BUILDING ENERGY CONSUMPTION FACTORS: A LITERATURE REVIEW AND FUTURE RESEARCH AGENDA

M. N. K. De Silva* and Y. G. Sandanayake
Department of Building Economics, University of Moratuwa, Sri Lanka

ABSTRACT

The Sri Lankan energy supply system faces several major strategic challenges due to high annual electricity demand growth rate and hence it is required to double the electricity generation capacity in every ten years. Ministry of Power and Energy predicted regular power cuts in the foreseeable future due to lack of rainfall within the hydro-catchments areas. In the coming years, oil price hikes will have a great impact on the operation of thermal power plants. Sri Lanka has now become the highest electricity bill spender in Asia and the status of energy poverty seems rather alarming. Sri Lankan energy statistics confirm that the building sector has contributed heavily on the energy, exceeding the industrial and transportation sectors. Occupant behaviour toward energy consumption have a significant impact on energy poverty and the initiation of large scale development projects after the three decades conflict pave the way to energy poverty to step up. In order to alleviate energy poverty, it is important to investigate the factors influencing the building energy consumption and their impact on power crisis. Therefore, the aim of this paper is to critically review the factors affecting building energy consumption. A comprehensive literature review and a desk study of Sri Lankan energy reports were used out to investigate the power crisis in Sri Lanka and the factors influencing building energy consumption. Five factors and 36 sub factors identified from the literature review will be used to identify critical factors affecting building energy consumption during the next phase of the study.

Keywords: *Energy Poverty, Power Crisis, Building Energy Consumption, Building Energy Consumption Factors.*

1. INTRODUCTION

The planet is progressively stepping towards a serious energy crisis due to an escalating energy demand compared to supply. Energy crisis is a situation in which the nation suffers from a disruption of energy supplies accompanied by rapidly increasing energy prices that threaten economic and national security (Williams and Alhajji, 2003). Energy consumption causes a wide range of environmental problems, and with the increase in energy demand, the issue of energy crisis becomes cited. Energy use has recently become a major issue due to growing concern about CO_2 and other greenhouse gas emissions and the scarceness of fossil fuels (Escrivá-Escrivá, 2011). According to the current statistics and demands, the world's oil reserves will decline by 2052, gas resources are expected to run out within the next 60 years and coal will dwindle within the next 80 years (Dissanayake, 2012). Yanbin *et al.* (2011) states that in 21st century, all countries are facing the challenge of energy, whilst power crisis is one of the greatest crises in energy.

This study therefore, aims at finding factors influencing building energy consumption and to set future research agenda. The paper structure begins with a literature review on Sri Lankan energy crisis and building energy consumption. The paper then reviews major influential factors on building energy consumption and finally presents the discussion and future research agenda.

2. ENERGY CRISIS IN SRI LANKA

The Sri Lankan energy supply system faces several major strategic challenges due to high annual electricity demand growth rate and hence it is required to increase the electricity generation capacity. According to Abegunawadana (2011), electricity demand was rising at a rate of 7% per annum during the

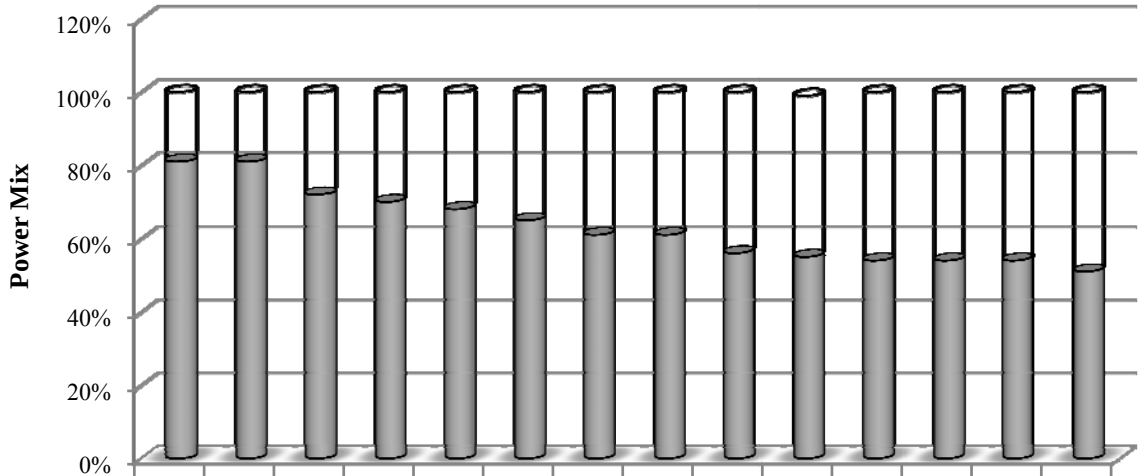
* Corresponding Author: E-mail - nawodads@gmail.com

last two decades. The assessment of the Ceylon Electricity Board (CEB) reveals that the demand for electricity will increase by 7-10% per annum over the next twenty years, thereby, demand shall double every ten years (Abeygunawardana, 2008). Therefore, it is required to double the electricity generation in every ten years (Abeygunawardana, 2011).

The large-scale construction and development projects, following the end of three decades conflict in Sri Lanka pave the way to energy poverty to step up (Wijekoon, 2012). Sri Lanka Energy Balance (2007) anticipated a parallel growth in energy demand, with the rapid economic development drive launched by the Sri Lankan government. Consequently, the influx of foreign investments to the country and the population explosion over the last few years had been the principal reasons for the excessive demand for electricity at present (Wijeykoon, 2012). As energy demand rises, the energy consumption in Sri Lanka has become an act of suffer, being the highest electricity bill spender in Asia (Kumara, 2011). Hence, the status of energy poverty in Sri Lanka seems rather alarming.

According to Abeygunawardana (2008), a dialogue on the energy crisis commenced in Sri Lanka in the eighties when the goal of utilising the electricity generated from the newly constructed reservoir system of the Mahaweli scheme to feed the power needs of the entire nation and even sell excess power to India turned into a pipe dream. Abeygunawardana (2008) further explained that the anticipated outputs were never achieved due to various environmental and technological problems and "electricity" became a permanent crisis in Sri Lanka.

Thus, the energy generation attention has turned towards the thermal power apart from hydro power and other domestic energy sources such as wind and biomass. According to Jerome (2009), CEB had diversified into thermal power in the interest of speedy capacity augmentation. Figure 1 shows the thermal and hydro power generation mix from 1995 to 2008. According to the figure, there is a clear increment in thermal power generation and decline in hydro power generation during last two decades.



	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Thermal	19%	19%	28%	30%	32%	35%	39%	39%	44%	44%	46%	46%	46%	49%
Hydro	81%	81%	72%	70%	68%	65%	61%	61%	56%	55%	54%	54%	54%	51%

Figure 1: Thermal and Hydro Power Generation Mix during 1995-2008
(Source: Economic and Social Statistics of Sri Lanka 2009 cited Jerome 2009)

Indratissa (2010) pointed out that the Sri Lankan energy future is uncertain as the electricity mix is very much depending on imported fossil fuel. In the coming years, oil price hikes will have a great impact on thermal power plants and climate change will interrupt the hydro power generation and therefore, Sri Lanka cannot sustain with the existing energy mix in the years to come (Abeygunawardana, 2011).

The present trend of increasing energy demand will continue while increasing energy costs and demand side management measures might dampen the rate of growth of energy demand (Sri Lanka Sustainable Energy Authority, 2007). Therefore, solutions should adhere and there is tremendous potential for alleviating energy poverty by reducing energy consumption or conserving energy itself.

3. BUILDING ENERGY CONSUMPTION

The European energy context identified buildings, industry and transport sectors as the three largest sectors of energy consumption (Paris *et al.*, 2010), while this is largely correct for many other countries. The built environment is a significant contributor to global greenhouse gas emissions, and buildings accountable for 30–40% of all primary energy used worldwide (Asif *et al.*, 2009 as cited in Ramesh *et al.*, 2010). According to forecasts energy use in the built environment will grow by 34% in the next 20 years, at an average rate of 1.5%.

In China, around 30% of the national energy consumption can be attributed to buildings and it is expected that the proportion of building energy consumption in national energy consumption will keep rising in the coming years (Liu *et al.,* 2012). The energy consumption of buildings accounts for 38.9% of the total primary energy requirement in United States (Wan *et al.*, 2011), where the particular contribution in United Kingdom is 44% (Energy Information Administration, 2011). In France, 25% of greenhouse gases emissions and 46% of energy consumption are due to buildings (Paris *et al.*, 2010). According to statistics of Sri Lanka, building sector also stands for the highest contributor to the total national energy consumption, which is about 48.5% (SSEA, 2010). The rest of national energy consumption is contributed by transport (26.64%), industrial (24.75%) and agriculture (0.11%) sectors. Therefore, global energy statistics confirm that the building sector has contributed heavily on the energy, exceeding the other major sectors of industrial, agriculture and transportation.

The annual electricity consumption by buildings increased from 45% to 60% of the total electrical energy use in Sri Lanka from 2002 to 2010 (SSEA, 2010), which accounted for the highest sector-wide electricity consumption growth in the past years. According to the total energy consumption trend analysis shown in Figure 2, electricity consumption in 2010 is 9208.5Gwh and the predicted electricity consumption in 2015 will be 11200Gwh. Therefore, an energy gap of approximately 2000Gwh is expected along with the increasing consumption of about 20% in next five years. Besides, the government of Sri Lanka recognises that improving energy performance of building is an important part of the strategy of the country's sustainable energy development (SSEA, 2008).

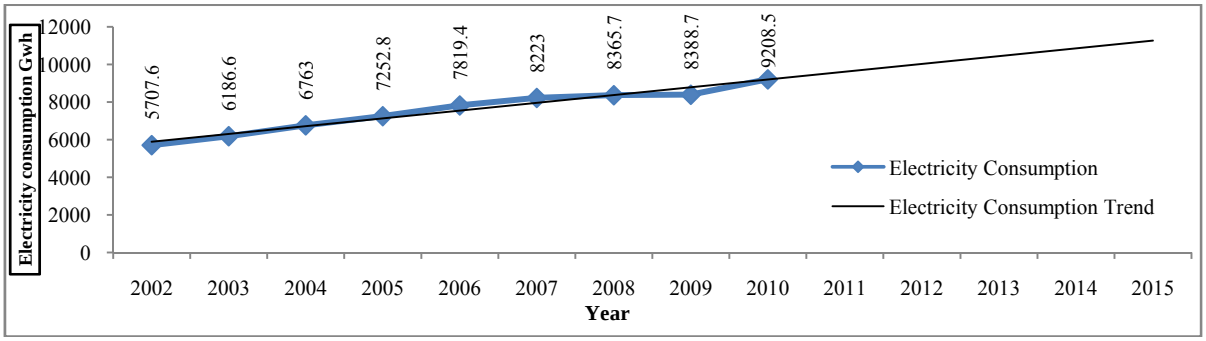


Figure 2: Trend Analysis of Total Energy Consumption in Sri Lanka from 2002 to 2015
(Source: Adapted from SSEA, 2010)

4. FACTORS INFLUENCING BUILDING ENERGY CONSUMPTION

Over the last decade, the potential of the building sector to contribute towards reductions in energy consumption and CO_2 emissions has increasingly recognised within the Sri Lankan context. However, study of the factors influencing energy consumption of buildings is essential for a better understanding of energy conservation. Past researches identified an array of factors influencing building energy consumption. This research study is analysed only a sample of 20 key research papers written on building energy consumption. A review of 20 key research papers that discovered factors influencing building energy consumption and their impact on energy crisis is presented in Table 1. Some referred articles were based on building categories (e.g. residential, hotel and office), while other were on the basis of broad-spectrum. A total of five (05) major influential factors and 36 sub factors identified from the literature are listed in Table 1. Given the ambiguity surrounding the terminology used by the different authors, best judgment has been used in grouping the main and sub factors.

Table 1: Factors Influencing Building Energy Consumption
Different Studies, Authors and the Factors Identified by Them

Factors \ Studies' Authors	General						Hotel specific			Office specific					Residential specific					
	Yu et al 2011	Killip 2009 cited Janda 2011	Liu & Harris 2008	Saidur 2009	Papadopoulof et al 2002	Yildiz & Arsan 2011	Bohdanowicz and Martinac 2006	Deng and Burnett 2000	Priyadarsini et al 2009	Stoy et al. 2009	Kong et al. 2012	Wong et al 2007	Balaras et al 2002	Escriva-Escriva, 2011	Tso & Yau 2003	Yun & Steemers 2011	Yohanis 2012	Santamouris et al 2007	Yoshino et al 2006	Dascalaki et al 2011
Climate																				
Climatology/ Climatic location/ zone							■		■					■				■		
Weather parameters	■								■				■			■				■
Building related characteristics																				
Type															■	■		■		
Age				■			■	■	■		■				■	■	■	■	■	■
Size/ Gross Floor Area/ Number of floors				■	■			■	■		■				■	■	■	■	■	■
Class								■	■											
Usage hours			■	■						■										
Geographical Location							■													
Design/structural parameters			■		■	■	■							■		■		■	■	
Orientation			■		■	■				■				■						
Envelop/ fabric		■		■								■								■
Construction quality													■	■						
Worker density									■		■						■			
Share of areas served by a/c, lifts & illumination					■					■	■					■	■			
IEQ/ Indoor Thermal Quality	■								■										■	
Nature of surrounding			■																	
Rent															■					
Availability of infrastructure																		■		
Occupant-related characteristics																				
Occupancy Rate				■			■	■	■	■					■	■			■	
Occupant behavior/ activities	■	■														■			■	
Preference relevant to indoor comfort							■												■	
Awareness of energy consumption							■													
Building services systems related characteristics																				
Building services systems specification							■				■		■				■		■	■
Building services systems load		■						■		■		■	■			■			■	
Operation and maintenance schemes							■						■							
Efficiency/condition of building services systems				■	■									■						■
Age of building services systems							■		■											■
Sub facilities, services offered																				
Appliance ownership															■					
Socio-economic & legal related characteristics																				
Education	■																			
Culture							■													
Income/ social class															■	■		■	■	
Age of the head/householder																■				
Availability of energy resources locally							■													
Energy market prices				■										■						
Energy use regulations				■			■													

According to the above review, 'climate', 'building related characteristics', 'building systems and/services related characteristics', 'occupant related characteristics', 'socio-economic and legal related characteristics' are the most frequently addressed factors influencing building energy consumption. A review of these major factors now follows.

4.1. CLIMATE

Building acts as a climatic modifier, separating the indoor built environment from the external climate (Lam *et al.*, 2005). Energy demand of buildings is influenced by many climatic parameters (Kalamees *et al.*, 2012). Drake and Foster (1995) categorised the short-term behaviour of the atmosphere as "weather", while the investigation of long-term trends in the weather system as "climate". Ministry of Construction of People's Republic of China (1993 as cited in Wan *et al.*, 2011) identifies five climatology (climate types), namely severe cold, cold, hot summer and cold winter, mild, and hot summer and warm winter. The extent to which overall energy use for space conditioning would depend very much on the prevailing local climates and the actual climate change in future years (Wan *et al.*, 2011). Jim and Peng (2012) identified weather as a huge influential factor on building energy consumption in Hong Kong. Wan *et al.* (2011) listed temperature, solar radiation, wind speed/direction, moisture content of air as major weather parameters.

Kalamees *et al.* (2012) stated that in a cold climate, temperature has the strongest influence on the heating energy demand, and during summer, it has a similar influence on the cooling energy demand. The peak of Heating Ventilation and Air Conditioning (HVAC) occurred in the heating season, while the trough of HVAC occurred in the cooling season whereas, the peak of Hot Water Supply (HWS) occurred in cooling season where trough of HWS occurred in heating season due to the weather conditions (Yu *et al.*, 2011). According to Liu and Harris (2008), a small rise in ambient temperature could still give rise to a significant reduction in building energy consumption. Yu *et al.* (2011) discussed the impact of weather conditions on occupant behaviour and thereby on building energy consumption. Climatic data are however crucial for the building industry since a building's role is to provide comfortable and protective indoor conditions to its occupants against outdoor environment (Oxizidis *et al.*, 2008).

Although the Sri Lankan context is not largely affected by seasonal climatic changes, SSEA (2008) identifies three climatic zones as warm-humid (Dry Bulb Temperature (DBT) - 310^0C, Wet Bulb Temperature (WBT) - 270^0C), warm-dry (DBT- 330^0C, WBT- 260^0C) and uplands (DBT- 280^0C, WBT- 230^0C). The outdoor design condition would vary based on the corresponding climatic zone and this will in turn dictate the thermo-physical properties of all building elements (SSEA, 2008). Therefore, climate can be identified as a major factor affecting building energy consumption in Sri Lanka. Further, long-term trend, which is 'climatology' and short-term behaviour of the atmosphere, i.e. 'weather' can be identified as two sub factors under the 'climate' category.

4.2. BUILDING RELATED CHARACTERISTICS

The European Union's energy performance of buildings directive mentioned that reducing energy consumption is affected by not just how buildings are designed, but also how they are built, commissioned and used (Janda, 2011). Liu and Harris (2008) argued that although many factors such as design and use influence the energy consumption of buildings, other factors such as orientation and the nature of the surroundings, also have an influence, but are often ignored. Yu *et al.* (2011) sated that even a slight difference in some building related parameters would result in remarkable fluctuations in the building energy consumption. Mourshed (2011), Yu *et al.* (2011) and Papadopoulof *et al.* (2002) identified floor area/size, age, envelope / fabric / shell, form, shape, materials and construction as building-related parameters.

Papadopoulof *et al.* (2002) highlighted some design parameters such as size of the building, surface to heated volume ratio as well as some structural parameters such as thermal insulation of roofs, windows and walls with related to influences of building energy consumption. Chan (2011) reports that the indoor climate and electricity consumption of a building can be affected by various building envelope

characteristics such as building shape, thermal insulation, wall colour, window-to-wall ratio, glazing material, shading devices and green roof system.

According to the literature review presented in Table 1, type, age, size, class, usage hours, geographical location, design/structural parameters, orientation, envelop, construction quality, worker density, share of areas served by air-conditioning, lift and illumination, indoor environmental/thermal quality, nature of surrounding, rent and availability of infrastructure were identified as sub factors of 'building related characteristics'. These building related characteristics have very high impact on building energy consumption. Therefore, owners can considerably save energy by considering and upgrading the aforementioned building related characteristics.

4.3. OCCUPANT RELATED CHARACTERISTICS

Buildings do not use energy, but people do (Janda, 2011). Once the level of occupancy increases, the energy consumption of HVAC, lighting, elevators and other plug loads also increase. Janda (2011) argued that building users play a critical but poorly understood and often overlooked role in the built environment. The role of people in energy use can be seen as being even more influential. Yu *et al.* (2011) divided the effects of occupant behaviour into two categories, as the effects of building user presence and the effects of actions occupants took to influence energy consumption. For example, Emery and Kippenhan (2006 as cited in Yu *et al.*, 2011) found that the presence of occupants increase the total energy consumption, while Ouyang and Hokao (2009 as cited in Yu *et al.*, 2011) investigated energy-saving potential by improving user behaviour. However, it may be difficult to change the behaviour of people (Kempton *et al.*, 1992 as cited in Nair *et al.*, 2010) who do not have energy efficient habits, especially when the change involves personal inconvenience (Nair *et al.*, 2010). A survey of Swedish households showed that only 17% of the respondents regularly switched off lights when leaving a room (Linden *et al.*, 2006 as cited in Nair *et al.*, 2010).

According to the Janda (2011), the exact proportion of occupant influence is varying and it can be suggested that occupants are responsible for about one quarter of the problem with some probable influence over plug loads. Another research has shown that, while approximately half of the energy used in the home depends on the characteristics of a house and its equipment, residents and their behaviour influence the rest (Schipper *et al.*, 1989 as cited in Janda, 2011). As pointed out by Yu *et al.* (2011), different occupant behaviour, especially those associated with HVAC, can significantly affect indoor climate, thereby causing dramatic differences in building energy consumption. The work of Yun and Steemers (2011) found that behavioural patterns of air conditioning use as a highly influential factor in space cooling energy consumption, apart from climate conditions. Therefore, there has to be a trade-off between human thermal comfort and building energy consumption, and it is necessary to strike a balance between achieving a high comfort level and reducing energy consumption through modifying occupant behaviour (Yu *et al.*, 2011).

Occupancy rate and their behaviour are highly cited and influential factors on building energy consumption. However, complex need of occupants, their satisfaction and awareness are some other critical factors rarely investigated in past researches. Therefore, four sub factors, namely, occupancy rate, occupant behaviour/activities, preference relevant to indoor comfort and awareness on energy consumption were identified under the 'occupant related characteristics'.

4.4. BUILDING SERVICES AND SYSTEMS RELATED CHARACTERISTICS

According to International Energy Agency (2008 as cited in Oldewurtel *et al.*, 2012), energy efficient management of building systems plays a major role in minimising overall energy consumption and costs. The type, specification, load, operation and maintenance, management, efficiency/condition and age can be identified as sub factors under building systems and services related characteristics. Mourshed (2011) states systems' type, performance, control and schedules are influential towards building energy consumption. Yun and Steemers (2011) reveals that the type of cooling equipment (i.e. central or local systems) is also an influential determinant of cooling energy consumption as households with local air

conditioning systems (individual units in windows or walls) consume only 34% of the cooling energy for those with central systems. Further, SSEA (2008) provides designs and/or retrofits on selection/specification, operation and maintenance, efficiency for Lighting, Ventilation and Air-conditioning, and service water heating through 'the code of practice for energy efficient buildings in Sri Lanka' to reduce energy consumption and reduced electricity demand in the country.

According to the review shown in Table 1, the 'building services and systems related characteristics' consists of seven sub factors, such as building services and systems specification, building services and systems load, operation and maintenance schemes, efficiency/condition of building services and systems, age of building services and systems, sub facilities/services offered and appliance ownership. Due to the long lifespan of buildings, it is important to increase the energy efficiency of the existing building services and systems by reducing energy use and utility costs, while guaranteeing comfort for the building's occupants. Therefore, proper selection, commissioning, installation, operation and maintenance of services and systems within a built-environment are essential for the energy conservation.

4.5. SOCIO-ECONOMIC AND LEGAL CHARACTERISTICS

How societies are motivated to use or conserve energy has been a topic addressed sporadically by social scientists for more than a century (Rosa *et al.*, 1988 as cited in Janda, 2011). Few studies identified level of education as a factor influencing the acceptance of energy efficiency measures (Held, 1983; Olsen, 1983; Urge-Vorsatz and Hauff, 2001 as cited in Nair *et al.*, 2010). Income is another important factor affecting energy use, but the fact that the relationship of income to education and awareness of environmental issues is complex, makes the relationship of income and energy use more complex (Kerkhof *et al.*, 2009; Roberts, 2008; Summerfield *et al.*, 2007; Wall and Crosbie, 2009 as cited in Yohanis, 2012).

Yu *et al.* (2011) found that a rational combination of electricity rates and primary heating/cooling sources could help reduce building energy consumption through influencing occupant behaviour, since a high electricity rate tends to restrict occupants' usage of electrical heating/cooling equipment. Homeowners' age influences their energy efficiency behaviour (Carlsson-Kanyama *et al.*, 2005; Mahapatra and Gustavsson, 2008 as cited in Nair *et al.*, 2010) where, older homeowners are less likely to adopt energy efficiency investment measures (Mahapatra and Gustavsson, 2008 as cited in Nair *et al.*, 2010). Further, homeowners' awareness of energy efficient measures may influence the adoption of such measures as awareness of an innovation may lead to a need creation and its subsequent adoption (Rogers, 2003 as cited in Nair *et al.*, 2010). From this perspective, it can be argued that reducing energy use in buildings requires changes in the entire fabric of society, not just changing the shape and nature of buildings (Janda, 2011).

Energy policy plays an important role in any country's sustainable development (Saidur, 2009). He further discussed different types of regulation (i.e., voluntary, mandatory and mix model) aimed at reducing energy use in appliances, machinery and buildings, such as energy efficiency labels, energy efficiency standards and building codes. Kofoworola and Gheewala (2009) state that existing building energy codes, utilised in combination with appliance standards, and labelling and information programs can reduce energy consumption. Building energy regulations, also referred to as building energy codes, emerged as an essential tool for improving energy efficiency and minimising energy consumption in buildings (Lombard *et al.*, 2011). Many governments use regulations on energy intensity to reduce building energy use (Saidur, 2009) and the local governments' actions to promote energy efficiency measures (Nair *et al.*, 2010).

Therefore, education, culture, income, age of the head / householder, availability of energy resources locally, energy market prices and energy use regulations can be identified as different socio-economic and legal factors affecting building energy consumption.

5. DISCUSSION AND FUTURE RESEARCH AGENDA

Building energy consumption is one of the major issues to be addressed in this era of energy poverty. Buildings stand for the highest energy consuming sector in most countries, exceeding other sectors, namely, industry and transport. In Sri Lankan context, energy statistics confirms the larger share of

building sector to the nation's total energy consumption. Since, the status of energy poverty in Sri Lanka seems rather alarming, any decrease in energy usage in buildings would lead to significant energy conservation in the total energy consumption, hence alleviating the energy shortage.

Many factors are affecting the building energy consumption. The study identified five major factors, namely, 'climate', 'building related characteristics', 'building systems and services related characteristics', 'occupant related characteristics', 'socio-economic and legal related characteristics' and 36 sub factors by reviewing 20 research papers.

Under the 'climate' category, climatology and weather were identified as sub factors affecting energy usage of a building. The type, age, size, class, usage hours, geographical location, design/structural parameters, orientation, envelop, construction quality, worker density, share of areas served by air-conditioning, lift and illumination, indoor environmental / thermal quality, nature of surrounding, rent and availability of infrastructure were identified as sub factors of 'building related characteristics'. Further, four sub factors, namely, occupancy rate, occupant behaviour/activities, preference relevant to indoor comfort and awareness on energy consumption were identified under the 'occupant related characteristics'. The 'building services and systems related characteristics' consists of seven sub factors, such as building services and systems specification, building services and systems load, operation and maintenance schemes, efficiency/condition of building services and systems, age of building services and systems, sub facilities / services offered and appliance ownership. Moreover, 'socio-economic and legal related characteristics' comprises of seven factors, i.e. education, culture, income, age of the head/householder, availability of energy resources locally, energy market prices and energy use regulations.

Although the study identified a comprehensive set of five main categories and 36 sub factors affecting building energy usage, there is a common rule of thumb that roughly 80% of the effects come from 20% of the causes (Pareto Rule). Therefore, it is interesting and essential to identify key factors affecting building energy usage in order to reduce total energy consumption in an efficient and effective manner. Therefore, the article motivates an agenda for future research that advocates the identification of key factors affecting building energy consumption, from the factors identified through the critical review. These key factors can be used to reduce building energy consumption when designing new buildings and making improvements to existing buildings and hence to alleviate energy poverty in Sri Lanka in future.

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