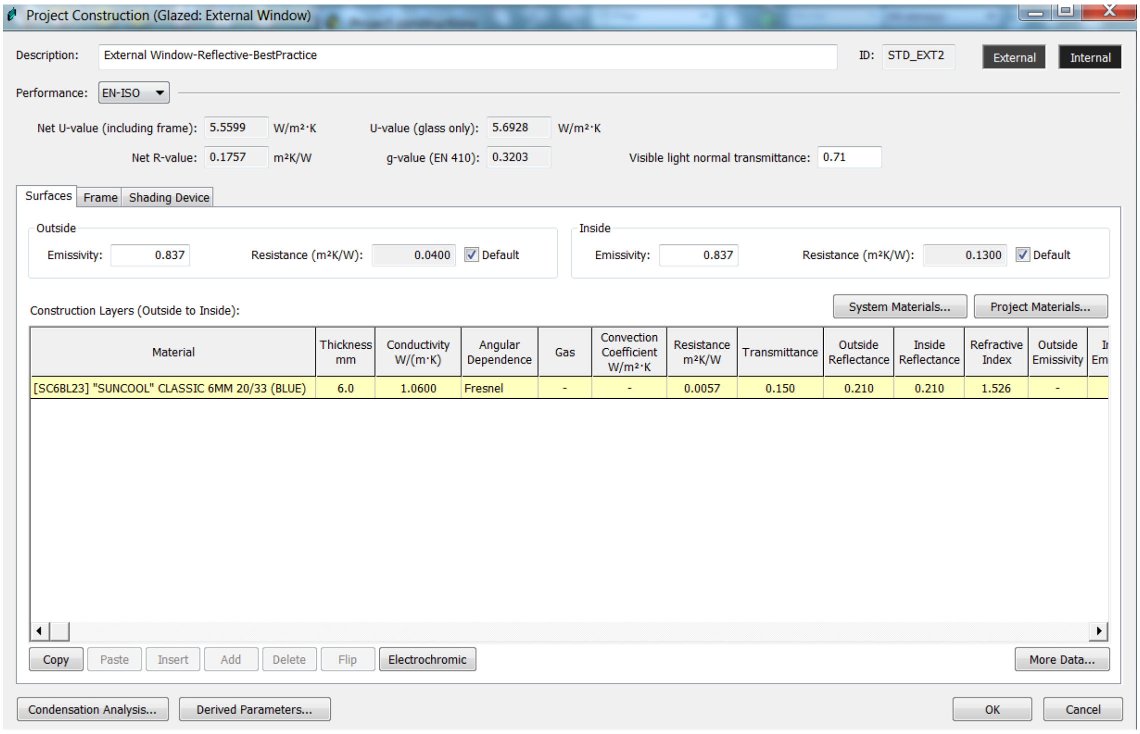
Outside
Emissivity: 0.837
Resistance (m²K/W): 0.0400 ☑ Default

Inside
Emissivity: 0.837
Resistance (m²K/W): 0.1300 ☑ Default

Construction Layers (Outside to Inside):

Material	Thickness mm	Conductivity W/(m·K)	Angular Dependence	Gas	Convection Coefficient W/m²·K	Resistance m²K/W	Transmittance	Outside Reflectance	Inside Reflectance	Refractive Index	Outside Emissivity	In Em
[EXTW2] CLEAR FLOAT 6MM	6.0	1.0600	Fresnel	-	-	0.0057	0.780	0.070	0.070	1.526	-	

Figure A.13: External Window Construction Layer_ BaU Scenario



Description: External Window-Reflective-BestPractice
ID: STD_EXT2
Performance: EN-ISO
Net U-value (including frame): 5.5599 W/m²·K
U-value (glass only): 5.6928 W/m²·K
Net R-value: 0.1757 m²K/W
g-value (EN 410): 0.3203
Visible light normal transmittance: 0.71

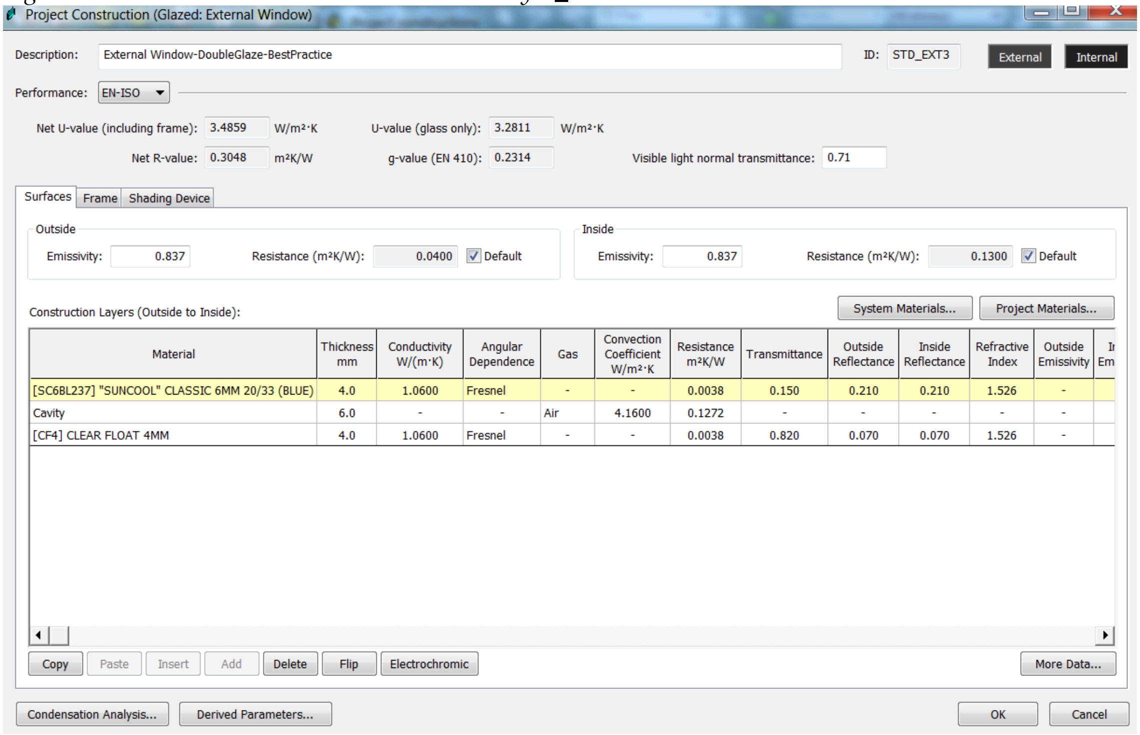
Outside
Emissivity: 0.837
Resistance (m²K/W): 0.0400 ☑ Default

Inside
Emissivity: 0.837
Resistance (m²K/W): 0.1300 ☑ Default

Construction Layers (Outside to Inside):

Material	Thickness mm	Conductivity W/(m·K)	Angular Dependence	Gas	Convection Coefficient W/m²·K	Resistance m²K/W	Transmittance	Outside Reflectance	Inside Reflectance	Refractive Index	Outside Emissivity	Ir Em
[SC6BL23] "SUNCOOL" CLASSIC 6MM 20/33 (BLUE)	6.0	1.0600	Fresnel	-	-	0.0057	0.150	0.210	0.210	1.526	-	

Figure A.14: External Window Construction Layer_ Best Practice Scenario 1



Description: External Window-DoubleGlaze-BestPractice
ID: STD_EXT3
Performance: EN-ISO
Net U-value (including frame): 3.4859 W/m²·K
U-value (glass only): 3.2811 W/m²·K
Net R-value: 0.3048 m²K/W
g-value (EN 410): 0.2314
Visible light normal transmittance: 0.71

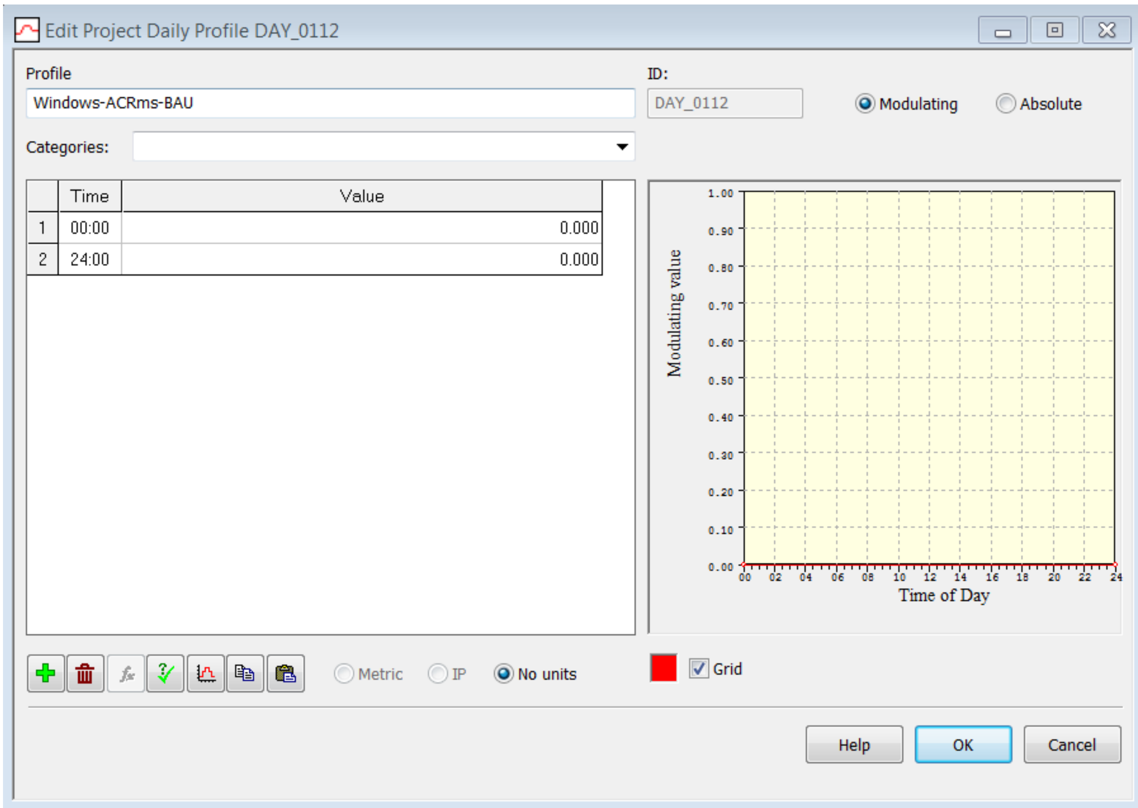
Outside
Emissivity: 0.837
Resistance (m²K/W): 0.0400 ☑ Default

Inside
Emissivity: 0.837
Resistance (m²K/W): 0.1300 ☑ Default

Construction Layers (Outside to Inside):

Material	Thickness mm	Conductivity W/(m·K)	Angular Dependence	Gas	Convection Coefficient W/m²·K	Resistance m²K/W	Transmittance	Outside Reflectance	Inside Reflectance	Refractive Index	Outside Emissivity	Ir Em
[SC6BL237] "SUNCOOL" CLASSIC 6MM 20/33 (BLUE)	4.0	1.0600	Fresnel	-	-	0.0038	0.150	0.210	0.210	1.526	-	
Cavity	6.0	-	-	Air	4.1600	0.1272	-	-	-	-	-	
[CF4] CLEAR FLOAT 4MM	4.0	1.0600	Fresnel	-	-	0.0038	0.820	0.070	0.070	1.526	-	

Figure A.15: External Window Construction Layer_ Best Practice Scenario 2



Edit Project Daily Profile DAY_0112

Profile: Windows-ACRms-BAU

ID: DAY_0112

● Modulating ○ Absolute

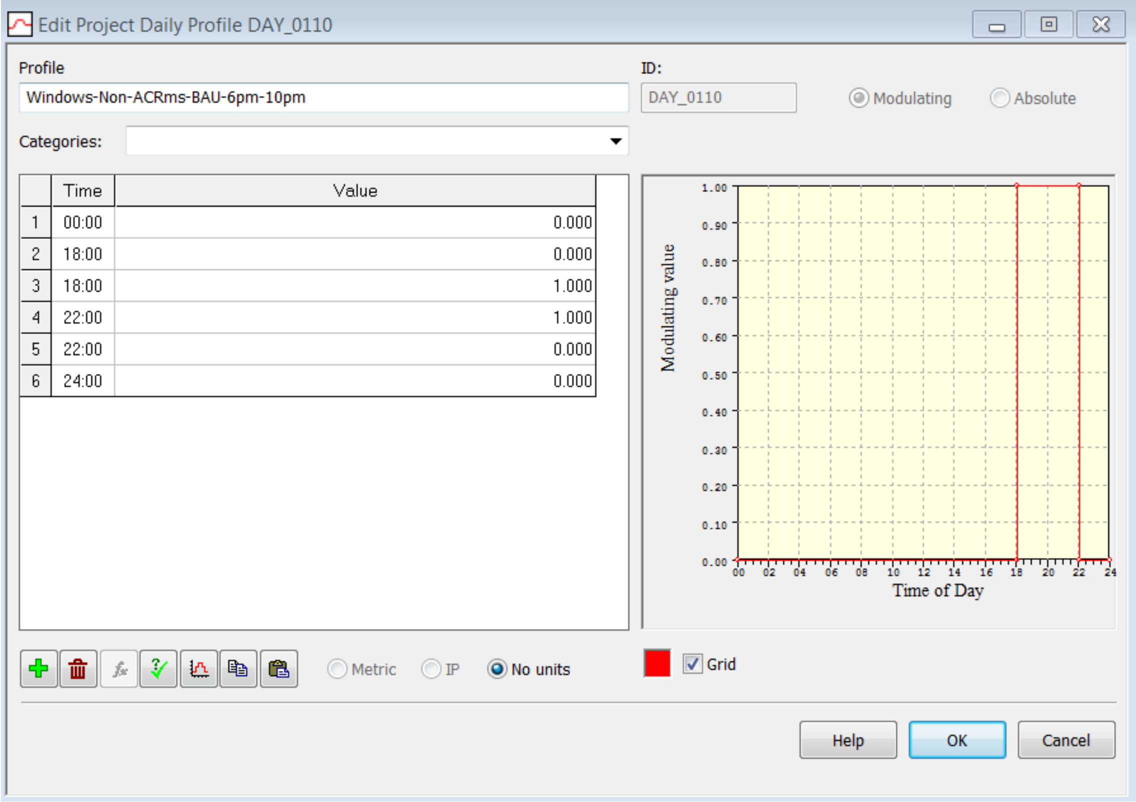
Categories:

	Time	Value
1	00:00	0.000
2	24:00	0.000

○ Metric ○ IP ● No units

🟥 ☑ Grid

Figure A.16: Window Operation in AC rooms: BaU Scenario



Edit Project Daily Profile DAY_0110

Profile: Windows-Non-ACRms-BAU-6pm-10pm

ID: DAY_0110

● Modulating ○ Absolute

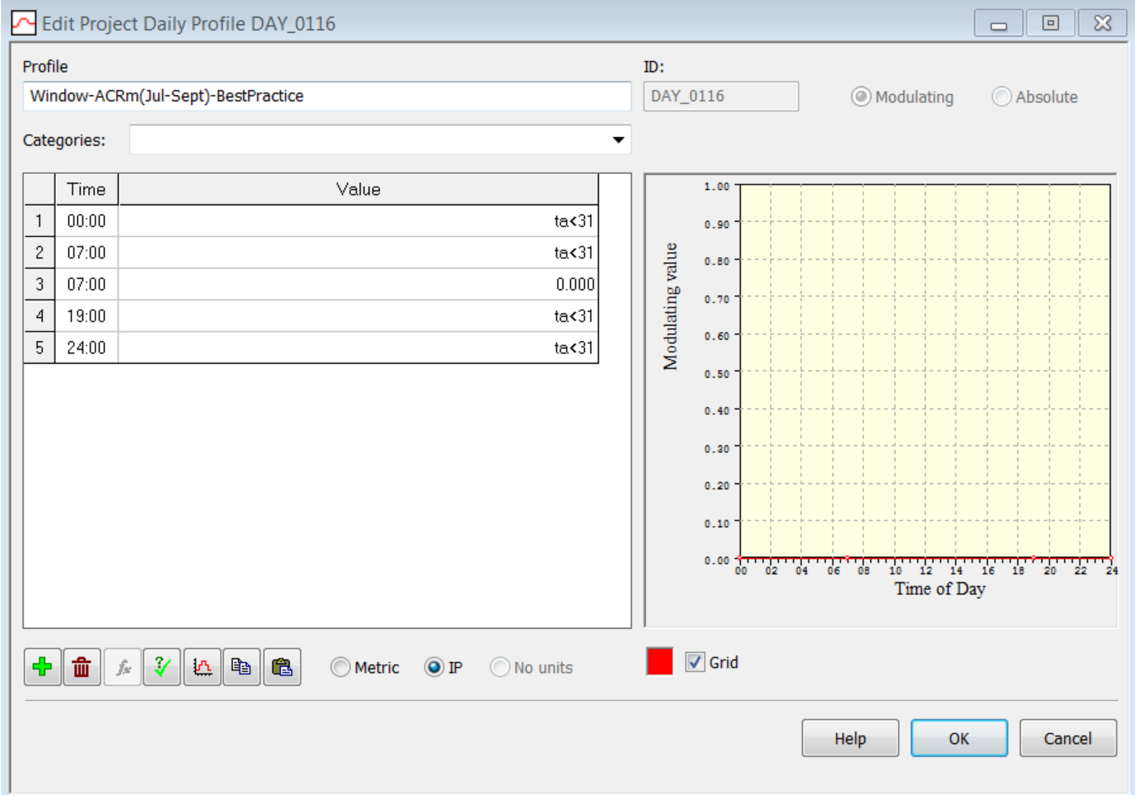
Categories:

	Time	Value
1	00:00	0.000
2	18:00	0.000
3	18:00	1.000
4	22:00	1.000
5	22:00	0.000
6	24:00	0.000

○ Metric ○ IP ● No units

🟥 ☑ Grid

Figure A.17: Window Operation in non-AC rooms: BaU Scenario



Edit Project Daily Profile DAY_0116

Profile: Window-ACRm(Jul-Sept)-BestPractice

ID: DAY_0116

● Modulating ○ Absolute

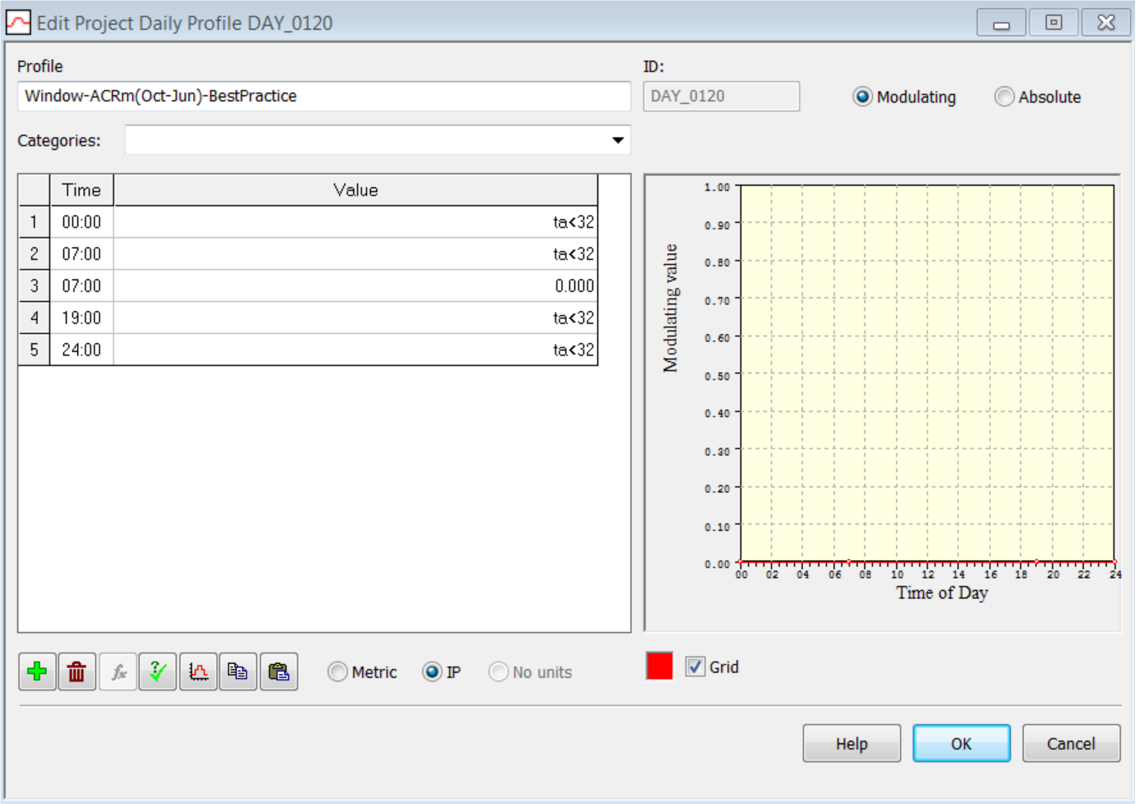
Categories:

	Time	Value
1	00:00	ta<31
2	07:00	ta<31
3	07:00	0.000
4	19:00	ta<31
5	24:00	ta<31

○ Metric ● IP ○ No units

☑ Grid

Figure A.18: Window Operation in AC rooms (Jul.-Sept.): Best Practice Scenario



Edit Project Daily Profile DAY_0120

Profile: Window-ACRm(Oct-Jun)-BestPractice

ID: DAY_0120

● Modulating ○ Absolute

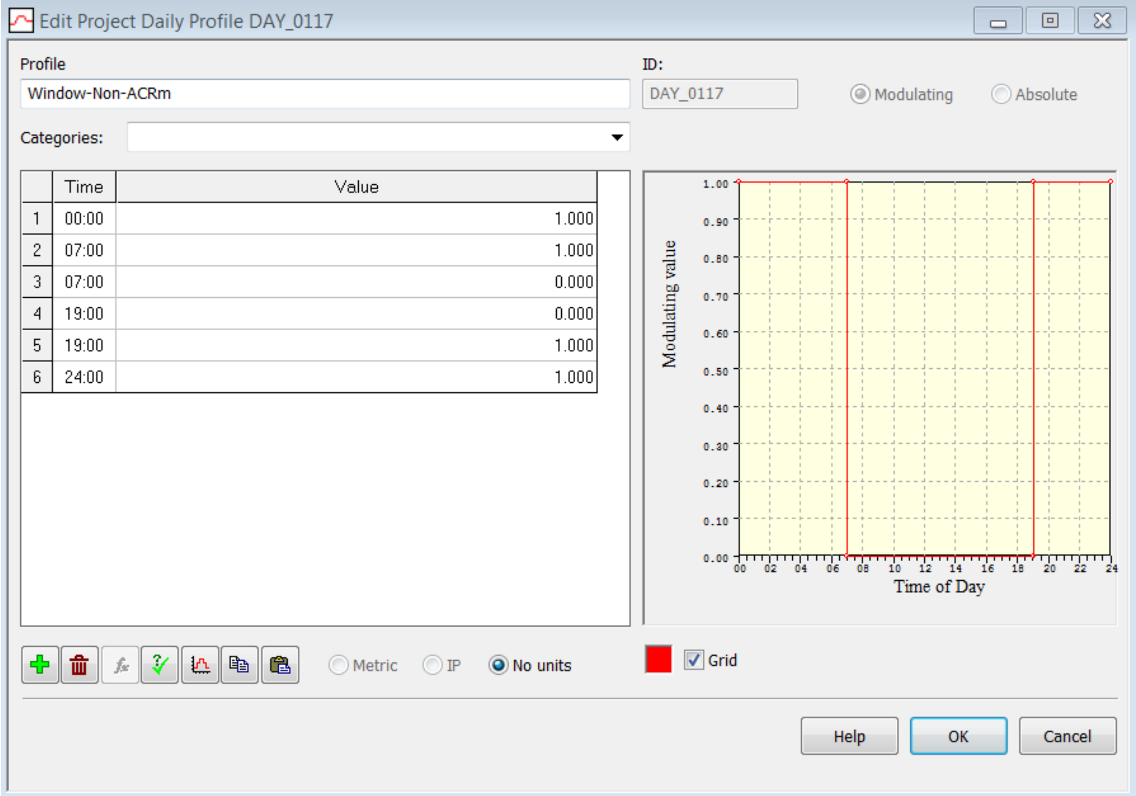
Categories:

	Time	Value
1	00:00	ta<32
2	07:00	ta<32
3	07:00	0.000
4	19:00	ta<32
5	24:00	ta<32

○ Metric ● IP ○ No units

☑ Grid

Figure A.19: Window Operation in AC rooms (Oct.-June): Best Practice Scenario



Edit Project Daily Profile DAY_0117

Profile: Window-Non-ACRm

ID: DAY_0117

● Modulating ○ Absolute

Categories:

	Time	Value
1	00:00	1.000
2	07:00	1.000
3	07:00	0.000
4	19:00	0.000
5	19:00	1.000
6	24:00	1.000

○ Metric ○ IP ● No units

☑ Grid

Figure A.20: Window Operation in non-AC rooms: Best Practice Scenario