Climate change, renewable energy and population impact on future energy demand for Burkina Faso built environment

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<th>Description</th>
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<tr>
<td>AOGCM</td>
<td>Atmosphere-Ocean General Circulation Model</td>
</tr>
<tr>
<td>CDF</td>
<td>Cumulative distribution functions</td>
</tr>
<tr>
<td>EKC</td>
<td>Environmental Kuznets Curve</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse gases</td>
</tr>
<tr>
<td>HadCM3</td>
<td>Hadley Centre Coupled Model version 3</td>
</tr>
<tr>
<td>IPCC</td>
<td>The Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>INSD</td>
<td>National Institute of Statistics</td>
</tr>
<tr>
<td>IES VE</td>
<td>IES Virtual Environment</td>
</tr>
<tr>
<td>IMF</td>
<td>International Monetary Fund</td>
</tr>
<tr>
<td>STIRPAT</td>
<td>Stochastic Impacts by Regression on Population, Affluence, and Technology</td>
</tr>
<tr>
<td>SIMA</td>
<td>Statistical Information Management and Analysis</td>
</tr>
<tr>
<td>SRES</td>
<td>Special Report on Emission Scenarios</td>
</tr>
<tr>
<td>SHGC</td>
<td>Solar heat gain coefficient</td>
</tr>
<tr>
<td>TRY</td>
<td>Test Reference Year</td>
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<tr>
<td>WWR</td>
<td>Window to Wall Ratio</td>
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Abstract

This research addresses the dual challenge faced by Burkina Faso engineers to design sustainable low-energy cost public buildings and domestic dwellings while still providing the required thermal comfort under warmer temperature conditions caused by climate change. Past and potential climate induced future energy demand for air conditioning has been investigated. It was found based on climate change SRES scenario A2 that predicted mean temperature in Burkina Faso will increase by 2°C between 2010 and 2050. Therefore, in order to maintain a thermally comfortable 25°C inside public buildings, the projected annual energy consumption for cooling load will increase by 15%, 36% and 100% respectively for the period between 2020 to 2039, 2040 to 2059 and 2070 to 2089 when compared to the control case. It has also been found that a 1% increase in population growth will result in a 1.38% and 2.03% increase in carbon emission from primary energy consumption and future electricity consumption respectively.

Furthermore, this research has investigated possible solutions for adaptation to the severe climate change and population growth impact on energy demand in Burkina Faso. It has been found that shading devices could potentially reduce the cooling load by up to 40%. Computer simulation programming of building energy consumption and a field study has shown that adobe houses have the potential of significantly reducing energy demand for cooling and offer a formidable method for climate change adaptation. Finally this research has shown, based on the Net Present Cost that hybrid photovoltaic (PV) and Diesel generator energy production configuration is the most cost effective local electricity supply system, for areas without electricity at present, with a payback time of 8 years when compared to the business as usual diesel generator stand-alone configuration. It is therefore a viable solution to increase electricity access to the majority of the population.
Declaration

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I would like to dedicate this thesis to my parents for her love and support.

Finally, I would like to thank my Dutch family and all my friends for their encouragement and support.
Chapter 1 Introduction

Climate change (considered to be changes in the state of the climate that persists for an extended period, typically in decades or centuries) has been observed recently. There has been an increase in carbon dioxide, a primary greenhouse gas since the start of the Industrial Revolution, and especially recent measurements at Mona Luao [1]. The recent increase in global air temperature has also been measured and a comparison to temperature data from ice cores and tree ring analyses has shown a significant recent rise [2]. Today, there is a general consensus amongst scientists that the climate change is an anthropogenically induced increase. There is already evidence that anthropogenic emissions of greenhouse gases (GHGs) have changed the patterns of temperature over the twentieth century [3]. However, natural factors, including changes in solar output and episodic volcanic emissions, may also have contributed. Evidence shows that in the past 25 years, the hemispheric annual sea ice in the Arctic has been decreasing by 3% per decade, with perennial sea ice decreasing at 9% per decade, shifts in thermohaline circulation, and reorganization of marine zooplankton communities. All these observations leave growing scientific consensus that the climate is undergoing considerable change due to global warming [4]. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report: Climate Change 2007 (AR4) indicated that there has been a significant increase of CO$_2$ concentration in the atmosphere, from 280 ppm in 1750 to 380 ppm in 2005 with an accelerated rate of increase. The report also projected a rise in the sea level of 180 to 590mm between 2007 and 2100 [5]. In addition, Church et al. (2010) provides an opportunity to reassess the possible impact of climate change on extreme sea levels in the South Pacific. The analysis based on tide-gauge data from 1978 to 2004 inclusive indicates a sea-level rise of $2.3 \pm 1.6$ mm yr$^{-1}$ for Truvalu and Funafuti (located in Oceania, the South Pacific Ocean) [6]. However, despite all these
alarming observations, no significant international agreement and commitment to reduce carbon emission has been achieved so far. The IMF (2000) shows that climate change will affect developing countries the most even though these countries contribute the least to the problem, because they are less well equipped to deal with global warming impacts due to the lack of financial and technical resources [7]. This is particularly true for those communities in sub-Saharan Africa who rely largely or totally on rain-fed agriculture or pastoralism for their livelihoods. Such communities, already struggling to cope effectively with the impacts of current climatic variability, will face a daunting task in adapting to future climate change [8]. The climate of Burkina Faso has multiple similarities with most sub-Saharan countries; therefore evidence from the example of Burkina Faso can provide significant help in outlining climate change adaptation policies in other Sub-Saharan African countries. Several literatures have identified rapid population growth as an additional driver of carbon emission and a major barrier to climate change adaptation and mitigation [9]. It is therefore important to factor in these drivers to the assessment of climate change impacts in the context of Burkina Faso.

Shi (2002) in this respect used the STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) model to assess and forecast the impact of population change on energy consumption and CO₂ emissions for 93 nations over the period 1960–1996. It was found that population had a disproportionately large (and highly elastic) effect on energy consumption and CO₂ emissions [9-10]. Furthermore, in a cross-sectional analysis of the carbon dioxide emissions of 111 nations, Dietz and Rosa (1997) also found that the effect of population on energy consumption exceeded unitary elasticity [11]. Burkina Faso is experiencing a rapid population growth which is projected by the United Nation to increase from 14 million to 29 million between 2010 and 2030. It has been shown that the
rapid global population growth as well as the world's economic growth induced dramatic growth of urban areas. Currently nearly half of the world's population live in cities and over the next 30 years most of the two billion increase in global population is expected to take place in urban areas in the developing countries [20]. The level of world urbanisation today and the number and size of the world's largest cities are unprecedented. Today, almost 400 cities have a million people or more, and about seventy per cent of them are in the developing world. By 2017 the developing world is likely to have become more urban in character than rural [21]. The rapid urban growth in developing countries such as Burkina Faso is seriously exceeding the capacity of most cities to provide adequate services for their citizens. Thus, projected rapid population and urbanization growth will likely put an additional pressure on energy supply in Burkina Faso. In addition, the country is characterised by the scarcity of its financial resources, therefore, it needs to explore cheap possibilities to increase its energy supply and settle a sustainable development.

Currently, Burkina Faso electricity production is mainly based on fossil fuel which is imported from neighbouring countries (Ghana, Ivory Coast or Togo). According to the National Institute of Statistics (INSD) the government yearly subsidy for fossil fuel electricity production was £20 million in 2010 [12]. Fossil fuel electricity generation represents about 70% of the country’s total electricity production [12]. It has been estimated that in 2002 buildings worldwide accounted for about 33% of the global greenhouse gas (GHG) emissions [13]. In Burkina Faso, 30 to 35% of the total electricity produced in the country is allocated to the built environment, with 60 to 67% of the building sector electricity going to air conditioning. This is about 25% of the primary energy consumed in the country [14]. In 2008 total electricity consumption was about 755,116MWh with only 13.7% of the population who have access to electricity mainly in urban areas. The national primary energy consumption
Recent literature has shown that energy consumption contributes to economic growth and social improvements. It is the basis for raising standards of living, improving the quality and quantity of human capital and enhancing business opportunities [15-17]. However, approximately 1.6 billion people mostly in the rural areas of Sub-Saharan Africa, South and East Asia, and Latin America still lack access to electricity [18-19]. The projected exponential increase of Burkina Faso population will accentuate the present gap between energy demand and supply capacity if the policy follows business as usual. Therefore, there is an urgent need for policy makers to tackle this problem if the country wants to improve its economic growth and development without further contributing to climate change. The statistics suggest that the built environment offer room for improvement in term of energy consumption reduction.

It has been proven that buildings worldwide contribute to a significant rise in global greenhouse gas (GHG) emissions [22]. A significant proportion of the GHG emission was due to growing energy demand for better thermal comfort in terms of space cooling during the hot/humid summer months [22]. Buildings typically have a long life span, lasting for a minimum of 50 years. Therefore it is particularly important not to encourage mal-adaptation practices which are locked into the built environment for many years to come.

This research investigates the thermal performance of different types of buildings and dwellings and shows how climate change could affect energy consumption patterns. The impact of Burkina Faso’s rapid population growth on its future energy demand has also been
investigated. It is widely accepted that the poorest countries are the most vulnerable, because they lack access even to the most basic services therefore placing them at a disadvantage and challenging position to tackle the additional stresses caused by climate change. Such vulnerabilities require comprehensive responses that link climate change adaptation and mitigation efforts for sustainable development. This research will also explore the challenges of climate change adaptation in the built environment that Burkina Faso may face.

The United Nations Development Programme points out that regarding climate change, the science is clear and the debate is over: climate change is happening and there is a need to act now [23]. The question then is how. The most common strategies aim to reduce the impacts of climate change (mitigation) and to cope with it impacts (adaptation). The contribution to reduce greenhouse gas emissions is global, however the impacts of climate change disproportionately affect residents in low-income urban areas, less equipped to adapt to such changes [24-25]. Mitigation includes technical and infrastructural investments such as renewable energy use and improving energy efficiency especially for developing countries. Mitigation measures can be expensive at the policy or private industry level (Clean Development Mechanisms and technology transfer) or at the individual (behaviour) level. Mitigation strategies aim at reducing energy consumption and saving individuals or governments financial or other resources [26]. The mitigation debate is in fact highly controversial, due to the fact that the climate related burdens that developing countries are facing is directly or indirectly a result of fossil fuel consumption from industrialized nations over the last 150 years [27]. In addition to mitigation, it is important to add adaptation strategies. Adaptation strategies as with mitigation strategies are based on the long-term, which may not be popular with government because they prefer to focus on shorter time
frames and quick fixes [24]. A focus on adaptation now may be perceived as an acknowledgement of allocating scarce public resources to a threat that is not yet perceived as imminent. Therefore, due in part to insufficient infrastructure, climate change policy internationally has so far largely been focused on mitigation despite the crucial need to incorporate adaptation [28]. Despite operating at different levels, adaptation and mitigation strategies are inherently interlinked and can also provide ‘win-win’ solutions. This research considered that synergies exist between mitigation and adaptation and should be highlighted, in order to support to need to implement both strategies simultaneously.

### 1.1 Research hypothesis

1. Climate change will result in higher temperatures for Burkina Faso this century.
2. Population increase will increase energy consumption and carbon emission in the building sector for the future.
3. Climate change impacts will increase energy consumption and carbon emission from the built environment in the future.
4. Better building design will reduce indoor temperatures, energy needs for cooling and carbon emissions from the built environment.
5. Combined hybrid renewable and diesel back-up diesel generators will help increase electricity production and reduce carbon emissions on aggregate.
6. Adobe house could help reduce cooling load for the built environment in Burkina Faso.
1.2 Research questions

1. What temperature increases are expected in Burkina Faso for this century?

2. What is the impact of future temperature and population increase on energy consumption in the built environment?

3. What type of buildings could provide the best climate adaptation solutions for Burkina Faso in respect to thermal comfort and what are the implications for mitigation on these building choices?

4. What energy production configurations are available and what is their relative potential?

5. What are the implications of the research for informing future building regulations in Burkina Faso?

1.3 Objectives

- Examine current and future climate data for Burkina Faso
- Assess Burkina Faso’s rapid population growth and its impact on energy consumption
- Estimate energy consumption and CO₂ emissions for selected domestic and public buildings now and for the future
- Estimate the optimum energy production configuration by looking at the Net Present Cost and Pay Back time of each system.
- Outline recommendations for Burkina Faso future building regulations to reduce supply and demand CO₂ emissions.
This research will focus on office buildings and dwellings in the capital city Ouagadougou. There are several reasons for this. First of all, air conditioning represents up to 67% of the total energy consumed in office buildings in the city [12]. Unemployment in rural areas causes many young people to migrate. Massive immigration toward cities has transformed the capital city in the most populated area in the country. Moreover, future global warming might put additional burdens on energy consumption for cooling. Therefore, the office buildings sector represents the sector in which significant energy savings can be targeted. Government is dedicating significant financial means for electricity production for public building to maintain a comfortable indoor temperature through air conditioning. Therefore, reducing energy consumption in the built environment constitutes an additional source of revenue for the Burkina Faso government. Therefore, government can redirect this financial revenue toward improving education and health care sectors which are currently underdeveloped. Finally, in the last ten years, Burkina Faso experienced a rapid population growth and an exponential increase in household energy consumption especially in the capital city Ouagadougou [42]. Furthermore, the capital city has the highest percentage of high income household able to afford air conditioning in their houses. Therefore, the combined impact will result in higher energy demand for domestic households. Ouagadougou electricity consumption is about 56% of the total electricity produced in the all country in 2010 [12]. In addition, due to the dynamism of its economy, household consumption is higher in the capital city than any other city of the country [42]. These conditions contribute to make Ouagadougou particularly suitable case study for this research.
1.4 Research significance

This research novelty resides in the fact that it is the first study that investigates the combined impact of global warming and population increase in Burkina Faso as well as the rapid growth of urbanisation on energy demand in the built environment. Moreover, Burkina Faso future Test Reference Year (TRY) for has been developed for the first time. These TRYs could be used by any engineer to simulate Burkina Faso future energy consumption in the built environment. (TRYs are sometimes confused with Design Summer Years (DSYs). DSYs are used to assess the plant size for air conditioning and TRYs are used for assessing the average energy consumption. This research is examining the TRY for average energy consumption.) This research methodology to assess climate change impact on future energy consumption in the built environment could be replicated in any other country. Moreover this research contributes to the wider significance of multi-disciplinary science for several reasons. First this research combined engineering and socio-economics to assess climate change and population growth impact on future energy consumption. In addition, the results from the Burkina Faso case study can provide a framework of recommendations for developing countries which have similar climate and socio economic conditions. This research serves the agenda of climate change mitigation and adaptation and supports conditions for a sustainable development.

A paper based on the results of this research published in Building and Environment journal has been identified by the editorial board in the special issue of Building and Environment (2012) as one of the few publications that deals with the issue of the impact of climate change on typical public and commercial (office) buildings in an African nation (Burkina Faso) [264]. Two additional papers which are currently under review have been written based on
the finding of this research. Moreover, this research has got a large coverage in the press. Articles on this PhD have been published in the University of Manchester Journal Unilife and in the School of Mechanical Aerospace and Civil Engineering newsletter (See Appendix A and C). Finally, this research outlined a methodology to forecast future electricity demand based on population growth and defined building regulations which is currently nonexistent in Burkina Faso.

1.5 Research approach and scope

The research method used in this work is mainly based on modelling, computer simulation and field study. The STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) [9] model has been used to assess the impact of population and urbanisation rapid growth on future energy demand for Burkina Faso built environment. In addition, based on population growth scenarios, future energy consumption scenarios have been developed using the STIRPAT model. Then the computer simulation program IES VE [43] was used to design office buildings and domestic dwellings with different thermo physical characteristics to analyse the carbon emissions. The Hadley model [268] was used to explore future climate change scenarios and develop climate data for use in simulation. Each type of building thermal performance has been assessed based on the IES VE program. Finally field observation and primary data collection of a selected set of domestic dwellings in Ouagadougou primarily has been used to validate the simulation results on thermal performance. Finally this research used the HOMER software to assess power optimisation system that will help reduce the price of the kWh and achieve a wide coverage of electricity production to the maximum of people.
1.6 Thesis layout

This research is structured in three parts. It first provides a general overview of carbon emission and energy consumption anthropogenic drivers. It then focuses on population and climate change impact on future energy consumption in the built environment. Finally, this research develops some possible solutions that could help Burkina Faso built environment adapt to the projected increase of energy consumption. The chapters are organized as following.

Chapter 1 outlines the research hypothesis and questions. It also provides an overview of the objectives and significance of the research.

Chapter 2 develops the literature review on previous studies that deal with climate change drivers, STIRPAT model, building energy simulation programs and climate change adaptation measures.

Chapter 3 provides the overall methodology that was used in this research.

Chapter 4 provides a background on Burkina Faso geography and climate. These are essential information that impact energy consumption in the built environment. In addition, this chapter develops the past and current economic situation. Finally, current and projected demographic trend was investigated in this research. This information has the potential of impacting energy consumption in the built environment.

Chapter 5 identifies the main drivers of climate change based on the STIRPAT model.
Chapter 6 explores the scope of future climate change using the Test reference Year (TRY) as standard for the comparison.

Chapter 7 and 8 simulate future energy consumption in a typical office building and domestic household. These chapters also present adaptation strategies that will ensure sustainable response to climate change in the built environment.

Chapter 9 presents the potential of adobe house to provide sustainable climate adaptation measures. Chapter 10 analyses the potential of renewable energy to provide sufficient electricity that will cope with the need of energy to adapt to climate change.

Chapter 11 proposes some recommendations for future buildings regulations in Burkina Faso.

Finally, chapter 12 concludes and summarizes the key findings of this research. This chapter also suggests some guidelines for future work in order to improve the future energy consumption simulation in the built environment.
Chapter 2 Literature review

2.1 Evidence of climate change

Over the past decades, man-made activities have added significant quantities of greenhouse gases (GHGs) to the atmosphere. According to the IPCC (2001) report, the atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have grown by about 31%, 151% and 17%, respectively, between 1750 and 2000. An increase of GHGs could result in higher warming, which, in turn, could have a significant impact on the world’s climate. In addition this could lead climate change as well. Scientists’ observations have shown that over the 20th century the mean temperature increased by 0.6°C. They also found that since 1860 the 1990s have been the warmest decade. That results in troubles with the economy, health and safety, food production, security, etc. Moreover, shifting weather patterns threaten food production through increased unpredictability of precipitation, rising sea levels contaminating coastal freshwater reserves and increasing the risk of catastrophic flooding [104]. The combined thermal expansion and melting of ice sheets in the world is contributing to sea-level rise that could far exceed those anticipated in the most recent global scientific assessment. There is evidences that tipping points, leading to permanent changes in major ecosystems, might have already been reached [105]. For example, ecosystems such as the Amazon rainforest and the Arctic tundra may be approaching the thresholds of dramatic change. Mountain glaciers are reducing rapidly affecting water supply during the warmest months. That will results in huge impacts for the coming generations [106].

According to the IPCC Fourth Assessment Report, the evidence of rapid climate change is compelling [5] [104] and the following effects are already noticeable:
(1) “Sea-level rise: Global sea-level rose about 17 cm in the last century. The rate in the last decade, however, is nearly double that of the last century.

(2) Global temperature rise: Most of this warming has occurred since the 1970s, with the 20 warmest years having occurred since 1981 and with all 10 of the warmest years occurring in the past 12 years.

(3) Warming oceans: The oceans have absorbed much of this increased heat, with the top 700 m of ocean showing warming of 0.302ºC since 1969.

(4) Shrinking ice sheets: The Greenland and Antarctic ice sheets have decreased in mass. Data from NASA’s Gravity Recovery and Climate Experiment show Greenland lost 150–250 km³ of ice per year between 2002 and 2006, while Antarctica lost about 152 km³ of ice between 2002 and 2005.

(5) Declining Arctic sea ice: Both the extent and thickness of Arctic sea ice has declined rapidly over the last several decades.

(6) Glacial retreat: Glaciers are retreating almost everywhere around the world – including in the Alps, Himalayas, Andes, Rockies, Alaska and Africa.

(7) Ocean acidification: Since the beginning of the Industrial Revolution, the acidity of surface ocean waters has increased by about 30%.”

The increasing trend of CO₂ emissions, Arctic sea Ice, CO₂ concentration, sea level and global surface temperature is shown in Figs.2.1-2.5 respectively.
Figure 2-1 CO2 (ppm) trend over years.

Source NASA satellite observations

Figure 2-2 Arctic sea-ice level

Source NASA satellite observations
Figure 2-3  Carbon dioxide concentration level over different time periods

Source NASA satellite observations

Figure 2-4  Sea level change

Source NASA satellite observations
Figure 2-5 Global temperature variation

**Global Surface Temperature**

Data updated 4.18.11

**GLOBAL LAND-OCEAN TEMPERATURE INDEX**

Source: NASA/GISS. This research is broadly consistent with similar constructions prepared by the Climatic Research Unit and the National Atmospheric and Oceanic Administration. Credit: NASA/GISS

![Global Surface Temperature Chart](image)

Source NASA satellite observations

**Fig. 2.1 to 2.5** illustrates the dramatic change that the climate has undergone during the past decade. Therefore, mitigating and adapting measure should be taken in order to reduce the current trend of global climate change. Mitigation measures include carbon sequestration, clean development mechanism the use of non-polluting sources of energy such solar, wind and geothermal energy sources. Adaptation measures centre on refurbishing buildings, for instance adding window shading and insulation [281].

### 1.7 Limitations

However, recent carbon emission trends show that SRES scenarios are outdated. The development of the Representative Concentration Pathways (RCPs) provide information on possible development trajectories for the main forcing agents of climate change, consistent with current scenario literature allowing subsequent analysis by both Climate models (CMs) and Integrated Assessment Models (IAMs). The RCPs provide a starting point for new and
wide-ranging research and map a broad range of climate outcomes. However, it is important to recognize their uses and limits.

They are neither forecasts nor policy recommendations, but were chosen to map a broad range of climate outcomes.

In addition, research by Bows et al. (2010) shows that there is now a little or no chance to maintain the rise in global mean surface temperature at below 2°C. In this respect, the impacts associated with 2°C have been revised upwards [288].

### 2.2 Population impact on environment

The role of population pressure on the environment can be traced back to the early debate on the relationship between population and natural resources. There are two main perspectives on the demographic growth impact on the environment: the Malthusian tradition and the Boserupian approach. The Malthusian tradition (Malthus, 1967) suggests that environmental degradation is due to the pressure that the population puts on resources [63]. Malthus was concerned that the increasing population growth would put additional pressure on limited resources and land. Because of a lower marginal product of labour, the potential growth in food supply could not meet the need of the exponentially rising population. He predicted that if mankind did not exercise preventive action to control population growth, its growth would be contained by poverty, disease, famine or war [63]. In contrast, the Boserupian (Boserup, 1965 and 1981) perspective holds that population growth will stimulate technological innovations and that will result in an attenuation of the negative impact on the environment. In particular, Boserup argues that high population densities were a prerequisite for technological innovation in agriculture. He develops the argument that technological innovation makes possible the increase of yields and more efficient distribution of food. This
enables the natural environment to support a large population at the same level of welfare [64]. As a result, Malthusian scholars forecast that population growth will have an exponential impact on greenhouse gases emissions, while Boserupian academics argue that this relationship does not exist or, if it does, it has a negative elasticity. Therefore, population growth will result in reduction of carbon emission per person due to development of technology [64].

Although both authors were not specifically concerned with environmental issues, but rather the resource for food production, their positions have been considered in recent environmental debates. On the one hand, some scholars have demonstrated that the exploitation of natural minerals, energy resources and the ability of the environment to absorb wastes generated by mankind’s activities were not keeping pace with population growth [134-135]. Others, defend the fact that the larger the population the more vigorous the development of science and technology. That results in better ability to provide technological solutions to environmental problems [136].

The impact of population growth on the environment is such that each person in a population makes some demand on energy for his daily life need such as food, water, clothing, shelter, and so on. Thus, if all else is equal, the greater the number of people, the greater the demands on energy. Birdsall (1992) specified two mechanisms through which population growth could contribute to greenhouse gas emissions. First, a larger population could result in greater need for energy in industry, and transportation, therefore increasing carbon emissions. Second, population growth could contribute to greenhouse gas emissions through deforestation for agricultural land. That could significantly contribute to higher greenhouse gas emissions [137].
It is becoming clear that humans are modifying the global environment on an unprecedented scale [50-51]. Several studies have been developed on the relationship between population and environment. Paul Ehrlich and his colleagues are perhaps the best-known among them. Ehrlich (1968, 1971, 1974 and 2004) in his work has raised the awareness about population impact on environment. He laid out the fundamental aspects of the pressure that human population places on ecosystems and natural resources [52-55]. Following Ehrlich’s research, Cohen (1995) in his book, “How many people can the Earth support?” investigates the complexity of assessing the extent to which population is limited by the environment [56]. His general conclusion is that many factors influence the “carrying capacity” of the earth that includes economics, social, cultural, and political conditions in which humans live. As a result it is difficult to present a definite estimate of the carrying capacity [56].

2.3 Models on CO₂ emission drivers

Population size and growth have by far received the most attention in debates about the anthropogenic impact on environment. However, other drivers of climate change exist. The question is therefore, what is the correlation between economy levels, population, technology levels and CO₂ emissions in a given country? To solve this question, substantive studies and models have been developed over the past years. This literature review will highlight different models that explaining the main relationship between carbon emissions and its drivers.

2.3.1 Kaya identity

Many factors such as economic and demographic developments, technological change, resource, institutional frameworks, lifestyles and international trade influence GHG
emissions. The Kaya identity is an analytical tool that is mainly used to explore the main driving forces behind CO₂ emissions [138-139]. It is illustrated by the following formula:

\[
\text{CO}_2 = P * \frac{\text{GDP}}{P} * \frac{\text{Energy}}{\text{GDP}} * \frac{\text{CO}_2}{\text{Energy}} \text{ or } \frac{\text{CO}_2}{\text{GDP}} = \frac{\text{Energy}}{\text{GDP}} * \frac{\text{CO}_2}{\text{Energy}} \tag{Eq 2.1}
\]

Where, CO₂ represents carbon emissions from fossil fuel, wood and nuclear power. P represents the total population of a given country and finally, Energy represents primary energy consumption. The Kaya identity could be used to measure the influences of energy intensity (Energy/GDP) and carbonization index (CO₂ /Energy) or emission intensity (CO₂ /GDP). As presented, the Kaya factors approach is flexible and rather easy to use and it allows the main driving forces of CO₂ emissions to be decomposed. It can also be used to forecast future CO₂ emissions levels when all factors considered are known. However, the Kaya identity has a couple of limitations. One of these limitations is that it is just a multiplicative identity and therefore assumes proportionality between the effects of the different factors ceteris paribus. In addition, these main driving forces may not be independent of each other, leading to possible inter correlation between different parameters. For example a country with greater economic growth might develop more efficient technologies because of its high capital turnover therefore, resulting in lower energy intensities [277]. As a result, the Kaya identity is not a suitable indicator to fully assess Burkina Faso carbon emission drivers.

### 2.3.2 IPAT and STIRPAT

The IPAT model emerged out of the Ehrlich-Holdren/Commoner debate in the early seventies (1970) about the principle driving forces of anthropogenic environmental impacts.
It continues to be widely utilized as a framework for analysing the driving forces of environmental change [239].

Ehrlich et al. (1971) used the IPAT initial model to attempt to answer the question: Are wealthy countries responsible for the increasing stress on the global environment, or is it the exponential growth of populated cities that is responsible? The model has been since modified a multitude of times. It specifies that population and consumption are interrelated phenomena which foster environmental degradation. Their initial model was illustrated by the following formula:

\[ I = P \times F \quad \text{Eq. 2.2} \]

Where I is total impact, P is population and F is the per capita impact [55] [140]. The relationship shows that population is not only a key factor, but that spatial difference in per capita impact suggest that environmental impact is not a uniform function. Highly industrialized places are likely to have a higher F, and therefore greater contribution to environmental change, given a constant population. However, Commoner et al. (1972) argued that this formula is incomplete [141]. They did not deny the fact that population plays an important role in environmental degradation. However, they argued that consumption, wealth and development were the components of anthropogenic impact on the environment that should be tackled first. Population might still be an issue, but it still take decades to bring population growth under control. Countries like China (with its one child policy) and India have been struggling for decades to control their population growth. They have been unsuccessful in many ways. Affluence and technology were added to the model in order to address these shortcomings, leading to the now widely recognized IPAT identity formula for analysing the effects of human activities on the environment:
\[ I = P \times A \times T \quad \text{Eq. 2.3} \]

Where \( I \) is the environmental impact, \( P \) the population, \( A \) the affluence (per capita GDP), and \( T \) is the level of environmentally damaging technology (impact per unit of consumption or production) [141].

The IPAT equation represents a useful tool to assess anthropogenic impact on climate change [10]. However, this model has been subject to several criticisms [142-143]. Waggoner et al. (2002) revised this model by separating the consumers’ choice (C) from the producers’ accomplishment (T). The equation is then transformed into \( I = PACT \) and they renamed it ImPACT. ImPACT simply shows that changing environmental impact means changing four multiplying forces: the number of people, the economic force, the fraction of economic activity devoted to a good, and the impact of making the good [143].

For example, to assess CO\(_2\) emissions using the traditional IPAT identity would indicate that total emissions (\( I \)) are the product of population (\( P \)), per capita GDP (\( A \)) and CO\(_2\) emissions per unit of GDP (\( T \)). In contrast, the ImPACT model assumes that total CO\(_2\) emissions is the product of population (\( P \)), per capita GDP (\( A \)), energy consumption per unit GDP (\( C \)) and CO\(_2\) emissions per unit of energy consumption (\( T \)). The main objective of the ImPACT model is to identify the key factors that could influence each factor in order to reduce their autocorrelation factor. The key limitation of IPAT and ImPACT is that they do not allow hypothesis testing. Furthermore, they assume proportionality in the relationship between factors. For instance, the models assume that doubling of population will lead to doubling of impact, all else held constant [9].

Schulze (2002) considered that the IPAT equation was useful as a starting point for extracting the drivers of climate change [144]. However, he was concerned that the equation fails to
give sufficient emphasis on the role of behaviour (B). Therefore, he proposed that behaviour (B) should be introduced into I = PAT, to give I = PBAT. He argues that people may be driven by change in their own behaviour. That could lead to reduction in affluence or more efficient technology that reduces environmental impact [144]. However, the solution proposed by Schulze makes the model more complex. It adds a new term without any indication of how such a term could be calculated. Introducing a new term B (behaviour), which is difficult to quantify does not solve the limitation of the IPAT but may also introduce greater confusion. Schulze’s approach has also been subject to enormous criticisms. Diesendorf (2002) argues that some aspects of behaviour are implicitly involved in each factor Population, Affluence and Technology. Thus, B could only represent those aspects of behaviour that are not already included in P, A and T. Therefore, it makes B very difficult to define precisely [145].

On overall the main criticism and key limitation of I = PAT, I = PBAT, or I = PACT model is that it assumes proportionalities between drivers and does not allow hypothesis testing. It is not possible to test non-proportional impact of the driving forces while using these models. Therefore, to overcome this limitation, the IPAT model has been transformed by Dietz and Rosa (1994) into a stochastic model STIRPAT. STIRPAT means Stochastic Impacts by Regression on Population, Affluence, and Technology [9]. The equation of the STIRPAT model is as following:

\[
I_{it} = aP_{it}^b A_{it}^c T_{it}^d e_i \quad \text{Eq. 2.4}
\]

The STIRPAT model still keeps the multiplicative aspect of the IPAT and uses population (P), affluence (A) and technology (T) as drivers of environment change (I). However, the model suggests that I, P, A and T vary across observational units and b, c, and d are the
exponents of P, A, and T, respectively while e represents the error term [9]. After taking logarithms, the model takes the following form:

$$\ln I_{it} = a + b \ln P_{it} + c \ln A_{it} + d \ln T_{it} + e_i \text{ Eq. 2.5}$$

Where $I_{it}$ represents impact (CO$_2$ emission), $P_{it}$ represents the total population, $A_{it}$ is the affluence and it represents the GDP per capita, $T_{it}$ represents the technology which refers to energy intensity, that is energy use per constant 2000 PPP$ GDP (kg of oil equivalent per constant 2000 US$), $a$ is a constant and $e_i$ the error term. The unit of analysis is the country, the subscript $i$ denotes the country, $t$ represents the year. The use of logarithms in the initial STIRPAT model gives a linear relationship between population, affluence and technology. The additive regression model (Eq.2.5) in which all variables are in logarithmic form facilitates estimation and hypothesis testing. The STIRPAT model has been successfully validated and widely used to analyse the effects of driving forces on environmental impacts [57-62].

Several studies agree on the robustness of the STIRPAT model as analytical tool but propose that it could be improved to further develop its utility for empirical analyses. In this respect, Shi (2003) advocates that difference in energy intensity or emissions intensity ($T$) could be due to the difference in economic structure of each country [10]. Therefore, $T$ can be disaggregated by including additional factors that influence impact per unit of production. Economies with GDP mainly from manufacturing will be energy-intensive and will produce higher emissions while economies that GDP is largely derived from services will be less energy-intensive and will produce lower emissions [10]. As a result it was suggested that percent of manufacturing ($M$) and percent of services ($S$) be used in order to capture the difference in $T$. Therefore, transforming the STIRPAT model into:
\[ \ln I_{it} = a + b \ln P_{it} + c \ln A_{it} + d \ln M_{it} + f \ln S_{it} + e_{it} \text{ Eq. 2.6} \]

It is important to point that consumers from one country influence emission in another (Consumption based accounting). However, this particular aspect wasn’t covered by the STIRPAT model and is beyond the scope of this present research. Furthermore, the impact of urbanisation on primary energy emission was also investigated in Shi (2003) research. Urbanisation (U) as percentage of total population living in urban areas was included in STIRPAT model as a driving factor. Therefore, the STIRPAT model could be defined as following:

\[ \ln I_{it} = a + b \ln P_{it} + c \ln A_{it} + d \ln U_{it} + f \ln T_{it} + e_{it} \text{ Eq. 2.7} \]

The population of developing countries is growing at an exponentially rate and emissions from urban areas are by far more important than rural areas one. Unemployment and difficult conditions in rural areas lead to massive immigration which results in an increasing urbanization. This research will investigate the impact of population and urbanisation on CO\(_2\) emission from primary energy consumption in Burkina Faso. That will provide an overall understanding of the extent to which the rapid population growth could have an impact on primary energy consumption.
2.4 STIRPAT application and validation

The STIRPAT model has been extensively used to estimate the level of climate change driver’s impact on carbon emissions.

2.4.1 Population impact on emission

Dietz et al. (1997), Shi (2003) and York et al. (2003) in their respective studies used the STIRPAT model to analyse the correlation between population and its impact on the environment [9-10]. York et al. (2003) have shown that population has a roughly proportional relationship with emissions. However, the study suggests that the non-dependent population (population aged between 15 and 65) has a significant effect. As a result, a population with higher proportion of non-dependent population will result in higher emissions [57-59]. Shi (2003) conducted empirical research based on a data set of 93 countries over the period between 1975 and 1996. The study specifically, looked at the impacts of changes in population, income level, and energy efficiency of economic production on emissions. The findings show that on average, a one per cent increase of population growth is associated with a 1.41 to 1.65 percentage increase in emissions. However, the results highlighted the fact that the impact of population pressure on emissions has been more pronounced in developing countries than developed countries [10].

In the same order, Ying et al. (2006) analysed the impact of population on total CO₂ emissions of countries at different income levels over the period between 1975 and 2000. The results show that the impact of population on emission is greatest at the upper – middle income countries, followed by the low income countries and it is the least at the lower – middle income country. In addition, the portion of the population aged 15-65 has the greatest
impact on emissions. However, the impact is negative at the high income countries while it is still positive at the lower income countries. Due to their awareness on environmental issues and energy efficiency, the labour force in high income countries are likely to use less energy and therefore, less impact on the environment [60-62]. Altogether, these findings emphasize the fact that population’s impact on CO₂ emissions varies at different levels of development. Thus policy-makers should consider these issues fully when constructing long-term strategies for CO₂ abatement. The findings of these different studies are all in agreement and suggest that population growth has a positive correlation with environmental impact. The results also suggest that the STIRPAT model could be confidently used to assess population growth impact on environment for any given country.

2.4.2 Urbanization impact on energy consumption

Urbanization is a socio economic phenomenon. It is a process of transferring rural labour based on agriculture to urban areas where industrial and service sectors dominate. According to the UN (2008), the world has undergone rapid urbanization in recent decades, with the world urban population increasing from 1.52 billion in 1975 to 3.29 billion in 2007. Furthermore, the urban population is projected to double to about 6.4 billion by 2050 [65]. To support such unprecedented growth, additional urban infrastructure will inevitably be needed. In 2006, it was estimated that cities consumed about two-thirds of global energy while emitting more than over 70% of total carbon dioxide (CO₂) emissions [66]. The relationship between urbanization and various environmental issues, including energy use and emissions, has been studied extensively in recent years [58-59].

In this respect, Cole and Neumayer (2004), Jones (1991) and York (2007) have shown that urbanization growth results in energy demand increases and as a result generates more
However, other scholars argue that urbanization and urban density improve the efficient use of public infrastructure such as public transport thus, lowering energy use and emissions [68-70]. The disagreement in the literature can be attributed to differences in methodologies and data. There are studies that assume the impact of urbanization on energy use and emissions is homogeneous for all countries. These types of assumptions can be biased as there are many characteristic differences among countries which enjoy different levels of wealth [71]. Jones (1991) used a national level analysis with cross-sectional data, to derive a positive correlation between urbanization and energy use per capita, noting that while urbanization enabled cities to benefit from economies of scale in production, it increased transport energy use and energy use per unit of output. Moreover, York et al. (2003a) use the STIRPAT model, and found that urbanization has a positive impact on national energy consumption and carbon emissions [57] [67].

Liu (2009) using China data for the period between 1978 and 2008 found that urbanization increases energy use, but the scale of the influence is declining [72]. Therefore, Liu attributed this decreasing influence to improvements in industrial and technological structure and more efficient utilization of resources. Similarly, Holtedahl et al. (2004) demonstrate that urbanization increases residential energy consumption for two reasons. First of all, population moving to urban areas increases their household accessibility to electricity. Second, households that had previously access to electricity in rural areas may increase their energy consumption after moving to urban areas by using existing electric appliances and after the purchase of new items only available in cities [73]. Parikh et al. (1995) provided an analysis of the effect of urbanization on energy consumption as well as its impact on greenhouse gas emissions in developing countries. They demonstrate that urbanisation increases the per capita energy consumption and that urbanization affect the energy uses in three ways. First of all, it shifts the energy use from traditional fuels to modern fuels; second,
it increases the embodied energy consumption through goods and service demands and through transport consumption [74]. Their results for the period 1965–1987 indicate that a 10% increase in a country's urban population leads to a 4.7% rise in its per capita total energy consumption. The effect on CO₂ emissions is only calculated with 1986 data and it is somewhat lower: a 10% increase in a country's urban population leads to a 0.3% rise in its per capita CO₂ emissions. Following that, Cole et al. (2004) also demonstrate that urbanization growth leads to an increase of CO₂ emissions. However several other scholars held an opposite point of view illustrated in their research.

In this respect, Mishra et al. (2009) showed that the relationship between urbanization and the per capita energy consumption was negative in New Caledonia [75]. In addition, using the Environmental Kuznets Curve (EKC) model with OECD data, Liddle (2004) found that urbanization and population density negatively affect the per capita road transport energy use [76]. It implies that populous and highly urbanized cities have less demand for personal transport. Likewise, Newman et al. (1989) examined the relationship between urban density and transport energy use. They found using 32 cities data in high-income countries that high urban density is associated with less per capita transport energy use [77]. Moreover, Dodman (2009) has shown that per capita greenhouse gas emissions of numerous wealthy cities were far lower compared to the national average because of two main reasons. First, most of these cities have highly dense building with relatively small average household sizes. As a result it requires less energy for heating, lighting and cooling compared to those in suburban or rural areas. Second, these cities have better public transport systems [78].

For the specific case of a developing country such as Burkina Faso the study by Pachauri shed a light on urbanisation growth impact. The Pachauri (2004) study conducted at the domestic dwelling level shows that per capita household energy consumption in urban areas
in India were higher than the rural one. However, the investigation of the impact of household expenditure, size and attributes, urban residents had lower energy requirements than those in rural area [79]. Moreover, Pachauri et al. (2008) also found similar evidence and proposed two reasons to explain the difference between urban and rural household energy consumption. First, these observations are due to the continued reliance on inefficient solid fuels such as biomass, charcoal in rural areas. In addition, rural households shift from inefficient solid fuel use to more efficient one after moving to urban areas [80]. Urbanization increases urban density and modern fuels are producing less indoor air pollution compared with traditional fuels. That result in an overall emissions reduction from urban household [80].

Despite the conflicting results from the above literature, most of the investigations suggest that urbanization increases energy use and emissions. The negative elasticity between urban density, energy use and emissions is based on studies at the city level.

This research will investigate at a broader scale Burkina Faso’s rapid population growth and urbanisation impacts on its emissions as well as its energy consumption. However, the research will particularly focus on energy consumption in the built environment.

2.5 Test Reference Year (TRY)

Due to the growing concern about energy consumption and environmental impact, interest in passive energy efficient buildings and renewable energy has increased significantly. Therefore, building energy simulation is becoming an important part in the design of new efficient buildings. These simulations required complete long-term climatic data of the studied area. Long-term data of weather parameters that influence climate are required for complete climatic study of any given area. For climatic studies, the mean monthly values of
weather parameters are calculated in order to give an estimate of the mean annual variation of these parameters. Although mean annual cycles are indicative for the climate of an area, they are impractical since a smooth annual course hardly ever exists [83]. There are maximum and minimum Daily? values fluctuating continuously. Especially when temperature is the main parameter considered. Almost every year some extreme daily and monthly values are recorded causing considerable deviations of the annual cycle from the climatic mean. Building engineers, architects and climatologists consider the usefulness of the mean annual variation of a parameter as very limited. Thus, a representative year consisting of raw and not averaged data is preferable [83].

The above problem is solved by deriving the so called Test Reference Year (TRY) or Typical Meteorological Year (TMY), which is a synthetic year consisting of twelve months of real data each but not belonging necessarily to the same calendar year [174]. The TRY describes the climatic conditions of the studied area. The TRY was selected purely by taking the actual occurrence of the relevant month that has the smallest value of the Finkelstein–Schafer (FS) statistic. This method is simple and produces selected months with the desired statistical properties. The FS statistic [84] measures the similarity of two distributions. When two distributions are similar its value is small, and when they are identical its value is zero. In selecting a TRY, the FS statistic may be used to compare the distribution of the chosen variable in an actual month to its long-term distribution in that month. If the FS statistic for an actual month is small then the actual data will have similar mean, median, mode, standard deviation, percentiles, and other statistics to the long-term data for that month [85]. The adequacy of using an average or typical year of meteorological data with a simulation model to provide an estimate of the long-term system performance depends on the sensitivity of system performance to the hourly and daily weather sequences. Regardless of how it is
selected, an “average” year cannot be expected to have the same weather sequences as those occurring in the long term. However, the simulated performance of a system for an “average year” may provide a good estimate of the long term system performance if the weather sequences occurring in the average year are representative of those occurring in the long term, or if the system performance is independent of the weather sequences.

Levermore et al. (2002) and Lee et al. (2010) argued that the most common form of data in buildings energy simulation softwares is in a form of a test reference year [81-82]. For building energy simulation program, using the most typical year from a 20 years data set avoids having to run a simulation with a 20 years hourly data for weather parameters. The TRY will be used in this research as the time frame for future energy consumption simulation in Burkina Faso built environment.

2.6 Building energy simulation program

There is a rapid growing demand for better energy performance in buildings. That leads to an on-going development of strategies and technologies to improve energy efficiency in construction without compromising on comfort, cost, aesthetics and other performance considerations [86]. As performance issues like comfort and energy efficiency are becoming an important issue, the capabilities of building simulation programs are increasingly in demand to provide more and more information for decision makers during the building design process. Therefore, this need triggered the development of design advice tools where the common objective is to facilitate the use of building simulation in the design process [89].

Choosing an appropriate combination of design and performance options is a complex task for building designers. There exists a risk of missing design opportunities which could lead to
a better performance. Making informed design decisions requires the management of a large amount of information on the detailed properties of design options and the simulation of their performance [89]. Therefore, computer-based building simulation tools are ideal for this. Over the past 50 years, a wide variety of building energy simulation programs have been developed, enhanced and used throughout the building energy community.

The commonly used energy performance simulation programs used by engineering consultants are DesignBuilder [165], Hevacomp [166], IES Virtual Environment [43] and Tas Building Designer [167]. Two of these programs, DesignBuilder and Hevacomp, in effect represent user interfaces using the simulation engine EnergyPlus [168] which is open-source code software without an extensive graphical interface published by the U.S. Department of Energy. By contrast, both, IES Virtual Environment and Tas Building Designer use individual calculation cores which consist of a suite of underlying software products.

A study by Crawley et al. (2006) summarises building energy software development describing 20 major building simulation programs. The comparison is based on information provided by the program developers and their performance. The study indicates that there was not a common language to describe what the tools could do. In addition, there was much ambiguity which will continue to require additional work to resolve in the future for several programs [87-88]. The reason is that building simulation tools often are a product of research activities. Many available tools are developed by researchers, for research purposes. As a result, the tools are not easy to use, as they require a significant level of expert knowledge. However, out of these 20 programs, the IES VE software alongside with EnergyPlus emerged as one of the best tool for building energy simulation. Moreover, the IES VE program has been validated through several studies by comparing simulated result to observed field data [274-275]. Nedhal et al (2011) compared the output of IES VE simulation results for the fieldwork data and the simulation was proven to be very reliable [276]. IES VE represents a
valuable tool for engineers, architects and policy makers to evaluate future building energy consumption before the building is even built. It can also be used to study the impact of building modifications on building energy use. Alternative designs or materials can immediately be evaluated to see how much they affect the annual energy consumption. This could lead to selecting energy efficient designs without sacrificing indoor thermal comfort. For all these reasons, the IES VE will be selected as building energy simulation tool for this research. This program will be investigated in details and validated through a robust process in Chapter 7.

2.7 Buildings thermal performance and climate change

Simulations of climate change impact on buildings have been mainly based on the impact that future weather conditions will have on buildings thermal performance. Such predictions of future performance have uncertainties, related to climate conditions, the future operational conditions of the building, as well as interventions in the building fabric and systems [241]. Therefore, in order to improve the sustainability of buildings one of the challenges is to address the role of the building envelope which is a key climate moderator between the internal and external environments.

Battle et al. (1999) argued that the primary function of a building is to provide a secure shelter from its occupant, regardless of the climatic zone where it is located [242-243]. A building’s facade, which acts as the primary climate moderator, is a key component in ensuring comfortable indoor conditions [244]. Likewise, Coch et al. (1998) in his research has shown that over the centuries the facade, in vernacular architecture, has been optimised according to specific regions and climates [245]. He also argues that temperature levels and
the availability of sunlight play key roles in determining the architectural appearance of traditional building forms. It is therefore, possible to distinguish between daylight architecture as it is found in central Europe and the sunlight architecture of hot arid climates. Daylight architecture is characterised by window openings of a large height to maximise daylight penetration into the building. However, sunlight architecture tries to avoid solar gain by using small windows such as those of the traditional adobe house window opening in Burkina Faso.

For centuries, window glass was an expensive product and therefore large glazed areas were seen as a visible indicator of the wealth of a building owner. Bahaj et al. (2008) affirmed that in the UK between 1696 and 1851 building taxation was imposed based on the number of windows above 6 on the main façade [246]. This wealth indicator tradition continues today with glass still being considered to be a prestigious material especially in developing countries such as Burkina Faso. Furthermore, glazed buildings have been associated with positive values such as openness, transparency, inside/outside connection, freshness, modernity and brightness [246].

However, Askar et al. (2001) highlighted the fact that highly glazed buildings constructed in Europe and America within the modern architecture movement at the beginning of the 20th century soon revealed negative effects in terms of indoor comfort [247]. Buildings were difficult to heat in winter and tended to overheat in summer. This was compensated by advances in central heating systems, glazing technology such as double glazing with low U-value and the invention of air conditioning systems at the beginning of the 20th century [247]. These technologies as a result, enabled the construction of fully glazed skyscrapers, as first conceived by Van der Rohe in the 1920s [248]. However, extensive utilisation of heating and cooling facilities to compensate for the negative effects caused by large glazed areas
implicitly leads to high energy consumption and, increasingly, high costs. Nevertheless, highly glazed buildings, which have their roots in daylight architecture, have become standard for non-domestic constructions such as offices buildings in Burkina Faso which historically is a sunlight architecture country.

Henning et al. (2004) have shown that in Germany, highly glazed buildings such as glass towers in particular consume large amounts of energy. In addition, they are exposed to the risk of having an uncomfortable room climate if full mechanical cooling system is not provided [249]. However, based on the Jumeirah beach hotel case study in Dubai, Bahaj et al. (2009) have shown that the cooling load could be reduced in glazed buildings using reflective Holographic Optical elements HOE [246]. The study predicts that for fixed glazing, reflection HOE could significantly reduce the annual air conditioning loads by approximately 16%. This is a third of the level that can be achieved using radiation blocking external blinds. HOEs are light guiding elements made of a holographic film laminated between two sheets of glass. Direct sunlight incident on a facade is redirected at a predefined angle through diffraction at the holographic interlayer [249]. The view from the window remains relatively unobstructed and the HOE glazing can be incorporated into the normal facade construction. Moreover, Green (2006) predicted that glazing integrated thin film PV solutions are potentially the most promising solution for fully glazed buildings in hot regions such as the Middle East, especially if the goal of a 60% efficient, third generation cell can be achieved [250]. The simulations predict that such a PV solution covering about 40% of the area of a fully glazed high rise building in the Middle East would yield a net energy gain over the air conditioning loads. This could help to create truly sustainable glass buildings in hot, arid climates by saving fossil fuel for their operation. However, due to the fact that the materials
are not produced locally, this solution might not be ideal for Burkina Faso. The high level of cost linked to manufacture and transportation make it unsustainable for the local economy.

Climate change is expected to have significant impact on the future thermal performance of buildings to varying degrees depending on the scenarios (discussed later). Building simulation can be employed to predict these impacts, guiding interventions to adapt buildings to future conditions. In this respect, studies covering single building types for specific locations are proliferating [251-253]. The overall conclusions of these studies are well articulated by Crawley [254] who studied the impact of climate change on a small office building, with ‘low energy’ and ‘developing country’ variants, at the 25 locations all over the world covered by his climate data work. He stated that the impact of climate change will result in reduction in building energy use of about 10% for buildings in cold climates, an increase of energy use of up to 20% for buildings in the tropics, and a shift from heating energy to cooling energy for buildings in temperate climates. More recently, further work has started to appear that deals with the impact of climate change on specific building systems, especially ventilation [255].

In this research, the appropriateness of large glazed buildings in Burkina Faso has been investigated in the context of climate change. Thermal performance of different type of modern buildings has also been addressed in order to outline appropriate thermal comfort solutions.
2.8 Adobe dwellings

The continuous search for better sustainable and economic processed solutions has been receiving the attention of a broad research community worldwide. The building industry is not immune to this reality and huge efforts have been done in order to find alternative sustainable building materials and low technology methods which result in a more sustainable and affordable construction, complemented with the comfort standards required nowadays. CO₂ emissions to the atmosphere, energy and water consumptions are some parameters that have significant impact in this equation. Reusing, opting for green building materials (which must be renewable, local, and abundant), retrofitting, choosing low technology methods and techniques are some practices that have given good results in this context. Adobe houses present a huge potential in this respect. Adobe (Earth or mud) is a cheap, environmentally friendly and abundantly available building material. It has been used extensively for wall construction around the world, particularly in developing countries [113]. The soil used in adobe construction consists only in its mineral phase excluding the organic phase usually present in the first layers. This phase consists of mineral particles including clays, silts and sandy material, which are mixed together in varying proportions. The soil stabilization means changing the soil characteristics in order to improve its mechanical or physical behaviour. The stabilization processes aim at the reduction of the soil plasticity, improvement of its workability and also the resistance to erosion. In this respect, Burroughs (2008) [114] analyzed 104 soil types, compacted and stabilized with lime or cement in a total of 219 mixtures. According to this author a soil could be considered suitable for stabilization if its compressive strength exceeds 2 MPa. Moreover, molasses, cow-dung and saw dust could also be used to stabilize adobe bricks [115]. Binici et al. [116] shows that using straw fibers in adobe bricks reduces the compressive strength. Nevertheless, the compressive strength is dependent on the brick dimensions. In this respect, Piattoni et al. (2011) demonstrate that a
15x23x13cm adobe bricks with straw are reaching on average a strength of 2.5 MPa [117-118].

Adobe houses might have been used over 9000 years ago according to Minke (2006) [107]. The results show that earth blocks based dwellings discovered in Turkmenistan dated from a period between 8000 and 6000 BC. Other authors mentioned that the use of earth for construction purposes dates from the period of El-Obeid in Mesopotamia (5000–4000 BC) [108]. According to Berge (2009) the oldest adobe blocks, were discovered in the Tigris River basin date back to 7500 BC so earth construction could have been used for more than 10,000 years [109]. In 1990 approximately 30% of the world’s population lives in adobe based dwellings as reported by Cofirman et al. (1990) [110-111]. The majority of adobe construction is located in less developed countries, however, this kind of construction can also be found in Germany, France or even the UK which has an excess of 500,000 earth based dwellings [112]. Earth construction has also increased substantially in the US, Brazil and Australia largely due to the sustainable construction agenda, in which the earth construction assumes a key role.

For developing countries the cost-efficiency aspect of building construction remains of paramount importance. Zami and Lee (2010) [119] in their study quotes several authors for whom adobe construction is economically beneficial, nevertheless they suggest that one cannot take this as a guaranteed truth because the economics of adobe construction depends on several aspects such as: construction technique, labour costs, stabilization process, durability, repair needs. Williams et al. (2010) study has shown that materials used in earth construction in the UK do not have a significant impact in the final cost [120]. This study highlighted the fact that production and construction costs represent the most important part because adobe construction is labour intensive. However, this is not the case in less developed countries in which labour is available for a very low cost. According to Sanya
(2007) this provides a very important way to create decentralized jobs [121]. For developing countries the cost-efficiency is function of the nature and the amount of binder used in the stabilization process.

Miguel et al.’s (2008) study results indicate that the use of adobe construction and vernacular passive techniques give more comfort and are more economic than present lightweight buildings by a very wide margin. This research has shown that important energy savings can be obtained from incorporating adobe brick in outside walls in dwellings destined for the poor or lower income housing tenants. Passive techniques derived from that choice, including recessed windows and doors, contribute to the savings over the years, by shading windows from the sun’s rays. The research also points out that it is important to underline that adobe walls are about 5.1 times thicker than concrete block walls. In addition, the mathematical model they developed validated with experimental results projects very important savings in electrical requirements for power air conditioners, when adobe walls are employed instead of concrete block walls [122]. The savings have a present value of several times the going price for small, working class dwellings.

The continuous onward trend of urbanisation and the continuous growth of industrialisation throughout the world together with the increasing living standards have turned the creation of the built environment into a rising threat to the natural environment. Buildings account for one-sixth of the world’s freshwater withdrawals, one-quarter of its wood harvest and two-thirds of its material and energy flows [123]. Several papers [124-127] have highlighted the environmental benefits that are associated with adobe construction. Adobe construction is associated with low embodied energy, low carbon dioxide emissions and very low pollution impacts. The use of cement for soil stabilization increases embodied energy and CO₂. Adobe construction is also responsible for an indoor air relative humidity beneficial to the human health. Using mud bricks with lower densities will prevent energy loss from buildings.
Moreover, fibre reinforced adobe brick house has been found to be superior in keeping indoor temperatures stationary during the summer and winter. However, adobe dwellings have some limitations. Samar (2011) has conducted a research on adobe houses in Gaza (Palestine). The research finds that the overwhelming majority of the population think that adobe dwellings are for poor people and non-aesthetic. The acceptance of the population has proved to be the main barrier of adobe development [211]. In addition Cassell (1993) has shown that adobe dwellings are performing poorly in a situation of flooding and earthquake [256].

Despite the drawbacks, the majority of studies have shown that adobe construction has clear competitive advantages in the field of sustainability over conventional construction assuring it a promising climate change adaptation measure for the coming years. Therefore, there is value in understanding and applying attributes seen in ancient vernacular architecture to new buildings

2.9 Climate change adaptation measures

Global warming poses one of the most challenging threats to our planet. As the IPCC (2007) points out: “Societies can respond to climate change by adapting to its impacts and by reducing GHG emissions (mitigation), therefore, reducing the rate and magnitude of change”. Climate policy analytically comprises two different pillars: mitigation and adaptation to climate change [5]. In the early days of climate policy, research focused strongly on mitigation strategies. It is largely acknowledged that significant greenhouse gas (GHG) emission reductions have to be achieved in order to effectively combat the threat of global warming. According to Edenhofer et al. (2011), such reductions require a comprehensive global effort which includes both a complete change in the energy supply of industrialized countries and the establishment of low carbon systems in developing countries and emerging markets [90]. Industrialized and developing countries face the same challenge: Welfare
threatening global warming and the risks attached can only be prevented if both groups of countries participate in international mitigation efforts [91].

According to Stern (2007), while mitigation policies are global public goods because merits are non-excludable and there is non-rivalry in the consumption of these merits the adaptation impacts however, are mainly local or regional [92]. Thus, in contrast to mitigation, the benefits of adaptation are excludable (Barrett 2008) from individual countries point of view. As long as adaptation measures mainly yield excludable benefits, international free-rider incentives do not arise and it is in individual countries’ own interest to produce efficient adaptation measures because international coordination between countries is not required [93-94].

It is also probable that climate change could exacerbate current inequities due to the uneven distribution of damage costs, in addition to the cost of mitigation and adaptation efforts. Munasinghe et al. (2000) advocate that from a developing country perspective, it is essential that global agreements evolve on the basis of considerations of fairness and those developing countries participate actively in shaping and implementing the next steps toward mitigation and adaptation [95]. Broad participation in mitigation efforts opens the possibility to limit damage costs. In contrast, slow progress in mitigating global GHG emissions implies that climate impacts will constrain the potential for economic development in some of the poorest of developing countries [95]. Moreover, future agreements on mitigation and adaptation will need to recognise the diverse situations of developing countries with respect to their level of economic development, their vulnerability to climate change and ability to adapt to or mitigate it. Beg et al. (2002) suggest that economic growth and poverty reduction are clearly the main priorities for developing country policymakers, yet climate change mitigation can offer these countries the opportunity to revisit development strategies from a new perspective. Climate change considerations place renewed urgency on some options, such as
energy efficiency, renewable energy, and sustainable land-use policies, and argue for better understanding the connections to other environmental problems. They also argue for improving the integration of environment and development issues along with other issues, such as income distribution [96].

Schelling’s (1992, 1995) studies draw the attention to the fact that greenhouse gas emission abatement would primarily benefit the grandchildren and great-grandchildren of the people living in currently less developed countries. He has questioned whether there are not better ways of helping these developing countries [97-98]. Likewise, Tol (2001) analyses this issue from the narrow perspective of climate change impacts. He wonders if a dollar spent on emission abatement reduce impacts more than a dollar spent on facilitative adaptation. The result shows that Africa and Latin America would prefer money to be spent on development rather than on emission reduction [99].

Moreover, in the development of strategies and scenarios for mitigating climate change, the development of renewable energy resources could play a significant role. Economic development has been so far associated with huge volume production, mass consumption and mass disposal, with severe environmental cost. Solar and wind energy offer the advantage of providing clean and renewable energy close to the consumer and even at point of use and emit absolutely no CO₂ in the generation of electricity [278] although they do have embodied CO₂. Utilization of solar and wind power has become increasingly significant, attractive and cost-effective, since the oil crises of early 1970s [101]. However, a well-known difficulty with solar and wind energy is their unpredictable nature. They both entirely depend respectively on sunshine and wind speed and, in general, the variations of solar and wind energy do not necessarily match with the consumer energy demand, e.g. there is no solar and therefore PV electricity at night. Thus independent use of standalone photovoltaic (PV) or
wind energy systems without battery or diesel generator backup would result in larger PV and wind systems which make the design costly [102].

Overall, the above literatures show that mitigation of greenhouse gases can be viewed as a public good and adaptation to climate change as a private good, benefiting only the country or the individual that invests in adaptation. Dang et al. (2003) advocates that given the fundamental distinctions between mitigation and adaptation options, trying to simply amalgamate the two options and achieve double benefits from each action to reduce GHG emissions or adapt to climate change is not realistic at either the national or global scales [103]. Moreover, a “forced marriage” strategy may be counterproductive as it could depress the global effort to pursue the long-term objective. He rather asserts that adaptation is not necessarily opposed to mitigation, or a substitute for it, as many adaptation options are also pathways towards effective and long-term mitigation and, in turn, several mitigation options can facilitate planned adaptation as well. Therefore, if a comprehensive national climate policy could strike a rational balance between mitigation and adaptation instruments that maximises the potential synergies between them, climate policies could become socially and economically efficient and may offer greater opportunities for countries to achieve sustainable development targets despite the large scientific uncertainty. This is especially important given the limited financial and human resources in developing countries such as Burkina Faso.
Chapter 3 Methodology

The main objective of this research is to help mitigate the emissions from new buildings and adapt the existing built environment to the projected climate change and rapid population growth which will trigger an increase in energy demand for cooling. Fig.3.1 outlines the methodology used in this research in order to achieve the objectives. The first stage of this research consists of outlining the impact of population growth on the projected future energy consumption. The STIRPAT model has been used at this stage to find out the drivers of primary energy consumption emission as well as energy consumption. The performance of this model has been tested using a robust multiple regression method. The second phase of this research consists of assessing the projected climate change impact on Burkina Faso by comparing projected HadCM3 data to the observed historical data. Therefore, Test Reference Years (TRYs) developed from the projected HadCM3 data and historical data has been compared. This process gives an overview of the long term climate change in the country. The projected HadCM3 TRYs have been considered as weather parameters data for future energy consumption simulation. The IES VE energy simulation program has been used for the simulations. This program has been validated with CIBSE test data and a simple first order model based on heat transfer equations known formulas and field work data collections. The final stage of this research consisted of the data analysis and outline of climate change adaptation and mitigations measures. Field work findings were also added at this final stage. Furthermore, HOMER a computer program that optimizes small, local energy production systems has been used to assess the optimal configuration which lower energy cost and increases the national coverage of electricity.
It has been possible to outline recommended solution both for existing and new buildings based on the methodology of this research. Methods and their rationale are given in the subsequent thematic chapters.

Figure 3-1 Flow diagram of methodology
Chapter 4 Geography, Population, Climate and Economy

4.1 Geography

Burkina Faso (Fig. 4.1) is a landlocked Sahel country in West Africa that shares borders with six nations. Burkina Faso is bordered by Mali to the North, Niger to the Northwest, Ivory Coast and Ghana to the South, Togo and Benin to the Southeast. It lies between the Sahara Desert and the Gulf of Guinea, south of the loop of the Niger River. The main latitude and longitude of Burkina Faso is 13° North and 2° West. The land is green in the south favourable to agriculture, with forests and fruit trees, and desert in the north. Most of central Burkina Faso lies on a savanna plateau, 198-305 meters (650-1,000 ft.) above sea level, with fields, brush, and scattered trees. The country covers 274,200 square kilometres and is administratively divided into thirteen regional districts each administrated by a Governor, forty five provinces and three hundred and one communes. Burkina Faso has a democratic elected government since 1991. The constitution of June 2, 1991 established a semi-presidential government with a parliament (Assemblée) which can be dissolved by the President of the Republic, who is elected for a term of five years.
Figure 4-1  Map
4.2 Climate

Burkina Faso is a semi desert sub-Saharan African country located about 1000 km from sea. It has a primarily tropical climate with two very distinct seasons. In the rainy season, the country receives between 600 and 900 millimetres of rainfall, and in the dry season, the harmattan, a hot dry wind from the Sahara, blows. The climate is characterized by high temperatures, especially at the end of the dry season. Three climatic zones can be defined: the Sahel, the Sudan-Sahel, and the Sudan-Guinea. The humidity increases as one moves south. It ranges from a winter (November to February) lows of 12% to 45% to a rainy season (June to September) highs of 68% to 99%. The harmattan, a dry east wind, brings with it spells of considerable heat from March to May, when maximum temperatures range from 40°C to 45°C. From May to October, the climate is hot and humide, and from November to March, comfortable and dry with average temperature between 20°C to 35°C. January minimum temperatures range from 7°C to 13°C. Average annual rainfall varies from 115 cm in the southwest to less than 25 cm in the extreme north and northeast. The rainy season lasts for four months in the northeast to six months in the southwest, from May through October. The Sahel in the north typically receives less than 600 millimetres of rainfall per year and has temperatures range between 5°C and 47°C [29].

From 1969 to 1974, Burkina Faso suffered from drought, especially in the north which is in the semiarid Sahel zone. More recently, the Sahel in the north typically is receiving less than 600 millimetres of rainfall per year and has high temperatures, 45°C–47°C. A relatively dry tropical savanna, the Sahel extends beyond the borders of Burkina Faso, from the Horn of Africa to the Atlantic Ocean, and borders the Sahara to its north and the fertile region of the Sudan to the South. Situated between 11°3’ and 13°5’ north latitude, the Sudan-Sahel region is a transitional zone with regards to rainfall and temperature [12].
4.3 Rivers and lakes

The country owes its former name of Upper Volta to three rivers which cross it: the Black Volta (or Mouhoun), the White Volta (Nakambé) and the Red Volta (Nazinon). The Black Volta, along with the Comoé, which flows to the southwest, is one of the country's only two rivers which flow year-round. These rivers are not large enough to allow the exploitation of hydro power. The basin of the Niger River also drains 27% of the country's surface. Its tributaries, the Béli, the Gorouol, the Goudébo and the Dargol, are seasonal streams and only flow for four to six months a year. They still, however, can cause large floods during the raining season. The country also contains numerous lakes. The principal lakes are Tingrela, Bam and Dem. Finally, the dam Kompienga is the only source of hydro power in Burkina Faso. The Kompienga dam has a capacity of 14MW [12]. The country also contains large ponds, such as Oursi, Béli, Yomboli and Markoye. However, the country still experiences water shortage especially in its northern part.

4.4 Economy

Burkina Faso remains one of the poorest countries in the world with an average GDP per capita of 1,310$ (The comparable figures for USA and the UK are 48,442$ and 36 511$ respectively) [282]. Agriculture continues to be the leading sector in the Burkina Faso economy in terms of its contribution to real GDP and as depicted in Fig.4.2 it accounts for about 37% of Real GDP. According to the IMF, 2011 report the sector is the largest contributor to employment with more than 86% of the labour force mainly based in rural areas and accounts for about 70% of principal export earnings [31]. More than 80% of the population relies on subsistence agriculture, with only a small fraction directly involved in industry and services. Cotton is the principal export crop from agriculture sector [32].
Burkina Faso is Africa is the largest producer of Cotton. Cotton is a major pillar of its economy. Although it represents only 5-8% of GDP, it accounts for 60-70% of export earnings and is the main source of foreign exchange [33]. More than three million people in Burkina Faso depend on cotton production. The country's share of world cotton exports has tripled over the past 10 years (from 2000 to 2010) and as illustrated in Fig.4.3 the increase in cotton exportation boosted significantly the GDP growth. This is unprecedented for an African agricultural product and what makes it more remarkable is the fact that these successes were achieved despite a slump in world prices [34]. The decline in cotton price is due to subsidies distributed by US government to its famers. Oxfam (2002) shows that cotton subsidies in the US was amounting to $3.9bn in 2001/02 and have been the single biggest force driving down world prices, leading to huge losses for Burkina Faso economy. US subsidies in 2002 for its agricultural sector were greater than Burkina Faso entire GDP which was about $3.29bn. That resulted in a loss of 1 per cent in GDP and 12 per cent of export earnings for Burkina Faso [35]. However, Burkina Faso has revised investment code significantly attracted foreign investment. As a result of this new code and other legislation favouring the mining sector, the country has seen an upswing in gold exploration and production. By 2010, gold had become the main source of export revenue with about 33.7 tons of gold produced in 2010 which is about 10%GDP [36]. Burkina Faso now ranks at sixth place for potential gold production in Africa.

Due to the decline in cotton prices, a large number of the male labour force migrate to Côte d'Ivoire and (to a lesser extent) Ghana for seasonal work, but their labour contributes little to the national economy. Burkina Faso has experienced an average economic growth of about 5% per annum since 2004 but a decrease to about 3.5% in 2009. Burkina Faso’s
Macroeconomic performance has been generally strong somewhat above the African average, despite substantial economic challenges resulting from low world cotton prices and high oil prices. At the same time, average inflation remained at a low level of 2.4%. Real GDP per capita began to rise after the devaluation of the CFA Franc in January 1994 and growth averaged 2% per year between 1994 and 2003. This growth performance is attributed, among other things, to the gains in competitiveness following the devaluation, the large public investment program (mainly externally financed), and the financial and structural policies (including price and trade liberalization) aimed at consolidating the market orientation of the economy and maintaining macroeconomic stability [12].

Figure 4-2 Agriculture and industry as percentage of GDP

Source INSD 2011
Figure 4-3  Burkina Faso GDP and GDP growth

![GDP and GDP growth chart](chart.png)

Source INSD 2011

### 4.5 Demographic profile

As illustrated in Fig. 4.5, Burkina Faso total population in 2005 was estimated to be about 14.2 million with a sex ratio of 1:1.03 male to female respectively [37]. The country has a high total fertility rate, currently about 6.65 children per woman (Fig.4.4), mainly because of very high fertility in rural areas (85% of the population). However the fertility rate is projected to decline to approximately 2.82 children per woman by 2050 according the United Nations 2010 population estimates and projection [37]. In addition, life expectancy which is currently about 54 years is projected to reach 70 years by 2050 due to improvements in health care and nutrition and a decline in child mortality. Thus, the combined effect of high fertility rate and higher life expectancy will result in a dramatic increase of Burkina Faso total...
population which is projected to reach 46.7 million by 2050 as can be seen in Fig.4.5. Burkina Faso average population growth illustrated in Fig.4.6 suggests that it increases from 15 to 16.1% from 2000 to 2015 then population growth will continuously decline from 16.1% growth in 2015 to a 5% increase per year by 2100. Fig.4.5 illustrates different scenarios for Burkina Faso population future growth using low, medium and high variants. It suggests that even with low variants, the total population will still reach 42 million by 2050, while it is projected to be about 52 million for the same year when high variants are considered. All projected scenarios suggest that Burkina Faso total population will significantly increase within the next decades.

Figure 4-4  Life expectancy and fertility rate

Source: UN 2011
Figure 4-5  Projected total population using Low, Medium and High variants

Source: UN 2011

Figure 4-6  Average yearly population growth

Source: UN 2011
4.6 Electricity production supply and demand

Burkina Faso electricity production is mainly based on fossil fuel which is imported from neighbouring countries and subsidized by the government. According to the Burkina Faso National Institute of Statistics the government yearly subsidy for fossil fuel electricity production is about £20 million. However, despite the government subsidy, the cost of a 1kWh in Burkina is about £0.2, one the highest in the world [12]. In comparison, the cost per 1kWh in UK and US is respectively about £0.11 and £0.05. Currently electricity is produced through 28 fossil fuel power stations and 4 hydroelectricity stations. As illustrated in Fig.4.7 and Fig.4.8 fossil fuel electricity generation is the main source of electricity production and represents on average, about 70% of the total power generation capacity in the country. Imported electricity (from Ghana and Ivory Coast) and hydroelectricity (from Kompienga Dam) represent respectively, 10 and 20% of the total electricity produced in Burkina Faso. As illustrated in Fig.4.9 the total electricity production is increasing each year by about 10% on average with 2008 experiencing the lowest increase in the last two decades which is about 3% increase.
Figure 4-7  Different sources of electricity supply

Figure 4-8  Total electricity production
Electricity is mainly provided in urban areas and only 112 urban localities or districts out of 350 have access to electricity. Fig 4.9 shows the number of power stations installed each year. The number of new stations has been increasing, particularly since 2000. However, electricity production level is still low. In these urban areas which have electricity connections, the number of people who have access to electricity was estimated at 2,063,814 which represent 13.7% of the current total population [12]. This results in a huge gap between people who have access to electricity and those who do not. Electricity is important for rapid economic growth and poverty alleviation. It is one of the fundamentals of economic and social development [38]. Thus, regions without electricity suffer economic stagnation and little development [39]. In 2010, with increasing demand due to rising standards of living the lack of significant investment in the energy production sector, Burkina Faso has experienced significant shortfalls of electricity resulting in consequent rationing electricity in many cities especially in the capital city [263].

Figure 4-9 Number of new power stations installed each year
The National Electricity system of Burkina Faso is not configured to provide electricity through a national grid in a cost effective or optimal manner. Therefore, decentralized power generation facilities together with local distribution network would be a good option in providing greater access to electricity for households. Renewable sources of energy could be utilized even where grid connectivity exists, provided that it is cost effective. In addition, after decades of speculation and anticipation, it is increasingly accepted by energy scientists that global peak oil production will likely come within the next two to three decades, with some analysts estimating that the peak will be reached within this decade [40] [41] However, if a new gas reserve found, it might shift the peak oil production. Following the peak, oil production will begin a long decline as oil reserves are depleted. The inevitable decline in the availability of oil will almost surely lead to a dramatic escalation in energy prices and may lead to a global economic crisis, since oil is one of the most important sources of energy in the global economy. Burkina Faso is a developing country characterized by the scarcity of its financial resources. Thus, with its government subsidizing fossil fuel electricity production and the projected continuous increase of oil prices, it will surely become unsustainable to still subsidize electricity production and provide enough energy for most of Burkina Faso population. Therefore, the government need to reverse the trend of fossil fuel electricity generation.

In the recent years, the cultivation of Jatropha curcas for biofuel has been experienced. However, due to lack of sufficient fertile soil the production of biofuel in the country stayed at the embryonic stage.

Burkina Faso is a semi desertic country and has abundant solar radiation. Therefore, the country could be an excellent candidate of solar power use for remote area electrification
where grid connection is not economically feasible. Isolated systems using renewables can be powered by a single, or a combination of, renewable power sources. The power available from the renewable sources is stochastic in nature but could help significantly improve power generation in Burkina Faso.

**4.7 Energy demand in the built environment**

A typical office building in Burkina Faso is a three or four storey building operating 5 days a week. The operating time is between 7.30 and 12.30am in the morning and after the afternoon break resumes at 15.00 to 18.00pm. On average public office buildings energy consumption is estimated to around 208,000kWh per year with an estimated cost of £55,000. Public buildings usually are characterised by large single glazed windows with metallic frame. The total energy consumption is typically distributed as follows [14]:

- Air conditioning 66%
- Lighting 10%
- Ventilation fan 1%
- Computers 6%
- Photocopy machines 8%
- Others 9%

Air conditioning is the most important parameter which drives the increase in energy consumption for public office buildings. Warmer weather condition might increase the need for air conditioning thus, increasing energy consumption in the built environment. A study over the period between 1988 and 2003 has shown that the commercial and industrial sectors accounted for 54.52% of the total electricity consumption while domestic households
consumed 27.61% and public buildings about 17.37%. The share of electricity consumption for the primary sector was very low, about 0.50% [263].
Chapter 5 Scenarios on Burkina Faso population growth impact on emission and future energy demand: STIRPAT model

5.1 Introduction

Clearly identifying the main drivers of primary energy consumption and carbon emissions is a highly challenging task. Numerous studies that analyse the driving forces of energy consumption and carbon emissions have been widely discussed in the literature review (Chapter 2). The results suggest that technology level, affluence, energy structure, economic structure and population constitute the main driving forces. However, each impact factor might play different roles in explaining the growth of CO₂ emissions. This chapter identifies the underlying driving forces which affect CO₂ emissions in Burkina Faso based on the well-known STIRPAT model. The impact of Burkina Faso fast growing population on emission and future energy demand has been especially investigated.

5.2 Applying STIRPAT model to Burkina Faso

5.2.1 Model

The STIRPAT model has been investigated and validated in several studies and comfort this research that this model is suitable for the Burkina Faso case study [56-59]. The STIRPAT presented in a logarithmic form in Eq.2.5 is an additive regression model that allows estimation and hypothesis testing. However, additional factor urbanisation (U) has been included to the STIRPAT model (Eq.2.5) yielding the following STIRPAT model:

\[ \ln I = \alpha + \beta \ln P + \gamma \ln A + \delta \ln U + \varphi \ln T + e \quad \text{Eq. 5.1} \]
where $I$ is environmental impact using primary energy consumption as a surrogate of carbon dioxide emissions (The assumption is that the more fossil fuel is consumed in Burkina Faso, the more the CO2 emissions), $P$ is population, $A$ is affluence measured by GDP per capita and $U$ is urbanization measured by percentage of urban population. $\alpha$ is a constant, $\gamma, \delta$ and $\varphi$ are the coefficients of the independent variables and $e$ is the error term. These coefficients are used to represent the net effects of the variables and are referred to as Ecological Elasticity (EE).

### 5.2.2 Ecological elasticity

The Ecological Elasticity (EE) was defined by York et al. (2003) as the responsiveness or sensitivity of environmental impacts to a change in any of the driving forces \[9\]. The EE measure allows for a precise interpretation of the effects of anthropogenic driving forces. The general concept of elasticity is widely used in economics and refers to the responsiveness of one variable to changes in another. According to Samuelson et al. (1992) it refers to the proportional change (in percentages) in a dependent variable from a one percent change in an independent variable with other factors held constant \[257\]. For example, the price elasticity of supply tells us how sensitive the quantity supplied is to changes in price. In economics a model for price elasticity of the quantity supplied ($Q$) as a function of price ($P$) is:

$$\ln Q = \ln A + \beta \ln P \quad \text{Eq.5.2}$$

According to Wonnacott (1990), in this model, $\beta$ is the price elasticity of supply $\ln A$ is the scaling constant \[258\]. Therefore, Eq.5.2 could be rewritten as following:

$$\ln Q = \alpha + \beta \ln P \quad \text{Eq.5.3}$$
By adding a residual (error) term, Eq. 5.3 could become a stochastic model that can be estimated with multiple observations over time or cross-sectional data using traditional statistical techniques of regression. The $\beta$ coefficient is an empirical estimate of elasticity. The stochastic form of Eq.5.3 is, therefore, functionally equivalent to the STIRPAT model illustrated in Eq.5.1. As a result, the coefficient (EE) of the STIRPAT model could be defined as the proportional change in environmental impacts due to a change in any driving force.

STIRPAT coefficients are easy to interpret. A coefficient equal to 1 is referred to as unit elasticity, which indicates a proportional relationship between the driving force and the impact. It means that a percentage change in the driving force produces an identical percentage change in impact. Coefficients that are higher than 1 suggest an elastic relationship, indicating that an impact increases more rapidly than the driving force. Coefficients that are positive but smaller than 1 suggest an inelastic relationship, where impact is less responsive to changes in the driving force. Negative coefficients that are smaller than -1 indicate negative elasticity, meaning that impact decreases in greater proportion in response to an increase in the driving force. Finally, negative coefficients with values greater than 1 and inferior to zero indicate negative inelasticity, meaning that impact decreases in lesser proportion in response to an increase in the driving force.

### 5.2.3 Results and discussion

Data in Table 5.1 and 5.2 illustrates Burkina Faso population, urbanization, GDP, energy intensity (T) and emission from primary energy consumption for the period between 1980 and 2007. These data has been extracted from the Statistical Information Management and Analysis (SIMA) database of the World Bank and Tudorancea Bulletin data base [46] [149]. Affluence was illustrated by the GDP per capita while technology was defined by energy
intensity. The impact on environment was illustrated by the emission from primary energy consumption and urbanisation was defined by the percentage of the total population living in urban area. Table 5.2 illustrates the logarithm of the environment impact driving forces. It gives a quick overview of the environmental impact driver’s descriptive statistics. These data have been computed in statistical tool SPSS in order to test each of the driver’s impact on the dependent variable impact. Data from Table 5.2 will then be applied to the STIRPAT model in Eq.5.1 in order to assess the proportional change (EE) in environmental impacts due to a change in the driving force.

Table 5-1 Descriptive statistics of the data (N=28)

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
</tr>
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<td>1270000.0</td>
<td>756785.7</td>
<td>311901.7</td>
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<td>449.3</td>
<td>267.6</td>
<td>68.4</td>
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<td>Population</td>
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<td>14797000.0</td>
<td>9806821.4</td>
<td>2621913.4</td>
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<td>Urbanisation %</td>
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<td>19.1</td>
<td>14.6</td>
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<tr>
<td>Tech. Btu</td>
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<td>4535.4</td>
<td>3354.7</td>
<td>413.7</td>
</tr>
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<td>1993.5</td>
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</tr>
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<td>2.7</td>
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<td>8.4</td>
<td>8.1</td>
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Table 5-2 Log of impact and emission drivers for Burkina Faso

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<th>Year</th>
<th>ln (CO$_2$)</th>
<th>ln (GDP/Capita)</th>
<th>ln (Pop)</th>
<th>ln (Urb)</th>
<th>ln (Tech)</th>
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<td>7.99</td>
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Source: World Bank 2012
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<th>F</th>
<th>Sig.</th>
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<td>27.00</td>
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Type I Sum of Square illustrated in table 5.3 means that each variable on its own has been tested against the dependent variable impact. As it could be seen in the table 5.3, the significance value (sig) of each variable is null. That suggests that when tested on their own against impact, all the drivers are very highly significant. However, the correlation between variables illustrated in table 5.4 suggest that population and urbanisation are highly correlated. The Pearson correlation coefficient between the two drivers is unity. Therefore, one should keep in mind that these two drivers tested simultaneously against environmental impact will necessarily lead to a bias result since they are auto correlated. The urbanisation collinearity problem is confirmed in Table 5.5 which illustrates a robust multiple regression results for the analysis of CO₂ emissions from primary energy consumption.
### Table 5-4 Correlation between variables

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<th></th>
<th>ln (CO2)</th>
<th>ln (A)</th>
<th>ln (P)</th>
<th>ln (U)</th>
<th>ln (T)</th>
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<tr>
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<td>28.0</td>
<td>28.0</td>
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<td>ln (A)</td>
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<td>1.0</td>
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<td>28.0</td>
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<td>ln (P)</td>
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Table 5-5 Multiple regressions with lnCO₂ as depend variable

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</tbody>
</table>

Since the critical value for the significance level is set at 0.05, any value less than 0.05 implies significant effect of that variable on environmental impact. The multi regression analysis, results portrayed in Table 5.5 suggest that the correlation between the dependent variable environmental impact and the independent variables urbanisation and affluence is weakly significant. The significance level values are 0.28 and 0.4 respectively for affluence and urbanisation. On the contrary, population and technology (energy intensity) have shown to be highly significant. Furthermore, Table 5.5 shows that population and energy intensity (T) with coefficients of 1.78 and 1 respectively are the most important drivers of environmental impacts in Burkina Faso. In this study, urbanisation however was found to have a negative coefficient of -0.16.

The regressions yielded a model with a coefficient of determination of 0.98. The key findings from the multiple regressions analysis therefore are that the model determines 98% of the environmental impacts and that the coefficients which represent the ecological elasticity are 1.38, 0.7, -0.16 and 1 for population size, affluence, urbanization and technology.
respectively. Therefore, the regression coefficient for Burkina Faso data applied to the STIRPAT model illustrated in Eq. 5.1 gives:

$$\ln I = -16.76 + 1.38\ln P + 0.7\ln A - 0.16\ln U + 0.99\ln T$$ Eq. 5.4

### 5.2.4 Model validation

To verify the accuracy of the STIRPAT model Eq.5.4 adapted to Burkina Faso, historical CO₂ emissions data form primary energy consumption between 1980 and 2007 have been obtained from the Statistical Information Management and Analysis (SIMA) database of the World Bank [46]. The model predicted CO₂ emissions were then compared with the actual historical carbon emission obtained from SIMA data base. Fig.5.1 and 5.2 illustrate the comparative results for CO₂ emissions between 1980 and 2007. Fig.5.1 shows the correlation plot between the mean predicted CO2 emissions values and the actual observed CO2 emissions. The plot presents an excellent fit between the two variables. Fig.5.2 shows how well the model fits the historical data for the considered period.
Figure 5-1 STIRPAT predicted model and observed LogCO₂ emission

Figure 5-2 Historical and predicted data fit
As it can be seen the graphs indicate that the model fits very well with the corresponding data. In addition, $R^2$ which is the coefficient of determination is high (98%). The value of the $R^2$ indicates how well the dependent variable is explained by the independent variables. Therefore, in light of these results, the STIRPAT model explains 98% of carbon emission from primary energy consumption. The error term between the two set of data is estimated to be about 0.16. The error was calculated based on Eq.5.5.

\[ \sqrt{\sum ((\text{Observed value})_t - (\text{Predicted value})_t)^2} \quad \text{Eq. 5.5} \]

Since the error associated with the predicted environmental impact values is within the acceptable limits, the coefficients of the driving forces obtained using the proposed STIRPAT can be considered as reasonably accurate. Therefore, the results suggest that the STIRPAT model can be reliably used to estimate the proportional change in future environmental impacts due to a change in the driving force. However, it is important to note that the model is based on assumptions and simplification. Therefore, uncertainty exists in the overall results.

### 5.2.5 Population

The results illustrated in Table 5.5 and Eq.5.4 clearly show that population is the major driver of CO$_2$ emissions. It indicates a population ecological elasticity of impact (EE$_{IP}$) of 1.37. Thus, a 1% change in population corresponds to a 1.37% change in environmental impact. This finding is substantively similar to other STIRPAT analyses. In this regard, Dietz et al. (1997) and Shi (2003) in their respective studies found population to have a greater than proportional effect on CO$_2$ emissions. Shi results show that population increases emissions by 1.21 [10] [46].
Fig 5.3 illustrates the correlation between log of population and log of carbon emissions. It confirms the finding from the STIRPAT model and suggests that population growth will result in an increase of CO₂ emissions. These findings on population growth impact on primary energy consumption emissions are in agreement with the Malthusian point of view. It supports that a larger population could result in increased energy demand for power, industry, and transportation. Therefore, increases emissions from energy consumption.

5.2.6 Affluence

The interpretation of the ecological elasticity of affluence (EEₐ) suggests that a unit change in affluence bring about approximately 0.7% change in environmental impacts. This result accords with Dietz and Rosa (1997) cross-sectional data analysis for 111 countries which indicates that for the overwhelming majority of nations, economic growth that can be
anticipated for this century will produce increasing CO₂ emissions [10]. However, high income countries will experience a declining trend due to the shift from a manufactured based economy to a service-based economy and the ability for these economies to invest in energy efficiency.

### 5.2.7 Urbanization

For urbanization, the negative coefficient suggests the ecological inelasticity of impact. It means that a unit increase of urbanisation results in 0.16% decrease in environmental impacts. The negative sign could be explained by the fact that urbanization in Burkina Faso as in most other developing countries results mainly from rural–urban migration with a consequent change in life style of the migrants. The change in life style to some extent according to Dietz et al. (2007) has a reduction effect on environmental impact. In addition the economy of scale could be the reason in carbon emission reduction. The EE of urbanisation in Burkina Faso analysis are in line with Pachauri et al. (2008) findings. He also found similar evidence based on a study regarding the difference between urban and rural household energy use. He argue these results are explained by the fact that migrants from rural areas after moving to urban areas shift from inefficient solid fuel (biomass, charcoal and coal) use to more efficient commercial fuels and grid sources (kerosene, liquid petroleum gas and electricity) [80].

### 5.2.8 Energy intensity (Technology)

The STIRPAT model in Eq.5.4 shows that ecological elasticity of energy intensity is equal to unity. This indicates a proportional relationship between the energy intensity and the impact on environment. These findings are similar to earlier calculation by Fan et al. (2006) who
demonstrated that low income countries, because of high technology costs, their economic and energy consuming structures and technological barriers, these countries experience difficulties to improve their energy efficiency [60]. That will result in higher energy consumption and increasing CO₂ emissions. Fig. 5.4 illustrates the weak correlation between energy intensity and CO₂ emission. It confirmed that an increase in energy intensity results in an increase of the environment impact. For the particular case of Burkina Faso, the scarcity of financial resources makes CO₂ emissions reduction through improving energy efficiency a challenging task. In addition the difficulty in developing new technologies on the basis of relatively reasonable energy-consuming and current economic structures results in high energy intensity.

Figure 5-4 Correlation between technology level and impact

![Figure 5-4 Correlation between technology level and impact](image-url)
5.3 Scenarios of population growth impact on future electricity demand

Burkina Faso has been experiencing periodic power shortages for the last four decades and the problem is likely to worsen if no remedial action is taken. The main problem has been the inability to forecast the rapid growth in demand for electricity by households and industry alike. Hence, there is a shortage in electricity generating capacity in the country. The extent of power shortages has become acute in recent years due to rapidly increasing demand. However, despite the increasing demand for electricity, supply has not kept pace. Supply failure includes the delay in implementing the long-term power generation expansion plans of the National Electricity Company (SONABEL). As a result, generating electricity to meet the increasing demand is one of the major challenges facing Burkina Faso decision-makers. The projected future population growth illustrated in Fig.4.5 shows that the population growth will reach an average growth of 16.1% by 2020. The current population of 16 million will more than double by 2035 and reach 33 million. As suggested in the STIRPAT model, 1% increases in population result in a 1.36% increase in CO₂ emissions from primary energy consumption. Therefore, it is expected that the projected exponential increase of Burkina Faso population will result in a dramatic increase of energy demand. One of the main reasons for periodic power shortages, which are common to most developing countries, is inadequate ‘future demand’ planning and cost-cutting exercises undertaken by government authorities. Pillai (2000) and Hondroyiannis (2004) advocate that an effective electricity planning requires a thorough understanding of the prevailing electricity demand patterns, constraints and future challenges [151-152]. The major difficulty in modelling future demand arises due to the high variability in the electricity market. Hence, this uncertainty sends wrong signals to electricity generators and suppliers.
This research investigates the overall impact of Burkina Faso projected population growth on its electricity demand based on the STIRPAT model.

### 5.3.1 Model

It has been proven in this chapter that the STIRPAT model could be effectively used to estimate different drivers’ impact of on emissions from primary energy consumption. Holtedahl (2004) has done extensive work on electricity consumption drivers. He argues that electricity consumption is a function of population, urbanisation, GDP/capita, price/kWh, and price of oil. That leads to the following formula:

\[
\text{kWh} = f(\text{Population, GDP, Price/kWh, Price of oil, Urbanisation}) \text{ Eq.5.6}
\]

He then used OLS regression to estimate each variable impact on energy consumption. This research combined the STIRPAT and Holtedahl method (Eq.5.1 and Eq.5.6) in order to assess electricity consumption. The following equation has been considered to test energy consumption drivers:

\[
\ln E = \alpha + \beta \ln P + \gamma \ln A + \delta \ln U + \phi \ln PO + \epsilon \text{ Eq.5.7}
\]

Where, \(E\) represents the consumption of electricity and \(PO\) the price of oil. A similar approach has been developed by Alper (2008) to forecast future electricity supply in Turkey by 2025 [262]. The energy forecast however, was based on the following drivers: population, GDP, import and export.

Since both dependent variable and predictors are in logarithmic form, the coefficients should be interpreted as changes in percentage terms. Table 5.6 presents the findings from the
multiple regressions model based on Eq.5.7. The critical value for the significance level is set at 0.05. Therefore, the analysis of the results in Table 5.6 suggests that apart from urbanisation (autocorrelation to population growth Table 5.4), which has a significance value of 0.06, the rest of the independent variables to be tested are highly significant.

Table 5-6 Electricity consumption drivers’ analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>B</th>
<th>Std. Error</th>
<th>t</th>
<th>Sig.</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lower Bound</td>
</tr>
<tr>
<td>Intercept</td>
<td>-29.30</td>
<td>1.32</td>
<td>-22.19</td>
<td>.00</td>
<td>-32.04</td>
</tr>
<tr>
<td>ln(A)</td>
<td>.10</td>
<td>.04</td>
<td>1.11</td>
<td>.03</td>
<td>.01</td>
</tr>
<tr>
<td>ln(p)</td>
<td>2.03</td>
<td>.10</td>
<td>19.90</td>
<td>.00</td>
<td>1.82</td>
</tr>
<tr>
<td>ln(U)</td>
<td>-.25</td>
<td>.12</td>
<td>-1.99</td>
<td>.06</td>
<td>-.50</td>
</tr>
<tr>
<td>ln(PO)</td>
<td>-.01</td>
<td>.10</td>
<td>4.20</td>
<td>.00</td>
<td>.74</td>
</tr>
</tbody>
</table>

The analysis of energy consumption drivers illustrated in Table 5.6 clearly show that population is the main driver of energy consumption. The result suggests an elastic relationship between population and energy consumption. A 1% increase in population yields a 2.03% increase in electricity consumption. In the same order, Shin et al. (2004) shows a positive correlation between population increase and electricity demand [259]. However, this research suggests that oil price has a low impact on electricity consumption. A 1% increase in oil price results in a 0.01% decrease in electricity consumption. A study by Wassantha (2010) suggested that the elasticity of oil price is about -0.16 for Sri Lanka electricity consumption [260]. The same study shows that an increase of 1% of GDP leads to an increase of 0.78% of
electricity consumption. The present study estimates that, a 1% GDP increase results in a 0.1% increase in electricity consumption. These results are similar to the finding of Jumbe et al. (2004) who established the existence of an elastic relationship between electricity consumption and economic growth for Malawi [261].

Figure 5-5 Population impact on electricity consumption

![Graph illustrating the correlation between population and electricity consumption. It confirms the fact that population growth will result in an increase of electricity consumption. A sustained continuous economic growth combined with Burkina Faso exponential population growth mean that electricity supply is bound to lead to severe shortages in the future if the strategy of business as usual is kept.](image-url)
5.3.2 Forecast of future electricity demand

Burkina Faso is currently experiencing a severe electricity crisis [263]. Domestic households and industrial companies are suffering from black out. It is argued that one of the reasons is the lack of research on future energy supply locally. This chapter contributes to the research by estimating future electricity consumption in Burkina Faso based on a population forecast. Table 5.7 illustrates Burkina Faso projected future population growth scenarios (high, low and medium) based on the United Nation calculations [37]. It has been shown based on Eq. 5.7 that a 1% population increase leads to a 2.03% increase in electricity consumption. The increase in electricity consumption has been estimated based on the following formula:

\[
\text{Electricity increase} = \text{Population increase} \times \text{Correlation factor} \quad \text{Eq. 5.8}
\]

Table 5-7 Scenario for population growth

<table>
<thead>
<tr>
<th>Year</th>
<th>High</th>
<th>Low</th>
<th>Medium</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>17%</td>
<td>15%</td>
<td>16%</td>
</tr>
<tr>
<td>2015</td>
<td>17%</td>
<td>15%</td>
<td>16%</td>
</tr>
<tr>
<td>2020</td>
<td>17%</td>
<td>15%</td>
<td>16%</td>
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<tr>
<td>2025</td>
<td>16%</td>
<td>14%</td>
<td>15%</td>
</tr>
<tr>
<td>2030</td>
<td>16%</td>
<td>13%</td>
<td>14%</td>
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<tr>
<td>2035</td>
<td>15%</td>
<td>12%</td>
<td>14%</td>
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<tr>
<td>2040</td>
<td>15%</td>
<td>11%</td>
<td>13%</td>
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<tr>
<td>2045</td>
<td>14%</td>
<td>10%</td>
<td>12%</td>
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<tr>
<td>2050</td>
<td>13%</td>
<td>9%</td>
<td>11%</td>
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<tr>
<td>2055</td>
<td>13%</td>
<td>8%</td>
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<td>2060</td>
<td>12%</td>
<td>8%</td>
<td>10%</td>
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<td>2065</td>
<td>11%</td>
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<td>2070</td>
<td>11%</td>
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<td>10%</td>
<td>4%</td>
<td>7%</td>
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<tr>
<td>2085</td>
<td>9%</td>
<td>4%</td>
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<td>2090</td>
<td>8%</td>
<td>3%</td>
<td>6%</td>
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<tr>
<td>2095</td>
<td>8%</td>
<td>2%</td>
<td>5%</td>
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<tr>
<td>2100</td>
<td>7%</td>
<td>2%</td>
<td>5%</td>
</tr>
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</table>
Based on projected population growth scenarios, this research estimated the possible forecast of electricity consumption using the following formula:

\[
kWh_{t+1} = kWh_t \times (IE_{t+1} + 1) \quad \text{Eq. 5.9}
\]

Where kWh represents the electricity demand, t represents the year and IE the percentage increase in electricity consumption. Future electricity consumption forecasting is currently a nonexistent research field in Burkina Faso. From all the parameters that drive electricity demand in the country, this research could only rely on the population forecast. Therefore, the other variables have been assumed to be constant based on previous historical data. These assumptions constitute some important limitations to this research forecast. The uncertainty makes it impossible to make completely accurate predictions. However, a picture of what could be the electricity demand in the future can be drawn based on population growth. The forecast of projected electricity demand growth in Burkina Faso is illustrated in Table 5.8 based on and Eq.5.9. It represents low, medium and high scenarios for the yearly electricity consumption growth.

Table 5-8 Scenarios for electricity demand growth

<table>
<thead>
<tr>
<th>Year</th>
<th>High</th>
<th>Low</th>
<th>Medium</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>27%</td>
<td>24%</td>
<td>26%</td>
</tr>
<tr>
<td>2020</td>
<td>27%</td>
<td>23%</td>
<td>25%</td>
</tr>
<tr>
<td>2025</td>
<td>26%</td>
<td>22%</td>
<td>24%</td>
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<tr>
<td>2030</td>
<td>25%</td>
<td>21%</td>
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<td>2035</td>
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<tr>
<td>2040</td>
<td>23%</td>
<td>18%</td>
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<td>2045</td>
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<td>2050</td>
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<td>2055</td>
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<td>13%</td>
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<tr>
<td>2060</td>
<td>19%</td>
<td>12%</td>
<td>16%</td>
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</table>
Figure 5-6 Scenario of future electricity demand

Total electricity consumption in Burkina Faso was estimated at 756million kWh in 2011[12] and was considered as the basis for the forecast. Fig.5.6 illustrates the forecast of total electricity demand for different scenarios for the period between 2015 and 2060. Based on the estimation of current energy consumption level (2011), it is projected that electricity demand will double by 2025 based on the medium growth scenario. These findings attempt to provide some guideline for future electricity supply in Burkina Faso. In the light of these results this research has shown that the exponential future population will result in a significant increase of electricity demand for the country. Thus, Burkina Faso policy makers should adopt energy policies that will help cope with future electricity demand and sustain its development.
5.4 Conclusion

This chapter was a starting point to investigate at a global scale the drivers of energy consumption for Burkina Faso. The analyses based on the STIRPAT model have shown that between the different drivers, population has the most important impact on both CO₂ emissions and electricity consumption in Burkina Faso. A 1% increase of population results in a 1.38 and 2.03% increase of CO₂ emissions (from primary energy consumption) and electricity consumption, respectively. Additionally, the forecast of Burkina Faso future electricity demand has been investigated. It shows, based on 2011 electricity consumption and population growth that electricity demand will double by 2025 under medium growth scenario.

Forecasting is a tricky science. Limitations such as annual development for future year’s prediction, considering old technology development and forecasting the substitution of old technology makes the task even harder. This is particularly true in the energy sector where highly random behaviour of energy prices and technological changes make forecasting difficult. However, because these forecast are so integral to policy and business decisions, it worth trying and analysing where those forecast might eventually fail. The results of this chapter have limitations but constitute a starting point for future work. Future work might include a more disaggregated analysis or a full scenario analysis that will consider more assumptions to evaluate future electricity consumption. This should hopefully help avoid the policy mistakes of the past.

The findings of this chapter, give an overall idea of the main drivers of energy consumption at the macro level. However, this research will focus on future energy demand at micro level. Therefore, the next chapters of this research will particularly focus on future energy consumption in the built environment due to climate change. That could be useful for
planners, policy makers and the private sector to understand better future electricity consumption implementations and to decide for future investment.
Chapter 6 Climate change in Burkina Faso

6.1 Introduction

According to the IPCC (2001a), due to climate change, increases in both the mean and extremes of temperature are expected for many parts of the globe [55]. This chapter investigates future climate change in Burkina Faso by comparing the current historical data and future projected weather data (HadCM3 data) provided by the Hadley Centre. The HadCM3 data has been validated by comparing historical observations with the HadCM3 simulations. This chapter also discusses in detail the methods of selecting typical weather data and describes the selection of test reference years (TRYs) for Burkina Faso using the Finkelstein–Schafer statistic. The findings of this chapter have been published in the academic journal Building and Environment (Appendix A) [174].

6.2 Historical data

The historical data used in this research has been provided by the Burkina Faso Meteorological Office for 15 stations and for the period between 1977 and 2010. The data is for five climatic variables namely dry bulb temperature (°C), relative humidity (%), wind speed (m/s), global solar radiation (MJ/m²), and clearness index (%). Dry bulb temperature affects the amount of heat gain/loss through the building envelope and hence energy use for cooling, whereas relative humidity indicates the level of humidification. Information on solar radiation is crucial, especially for the case of Burkina Faso where humidity is often very low. Solar heat gain is often the most significant component of the air conditioning load. The clearness index indicates the prevailing cloud cover of the sky while wind speed affects natural ventilation and the external surface resistance and hence the thermal transmittance (U-
factor) of the building envelope elements [155]. All the above climate variables have to potential to affect comfort in building and impact energy consumption in building.

6.3 HadCM3 data

Predicting future climate change requires complex computer models that represent the full range of processes and interactions that have an impact on the climate. HadCM3 is a coupled global climate model that has been used extensively for climate prediction and other climate sensitivity studies [268-269]. HadCM3 stands for the Hadley Centre Coupled Model version 3. HadCM3 is an improved version of the Hadley Centre coupled model HadCM2 and produces a realistic and stable climate simulation without flux adjustments to prevent large climate drifts in the simulation [156]. The HadCM3 simulation is a coupled Atmosphere-Ocean General Circulation Model (AOGCM) developed at the Hadley Centre. The standard atmospheric component of HadCM3 has 19 levels with a horizontal resolution of 2.5° latitude by 3.75° longitude, which produces a global grid of 96 x 73 = 7008 grid cells. This is equivalent to a surface resolution of about 417 km x 278 km = 115,926 km² at the Equator, reducing to 295 km x 278 km = 82,010 km² at 45° of latitude. The oceanic component of HadCM3 has 20 levels with a horizontal resolution of 1.25° longitude × 1.25° latitude. At this resolution, it is possible to represent important details in oceanic current structure. The atmosphere component of the model also optionally allows the transport, oxidation and removal by physical deposition and rain out of anthropogenic sulphur emissions to be included interactively.

The simulations have been done using updated four emissions scenarios namely A1, A2, B2 and B1 from the Special Report on Emission Scenarios (SRES) [283], prepared for the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report. These
scenarios are considered to be more self-consistent in their socio-economic, population, energy-use and emissions structure than older scenarios like IS92a [157]. Therefore, that makes the model results more relevant to policy makers. According to the IPCC 2001 report, by 2100 the world will have changed in ways that are difficult to imagine, as difficult as it would have been at the end of the 19th century to imagine the changes in the next century. Each storyline of the SRES assumes a distinctly different direction for future developments, such that the four storylines differ in increasingly irreversible ways [158]. The main characteristics of the four SRES scenarios are:

- **“The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).**

- **The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented and slower than in other storylines.**
• The B1 storyline and scenario family describes a convergent world with the same
global population that peaks in mid-century and declines thereafter, as in the A1
storyline, but with rapid changes in economic structures toward a service and
information economy, with reductions in material intensity, and the introduction
of clean and resource-efficient technologies. The emphasis is on global solutions
to economic, social, and environmental sustainability, including improved equity,
but without additional climate initiatives.

• The B2 storyline and scenario family describes a world in which the emphasis is
on local solutions to economic, social, and environmental sustainability. It is a
world with continuously increasing global population at a rate lower than A2,
intermediate levels of economic development, and less rapid and more diverse
technological change than in the B1 and A1 storylines. While the scenario is also
oriented toward environmental protection and social equity, it focuses on local and
regional levels [158].”

Gordon et al. (2000) show that HadCM3 simulations run for sea surface temperature (SST)
over 400 years compared to the observed conditions are stable and realistic. The trend in
global mean SST is less than $0.009^\circ$C per century. In part, the improved simulation is a
consequence of a greater compatibility of the atmosphere and ocean model heat budgets.
Despite the limitations of the observed datasets, it is shown that the coupled model is able to
reproduce many aspects of the observed heat budget [156]. Furthermore, Weaver and Hughes
(1996) suggested that one of the key features improvements for HadCM3 has been the
improved simulation of both the surface heat fluxes and the ocean pole ward heat transport,
which in the HadCM3 model are in broad agreement with the observed data [159].
6.3.1 Other models

6.3.1.1 Ensemble modelling

Roeber et al. (2004) describe ensemble simulations in an effort to meet the growing need of quantifying and interpreting model uncertainty by using probabilistic simulations, where a range of likely outcomes are described [265]. The ensemble modelling consists in running multiple simulations using different input conditions or numerical models, and aggregating the results to identify the span of possible solutions. A range of model inter comparisons have been performed in the field of hydrology. Diekkruger et al. [266] used the ensemble model to compare the performance of 19 agro-ecosystems for two sites in Germany. They concluded that the model results differed substantially and that no superior model type, either simple conceptual or complex process-based, could be defined. Reyes et al. (2005) in his study has shown that most studies on the accuracy of multi model ensemble forecasts in weather prediction report that they tend to outperform individual models and that multi-model ensembles tend to perform better than single-model ensembles [267]. He therefore concluded that ensemble modelling has the potential to assist in providing better understanding of the physical processes and in informing the development of better models. However, ensemble modelling is not necessary for building simulation work.

6.3.1.2 Hadley Centre regional climate model HadRM3

Taking the case of UK, the HadCM3 has only four land grid points over the UK. Therefore, for more detailed spatial information for the UK it is necessary to use the downscaling technique [270]. In this respect, the Hadley Centre developed the regional climate model (HadRM3). HadRM3 uses a rotated pole grid with a resolution of 25 km and 19 levels in the
vertical [271]. The regional climate model showed substantial improvement in modelling spatial weather patterns compared to the GCM, due to the much finer spacial resolution (20Km). Nevertheless, an accurate reproduction of some weather statistics, including extreme events, still remains problematic [272]. Recent analysis by the Hadley Centre on the HadRM3 model has shown that it overestimates the rainfall in winter and spring and particularly at high elevations [273]. However, only HadCM3 data was available for Burkina Faso.

### 6.3.2 HadCM3 limitations

Climate predictions depend on available models of the climate simulation. However, all models have limitations in their application. There are two main reasons that explain this. “First, there is inherent uncertainty in predictions, which means that ensemble predictions are needed with many model integrations. Second, technological advances have not kept speed with scientific advances. A model that includes the latest understanding of the science at the highest resolution would require computers of several orders of magnitude faster than today's machines” [286]. Climate model scenarios are dynamic sophisticated mathematical models designed to simulate the physical processes of the atmosphere and oceans in order to predict future global and regional climate. The general circulation models (GCM) are the most complex of these models and the most powerful tools available for making realistic estimates of climate change. Currently, several centres around the world develop climate models to enhance our understanding of climate and climate change and to support the activities of the IPCC. However, climate models involve much uncertainty, especially in terms of estimating regional or local change essentially with reference to the extremes. HadCM3 model imperfections have attracted criticism, with some arguing that model-based projections of climate are too unreliable to serve as a basis for public policy. Lucio (2004) advocates that
the debate on the enhanced greenhouse effect continues to confuse climate change impact analysis and decision makers. He shows that there is evidence that the HadCM3 simulations are insufficient for reproducing future scenarios of extremes. Furthermore, he demonstrates that HadCM3 simulations produce unrealistically extreme temperature climatology for the winter in the North-eastern Europe and for the summer in the North-western Europe, where the cost of a false diagnostic seems to be very high [160]. Therefore, he concludes that in terms of annual extremes the HadCM3 simulations are not able to fit reasonably the regimes defined by the NCEP Reanalyses [160].

Figure 6-1 Mean ice thickness (a) HadGEM1 (b) HadCM3

To address the HadCM3 limitations, the Hadley Centre developed the Hadley Centre Global Environmental Model (HadGEM1). This model includes substantially improved representations of physical processes, increased functionality, and higher resolution than its predecessor, the HadCM3. Particular focus has been placed on improving the processes (such
as clouds and aerosol) that are most uncertain in projections of climate change. These developments lead to a significantly more realistic simulation [64]. Fig.6.1 illustrates the difference between HadGEM1 and the HadCM3 for ice thickness simulation. HadGeM1 data was not available for Burkina Faso and the differences from HadCM3 are sufficiently small for HadCM3 to be used with reasonable confidence.

6.3.3 HadCM3 data validation for Burkina Faso case study

Assessments of the possible impacts of projected future climate change require descriptions on appropriate space and time-scales of possible future climates. These descriptions, or scenarios, most commonly originate from climate change experiments made using global climate models (GCMs). For assessment of climate change in Burkina Faso, the only data available for this research is the HadCM3 data. Predicted future HadCM3 data for Burkina Faso have been provided by the Hadley Centre and represent four climatic variables namely: dry bulb temperature (C), relative humidity (%) and wind speed (m/s) and global solar radiation (MJ/m²) for the period between 1990 and 2100. However for the present study, it is essential to demonstrate how well the Hadley Centre Climate Model performs in simulating past climates in order to have more confidence in its ability to project future weather conditions. Therefore, the HadCM3 predicted baseline data (for 1990-2010) were plotted against observed data obtained from Burkina Faso Met office in order to assess discrepancy between the two sets of data.

The data provided by the Hadley centre is for a 250 x 250km grid box whereas the actual data is from a point location. Two sets of data for the period between 1990 and 2010 were compared and are displayed in the following graphs and tables. As can be seen in Fig.6.2 the illustration of the historical and projected data suggests that there is no significant difference
between the two trends and they seem to follow the same pattern. The average temperature over the 10 years illustrated in table 6.1 and 6.2 shows that the historical and projected HadCM3 data have almost identical mean temperatures which are respectively about 28.57°C and 28.21°C. In addition the standard deviations for the two sets of data are respectively 2.98 and 2.95 for historical and predicted data. However, the minimum and maximum temperatures vary a little with respectively a difference of 1.54°C and 2.17°C between the predicted HadCM3 data and the historical data. Moreover, a close look at the “tails” of the historical predicted data histogram highlighted in Fig.6.1(a) and (b) shows a very small percentage of data distributed at the extreme minimum and maximum. As a result 95% of the data are distributed between 22°C and 35°C as illustrated in Fig.6.2. The difference between the observed and predicted data appears not to be pronounced in the observed trends. Fig.6.3 shows the goodness of the fit for the correlation between the observed and the modelled daily temperature.

### Table 6-1 Summary of historical data

<table>
<thead>
<tr>
<th>Variable</th>
<th>Obs.</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>3960</td>
<td>28.57</td>
<td>2.98</td>
<td>19.2</td>
<td>38.1</td>
</tr>
</tbody>
</table>

### Table 6-2 Summary of modelled data

<table>
<thead>
<tr>
<th>Variable</th>
<th>Obs.</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modelled</td>
<td>3960</td>
<td>28.21</td>
<td>2.95</td>
<td>17.66</td>
<td>35.93</td>
</tr>
</tbody>
</table>
Figure 6-2 Histogram of historical and modelled data from 1990 to 200

(a) Historical data

(b) Projected data
The fitted line of the correlation between modelled (y) and observed (historical) temperature (x) has the following linear equation $y = 0.73x + 7.4$ with a coefficient of determination $R^2$ of 0.75 for the years between 1990 and 2000. In addition, for the same period, the year 1999 represents the best fit for the correlation between historical and observed data with a fitted line equation $y = 0.9x + 3.7$ and $R^2 = 0.87$ while the worst year fit is the year 1997 with fitted line equation $y = 0.7x + 8.5$ and $R^2 = 0.27$.

The comparison between the fitted line and the line $y = x$ displayed in Fig.6.3 suggests that the projected HadCM3 monthly average data is slightly higher than the observed one. These findings are considered to be acceptable because the historical data represents a particular point station data while the predicted HadCM3 data represents grid data. Overall, the
discrepancy between HadCM3 data and observed data is reasonably small and on average the predicted data are realistic even if HadCM3 data is slightly overestimated. Therefore, HadCM3 data can confidently be used in this research to assess the future energy consumption in the Burkina Faso built environment.

6.4 Test reference year (TRY)

Dynamic thermal simulation has been used for years to model the performance of buildings and their thermal systems and enable better understanding of their behaviour than is possible by simpler methods [162]. To model long-term average or typical building performance, it is necessary to simulate the system behaviour using either many years of real weather data or one typical year weather data. The need for such appropriate meteorological data led to the development of methodologies for generating the so-called typical meteorological years (TMYs), a term mainly used in the USA, or test reference years (TRYs), mainly used in Europe, or weather year for energy calculations (WYEC). All these data sets contain a sequence of 8760 hourly values of some chosen meteorological variables. The basic requirement of these “years” is that they have to correspond to a “typical” year regarding the occurrence and the persistence of warm/cold, sunny and/or dry/wet periods in all months or seasons. From the above methods, the TRY is considered the most reliable and will be used for the purpose of this research. The test reference year (TRY) is a synthetic year based on the most typical months taken from a twenty-year period. The TRY is extracted by taking the relevant month that has the smallest value of the Finkelstein - Schafer (FS) statistic [84]. The FS statistic measures the similarity of two distributions. When two distributions are similar its value is small, and when they are identical its value is zero. In selecting typical weather data, the FS statistic is used to compare the distribution of the chosen weather variable (solar radiation, dry-bulb temperature, relative humidity, and wind speed) in an actual month to its
long-term distribution in that same month. If the FS statistic for an actual month is small then the actual data will have similar mean, median, mode, standard deviation, percentiles, and other statistics to the long-term data for that month. The FS statistic does not explicitly consider whether there are periods in the data, which are unusually hot, cold, etc., but will tend to reject a month containing such a period on the basis of its frequency distribution. Although such periods are very important in designing plant size, they are by definition unusual and are therefore unlikely to have much effect on long-term performance [85].

6.4.1 TRY selection

Improved TRY selection algorithms are discussed in detail by Levermore and Parkinson [163]. TRYs were generated for 14 sites throughout UK composed of the most typical months from 20 or so years of data. The selection of the most typical month in the new CIBSE (Chartered Institution of Building Services Engineers) TRYs was based on the cumulative distribution functions (CDFs) of daily mean values of dry bulb temperature (DryT), global solar horizontal irradiation (GIRad) and wind speed (WS). Daily mean values were determined from the hourly values of the parameters for all months in the years considered. The most typical months were selected using the Finkelstein Schafer (FS) statistic to compare the CDFs. The FS statistic sums the absolute difference between the values for each day, \( i \), in an individual month’s CDF and the overall CDF for all the months considered:

\[
\text{CDF}_x(x) = \frac{1}{N} \sum_{x_n \leq x} 1 \quad \text{Eq. 6.1}
\]

\[
\text{FS}(p, m, y) = \sum_{i=1}^{N_m} |\text{CDF}(i|m, y) - \text{CDF}(i|m, N_y)| \quad \text{Eq. 6.2}
\]
Where $FS(p; m; y)$ is the FS statistic for weather statistic, $p$, month $m$, in year $y$, $CDF(i; m; y)$ being the CDF for month $m$, in year $y$ and day $i$. $CDF(i, m, N_y)$ being the CDF for the same month, $m$, but taken over all the years, $N$, of the data set considered. FS is summed over all the days of the month, $m$, for the weather parameter considered. The CDF is a monotonically increasing step function which is bounded by zero and one. For example, to calculate the long term CDFs of daily average temperatures of March, all the average temperature values over 20 years, i.e., $30 \times 20 = 600$ data, were sorted and put in increasing order, and then the CDF for every value of average temperature was calculated. To calculate the monthly CDFs for a March, 30 values were sorted in increasing order. This way, the two different CDFs, long term and for a single year, were calculated. For each month this procedure was applied to determine the long term and single year cumulative distributions of each weather parameter for this research. The total FS value is the sum of the FS values for each weather parameter. The month with the minimum total FS value is selected as the most average month.
Fig. 6.4 illustrates the cumulative distribution functions (CDF) of dry bulb temperature for two different Novembers in Burkina Faso, using the modelled HadCM3 weather data. As can be seen, the CDF of November 2002 represents the best (most typical) November because it is the most similar (smallest value of FS statistic) to the long-term average of 20 Novembers’ CDF, while the CDF for November 2006 is least similar (largest value of FS statistic) and therefore depicted as the worst November. The same procedure is done with the other months in order to construct the synthetic year which will represent the TRY.

For a given country, each weather element could have a different impact on the system. Therefore, a typical system might be expected to be more affected by one meteorological parameter than the others. However, weather data is selected before the system is studied and
at that point the relative importance of parameters is unknown. This research will investigate
the impact of the weighting factors on the parameters of weather data selection.

\[
FS_{\text{weighted}} = w_{\text{temp}}FS_{\text{temp}} + w_{\text{solar}}FS_{\text{solar}} + w_{\text{rh}}FS_{\text{rh}} + w_{\text{windspeed}}FS_{\text{ws}} \quad \text{Eq. 6.3}
\]

\[
w_{\text{temperature}} + w_{\text{solar}} + w_{\text{relative humidity}} + w_{\text{windspeed}} = 1 \quad \text{Eq. 6.4}
\]

The weighted FS statistics are ranked with the lowest value of FS being ranked first. The
first-ranked occurrence of each month is selected for the TRY.

### 6.4.2 Method of TRY selection using Finkelstein - Schafer (FS) statistic

Projected future HadCM3 weather data for 20 years (from 2020 to 2039) based on the SRES
A2 scenario have been considered for this TRY selection. The data set is composed of four
climate parameters namely: mean dry bulb temperature, solar radiation, relative humidity and
wind speed. As illustrated in table 6.3, each weather parameter FS value is computed and
ranked for each month of the data set. January is taken as an example in table 6.3. It shows
individual weather parameters FS values for all January’s of the data set. They are ranked
according to the FS value (lowest FS value ranks first and the highest FS value parameter
ranks twentieth). As can be seen in table 6.3, the rankings for different variables in the same
year can be very different. For example January 2031 is ranked first on dry bulb temperature
but eleventh on relative humidity. This implies that a January selected using only one of the
parameters may be inappropriate if other parameters affect the performance of the system
being studied. Similar results were obtained for other months. Table 6.4 shows for each
month the year with the highest rankings based on FS value for each individual weather
parameter. Therefore, they form the TRYs for those weather parameters. These TRYs could
be used to study the impact of a specific weather parameter on the system performance. However, it is much more useful to select a typical year which takes into account all the parameters over the set of 20 years.
<table>
<thead>
<tr>
<th>Year</th>
<th>Temperature</th>
<th>Solar radiation</th>
<th>Relative humidity</th>
<th>Wind speed</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>FS Rank</td>
<td>FS Rank</td>
<td>FS Rank</td>
<td>FS Rank</td>
</tr>
<tr>
<td>2020</td>
<td>0.084967</td>
<td>4</td>
<td>0.0433</td>
<td>2</td>
</tr>
<tr>
<td>2021</td>
<td>0.145733</td>
<td>10</td>
<td>0.081833</td>
<td>7</td>
</tr>
<tr>
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<td>18</td>
<td>0.230533</td>
<td>20</td>
</tr>
<tr>
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<td>14</td>
<td>0.1526</td>
<td>17</td>
</tr>
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<td>0.0308</td>
<td>1</td>
</tr>
<tr>
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<td>5</td>
<td>0.1062</td>
<td>13</td>
</tr>
<tr>
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<td>8</td>
<td>0.054533</td>
<td>4</td>
</tr>
<tr>
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<td>0.097467</td>
<td>10</td>
</tr>
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<td>0.053267</td>
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</tr>
<tr>
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<td>0.096267</td>
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</tr>
<tr>
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<td>0.1928</td>
<td>19</td>
</tr>
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<td>2032</td>
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<td>0.1424</td>
<td>16</td>
</tr>
<tr>
<td>2033</td>
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<td>2034</td>
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<td>0.0599</td>
<td>5</td>
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<td>2038</td>
<td>0.149267</td>
<td>11</td>
<td>0.100133</td>
<td>12</td>
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<tr>
<td>2039</td>
<td>0.369933</td>
<td>20</td>
<td>0.097867</td>
<td>11</td>
</tr>
</tbody>
</table>
Table 6-4 Selected months for TRY based on individual parameters

<table>
<thead>
<tr>
<th>Month</th>
<th>Dry bulb temperature</th>
<th>Solar radiation</th>
<th>Relative humidity</th>
<th>Wind speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>2031</td>
<td>2024</td>
<td>2038</td>
<td>2035</td>
</tr>
<tr>
<td>February</td>
<td>2029</td>
<td>2037</td>
<td>2039</td>
<td>2023</td>
</tr>
<tr>
<td>March</td>
<td>2028</td>
<td>2025</td>
<td>2026</td>
<td>2021</td>
</tr>
<tr>
<td>April</td>
<td>2038</td>
<td>2028</td>
<td>2025</td>
<td>2028</td>
</tr>
<tr>
<td>May</td>
<td>2039</td>
<td>2037</td>
<td>2039</td>
<td>2036</td>
</tr>
<tr>
<td>June</td>
<td>2031</td>
<td>2022</td>
<td>2022</td>
<td>2025</td>
</tr>
<tr>
<td>July</td>
<td>2024</td>
<td>2037</td>
<td>2031</td>
<td>2035</td>
</tr>
<tr>
<td>August</td>
<td>2033</td>
<td>2037</td>
<td>2037</td>
<td>2029</td>
</tr>
<tr>
<td>September</td>
<td>2027</td>
<td>2039</td>
<td>2028</td>
<td>2038</td>
</tr>
<tr>
<td>October</td>
<td>2028</td>
<td>2030</td>
<td>2030</td>
<td>2022</td>
</tr>
<tr>
<td>November</td>
<td>2039</td>
<td>2033</td>
<td>2033</td>
<td>2034</td>
</tr>
<tr>
<td>December</td>
<td>2021</td>
<td>2028</td>
<td>2038</td>
<td>2028</td>
</tr>
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</table>

Table 6-5 Weighting factor sets

<table>
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<tr>
<th>Weighting factor sets</th>
<th>W_{db}</th>
<th>W_{sr}</th>
<th>W_{rh}</th>
<th>SUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 1</td>
<td>0.5</td>
<td>0.25</td>
<td>0.25</td>
<td>1</td>
</tr>
<tr>
<td>Set 2</td>
<td>0.25</td>
<td>0.5</td>
<td>0.25</td>
<td>1</td>
</tr>
<tr>
<td>Set 3</td>
<td>0.25</td>
<td>0.25</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>Set 4</td>
<td>0.4</td>
<td>0.3</td>
<td>0.3</td>
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<td>Set 5</td>
<td>0.3</td>
<td>0.4</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>Set 6</td>
<td>0.3</td>
<td>0.3</td>
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</tr>
<tr>
<td>Set 7</td>
<td>0.33</td>
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<td>0.33</td>
<td>1</td>
</tr>
</tbody>
</table>

W_{db}: Weighting factor Dry Bulb Temperature

W_{sr}: Weighting factor Solar Radiation

W_{rh}: Weighting factor Relative Humidity
Table 6.6 shows the weighted sums of the FS statistics and their ranks for January. The FS selection is based on Eq.6.3 stated as follow:

$$FS_{weighted} = w_{temp}FS_{temp} + w_{solar}FS_{solar} + w_{rh}FS_{rh} + w_{windspeed}FS_{windspeed}$$

As can be seen in table 6.6, January 2020 ranks first for sets 3, 5, 6 and 7 and second for sets 2 and 4. Therefore has on overall the highest ranking for all weighting factor sets. As a result, January 2020 will be the January for the final weighted TRY. Similar procedures are conducted for the other months. Set 7 in Table 6.5, with equal weighting of the three parameters, is normally chosen (see below) since there is no prior information to indicate that one parameter is more significant than the others. A program by Kwanho Lee (2007) was used to extract the weighted TRY based on a 20 years data set.
Table 6-6 Weighted sums of FS statistics with different weighting factor sets for January

<table>
<thead>
<tr>
<th>Year</th>
<th>Set1</th>
<th></th>
<th></th>
<th>Set2</th>
<th></th>
<th></th>
<th>Set3</th>
<th></th>
<th></th>
<th>Set4</th>
<th></th>
<th></th>
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<th></th>
<th>Set6</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FS Rank</td>
<td></td>
<td></td>
<td>FS Rank</td>
<td></td>
<td></td>
<td>FS Rank</td>
<td></td>
<td></td>
<td>FS Rank</td>
<td></td>
<td></td>
<td>FS Rank</td>
<td></td>
<td></td>
<td>FS Rank</td>
<td></td>
<td></td>
<td>FS Rank</td>
</tr>
<tr>
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<td></td>
<td>0.057</td>
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</tr>
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<td>0.183</td>
<td>17</td>
<td></td>
<td>0.184</td>
<td>17</td>
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</tr>
</tbody>
</table>
This program has the additional feature that it can produce a TRY in which weights are applied to the product of the FS and standard deviation for each weather parameter (FSσ). However, this method usually leads to the same result as without the FSσ operation for the TRY selection. It also results in a weak correlation between the coefficients. Therefore, in this research in consultation with Dr J. B. Parkinson this feature was removed from the K. Lee program. This resulted in higher correlation between the coefficients and suggests that the standard deviation be ignored for result robustness.

Table 6.7 illustrates the correlation between the January ranks with different weighting factors. As can be seen in the table, the coefficients show that there are strong correlations between the January ranks using different weighting factors and that weighting factor set 7 has the best correlation (highest total correlation coefficient). Therefore, set 7 is considered weighting factor for January. The same operation applies to other each month and the total correlation coefficients between ranks are represented in table 6.7.

Table 6-7 Correlation coefficients between ranks for January

<table>
<thead>
<tr>
<th>Weighting factor set</th>
<th>Set 1</th>
<th>Set 2</th>
<th>Set 3</th>
<th>Set 4</th>
<th>Set 5</th>
<th>Set 6</th>
<th>Set 7</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.92</td>
<td>0.99</td>
<td>0.97</td>
<td>0.96</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
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<td>0.96</td>
<td>0.98</td>
<td>1</td>
<td>0.98</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
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<td>0.96</td>
<td>0.95</td>
<td>0.97</td>
<td>0.99</td>
<td>0.97</td>
<td></td>
</tr>
<tr>
<td>Set 4</td>
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<td>0.95</td>
<td>0.99</td>
<td>0.99</td>
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<td></td>
</tr>
<tr>
<td>Set 5</td>
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<td>0.99</td>
<td>0.99</td>
<td>1</td>
<td></td>
</tr>
<tr>
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<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
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<td></td>
</tr>
<tr>
<td>Set 7</td>
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<td>1</td>
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<tr>
<td>Total</td>
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<td>5.84</td>
<td>5.76</td>
<td>5.9</td>
<td>5.92</td>
<td>5.91</td>
<td><strong>5.93</strong></td>
</tr>
</tbody>
</table>

Table 6.7 gives the total sum of the correlation coefficients for each weighting set and for each month. For all months there were strong correlations between the ranks for different
weightings. For the twenty year HadCM3 data used for the TRY selection set 7, with equal weighting factors always gave the best correlations. As can be seen from table 6.7, the total correlation coefficient for set 7 is 71.32. It is, therefore, recommended that the TRY should be selected using equal weightings unless there are particular reasons for using some other weighting factor. However, a limitation of this method is that the total of the correlations coefficient are very close. So, it is better to stick with even weighting factors.

Table 6-8 Total correlation coefficients between ranks for all months

<table>
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<tr>
<th>Month</th>
<th>Set 1</th>
<th>Set 2</th>
<th>Set 3</th>
<th>Set 4</th>
<th>Set 5</th>
<th>Set 6</th>
<th>Set 7</th>
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</thead>
<tbody>
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<td>5.84</td>
<td>5.76</td>
<td>5.9</td>
<td>5.92</td>
<td>5.91</td>
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</tr>
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<td>5.97</td>
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<td>5.94</td>
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<td>5.98</td>
<td>5.99</td>
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<td>5.94</td>
<td>5.96</td>
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<td>5.97</td>
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Table 6.8 illustrates different TRYs selection based on 7 different weighting factors and table 16 presents the Test Reference Year (TRY) extracted from best weighting factor (Set 7). This unique TRY represents the most typical weather representation for the HadCM3 20 years (2020 – 2039) set of weather parameters. These weather parameters are: mean dry bulb temperature, solar radiation on the horizontal plane, relative humidity and wind speed. As noted above, the wind speed is not used in the selection process but is present in the final TRY. These parameters have the potential to affect building energy consumption.
Table 6-9 Selected months for TRY based on different weighting factor sets

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<th>Set 2</th>
<th>Set 3</th>
<th>Set 4</th>
<th>Set 5</th>
<th>Set 6</th>
<th>Set 7</th>
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<td>2024</td>
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Table 6-10 Final TRY

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</tr>
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<td>October</td>
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<td>November</td>
<td>2033</td>
</tr>
<tr>
<td>December</td>
<td>2021</td>
</tr>
</tbody>
</table>
Figs. 6.5 to 6.8 illustrate the TRY daily mean temperature, solar radiation, relative humidity and wind speed for the equal weighting factor (set 7) plotted against time.

Figure 6-5 Daily mean temperature for equal weightings Test Reference Year

![TRY Mean Temperature 2020-2039](image)

Figure 6-6 Daily solar radiations for equal weightings Test Reference Year

![TRY Solar Radiation 2020-2039](image)
The weather is one of the most important determinants of indoor thermal conditions and space air conditioning energy use. It is crucial parameter for dynamic building simulations.
programs. The test reference year (TRY) is a good illustration of the long term weather pattern. Therefore, Burkina Faso future energy consumption simulation will be done based on the TRY of its climate parameters.

**6.5 Temperature increase due to climate change**

Figure 6-9 Daily mean temperatures for TRY 1990-2009 and TRY 2050-2069

To assess the probable temperature increase in Burkina Faso due to climate change, this research considered the TRY of observed and projected future mean temperature data. The observed historical data TRY was selected for the period between 1990 and 2009 while the projected data TRY was selected from the period between 2050 and 2069. As it could be seen in Fig.6.9 the minimum mean temperature for the period between 1990 and 2009 is about 22°C and maximum mean temperature for the same period is about 37°C. However, the mean minimum temperature for the period between 2050 and 2069 is about 25°C with a mean
maximum temperature of 39°C. These results suggest that on average minimum temperature will increase by 3°C between 1990 and 2050 and the average maximum temperature will increase by about 2°C due to climate change. This increase in temperature will necessarily have an impact on thermal comfort in buildings as well as the energy demand for air conditioning.

6.6 Conclusion

The impact of climate change on future mean temperature has been investigated in this chapter. The projected future HadCM3 data was compared to the historical data and was found to be slightly overestimated. However, due to the fact that the HadCM3 data represent a grid data the overall discrepancy was found to be small and it was shown that on average the predicted data are realistic. It was found in this chapter that climate change will have a significant impact on the projected future average temperature of Burkina Faso. The average projected temperature will increase by 2°C between 2010 and 2050. In addition, projected extreme temperature will increase from 37°C to 39°C for the same period. In addition, it was found that the test reference year (TRY) is the best weather file format to assess the long term thermal performance of buildings. The TRY represents a typical year data of a 20 year period and could be used to simulate future energy consumption based on the projected future weather data. It represents the best set of data to assess energy consumption for a long period.

Weather data TRYS will be used in the next chapters to simulate projected cooling energy consumption in office buildings and domestic dwellings due to climate change.
Chapter 7 Climate change impact on office buildings cooling load

7.1 Introduction

Predicting future energy consumption and energy efficiency of a building before it is even built requires sophisticated and complex science. The growing complexity of buildings in function and design has made the whole building energy performance simulation an integral part of the planning process for building services engineers. Therefore, computer simulation software for predicting building performance in terms of energy and comfort are becoming increasingly important in the planning process. However, current industry standard weather files for building simulation are not suited to assess the potential impacts of changing climate. In addition, no Burkina Faso climate change weather files are readily available that can be loaded directly into building energy simulation software. Buildings energy performance simulation programs require appropriate weather data. This normally means hourly data of important weather variables, principally dry bulb temperature, relative humidity, direct and diffuse solar radiation and wind speed. Therefore, in this chapter different future period TRYs for weather parameters have been used to assess future energy demand in office buildings. This chapter also investigates different buildings thermo physical conditions and how they perform in terms of cooling load demand. Finally this chapter explores how shading devices and window to wall ratio (WWR) could help reduce energy consumption for cooling in office buildings using IES VE (Integrated Environmental Solutions Virtual Environment) building energy simulation program.

This work has published in a paper [164,174]. However more detailed content will be discussed in this chapter.
7.2 Integrated Environmental Solutions Virtual Environment: IES VE

IES VE incorporates ApacheSim, a dynamic thermal simulation tool based on first principles mathematical modelling of building heat transfer processes. It has been tested using ASHRAE Standard 140 and qualifies as a Dynamic Model in the CIBSE system of model classification [278]. The program provides an environment for detailed evaluation of building and system designs, allowing them to be optimized with regard to comfort criteria and energy use. The ApacheSim can be linked to MacroFlo for natural ventilation and infiltration analysis and to SunCast for detailed shading and solar penetration analysis [88]. A study conducted by Attia et al. (2009) on the comparison between different building energy performance simulation tools used among architects, designers, architect educators and students have shown that more than 85% of the combined groups strongly agree that IES VE results are accurate (within ±5% margin). Furthermore, the study shows that an overwhelming 95% of the above groups suggest that IES VE offers default values and templates. That facilitates quick entry and supports detailed analysis in early design phases [169].

7.2.1 IES VE validation

7.2.1.1 Analytical verification using excel program

Building energy simulation programs show the potential energy consumption savings associated with designed buildings. Several of them have been shown to be successful at reducing energy consumption, energy costs, and the impact of buildings emission on the environment. However, the process through which a simulation program has to go to simulate building energy consumption and its carbon emission is intrinsically complex. These program designers are very reluctant to communicate on the algorithms behind their programs. Even if
computer technology helps architects and engineers reduce buildings energy consumption by improving energy efficiency, the fact remains that simulation programs are black boxes in which we put input and generate output without a clear picture on how it works. However, it is important that users of building energy simulation tools are confident about the accuracy of the tools they are using. The uses of such tools highlight the potential for energy savings and comfort improvements. To ensure the credibility of the results, this study will compare IES simulation output to an Excel program results which is based on known formulas and accepted numerical method for isolated heat transfer mechanism under very simple conditions. The Excel program was developed by Hill (2010).

Modelling building energy consumption requires an energy simulation program that could address heat transfer processes through a building envelope. All of these processes are complex functions, and dependent not only on the building envelope but also the occupancy inside building. Environmental conditions also add to the complexity of the process. Building energy consumption is affected by the following factors:

- Building location (altitude, latitude, longitude and orientation)
- Local weather conditions
- Heat transfer and storage characteristics of the building’s elements, which depend on the various thermo-physical properties of the building’s components
- Windows, doors and other openings
- Shading of the exterior surface
- Building dimensions
- Indoor temperature, number and behaviour of occupants, lighting and building usage
- Primary and secondary air-conditioning systems
- Ventilation and infiltration
Each of these factors could influence the cooling load and have been considered for the calculations. However, understanding the process of the heat transfer through the fabric is the most important element in building energy consumption simulation for the cooling load.

7.2.1.2 Heat gains and losses through fabric and ventilation

Based on Hill et al. (2010) paper [284], heat lost from a building is calculated according to the following formula:

$$Q = \left( \sum U \cdot A + \frac{N \cdot V}{3} \right) (\Delta T) \quad \text{Eq 7.1}$$

Where $Q$ = heat flow (Watts), $U = U$ value (W/m²K), $A = \text{area} (m^2)$ of each element of the building envelope, $N = \text{ventilation rate} \ (\text{air changes/hour})$, $V = \text{volume of building} \ (m^3)$ and $\Delta T = \text{temperature difference between outside and inside} \ (K)$.

7.2.1.3 Thermal mass

The calculation method requires a figure for the time constant ($\tau$). This is the ratio of the thermal mass to the heat loss per degree temperature difference through building fabric and ventilation:

$$\tau = \frac{\text{Thermal mass}}{\left( \sum UA + \frac{NV}{T} \right)} \quad \text{Eq 7.2}$$
7.2.1.4 Hill excel program calculation main formula

By using the hourly time constant, and the temperature at the start of the hour $t_1$, the temperature $t_2$ at the end of the hour was calculated from:

$$t_2 = (p + t_{ao}) \times \left(1 - e^{(-\Delta T/\tau)}\right) + t_1 \times e^{(-\Delta T/\tau)} \quad \text{Eq 7.3}$$

With $p$ the plant sizes ration. Therefore, $t_2$ becomes the start temperature for the next hour, allowing the model to build a picture of the energy transfers and temperature profile throughout the day and onwards through the weeks.

7.2.1.5 Thermo physical conditions

Table 7.1 to 7.3 give an overview of the thermo physical input used for the two programs comparative analysis. Due to the complexity of the equations and the large quantity of data required for the simulation, the program was only set up to simulate a week-long period. Therefore, the comparative analysis will only focus on a cooling load of one week for January which is the coldest month and one week of April which is considered to be the warmest month [Appendix B]. The air conditioning system is set to start when the temperature reaches 25°C (based on observations [14]). Weather data for the year 2010 was used.
Table 7-1 Thermo physical characteristics

<table>
<thead>
<tr>
<th>Volume(m³) and area(m²)</th>
<th>U-Value in W.m⁻² K⁻¹</th>
<th>UA in W.K⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Width</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Height</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Volume</td>
<td>1920</td>
<td></td>
</tr>
<tr>
<td>Wall area - south</td>
<td>96</td>
<td>0.35</td>
</tr>
<tr>
<td>Wall - east</td>
<td>160</td>
<td>0.35</td>
</tr>
<tr>
<td>Wall - north</td>
<td>96</td>
<td>0.35</td>
</tr>
<tr>
<td>Wall - west</td>
<td>160</td>
<td>0.35</td>
</tr>
<tr>
<td>Roof area</td>
<td>230.4</td>
<td>0.25</td>
</tr>
<tr>
<td>Floor area</td>
<td>240</td>
<td></td>
</tr>
<tr>
<td>Roof light fraction</td>
<td>0.04</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Table 7-2 Thermal characteristics

<table>
<thead>
<tr>
<th>Volume in m³</th>
<th>Density in kg.m⁻³</th>
<th>Specific thermal capacity in kJ.Kg⁻¹*K⁻¹</th>
<th>mCp Thermal capacity in kWh.K⁻¹</th>
<th>mCp Thermal capacity in kJ.K⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1920</td>
<td>1.2</td>
<td>1.02</td>
<td>0.6528</td>
</tr>
<tr>
<td>Floor</td>
<td>2.4</td>
<td>2400</td>
<td>3.3</td>
<td>5.28</td>
</tr>
<tr>
<td>Total building mCp</td>
<td></td>
<td></td>
<td>5.9328</td>
<td>21358.08</td>
</tr>
</tbody>
</table>

Table 7-3 Roof light and ventilation

<table>
<thead>
<tr>
<th>Thermal transmisivity</th>
<th>Lighting time</th>
<th>lux required</th>
<th>Ac.h⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof light</td>
<td>0.55</td>
<td>6am - 12pm</td>
<td>900</td>
</tr>
<tr>
<td>&quot;arrival&quot;</td>
<td>0.8</td>
<td>12pm - 6am</td>
<td>400</td>
</tr>
<tr>
<td>Ventilation</td>
<td></td>
<td></td>
<td>0.36</td>
</tr>
</tbody>
</table>
Fig. 7.1 illustrates cooling loads for a week in January and a week in April using both IES and the Excel program. The result suggests a difference of 20.3% between the two set of results for January. With the Excel program experiencing a higher cooling load. The difference between the two programs for an April week cooling load is about 12.04% with IES VE experiencing this time the highest cooling load. Finally the aggregate total cooling load of the combined one January and April week gives a difference of 0.5%.

In light of these results, it can be said that the Excel program, which is based on known formulas and an accepted numerical methods for heat transfer calculations, and the IES program are in satisfactory agreement for the cooling load. This comparative analysis allows a better understanding of how the IES VE program operates.
7.2.1.6 CIBSE TM33 tests

The market for building services design software has been significantly growing in the recent years. These tools are now widely used for a range of tasks in the building services industry by consultants and contractors. In 2002 the Building Services Research and Information Association, supported by CIBSE and the Association of Consulting Engineers, published Design checks for HVAC (Heat, Ventilation and Air Conditioning)[171]. This quality control framework for building services design specifically addressed issues of verification and validation of design data. It particularly noted the need for software packages to be validated prior to use and warned of the possible professional indemnity implications of using software packages without validation.

The CIBSE TM33 tests arise from a need for the UK regulators to have a mechanism for the technical accreditation of detailed thermal models as part of their formal approval for use in the National Calculation Methodology [172]. The TM33 tests take into consideration the prediction of annual heating, cooling demand and overheating risk. These tests do not however provide a ‘truth model’ and so to demonstrate that the models can give credible results, further changes have been made to ensure that where appropriate, calculation methods meet the relevant British (European) Standards.

The TM33 tests are intended to provide a means by which software users can test if the software they use is producing results that are consistent with those produced by CIBSE methods. Software users will be able to test their software to assure themselves that it is consistent with published CIBSE methods and practices. The tests will enable software users to carry out a range of basic checks on the software they use, and to demonstrate that they have undertaken basic initial validation of the software.
To validate IES VE software and to ensure that it accords with CIBSE methods, a series of TM33 tests have been conducted in order to demonstrate that the software package was appropriate for the simulation of this research project. However, it is important to note that accurate software is a prerequisite of, but does not guarantee design quality.

Table 7.4 and 7.5 illustrate the results on building thermal performance and climate data generated by the IES <Virtual Environment> software for the CIBSE TM33 tests. These results show that IES <Virtual Environment> software gives satisfying output with an almost 100% accuracy with the CIBSE methods reference result. The minimum score required for software to be validated through CIBSE TM33 tests is 80% [172]. Therefore, this research could confidently rely on IES VE simulations to assess building energy consumption because it has proven to be consistent with CIBSE methods and meet the relevant British (European) Standards.
<table>
<thead>
<tr>
<th>Material</th>
<th>Source</th>
<th>Density kg.m(^{-3})</th>
<th>Thermal conductivity W.m(^{-1}).K(^{-1})</th>
<th>Specific heat Capacity J.kg(^{-1}).K(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ref.</td>
<td>User</td>
<td>Ref.</td>
</tr>
<tr>
<td>Outer brick</td>
<td>CIBSE Guide A</td>
<td>1700</td>
<td>1700</td>
<td>0.84</td>
</tr>
<tr>
<td>Cast concrete</td>
<td>CIBSE Guide A</td>
<td>2000</td>
<td>2000</td>
<td>1.13</td>
</tr>
<tr>
<td>Medium weight concrete</td>
<td>BS EN 1745</td>
<td>1800-2000</td>
<td>1900</td>
<td>1.15-1.65</td>
</tr>
<tr>
<td>Mineral fibre</td>
<td>CIBSE Guide A</td>
<td>30</td>
<td>30</td>
<td>0.035</td>
</tr>
<tr>
<td>Expanded polystyrene</td>
<td>CIBSE Guide A</td>
<td>25</td>
<td>25</td>
<td>0.035</td>
</tr>
<tr>
<td>Plywood sheathing</td>
<td>CIBSE Guide A</td>
<td>530</td>
<td>530</td>
<td>0.14</td>
</tr>
<tr>
<td>Timber board</td>
<td>BS EN 1745</td>
<td>300-1000</td>
<td>650</td>
<td>0.09-0.24</td>
</tr>
<tr>
<td>Asbestos cement</td>
<td>iSBEM</td>
<td>700</td>
<td></td>
<td>0.36</td>
</tr>
<tr>
<td>Brick inner leaf</td>
<td>iSBEM</td>
<td>1700</td>
<td></td>
<td>0.56</td>
</tr>
<tr>
<td>Carpet</td>
<td>iSBEM</td>
<td>20</td>
<td></td>
<td>0.058</td>
</tr>
<tr>
<td>EPS 50mm</td>
<td>iSBEM</td>
<td>15</td>
<td></td>
<td>0.04</td>
</tr>
<tr>
<td>Sandstone</td>
<td>iSBEM</td>
<td>2600</td>
<td></td>
<td>2.3</td>
</tr>
</tbody>
</table>
Table 7-5 Climate data test results

<table>
<thead>
<tr>
<th>Variable</th>
<th>Property</th>
<th>Climate set</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>January 6th 10:00am</td>
<td>6.1</td>
<td>6.1</td>
<td>-1.3</td>
<td>6.6</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>July 15th, 2:00pm</td>
<td>19.1</td>
<td>19.1</td>
<td>15.3</td>
<td>15.3</td>
<td>14.6</td>
</tr>
<tr>
<td></td>
<td>February average</td>
<td>4.5</td>
<td>4.55</td>
<td>4.8</td>
<td>4.81</td>
<td>2.7</td>
</tr>
<tr>
<td>Wind speed (m/s)</td>
<td>January 6th 10:00am</td>
<td>5.66</td>
<td>5.66</td>
<td>2.06</td>
<td>2.06</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td>July 15th, 2:00pm</td>
<td>4.63</td>
<td>4.63</td>
<td>4.63</td>
<td>4.63</td>
<td>3.09</td>
</tr>
<tr>
<td></td>
<td>November average</td>
<td>3.46</td>
<td>3.46</td>
<td>3.46</td>
<td>3.24</td>
<td>4.92</td>
</tr>
<tr>
<td>Global solar radiation (w.m-2)</td>
<td>January 6th 10:00am</td>
<td>59</td>
<td>59</td>
<td>67</td>
<td>67</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>July 15th, 2:00pm</td>
<td>336</td>
<td>336</td>
<td>238</td>
<td>238</td>
<td>210</td>
</tr>
<tr>
<td></td>
<td>July average</td>
<td>212</td>
<td>212</td>
<td>194</td>
<td>194</td>
<td>189</td>
</tr>
</tbody>
</table>

Weather data here is based on the TRY 02 weather data sets

### 7.3 Impact of projected climate change on cooling load

One of the major concerns for policy makers and building managers nowadays is how to evaluate and forecast buildings energy consumption, especially those with air conditioning systems. The main problems are caused by the variation in the energy consumption profile due to changes in the external weather conditions, occupancy patterns during the day, internal and external gains caused respectively by electronic devices and heat infiltration through doors, windows and the roof.
7.3.1 Public building description

Burkina Faso office building designs and operation conditions may vary largely. However, energy simulation of typical office buildings under representative operational conditions may help us to better understand the average energy performance of public buildings in Burkina Faso. A standalone three-story prototype of typical office building was chosen for this study. The floor plate size is 576m² (total floor area is 1725m²) and each floor is composed of 9 identical rooms with 8m (width) x 8 m (depth) x 4 m (height) dimensions as shown in Fig.7.2. The rooms are connected by concrete walls with opening doors to allow access and air circulation between them. Offerle et al. (2005) demonstrated that the tendency in Burkina Faso urban office buildings construction is directed toward concrete buildings with large glazed windows, copied from the North American and Western Europe building style. The
emphasis is more on external design and beauty than efficiency in low energy consumption [173-174]. As it could be seen in Fig.7.3a and b typical modern office buildings in Burkina Faso are particularly characterised by large glazed window.

Figure 7-3 Sample of current modern office building in Ouagadougou a
The typical office building illustrated in Fig. 7.2 was designed based on the actual tendency in public buildings construction. It has external concrete walls with 8 m² surface area of glazed window for each room, except for the middle one which does not have an external wall. The baseline window-to-wall ratio (WWR) is 25%, meaning that 25% of the wall area is covered with glazed windows. The bottom edge of the window is 1 m above the floor. Building occupancy is set to occur during the working time which is between 09.00 and 18.00 from Monday to Friday. Air conditioning during that period is programmed to start when temperature is higher than 25°C which is the commonly used setting point[14].
7.3.2 Thermo physical characteristics, internal and external heat gain

Table 7.6 & 7.7 summarize the overall case study building envelope thermo-physical characteristics used for the simulations. The solar absorptance is respectively about 0.7 and 0.55 for the external and internal surface. Different test reference years (TRY) have been considered in order to assess future energy consumption. The TRY represents average weather data for a 20 years period. Therefore, to analyse the potential impact of climate change the following TRY files were developed: TRY2000 – 2019, TRY2020 – 2039, TRY2040 – 2059 and TRY2070 – 2089. These TRYs represent four climatic variables namely: dry bulb temperature (C), relative humidity (%) and wind speed (m/s) and global solar radiation (MJ.m\(^{-2}\)) used to assess the average yearly cooling load for the considered periods.

Table 7-6 Building materials and components

<table>
<thead>
<tr>
<th>Components</th>
<th>Materials</th>
<th>Thickness m</th>
<th>Conductivity Wm(^{-1}).K(^{-1})</th>
<th>Density kgm(^{-3})</th>
<th>Specific heat capacity JKg(^{-1}) K(^{-1})</th>
<th>U-factor Wm(^{-2}).K(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>External wall</td>
<td>Brickwork (Outer leaf)</td>
<td>0.1</td>
<td>0.84</td>
<td>1700</td>
<td>800</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EPS slab insulation</td>
<td>0.055</td>
<td>0.025</td>
<td>30</td>
<td>1400</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Concrete block</td>
<td>0.1</td>
<td>0.51</td>
<td>1400</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plastering</td>
<td>0.015</td>
<td>0.42</td>
<td>1200</td>
<td>837</td>
<td></td>
</tr>
<tr>
<td>Internal wall</td>
<td>Plaster</td>
<td>0.013</td>
<td>0.16</td>
<td>600</td>
<td>1000</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>Brickwork (Inner leaf)</td>
<td>0.105</td>
<td>0.62</td>
<td>1700</td>
<td>800</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>Plaster</td>
<td>0.013</td>
<td>0.16</td>
<td>600</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Roof</td>
<td>Stone chippings</td>
<td>0.01</td>
<td>0.96</td>
<td>1800</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bitumen layers</td>
<td>0.005</td>
<td>0.5</td>
<td>1700</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Glass fibre quilt</td>
<td>0.1345</td>
<td>0.16</td>
<td>600</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ceiling tiles</td>
<td>0.01</td>
<td>0.05</td>
<td>380</td>
<td>1000</td>
<td></td>
</tr>
</tbody>
</table>
Table 7-7 Double glazed window characteristics

<table>
<thead>
<tr>
<th></th>
<th>Thickness (m)</th>
<th>Conductivity (W.m⁻¹.K⁻¹)</th>
<th>Resistance (m².K.W⁻¹)</th>
<th>Transmittance</th>
<th>Reflectance</th>
<th>Refraction index</th>
<th>U-factor (W.m⁻².K⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilkington K 6MM</td>
<td>0.006</td>
<td>1.06</td>
<td></td>
<td>0.69</td>
<td>0.09</td>
<td>1.526</td>
<td></td>
</tr>
<tr>
<td>Cavity</td>
<td>0.012</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.3247</td>
</tr>
<tr>
<td>Clear float 6MM</td>
<td>0.006</td>
<td>1.06</td>
<td></td>
<td>0.78</td>
<td>0.07</td>
<td>1.526</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>0.78</td>
<td>0.07</td>
<td>1.526</td>
<td>1.98</td>
</tr>
</tbody>
</table>

Occupants, electrical equipment and lighting affect the internal heat gains. Moreover, occupants contribute to both sensible and latent heat load in the building. Human presence is accompanied by a production of heat and moisture. The evacuation of this heat is done in a continuous way, primarily by convection (35%), by radiation (35%) and by evaporation (25%), according to conditions of air temperature, relative humidity and the activity of the individual [175]. The total heat produced per occupant is around 90W (Table 7.8) and the occupants’ presence in the building varies according to operating hours which is from 09.00 to 18.00. The unit area per occupant is assumed to be 20m². Office electronic equipment and lighting emit a certain quantity of heat in environment. For the lights, energy efficient lighting (fluorescent tubes) was considered with a power of 12W.m⁻² and the desired illuminance at the desk of 500 lux (Table 7.9). It is assumed that the consumed electric power is transformed completely into heat, diffused by convection with the ambient air or radiation to the surrounding walls and materials. These surroundings absorb and store a certain amount of heat depending on their density, conductivity and thickness. After a certain time the heat storage capacity of surrounding materials is saturated and the temperature of the room increases and that could potentially increase the cooling load. The heat load due to office electrical equipment is 15W.m⁻². The equipment and lighting loads follow the schedules of the occupants.
Table 7-8 Air exchange

<table>
<thead>
<tr>
<th>Air exchange</th>
<th>Max flow</th>
<th>Unit</th>
<th>Variation Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infiltration</td>
<td>0.25</td>
<td>ach</td>
<td>On continuously</td>
</tr>
<tr>
<td>Natural ventilation</td>
<td>1.2</td>
<td>ach</td>
<td>09.00-18.00</td>
</tr>
</tbody>
</table>

Table 7-9 Internal gain

<table>
<thead>
<tr>
<th>Max</th>
<th>Unit</th>
<th>Variation Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>People</td>
<td>90</td>
<td>W/p</td>
</tr>
<tr>
<td>Lighting</td>
<td>12</td>
<td>W/m²</td>
</tr>
<tr>
<td>Electrical equipment</td>
<td>15</td>
<td>W/m²</td>
</tr>
</tbody>
</table>

7.3.3 Trends of cooling load in future

Burkina Faso future climate (Fig.6.9) shows an increasing trend of temperature and summer discomfort and it is expected that energy use for maintaining comfort conditions in buildings will continue to grow under future climates. As illustrated in Fig.7.4 the simulation predicts that future trends of cooling load due to heat gain through office building envelope will increase with time. The results portrayed in Fig.7.4 suggest that the total yearly cooling load is respectively 142.7MWh, 163.92MWh, 193.39MWh and 285.12MWh for TRY2000 – 2019, TRY2020 – 2039, TRY2040 – 2059 and TRY2070 – 2089. This indicates that cooling energy consumption in Burkina Faso office building will increase by 15%, 36% and 100% in (2020 – 2039), (2040 – 2059) and (2070 – 2089) respectively.

Figure 7-4 Building yearly total cooling load using different TRYs
The simulation results portrayed in Fig.7.4 clearly suggest that air conditioning demand will continue to increase under future climates and likely to affect the energy infrastructure in the country which is already stressed. Most of the cooling energy demand will have to be met through fossil fuel electricity, a carbon intensive form of energy. This will have serious consequences for energy security as the existing electricity infrastructure in Burkina Faso is deemed as inadequate even to meet present demand [263]. Electricity consumption is likely to increase with the growth in gross domestic product (GDP) and income. The increasing trend of building cooling loads would result in more energy use and hence larger CO₂ emissions, which in turn would exacerbate climate change and global warming. The yearly carbon emission from this case study building is about 76,362 kgCO₂ and 87,055 kgCO₂ respectively for TRY2000 – 2019 and TRY2040 – 2059. Unless significant investment is made in order to develop low carbon cooling solutions, the impact of projected increased temperatures is likely to affect the country’s energy security. In addition, the STIRPAT
model (Chapter 5) also suggests that Burkina Faso rapid population growth will put additional pressure on electricity demand. Therefore the combination of rapid population growth and climate change will worsen the scarcity of energy and lead to more electricity shortage if business as usual. Therefore, urgent action has to be taken to deal with this issue if Burkina Faso is to reach a sustainable development.

**7.3.4 Adaptation of office buildings to increased temperatures**

Different energy efficient measures such as insulation, thermal mass, solar shading, night ventilation, indoor design condition and internal loads could have a significant impact on building cooling energy consumption [180]. The implications for total building energy use would vary, depending on the building and building services designs, its operation and weather parameters. Research on energy efficiency in residential and office buildings highlighted the importance of identifying key building design parameters that would have significant impact on the cooling/heating loads, especially in the assessment of the effectiveness of single and multiple energy retrofit measures [181]. Different building material characteristics were considered in this research and then adjusted individually to examine the effect of each factor on the whole building system cooling demand.

**7.3.4.1 Room orientation**

As illustrated in Fig.7.5 to 7.7, the annual room cooling load sensibly differs from one room to another according to window orientation and floor level. The results portrayed in Fig.7.5 suggest that the ground floor has the lowest total cooling load when compared to the first and top floor. The variation in cooling load between ground floor and the two other floors is about 5% and 6% respectively for first floor and top floor. The top floor which is adjacent to
the roof has the highest cooling load due to roof infiltration and more exposure to solar radiation. The air and heat that flows through the roof depends on the roof thermo physical properties. For the current simulation the roof U-factor was assumed to be about 0.25 W/m².K. Therefore, designing buildings and selecting construction materials in a way that reduces heat absorption and conduction through the roof would help reduce energy demand for cooling.

Furthermore, (see Figs.7.6 & 7.7), the middle room of ground floor is estimated to have the lowest cooling load of the building as a whole while the South West facing room on the top floor is estimated to have the highest cooling load. The difference between the two extremes is about 67%. As can be seen in table 7.12, irrespective of the floor level, the middle rooms followed by North facing window's rooms have the lowest cooling load. However, South West and South East facing window's rooms highlighted in table 7.12, experience the highest cooling load regardless of the floor level. This is mainly due to the sun's daily path and the fact that the South East room has two external façades which are exposed to direct sunlight throughout the day. Therefore, this room has a long duration exposure to sunlight. The analysis shows the increase in solar heat gain for the south-east and south-west facing facades over north facing facades and middle room of the building.

These results suggest that window orientation matters and has a significant impact on room cooling load and the total building energy demand. Moreover, room air cooling can also be achieved by improving the thermal performance of roofs. This is because roof surfaces are the most exposed to direct solar radiation and can cause excessive heat gain in hot periods. Lambert (1988) demonstrates that the use of low emissivity material in the top storey of buildings reduced the underside ceiling surface temperature, which lowered room air temperature and reduced cooling load demand [176]. Evaporative cooling approach for
passive cooling roofs in hot arid climates has also become an attractive subject and was investigated by Verma et al. (2005). They highlighted the relative advantages of evaporative reflective roofs in relation to many other approaches such as cavity wall, insulation, whitewash and large exposure orientations, vegetable pergola shading, roof with removable canvas, water film, soil humid grass and roof with white pots as cover [177-178]. Detailed investigations will be conducted in this research in order to assess potential savings in cooling load due to improved roof thermal performance.

Table 7-10 Window facing for ground floor (GF)

<table>
<thead>
<tr>
<th>Label</th>
<th>W</th>
<th>E</th>
<th>M</th>
<th>S</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window facing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7-11 Window facing for first floor (FF)

<table>
<thead>
<tr>
<th>Label</th>
<th>SE</th>
<th>SW</th>
<th>NE</th>
<th>NW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window facing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 7-5 Floor cooling load with TRY 2000-2019 weather conditions
Figure 7-6 Room cooling loads with TRY 2000-2019 weather conditions

Table 7-12 Cooling load per room and floor with TRY2010 - 2029 weather conditions

<table>
<thead>
<tr>
<th>Window</th>
<th>Ground Floor</th>
<th>First Floor</th>
<th>Top Floor</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW</td>
<td>5.48</td>
<td>5.75</td>
<td>5.82</td>
</tr>
<tr>
<td>S</td>
<td>5.26</td>
<td>5.49</td>
<td>5.57</td>
</tr>
<tr>
<td>SE</td>
<td>5.49</td>
<td>5.75</td>
<td>5.82</td>
</tr>
<tr>
<td>E</td>
<td>5.34</td>
<td>5.62</td>
<td>5.7</td>
</tr>
<tr>
<td>M</td>
<td>3.47</td>
<td>3.66</td>
<td>3.67</td>
</tr>
<tr>
<td>W</td>
<td>5.41</td>
<td>5.64</td>
<td>5.73</td>
</tr>
<tr>
<td>NW</td>
<td>5.23</td>
<td>5.48</td>
<td>5.53</td>
</tr>
<tr>
<td>N</td>
<td>5.01</td>
<td>5.22</td>
<td>5.28</td>
</tr>
<tr>
<td>NE</td>
<td>5.25</td>
<td>5.48</td>
<td>5.54</td>
</tr>
</tbody>
</table>
Finally, room orientation helps reduce cooling load. Therefore, a design which incorporates smart window orientation could help significantly reduce energy consumption in the long run and adapt to projected future temperature increase.

7.3.4.2 Window to wall ratio (WWR) impact on cooling load

Highly glazed office buildings (Fig.7.2) are designed by architects to be airy, light and transparent with more access to daylight. Their energy efficiency, however, has become questioned as there is a risk of high cooling load demand. This research investigates the impact of glazed windows on the energy use during the occupation stage. Therefore, alternative office buildings with 12%, 25%, 37.5% and 50% window to external wall area were studied. The results of the simulated alternatives are compared in order to study the influence of the glazed window to wall ratio (WWR) on energy consumption for cooling use during the occupation times. The results illustrated in Fig.7.7 show that a building with a 12% window to wall ratio has a 25% lower cooling loads demand compared to a building with a 25% window to wall ratio. The cooling load increases is as much as 49% and 84% when the WWR is increased to 37.5% and 50% respectively.
The results in Fig. 7.7 suggest that highly glazed buildings should be studied very carefully during the design stage since different types of glazed window constructions (WWR of 25%, 37.5% and 50%) have been proven to have a large impact on the energy demand compared to a 12% window to wall area ratio alternative. One of the main arguments for using increased glazed areas in buildings is the provision of better indoor environment due to daylight. However, our results have shown that increased window area does not lead to a significant reduction in energy use for lighting. In this case study the increase in lighting energy demand due to window to wall ration reduction from 50% to 12.5% is less than 1% with a 500lux light quality at the office desk. The main aim when designing glazed office buildings should be to avoid a high cooling demand therefore, it is crucial to ensure reasonable optimum window to wall ratio. Thus, the current trend in Burkina Faso which consists of designing large glazed window building should be reversed because these types of buildings are energy inefficient and lead to huge energy waste.
7.3.4.3 U – Value impact on cooling load

In Burkina Faso office buildings the cooling load is 67% of the total building energy use [14]. To reduce this it is crucial to choose appropriate building envelope materials with better thermal performance, especially the thermal insulation materials. This research investigates how to reduce building energy use by choosing appropriate building elements with better thermal performance which will reduce the need for air-conditioning, while maintaining a comfortable indoor environment for the occupants. Multiple simulations have been performed based on the typical office building illustrated in Fig.7.2 and the primary thermo physical characteristics listed in table 7.13.

The U-value of building envelopes and its effect on thermal performance is critical as the heat gain through building envelope accounts for large portion of the total heat gain. Building envelope is characterised by walls, windows as well as ceilings and floors. Each of these elements has its own equivalent resistance. The U-value or thermal transmittance of a building element is estimated by combining the thermal resistances of its component parts [179]. The thermal transmittance of simple walls and roofs composed of slabs is calculated by adding the thermal resistances of all element of the fabric and taking the reciprocal of the sum, thus giving the following formula:

\[ U = \frac{1}{R_{si} + R_1 + R_2 + \ldots + R_a + R_{so}} \] Eq. 7.4

Where

- \( U \) = overall thermal transmittance (W m\(^{-2}\) K\(^{-1}\))

- \( R_{si} \) = inside surface resistance (m\(^2\) K W\(^{-1}\))

- \( R_1 \) = conduction resistance of element 1 of fabric (m\(^2\) K W\(^{-1}\))

- \( R_2 \) = conduction resistance of element 2 of fabric (m\(^2\) K W\(^{-1}\))
\[ R_a = \text{airspace resistance, typically } 0.18 \text{ m}^2 \text{ K W}^{-1} \]

\[ R_{so} = \text{outside surface resistance} \]

The airspace is also included in the case of cavity walls. Heat loss through the fabric is calculated based on Eq.7.4.

The results illustrated in Fig.7.8 show that there is not much difference in cooling load for U-value between 0.12 and 0.54 Wm\(^{-2}\)K\(^{-1}\). In fact the increase in cooling load between U-value 0.12 and 0.22, 0.35 and 0.54 are respectively of 1%, 2% and 2%. These results suggest that trade-off between improving (i.e. reducing) the building envelope U-value and saving in cooling has an optimum U value level around 0.54 Wm\(^{-2}\)K\(^{-1}\) for this particular case scenario. However, the increase in cooling load between the lowest external wall U-value 0.12Wm\(^{-2}\)K\(^{-1}\) and a brick cavity with dense plaster wall, with U=1.49Wm\(^{-2}\)K\(^{-1}\), is about 12%. Moreover, the increase is about 18% when compared to a brickwork single-leaf construction with dense plaster wall with U=2.18Wm\(^{-2}\)K\(^{-1}\). A lower U-factor helps to prevent excess heat gain through the building envelope that increases indoor temperature. Properly placing the insulation layer and selecting efficient thermal insulation materials can help reduce cooling load demand. In addition it could help reduce the heat gain though the envelope. Thus, Burkina Faso office building designers should aim to utilise materials with the optimum U-values.
Table 7-13 Thermo physical characteristics for enhanced U-factor

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness m</th>
<th>Conductivity Wm(^{-1})K(^{-1})</th>
<th>Density kgm(^{-3})</th>
<th>Specific heat capacity Jkg(^{-1})K(^{-1})</th>
<th>U Value Wm(^{-2})K(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPS SLAB</td>
<td>0.166</td>
<td>0.035</td>
<td>25</td>
<td>1400</td>
<td>0.12</td>
</tr>
<tr>
<td>SAND</td>
<td>1</td>
<td>0.35</td>
<td>2080</td>
<td>840</td>
<td></td>
</tr>
<tr>
<td>CAST CONCRETE</td>
<td>0.3</td>
<td>1.4</td>
<td>2100</td>
<td>840</td>
<td></td>
</tr>
<tr>
<td>BRICKWORK (OUTER LEAF)</td>
<td>0.105</td>
<td>0.84</td>
<td>1700</td>
<td>800</td>
<td></td>
</tr>
<tr>
<td>DENSE EPS SLAB INSULATION</td>
<td>0.1</td>
<td>0.025</td>
<td>30</td>
<td>1400</td>
<td></td>
</tr>
<tr>
<td>CONCRETE BLOCK (MEDIUM)</td>
<td>0.105</td>
<td>0.51</td>
<td>1400</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>GYPSUM PLASTERING</td>
<td>0.015</td>
<td>0.42</td>
<td>1200</td>
<td>837</td>
<td></td>
</tr>
<tr>
<td>BRICKWORK (OUTER LEAF)</td>
<td>0.1</td>
<td>0.84</td>
<td>1700</td>
<td>800</td>
<td>0.22</td>
</tr>
<tr>
<td>DENSE EPS SLAB INSULATION</td>
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<td>1400</td>
<td></td>
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<tr>
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<td>0.51</td>
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<tr>
<td>GYPSUM PLASTERING</td>
<td>0.015</td>
<td>0.42</td>
<td>1200</td>
<td>837</td>
<td></td>
</tr>
<tr>
<td>BRICKWORK (OUTER LEAF)</td>
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<td>0.84</td>
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<td>800</td>
<td>0.35</td>
</tr>
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<td>CAVITY</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>POLYURETHANE BOARD</td>
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<td>0.025</td>
<td>30</td>
<td>1400</td>
<td></td>
</tr>
<tr>
<td>CONCRETE BLOCK (MEDIUM)</td>
<td>0.1</td>
<td>0.51</td>
<td>1400</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>CAVITY</td>
<td>0.01</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GYPSUM PLASTERBOARD</td>
<td>0.013</td>
<td>0.16</td>
<td>950</td>
<td>840</td>
<td>0.54</td>
</tr>
<tr>
<td>BRICKWORK (OUTER LEAF)</td>
<td>0.1</td>
<td>0.84</td>
<td>1700</td>
<td>800</td>
<td></td>
</tr>
<tr>
<td>CAVITY</td>
<td>0.05</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BRICKWORK (INNER LEAF)</td>
<td>0.105</td>
<td>0.62</td>
<td>1700</td>
<td>800</td>
<td>1.49</td>
</tr>
<tr>
<td>PLASTER (DENSE)</td>
<td>0.013</td>
<td>0.5</td>
<td>1300</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>BRICKWORK (OUTER LEAF)</td>
<td>0.22</td>
<td>0.84</td>
<td>1700</td>
<td>800</td>
<td>2.18</td>
</tr>
<tr>
<td>PLASTER (DENSE)</td>
<td>0.013</td>
<td>0.5</td>
<td>1300</td>
<td>1000</td>
<td></td>
</tr>
</tbody>
</table>
7.3.4.4 Shading devices

Daylight is desired because of the visual quality it ensures for occupants and because it reduces electricity consumption for lighting. However, daylight is a factor of solar radiation and glazing and becomes a source of heat by transmitting solar radiation into the building while preventing the emission of long-wave radiation to dissipate some of the absorbed solar energy (greenhouse effect). In addition, visual discomfort can occur when direct solar radiation is transmitted into rooms. Therefore, shading could play an important role in preventing thermal and visual discomfort. Changes in solar lighting load density affect not only energy use for electric lighting, but also energy requirements for space cooling. In general, a reduction in electric energy use would tend to lower the cooling requirement in warm climate countries [182-183]. Shading could be a significant means for reducing cooling
loads and can be achieved by several means. For this simulation analysis, four different levels of shading were taken into account, ranging from unshaded conditions (base scenario) to heavily shaded conditions (shutters). Two types of shading devices were considered. The external one illustrated by the balconies (Fig.7.9) and external shutters while curtains were used as internal shading devices. The thermo physical characteristics are detailed in tables 22 to 24. As illustrated in Fig.7.9, each storey is composed of 9 identical rooms with the following dimensions: 10m (width) x 10m (depth) x 4 m (height).

Figure 7-9  Building with balcony as shading device

The results shown in Fig.7.10 illustrate the shading devices’ performance in terms of cooling load compared to the unshaded base case scenario. The case study simulations were conducted based on TRY2010-2029, TRY2030-2049 and TRY2060-2079. Table 7.14 summarises the cooling load reduction achieved by each shading device compared to the unshaded base case scenario. It was observed that the external shutter is the most efficient
The shading device showed an average cooling load of 53% over the three TRYs considered. An average cooling load reduction of 38% and 19% respectively was obtained for the curtain and balcony.

Figure 7-10  Cooling load for different shading devices

![Cooling load for different shading devices](image)

Table 7-14 Cooling load reduction for shading devices

<table>
<thead>
<tr>
<th>TRY</th>
<th>Shutter</th>
<th>Curtain</th>
<th>Balcony</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRY2000-2019</td>
<td>66%</td>
<td>46%</td>
<td>22%</td>
</tr>
<tr>
<td>TRY2020-2039</td>
<td>53%</td>
<td>38%</td>
<td>19%</td>
</tr>
<tr>
<td>TRY2040-2059</td>
<td>41%</td>
<td>30%</td>
<td>15%</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>53%</td>
<td>38%</td>
<td>19%</td>
</tr>
</tbody>
</table>
The excellent performance of the shutters is attributed to the fact that external shading devices are more effective because they are able to block solar radiation effectively before it passes through the fenestration. Therefore, a large part of the solar radiation is absorbed by the shutter device then reflected and convected into the outdoor air. In addition, when interior shading devices are applied, IR (Infra-Red) radiation reradiated from the interior surfaces cannot go back out through the glass, which increases cooling energy consumption. However, shading devices significantly reduce the transmittance of daylight into the room and as a result, increase the energy demand for artificial lighting in the building [280].

7.3.4.5 Impact of shading devices on building artificial lighting demand

Good day lighting requires that the illuminance level does not negatively affect occupant’s heath but it contributes to increase their productivity. There are many variables that affect the illuminance level in spaces and shading is one of them. This study aims at assessing the performance of different shading devices and its impact on lighting energy demand while keeping good lighting quality which is about 500 lux illuminance on work plane.
The results illustrated in Fig.7.11 suggest that, when the shutter is operating, it increases artificial light energy consumption by about 9% on average while the curtain and balcony increase artificial light energy demand respectively by 5.6% and 2.5%. The increase in energy consumption for artificial lighting could be reduced if advanced and innovative day lighting/shading devices systems are being implemented in order to control solar gains, reduce glare and create a high quality indoor environment.

The SunCast algorithm used in IES VE, calculates hourly daylight levels, controls the solar shading system, and determines its effect on daylight levels, making photo-responsive lighting control possible. Therefore, for further research, dynamic fenestration and shading systems could be implemented and help to achieve optimal control of day lighting and solar
gain. Thus, an optimal balance between solar gains and internal gains is achieved and the total annual energy demand could be reduced.

7.4 Uncertainty

Evaluation of thermal building performance at a time that the building is still under design, implicates uncertainty. In this research, uncertainties in thermal performance assessments are not been quantified. It is important to acknowledge that many of the uncertainties cannot be estimated by straightforward statistical analysis of available data. This raises the question by which method these uncertainties could be assessed. Would such a method be applicable in design practice? It is therefore suggested that future work investigates in more detail the uncertainty linked to building thermal performance and future energy consumption simulation. This will contribute to more rational design decisions. A necessary requirement for the adoption of uncertainty analysis in practice would enhance the functionality of most building simulation tools, facilitate uncertainty and sensitivity analyses.

7.5 Conclusion

IES VE building energy simulation program has shown to have the potential of reducing energy consumption. However, to ensure the accuracy of the IES VE program results, it has been validated through comparison to an Excel program and the CIBSE TM33 test. The results were found to be excellent, suggesting that the IES VE program can confidently be used to assess projected future energy consumption in buildings. Energy consumption simulations based on a typical office building have shown that climate change will lead to a significant increase of cooling load demand in office buildings. It was found that current
energy consumption for cooling in office buildings will increase by 15%, 36% and 100% respectively for the period TRY (2020 – 2039), TRY (2040 – 2059) and TRY (2070 – 2089).

In this chapter it has been shown that despite the projected future increase of cooling load, adequate design could help tackle the projected increase in temperature. The results of the analysis have shown that architectural elements like window to wall ratio (WWR) and the orientation of the glazed windows has an impact on solar gains. Irrespective of the storey level, South West and South East facing window’s rooms are experiencing the highest cooling load demand. The effects of lowering the WWR have been investigated with a base case having 12% WWR. The results of the comparison with buildings having 25, 37.5 and 50% WWR have shown an increase in cooling load by 25%, 49% and 84% respectively.

Finally, it has been proven in this chapter that the external shutter is the most efficient shading device with an average of 53% reduction in cooling load. Curtain and balcony achieved an average cooling load reduction of 38% and 19% respectively.

Different design strategies applied in the study can contribute to improved thermal performance of buildings with significant decrease in cooling load. The study has shown the importance of architectural design and the choice of materials on the thermal performance of buildings as well as analysing the potential of mixed mode schemes. It aims to inform the architect and engineer to the significance of taking these features into account during the design stage.
8.1 Introduction and context

As demonstrated in Chapters 6 and 7, global warming will significantly affect office building energy consumption for cooling in Burkina Faso. The current trend implies that the uptake of air conditioning in the residential sector will also go up, thus potentially increasing domestic cooling energy consumption as well. In this context, this chapter investigates the significance of climate change and socio-economic parameters on energy consumption for cooling in domestic household.

Figure 8-1 Household expenditure levels
Fig. 8.1 illustrates household expenditure increase over 50 years in Burkina Faso. The result shows a continuous increase in household expenditure with a huge 112% increase in expenditure between 2000 and 2006 due to significant economic growth and improved household income levels and standards of living [184]. Previous studies have confirmed the relationships between demographic and economic factors and household energy consumption. In particular, links between household income level and energy consumption were found in numerous studies [185-189]. Santamouris et al. (2007) [186] have found that household income was an important determinant of dwelling envelope quality, type of equipment and cooling energy demand. Finally, Joyeux et al. (2007) demonstrates an economically significant and positive relationship between household energy consumption and standard of living [190]. Therefore, it is expected that the exponential increase in household income level and expenditure will make air conditioning more affordable for numerous household in Burkina Faso cities and therefore increase the energy demand for cooling. Therefore, this chapter deals with the following issues:

- What are the future trends of domestic building energy use for cooling in Burkina Faso, and how do these trends differ according to dwelling envelope?
- Given the data availability, is it possible to suggest an adequate domestic dwelling model which optimizes energy use for cooling?

### 8.2 Description of typical domestic house

The overwhelming majority of domestic dwellings in Burkina Faso urban areas have walls made of hollow concrete bricks illustrated in Fig. 8.2. A study conducted by the National Statistics Institute found that in 2008, for urban areas, concrete hollow brick houses were
estimated to be around 70% of the total domestic dwelling stock while in the capital city Ouagadougou, this proportion was about 75% and the trend is continuously increasing [191]. In addition, for urban areas, 89% of house roofs are made of steel metal with a ratio of 92% for Ouagadougou. In rural areas, a steel roof house is a sign of wealth and brings social pride. Currently the percentage of houses with steel metal roof in rural area is about 27% [191] [192].

Figure 8-2 Concrete hollow brick

![Concrete hollow brick](image_url)

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness m</th>
<th>Conductivity Wm⁻¹K⁻¹</th>
<th>Density kgm⁻³</th>
<th>Specific heat capacity Jkg⁻¹K⁻¹</th>
<th>U Value Wm⁻²K⁻¹</th>
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</thead>
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<tr>
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<td>0.5</td>
<td>1300</td>
<td>1000</td>
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</tr>
<tr>
<td>GYPSUM PLASTERING</td>
<td>0.013</td>
<td>0.42</td>
<td>1200</td>
<td></td>
<td>837</td>
</tr>
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<td></td>
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<td>Steel sheet</td>
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<td>480</td>
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<td></td>
<td></td>
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<td>5.87</td>
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</table>
Table 8-2 Single glazed window thermo physical characteristics

<table>
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<tr>
<th>Description</th>
<th>Thickness (m)</th>
<th>Conductivity W/m.K</th>
<th>Transmittance</th>
<th>Reflective index</th>
<th>Refraction index</th>
<th>U-factor (W/m².K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear Float 6mm</td>
<td>0.006</td>
<td>1.06</td>
<td>0.78</td>
<td>0.07</td>
<td>1.53</td>
<td></td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>5.39</td>
</tr>
</tbody>
</table>

Figure 8-3 Typical domestic household

A typical occupancy pattern was guided by the specific climate, culture and economy present in Burkina Faso. Cooling is provided in rooms, such as the living room and bedrooms but some other rooms such as bathrooms and kitchens are not normally equipped with air conditioners. Therefore, it was assumed that in the living room and dining rooms air conditioning would be turned on most often in the evening between 19.00 and 00.00 and sometimes during daytime from 13.00 to 15.00 but would be switched off at night from 00.00 to 06.00. However, air conditioners serving bedrooms would be turned on to run throughout
the night from 00.00 to 06.00. The activity level was assumed to be 90W per person and the unit area per occupant is assumed to be 50m². The energy load profiles are different in each room. Lights in the bedrooms were turned off when they were occupied from 00.00 to 06.00 and turned on in living room and dining room when they were occupied between 19.00 and 00.00. For lights, fluorescent tube lighting was assumed with a power of 12 W/m² and desired illuminance of 500 lux. These details enable the IES VE software to calculate the heat gains from the resident. Finally, the air infiltration rate including window, door and roof air gap was 0.25ach with the cooling set point is at 25°C (based on observation during field work). These occupancy patterns have been applied to all days through the year.

8.3 Future cooling load trends for domestic households

Fig.8.4 illustrates the future cooling load demand trends for a typical domestic dwelling. The simulation prediction based on TRY2000-2019 climatic conditions shows that energy demand for air conditioning in domestic household increases by about 14% and 45% by TRY2020-2039 and TRY2040-2059 respectively. This increase is mainly attributed to climate change which result in warmer outdoor and indoor air temperature and trigger the need for a higher air conditioning load.
As global warming continues and standard of living is still increasing, the current trends shown in Fig.8.4 imply that energy demand for air conditioning per household will also continue to increase. However, housing design and refurbishment of old buildings could help reduce overheat gain risks due to the dwelling envelope. As a result the expected increase in cooling load could be counteracted.

8.4 Impact of roof types on cooling load demand

Most dwelling roofs in Burkina Faso urban areas are made of steel-based materials [191]. However, steel-based materials exhibit undesirable thermal properties including high thermal conductivity which can make living conditions almost unbearable in these dwellings during April and May when the country is experiencing highest temperature. The IES VE SunCast algorithm calculation in this case demonstrates that most of the solar heat gain is transferred
through the roof into the dwelling. For most of the year the simulation show that the horizontal roof surface receives stronger solar radiation than that received by vertical walls. Therefore, the improvement of indoor thermal environment will be profound if methods are adopted in order to reduce the heat received through the roof.

Refurbishment of existing dwellings could show great potential for energy savings and better performances of cooling systems. This research investigates the potential benefit of several roof designs which could minimize heat transfer through roofs and how it affects dwellings annual cooling load demand. The selected roof constructions for the simulations and the characteristics of the roof materials (steel, cavity, wood, lightweight and reinforced concrete) are illustrated in Fig.8.5 and Table 33. The upper level of the roof in Fig.8.5 (b) consists of a steel metal sheet of 0.6mm thickness separated from the lower structure by an air cavity of 78mm thickness. However, Fig.8.5 (d) upper and lower structures were composed of concrete layer made from gravel, sand and cement mixture. To ensure that solar radiation is dissipated before excessive heat is transferred into the occupied indoor space the cavity was equipped with openings for natural ventilation and air circulation in the roof cavity.
Figure 8-5 Different roof types, construction and materials with different thermo physical properties

(a) Roof 1, Steel roof

(b) Roof 2, Steel roof with cavity and wood false ceiling

(c) Roof 3, Clay tile roof with cavity and wood false ceiling

(d) Roof 4, Concrete roof with cavity and wood false ceiling

(d) Roof 5, Concrete roof with ventilated cavity and concrete false ceiling
## Table 8-3 Roof structure and thermal characteristics of structures

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness m</th>
<th>Conductivity Wm⁻¹K⁻¹</th>
<th>Density kgm⁻³</th>
<th>Specific heat capacity Jkg⁻¹ K⁻¹</th>
<th>U Value Wm⁻²K⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>STEEL SHEET</td>
<td>0.002</td>
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<td>7800</td>
<td>480</td>
<td>5.39</td>
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<tr>
<td>Roof 1</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STEEL SHEET</td>
<td>0.002</td>
<td>50</td>
<td>7800</td>
<td>480</td>
<td></td>
</tr>
<tr>
<td>CAVITY</td>
<td>0.012</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TIMBER</td>
<td>0.01</td>
<td>0.15</td>
<td>560</td>
<td>2500</td>
<td>2.58</td>
</tr>
<tr>
<td>Roof 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLAY TILE</td>
<td>0.025</td>
<td>0.8</td>
<td>1900</td>
<td>800</td>
<td></td>
</tr>
<tr>
<td>CAVITY</td>
<td>0.012</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TIMBER</td>
<td>0.01</td>
<td>0.15</td>
<td>560</td>
<td>2500</td>
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</tr>
<tr>
<td>CAVITY</td>
<td>0.012</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TIMBER</td>
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<td>560</td>
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</tr>
<tr>
<td>Roof 3</td>
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</tr>
<tr>
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<td>1400</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>CAVITY</td>
<td>0.012</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TIMBER</td>
<td>0.01</td>
<td>0.15</td>
<td>560</td>
<td>2500</td>
<td></td>
</tr>
<tr>
<td>Roof 4</td>
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<td></td>
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</tr>
<tr>
<td>CONCRETE</td>
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<td>1000</td>
<td></td>
</tr>
<tr>
<td>CAVITY</td>
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<td></td>
</tr>
<tr>
<td>CONCRETE</td>
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<td>0.51</td>
<td>1400</td>
<td>1000</td>
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</tr>
<tr>
<td>Roof 5</td>
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<td></td>
<td></td>
<td>0.8</td>
</tr>
</tbody>
</table>

172
A set of simulations were performed considering the above 5 types of roof, to study their thermal performance. The objective was to determine the energy performance throughout the year and suggest the optimum roof properties as a function of cooling demand of the building. The results are summarised in Fig.8.6 and show the net cooling demand for each roof type. All the roofs are effective in cutting on average 25% off the cooling energy demand compared to the reference steel roof dwelling (roof 1). When the concrete roof with ventilated cavity and concrete false ceiling (roof 5) is applied, it results in a decrease of the annual cooling load by 36% compared to the reference steel roof dwelling. The corresponding decrease in the cooling load is 21.2% for the concrete roof with cavity and wood false ceiling (roof 4). On the other hand, the clay tile roof with cavity and wood false ceiling (roof 3) cuts 27% off the cooling energy demand. The combination of steel roof with cavity and wood false ceiling (roof 2) results in a net energy demand reduction for cooling of 18%.
The results detailed in Figs. 8.6 and 8.7 demonstrate that a concrete roof with ventilated cavity and a concrete false ceiling is the best performing roof type among the several tested ones. However, to protect the air cavity from rainwater or leaves, openings should be attached with covers such as wire mesh. However, that increases the resistance for the airflow. Therefore, air flow resistances in the cavity due to these coverings remain to be investigated. The worst results were obtained with the reference steel roof dwelling which is widespread in Burkina Faso and represents a huge 92% of total domestic dwellings in Ouagadougou. Therefore any of the alternatives to current practise is likely to bring benefits.
Fig. 8.7 confirms the correlation between U-value and net cooling load demand. The histogram shows that cooling load is decreasing with the U-value. The thermal performance of the roof is a good indicator of its performance in terms of cooling demand. The cement combined with larger heat flux reductions in the ventilated cavity allow a better temperature control. In addition, for future work, careful material selection with high thermal mass and high surface reflectivity combined with the concrete based roof would be beneficial because it could help minimize heat absorption therefore, reducing the cooling load.
8.5 Impact of insulation on energy demand for cooling

At present, thermal insulation is not normally used in the fabric of residential dwellings in Burkina Faso. Buildings wall slabs usually have concrete layer covered on each side by plaster layers. This research investigates the influence of adding a thermal insulation into the walls layers and its impact on the yearly cooling load demand for domestic dwellings using detailed heat transfer simulation.

Figure 8-8 Wall slab composition

(a) Without thermal insulation

(b) With thermal insulation facing the outside

(c) With thermal insulation facing the inside
For these investigations a thermal insulation layer up to 7cm thick was placed either at the inside or at the outside or in the middle part of the wall structure. The original outdoor wall slabs are composed of three layers: a 13mm thick cement/sand plaster layer at the outdoor side, a 22cm thick concrete layer and a 13mm thick gypsum plaster layer at the indoor side illustrated in Fig.8.8 (a). The concrete layer was kept at 22cm thick and the thickness of the plaster layers were kept the same 13mm as in the original wall slabs in order to study the simulation predictions in terms of cooling load demand with the insulation and optimize the design of domestic household envelope. When the thermal insulation layer was placed at the outdoor side of the slab, it was inserted between the concrete layer and the plastering layer at the outdoor side (see Fig.8.8 (b)). The structure then has four layers: one of thermal insulation, one of concrete and two of plaster. When a thermal insulation layer was placed inside of the slab, it was inserted between the concrete layer and the plastering layer at the indoor side (see Fig.8.8 (c)). As the previous structure, this slab also has four layers. Finally, when the insulation layer was located at the middle of the slab, it was inserted between two concrete layers illustrated in Fig.8.8 (d). This wall slab consists of five layers: two of plaster, two of concrete and one of thermal insulation. Note that in this slab, the two concrete layers were of the same thickness each 11cm, so that the total concrete thickness was 22cm.

Simulations were performed for each of the four wall slab types, based on the domestic house illustrated in Fig.8.3. Furthermore, clay tile roof with cavity and wood false ceiling with insulation was applied to all models.
The results illustrated in Figs. 8.9 and 8.10 show that thermal insulation has the potential to significantly reduce energy consumption for cooling in domestic dwelling. The results presented in Fig. 8.9 represent cooling load demand for each of the above wall slab types (see Fig. 8.8). It was found that when thermal insulation is applied to wall slab it reduces the cooling on average by 25% compared to the baseline case (without thermal insulation). Furthermore, thermal insulation is located at the indoor side result in a 26% decrease in cooling load demand and the wall slab with thermal isolation located in the middle scoring the least cooling load reduction (23%).

Figure 8-9  Same roof (clay tile roof with cavity and wood false ceiling with insulation) and different thermal condition for walls
The results portrayed in Fig. 8.10 compare the cooling load demand for a typical steel based roof uninsulated dwelling to different insulated wall slab dwellings. It was found that when insulation is added to the wall it resulted in energy savings of about 72% compared to the non-insulated steel based roof dwelling. These results confirm the finding that steel based roof domestic dwellings have the worst thermal performance and therefore result in the highest cooling load demand.
Figs.8.10 and 8.11 show that generally, the use of the thermal insulation yields a lower yearly cooling demand. However, the provision of thermal insulation to the inner part of the wall structure leads to the maximum yearly cooling load reduction. Placement of the thermal insulation outside ranks second in energy saving while thermal insulation located in the middle of the wall slab gives the lowest cooling result in energy savings. Fig.8.11 investigates the effect of the thermal insulation thickness and location on the yearly cooling load. Every curve in Fig.8.11 represents one of the three cases: (1) when the thermal insulation was located either to face the indoor space, (2) to face the outdoor or (3) to be in the middle of the wall structure. The thickness of the thermal insulation was varied from 0 (none (baseline)) to 8cm. The thickness of the concrete layer was maintained at 22cm. For the base line case, the total yearly cooling load was recorded at 40.01MWh. Compared to the
base line case, when thermal insulation layer of 2cm thickness faces the inside, the yearly cooling load would drop from 40.01 to 29.7MWh, a decrease of 26%. When this layer faces the outside of the wall slab, then the cooling load drops from 40.01 to 30.2MWh, a decrease of 25%. When the layer is placed in the middle of the wall the yearly cooling demand drops from 40.01 to 30.5MWh, a 24% decrease. For all three cases, when the thermal insulation thickness is raised above 4cm, the yearly cooling load drops relatively slowly. For instance, when the thermal insulation faces inside, the increase in the thermal insulation thickness from 4 to 7cm would yield a decrease of the yearly cooling load from 28.2 to 27.1MWh which is a decrease of 4%. This suggests that the use of thermal insulation thicker than 4cm might not be economically the best way to decrease the yearly maximum cooling demand because it will only slightly decrease the yearly maximum cooling demand.

The investigation has shown that the optimum insulation position was the inner surface of the wall slab. Therefore it is suggested that existing energy inefficient domestic dwellings could be refurbished with polystyrene insulation added to the inner wall, roof and covered with an appropriate material, like gypsum plastering. This configuration is very practical and can be done without any difficulty during dwelling refurbishment. However, placement of the thermal insulation in the middle of the wall slab result in the least cooling load reduction. Moreover this configuration is not practical because it can only be performed during the construction. Future research should be conducted to investigate the optimum insulation thicknesses as a function of total cost, fuel and insulation costs and the pay back periods.
8.6 Window impact on domestic dwelling cooling demand

In the previous section, it was found that in order to maintain comfortable indoor conditions and helps reduce high electricity consumption for cooling, it is recommended that domestic dwelling wall slabs be insulated in order to decrease heat gains through the envelope. Previous simulation to predict domestic dwellings cooling load were performed based on single glazed window thermal conditions (see Table 8.2). This research investigates double glazing window’s performance in terms of energy efficiency based mainly on its U-value and solar heat gain coefficient (SHGC).

The U-value indicates the rate of heat flow due to conduction, convection, and long wave radiation through a window as a result of a temperature difference between the inside and outside while the SHGC indicates how much of the sun’s energy striking the window is transmitted through the window as heat. The window heat load is calculated by the following components:

- Heat load by through window

\[ Q = U \times A \times \Delta T \times \Delta t \quad \text{Eq. 8.1} \]

Where \( U \) is the overall coefficient of heat transfer (kWh/m²K), \( A \) is the window area (m²), \( \Delta T \) is the total equivalent temperature difference, which takes into consideration the increase of wall temperature due to absorption of solar radiation and \( \Delta t \) is the length of the time step.
- Load due to transmission of solar radiation which is calculated by the following equation:

\[ Q_{tr.} = SC \times SHGC \times CLF \times A \times \Delta t \quad \text{Eq. 8.2} \]

Where SC is the shading coefficient, SHGS is the solar heat gain coefficient (kW/m²) and CLF is the cooling load factor.

As it can be seen from Eq.8.1, the higher the window U-value the more heat is transferred. Table 8.4 illustrates the thermo physical characteristics of single and double glazed windows. It shows that the single glazed window U-value is 2.7 times higher than the double glazed one. Therefore, single glazed windows widely used in Burkina Faso domestic dwellings are a source of thermal heat gain (see Q. in Eq.8.1), resulting in higher electricity consumption for cooling load.

<table>
<thead>
<tr>
<th>Description</th>
<th>Thickness (m)</th>
<th>Conductivity W/m.K</th>
<th>Transmittance</th>
<th>Reflective index</th>
<th>Refraction index</th>
<th>U-factor (W/m².K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear Float 6mm</td>
<td>0.006</td>
<td>1.06</td>
<td>0.78</td>
<td>0.07</td>
<td>1.53</td>
<td>5.39</td>
</tr>
<tr>
<td>Single domestic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PILKINGTON 6mm</td>
<td>0.006</td>
<td>1.06</td>
<td>0.69</td>
<td>0.09</td>
<td>1.53</td>
<td>5.39</td>
</tr>
<tr>
<td>Cavity</td>
<td>0.012</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clear Float 6mm</td>
<td>0.006</td>
<td>1.06</td>
<td>0.78</td>
<td>0.07</td>
<td>1.53</td>
<td>1.97</td>
</tr>
<tr>
<td>Double domestic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 8.12 illustrates the yearly cooling load as a function of glazing type and glazing U-value. It shows that generally cooling is decreasing with the glazing U-value and that the use of double glazing yields lower yearly cooling load demand. As can be seen in Fig. 8.12, single glazed domestic window with U-value of 5.39 W/m²K has a yearly cooling load demand of 29.05 MWh. However, when a double glazed window with U-value of 1.97 W/m²K is used instead, then the yearly cooling load drops from 29.05 to 25.82 MWh, a decrease of 11%. In addition, Eq. 8.1 and 8.2 shows that the solar heat gain is function of the glazing surface A. As the window area increases, the solar gain potential through a given window increases. Therefore, glazed window size and U-value is crucial in domestic dwellings cooling load. Designers should aim at optimum double glazed window size which will optimize the cooling load demand.
8.7 Thermal comfort and cooling load

Thermal comfort can be defined as the condition of mind which expresses satisfaction with the thermal environment [198]. In this research, all previous simulations on predicted building energy consumption for cooling have been performed based on the standard ISO 7730 [195]. These guidelines are widely used from climates temperate to tropical climates, for building design and thermal comfort. However, several studies have drawn some criticisms about the ISO 7730 and the ASHRAE 55 standards. Subsequent works by Humphreys and Nicol (2004) based on results of field studies in India, Iraq and Singapore demonstrates that standard ISO 7730 and the ASHRAE standard 55 guidelines do not result in comfort for naturally ventilated buildings where people adapt to the warmth and adapt their clothing according to the outside weather conditions. Therefore applying these standards does not produce energy savings as air conditioning might well be required, therefore, implying that these standards should not be applicable to these cases [194]. In addition, due to the fact the ISO 7730 does not provide information about the type of clothing that people wear; there is a tendency to assume a unique clothing level and that result in more cooling load demand [195].

As households are getting more affluent in Burkina Faso [184], air-conditioning is becoming more popular to help in achieving a comfortable internal thermal environment. Amidst today’s energy supply shortage crises, the importance of finding ways to reduce the high-energy consumption has become increasingly clear. Different comfort levels have been considered to assess the potential savings in yearly energy consumptions. Therefore, the following adjustment 25°C to 26°C, 27°C, 28°C and 29°C of the thermostat setting have been considered. Simulations where performed based on the typical domestic dwelling illustrated
in Fig.8.3 and with double glazed windows (see thermo physical characteristics in Table 8.4 and Table 8.5).

### Table 8-5 Wall and roof thermo physical conditions

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness m</th>
<th>Conductivity Wm⁻¹K⁻¹</th>
<th>Density Kg⁻¹m⁻³</th>
<th>Specific heat capacity JK⁻¹K⁻¹</th>
<th>U-value Wm⁻²K⁻¹</th>
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</thead>
<tbody>
<tr>
<td>GYPSUM PLASTERING</td>
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<td>0.42</td>
<td>1200</td>
<td>837</td>
<td></td>
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<tr>
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</tr>
<tr>
<td>GYPSUM PLASTERING</td>
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<td>0.42</td>
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<td>0.35</td>
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<td>1900</td>
<td>800</td>
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<td>CAVITY</td>
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<tr>
<td>TIMBER</td>
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<td>0.15</td>
<td>560</td>
<td>2500</td>
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<td>CAVITY</td>
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</table>
Fig. 8.13 illustrates the simulation results for predicted cooling load demand based on different cooling set points. It shows that in general, increasing the cooling set point represents an opportunity to save energy for air conditioning. The energy consumption for cooling load is reduced by 29% when the set point drops from 25°C to 27°C. In addition, the yearly cooling load drops from 26MWh to 14.84MWh, when the set point is down from 25°C to 28°C, a 43% decrease. Thermal comfort standards are the means to provide information to building designers on defining a good indoor climate. However, thermal comfort standards are not defined specifically for Burkina Faso, as there is no past research conducted. As can be seen in Fig. 8.11 the choice of this thermal comfort level choice will influence the resulting energy use for air conditioning.

Various research on thermal comfort in domestic dwellings conducted in India have found that subjects were comfortable for temperatures between 26°C and 32.5°C, much higher than
the range specified in the Indian Code which is set to be between 23°C and 26°C [196-197]. This finding has enormous energy implications and reveals the high potential of adjusting cooling set point. Therefore, it is suggested that cooling setting point in Burkina Faso be considered between 27°C and 29°C because the population is likely to be more comfortable in warmer indoor conditions. This alone could result in an energy consumption saving for cooling of between 29% and 56%. It is also recommended that thermal comfort adaptation measures be promoted. For a warm country such as Burkina Faso, there is a broad range of adjustments that could be proposed. Personal or behaviour adjustments involve various conscious actions that are related to the human body such as drinking more liquid, changing to more suitable clothing, sitting in a ventilated place etc. Environmental adjustments are in the form of active controls over the surrounding spaces such as opening windows, using fans instead of air conditioning, etc. Studies, also suggest that psychological adaptation makes occupants more tolerant to temperature swings [198-199].
8.8 Conclusion

The results have shown that climate change will result in an increase of cooling load for domestic dwellings. Current energy demand for air conditioning in domestic household will increase by 14% and 45% respectively for the period TRY2020-2039 and TRY2040-2059. However, the potential benefit of different type of roofs in reducing cooling load has been investigated in this chapter. It has been shown that all studied roofs are effective in cutting on average 25% off the cooling energy usage compared to the reference steel roof dwelling. However, compared cost of the different roofs studied in this study has not been considered because it was out of scope. A concrete roof with ventilated cavity and concrete false ceiling has proven to be the optimal roof design. This particular type of roof leads to a decrease of the annual cooling load by 36% compared to the reference steel roof dwelling. The corresponding decrease in the cooling load is 27%, 21.2% respectively for the clay tile roof with cavity and wood false ceiling; concrete roof with cavity and wood false ceiling dwelling. It was also found that thermal insulation has the potential of reducing the average cooling load by 25% compared to the baseline case (without thermal insulation). The location of the thermal insulation has an impact on the cooling load. It has been shown in this chapter that thermal insulation located indoor result in a 26% decrease in cooling load demand. The decrease is 25% and 23%, when placed outdoor and in the middle of the wall slab. Therefore, optimum insulation position was to place the thermal insulation in the inner surface of the wall slab. This research has also shown that thermal insulation possesses an optimum level of thickness. With 2cm of thickness of insulation it is possible to achieve up to 26% cooling load reduction while the reduction is about 4% when the thermal insulation thickness is increased from 4cm to 7cm. Thus, the results suggest that the use of thermal insulation
thicker than 4cm might not be economically viable because it results in a small reduction of the yearly cooling demand.

The findings of this research confirmed the fact that steel based roof domestic dwelling has the worst thermal performance and therefore results in a high cooling load demand. The investigation has shown that the cooling load decreases with the glazing U-value. It was found that double glazing yields lower yearly cooling load demand with an 11% cooling load reduction when compared to the single glazed window domestic dwelling.

Finally, it has been shown that significant yearly energy consumption savings could be achieved by adjusting the thermostat setting from 25°C to 26°C, 27°C, 28°C and 29°C. This research argues that the cooling setting point could be set between 27°C and 29°C because population in warmer countries is likely to be more comfortable in warmer indoor conditions. That could result in an energy consumption saving for cooling of between 29% and 56%.
Chapter 9 Traditional adobe house thermal performance

9.1 Introduction

Adobe houses have been well known in the world of construction for millennia. Adobe is a construction technique that uses a mixture of mud, clay, sand and water as raw materials which are moulded to form sun-dried blocks [200]. In Burkina Faso an overwhelming majority of houses in villages and the older parts of many cities are made of sun dried mud bricks mixed with straw (agricultural waste). The straw provides improved the adobe by preventing cracks and offers a better thermal insulation [200].

Over the past decades Burkina Faso has experienced fundamental changes in its social, economic, cultural and political fields. In the built environment these changes have brought the introduction of new technologies and materials. Buildings design are shifting, from heavy weight to lightweight with the use of large glazed windows and hollow concrete bricks with little consideration of passive methods of heat control or human adaptation to comfort. The use of new building materials, systems and techniques, to replace the existing traditional building materials and techniques has been done rapidly without testing the performance of the new materials. There is no doubt modern building materials have some advantages but, these materials have limitations in their adaptability to the Burkina Faso climate.

This research investigates the potential of adobe houses for reducing the rising energy consumption for air conditioning in the built environment. To address this issue, a field study was conducted on adobe and typical “modern” domestic dwellings thermal performance. All houses chosen for this field study are located in the capital city, Ouagadougou.
9.2 Houses description

The field study performed thermal performance data collection on three different domestic dwellings in Ouagadougou namely an adobe domestic house, a typical concrete hollow bricks dwelling with a steel based roof and a concrete hollow bricks dwelling with steel based roof, cavity and wooden false ceiling. These types of houses are the most representative in the country. Fig.9.1 illustrates a typical one storey domestic adobe dwelling. It has a ground surface of 180m² with 60cm width external walls. The roof and walls are both made of mud bricks with dimensions 40cm x 20cm x 10cm for the external walls bricks. However, the roof is characterised by smaller brick which 24cm x 12cm x 4cm dimensions. The windows are wooden based window. Fig.9.2 portrays a single storey concrete hollow bricks dwelling with a steel based roof. It has a ground surface of 150m² and the external walls are made of 22cm width concrete hollow bricks with 15mm plaster on both side. This dwelling is equipped with an air conditioning system and single-glazed windows with metal frame. However, the air conditioning system was turned off during the field study data collection time frame. Finally, this research considered a concrete hollow bricks dwelling with a steel roof only which is illustrated in Fig.9.3. The floor area is 120m² and the windows are metal based. The walls comprise a concrete layer made of hollow bricks of 22cm width covered on each side by 15mm plaster layers. This type of dwellings is the most common in urban areas with up to 92% of total domestic dwellings in Ouagadougou [192].
Figure 9-1 Adobe house

Figure 9-2 Concrete hollow bricks with steel roof, cavity and wooden ceiling
9.3 Temperature sensor-logger and Data collection

The objective of the field study was to collect data related to the thermal environmental conditions indoor and outdoor for the selected houses. For each of the above houses a south facing room without air conditioning was selected. Measurement variables include indoor and outdoor air temperature and relative humidity sampled every hour for the period between January 2011 and October 2011. Temperature and relative humidity are the most representative weather parameters for thermal comfort in Burkina Faso. To implement such a data collection, a computerized measurement and data acquisition system was established. The following sections describe the development and operation of the instrument system (i-button).
9.3.1 Data logger and calibration

The i-button illustrated in Fig.9.4 with a 9mm radius and 6mm height was selected for the temperature and humidity measurement. It can measure temperatures from -20°C to 85°C with minimum logging interval of one second. For more accuracy, the sensor-loggers needed to be accurately calibrated before being installed in the field. A calibrated sensor-logger, certified to standard EN 13005 and ISO 17025 was obtained. All sensor-loggers alongside the calibrated sensor-logger were placed in an oven at 30°C. The same calibration experiment was conducted in a colder environment 6 °C. The certified sensor-logger was used to adjust the error value of each sensor.

Figure 9-4  I-button
Table 9.1 shows that an average value of -0.108°C was used as adjustment value for a reference sensor-logger.

Table 9-1 Difference between reference and certified sensor-logger

<table>
<thead>
<tr>
<th>Differences</th>
<th>Difference</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Difference at 30°C</td>
<td>0.031°C</td>
<td>-0.108°C</td>
</tr>
<tr>
<td>Difference at 6°C</td>
<td>-0.247°C</td>
<td></td>
</tr>
</tbody>
</table>

However for more accuracy of ambient air temperature measurement, a radiation shield was required. The radiation shield was used to shelter the sensor from the rain and solar radiation. Furthermore, sufficient ventilation should also be used to avoid accumulation of hot air inside the shield. Readymade shield available in the market were either too expensive or not suitable for the present research. Thus, a new radiation shield made of a simple plastic box with openings for air circulation as illustrated in Fig.9.5 was designed and fabricated by the author to accommodate the temperature sensor-logger. The author’s radiation shield was always placed in shaded places.
In order to test the efficiency of this radiation shield, a calibration experiment was performed using certified radiation shield (see Fig.9.6) which had been tested based to an international standard [201]. A calibration experiment for the two different types of radiation shield was conducted under the same thermal environment and the temperature was measured for a period of three days. Fig.9.7 shows that the “author’s shield” and the “certified shield” temperatures were very similar.
Figure 9-6 Certified radiation shield

Figure 9-7 Sensor loggers temperature variations for different radiation shield
Table 9-2 Temperature comparison for the two type of shield

<table>
<thead>
<tr>
<th>Sensor logger</th>
<th>Mean(ºC)</th>
<th>Std. Dev(ºC)</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Certified shield</td>
<td>28.1</td>
<td>2.7</td>
<td>22.5</td>
<td>33.9</td>
</tr>
<tr>
<td>Author shield</td>
<td>28.2</td>
<td>2.9</td>
<td>22.3</td>
<td>34.9</td>
</tr>
</tbody>
</table>

Table 9.2 tabulates the mean and standard deviation of the data from both sensor-loggers. The result shows that mean temperature difference is about 0.1ºC and the standard deviation difference is about 0.2ºC. Little discrepancies have been recorded between the two shields. The result indicates a very close performance of the radiation shields. Therefore, it can be concluded that the author’s shield is capable of providing accurate thermal performance data.

9.4 Data collection

The sensor-loggers used in this project had an internal memory of 8kB. According to the data provided by the manufacturer [202] the battery life is expected to last for three years when measuring at 30 minutes intervals. For this research a 30 minutes logging interval was used because it can give a better resolution for any time lag between different sensor-loggers. On the other hand, the battery inside the sensor-logger will be consumed a lot quicker with shorter logging intervals. A shorter logging interval also means more frequent data collection process which will be expensive and time consuming. Four types of data were recorded: Date, time, temperature unit and temperature reading. Each sensor-logger is capable of storing three months data without being overwritten. Data was collected every two months. In general, the measurement and data acquisition system performed satisfactorily during the 10 months study period. The system allowed the collection of an enormous amount of valuable
data which otherwise could not have been obtained from the selected houses. Routine maintenance of the system included periodically cleaning and adjusting the sensor loggers.

9.4.1 Results

Table 9.3 summarised the statistics of 10 months temperature data collected for the different case study dwellings. The thermal analysis results shed a light on the appropriateness of using traditional architecture (adobe) in Burkina Faso. It shows that a hollow concrete brick house with a steel roof performs very poorly in term of thermal comfort. It has the worst thermal performance with an average indoor temperature of 32.5ºC. The adobe house ranks first in terms of thermal comfort with an average indoor temperature of 25.8ºC for the study period.

Table 9-3 Summary of the indoor and outdoor temperature

<table>
<thead>
<tr>
<th>Roof type</th>
<th>Mean temp</th>
<th>Std. Dev.</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adobe</td>
<td>25.8</td>
<td>1</td>
<td>24.5</td>
<td>29</td>
</tr>
<tr>
<td>Steel and wood</td>
<td>30</td>
<td>3</td>
<td>24</td>
<td>38</td>
</tr>
<tr>
<td>Steel only</td>
<td>32.5</td>
<td>5.7</td>
<td>20.5</td>
<td>46</td>
</tr>
<tr>
<td>Outdoor</td>
<td>29.7</td>
<td>5.8</td>
<td>18.5</td>
<td>45.5</td>
</tr>
</tbody>
</table>

In addition, as it could be seen in Table 9.3, the adobe house has the lowest standard deviation of 1. The standard deviation is defined by the following formula:

\[
\sigma = \sqrt{\frac{\sum_{i=1}^{n} a_i^2}{n} - \left(\frac{\sum_{i=1}^{n} a_i}{n}\right)^2} \quad \text{Eq. 9.1}
\]

A low standard deviation as portrayed in the case of the adobe house indoor temperature data suggests that the data are very close to the mean temperature, whereas the high standard
deviation (up to 5.7) in the case of the hollow concrete brick house with steel roof indicates that the data points are spread out over a large range of value. These results suggest that the adobe house has a relatively more stable indoor temperature.

Figure 9-8  Indoor and outdoor temperature for the adobe house
Figure 9-9 Indoor and outdoor temperature for dwelling with steel roof and false wood ceiling

Figure 9-10 Indoor and outdoor temperature for steel roof, concrete brick dwelling
Burkina Faso possesses low relative humidity level. Therefore, temperature is undoubtedly one of the most important factors when providing a comfortable indoor environment. Figs 9.8 – 9.10 illustrate indoor and outdoor temperature comparison for the three type of dwelling over the period between 15th April 2011 and 17th May 2011. The months of May and April are the warmest months in Burkina Faso (Appendix B), therefore represent the period of the year where energy demand reaches its highest level in terms of cooling load demand. The overview of the results portrayed in these graphs suggests that the adobe dwelling has a better thermal performance with low amplitude for indoor temperature. On the other hand, the concrete hollow brick dwelling with steel roof only shows an indoor temperature which is on average higher than the outdoor temperature. However, the hollow concrete brick dwelling with a steel roof & indoor wood false ceiling has a slightly better thermal comfort compared to the steel roof only.

The adobe house is characterised by its thick walls which measure 60cm that contribute to increase the adobe dwelling thermal mass. Studies have shown that in some locations cooling energy demands in buildings containing thick walls could be lower than similar buildings construction using lightweight wall [203]. As it could be seen in Fig 9.8 utilization of thermal mass in buildings can be one of the most effective ways of reducing building cooling loads. Higher thermal mass reduces temperature swings and absorbs thermal energy both from solar gains and internal heat gains resulting in a lower indoor temperature. In addition, massive building envelope components delay and attenuate thermal waves caused by exterior temperature swings [204]. Attenuation is indicated by a decrement factor, the ratio of the external wave amplitude to the emerging internal wave amplitude. Therefore, to assess with precision the thermal performance of each dwelling type, the heat transfer fluctuation through each dwelling fabric under Burkina Faso climate conditions was considered. Time lag,
decrement factor and time constant calculations were carried out to investigate the performance of each dwelling wallboard material with respect to the sinusoidal heat flux waves on the outer surface and compared with traditional adobe dwelling [204].

9.4.2 Time lag and decrement factor

“The heat wave flows through the wall from the outside to inside. Amplitudes of these waves show the temperature magnitudes and wavelength of the waves shows the time. The amplitude of the heat wave on the outer surface of the wall is based on solar radiation and convection in between the outer surface of the wall and ambient air. Its amplitude will decrease depending on the thermophysical properties of wall materials [208]”. When this wave reaches to the inner surface, it will have amplitude which is lower than the amplitude of the wave at the outer surface. The time it takes for the heat wave to propagate from the outer surface to the inner surface is called the ‘time lag’ and the decreasing ratio of its amplitude during this process is named as ‘decrement factor’ [205]. The schematics of time lag and decrement factor are illustrated in Fig.9.11.
Time lag and decrement factor are very important characteristics. Depending on the thermophysical properties and thickness of the wall material, different time lags and decrement factor can be obtained. The time lag is defined as follows:

\[
\phi = \begin{cases} 
  t_{T_{e}^{\max}} > t_{T_{0}^{\max}} & \rightarrow t_{T_{0}^{\max}} - t_{T_{e}^{\max}} \\
  t_{T_{0}^{\max}} < t_{T_{e}^{\max}} & \rightarrow t_{T_{e}^{\max}} + P \\
  t_{T_{0}^{\max}} = t_{T_{e}^{\max}} & \rightarrow P
\end{cases}
\]  

Eq 9.2

Where \( t_{T_{0}^{\max}} \) and \( t_{T_{e}^{\max}} \) represents the time in hours when indoor and outdoor temperature reach their maximum respectively and \( P \) is the period of the wave.

The decrement factor is defined by the following formula:
\[ f = \frac{A_o}{A_e} = \frac{T_o^{\text{max}} - T_o^{\text{min}}}{T_e^{\text{max}} - T_e^{\text{min}}} \] Eq 9.3

Where, \( A_o \) and \( A_e \) are the amplitudes of the wave at the inner and outer surface of the wall respectively. \( T_o^{\text{min}} \) and \( T_e^{\text{min}} \) represents the time in hours when inside and outside temperature are at their minimum level.

### 9.4.2.1 Time lag analysis

Based on Eq. 9.2 the time lag was estimated for each of the dwelling and illustrated in Figs.9.12 – 9.14. The yearly average time lag is then determined as the arithmetic average of these monthly values. As it can be seen in the graphs, temperature maximum peaks between the outer and the inner surfaces of the wall for the heat wave propagation is happening with a delay. The variation of outdoor temperature causes a related variation of indoor temperature depending of the type of dwelling fabric. The indoor temperature is not directly proportional to the outdoor temperature because the walls act as filters. As it could be seen in Fig.9.12, the adobe house has on average a time lag (\( \phi \)) of 9 hours and the magnitude of the indoor temperature oscillation is flat compared to the magnitude of the outdoor temperature oscillation. The results also show that the adobe dwelling indoor temperature magnitude is on average between 25.5°C and 29.25°C for the warmest period of the year. Fig.9.13 and Fig.9.14 confirmed that concrete hollow with steel roof and wood ceiling and concrete dwelling with steel roof only perform poorly in term of thermal performance. They have respectively a time lag (\( \phi \)) of 2 hours and ½ hour. The concrete dwelling with steel roof only has an indoor temperature magnitude which is varying between 28°C and 46°C while the concrete hollow brick with steel roof and wood ceiling has a magnitude between 28°C and 34.5°C for the same period.
Figure 9-12  Time lag for adobe dwelling

Figure 9-13  Time lag for dwelling with steel roof and wood ceiling
The time lag evaluation has shown that with extensive outdoor temperature swings, the adobe dwelling is capable of providing comfortable indoor conditions when compared to modern concrete hollow brick dwellings. The adobe house shows a relatively constant indoor temperature because of its high thermal mass. The stored energy during the day period by the wall can be radiated back during the night period when the outside temperature is low. That results in a very minor swing for indoor temperature. It is therefore suggested that a suitable wall fabric that has a high time lag (9 -12 hours) as the adobe house is highly recommended and could help significantly reduce energy demands for air conditioning in Burkina Faso built environment.

**9.4.2.2 Decrement factor analysis**

The decrement factor (Eq.9.3) was estimated for the case study dwellings as shown Figs.9.15 - 9.17. To calculate the overall decrement factor of each type of dwelling, a representative
day of each month of the year was first selected. Then the yearly average decrement factor is determined as the arithmetic average of these monthly values. The result demonstrates that the adobe dwelling has the lowest decrement factor \( f \) which was calculated to be about 0.13. On the other hand, the concrete hollow brick dwelling with steel roof only has proven to possess the worst indoor thermal comfort with the highest decrement factor \( f \) of almost 1. Finally the concrete dwelling with steel roof and wood ceiling decrement factor was estimated to be about 0.27.

Figure 9-15 Decrement factor for adobe house
Figure 9-16  Decrement factor for concrete house with steel roof and wood ceiling

Figure 9-17  Decrement factor for concrete dwelling with steel roof
The results suggest that the fluctuation of the heat fluxes through the wall can be reduced by increasing the thermal capacity of the wall [206]. The adobe house with a high thermal mass has proved to be very efficient and offers better indoor thermal comfort. The findings of this research show that the heat flux time lag increases with the increase of the thermal capacity and the thickness of the wall, while the heat flux decrement factor decreases with the increase of the thermal capacity and the thickness of the wall [207]. These findings are in line with several papers that have shown that building wall materials with high time lag and small decrement factors give comfortable inside temperatures even if the outside is very hot [208]. In a recent study by Asan (2006), it was shown that the thermophysical properties of walls have an important effect on the time lags and decrement factors [209]. It is therefore suggested in the case study of Burkina Faso that engineers, design walls in which decrement factors are very low and time lags are high, which produce in good thermal comfort levels. These results are very useful in designing passive solar building and could be applied to different regions.

### 9.5 Thermal mass and time constant

Thermal mass refers to the capacity that building materials have to store thermal energy for extended periods. Thermal mass can be used effectively to absorb daytime heat gains (reducing cooling load) and release the heat during the night (reducing heat load in this case study no heating required) maintaining constant indoor temperatures. The above results (on time lag and decrement factor) have proved that adobe houses show better thermal performance than the modern concrete dwellings. One of the most important mathematical concepts that assess building envelope thermal behaviour is the Thermal Time Constant (TTC). The TTC for a fabric element is defined as a function of the specific heat capacity, the
resistance and heat transmission. The time constant ($\tau$) is calculated based on the following formula:

$$\tau = \frac{\sum m \cdot C_p}{\sum (UA) + \frac{1}{3} NV}$$  \hspace{1cm} (Eq. 8.4)

Where $m = \text{mass of the fabric}$, $C_p = \text{specific heat capacity}$, $U = \text{U-value}$, $A = \text{surface area}$, $N = \text{Ventilation rate}$ and $V = \text{volume}$.

The time constants of the fabric element of a building are representative of the effective thermal capacity of a building. A high overall time constant ($\tau$) indicates a high thermal inertia of the building and results in a strong suppression of the interior temperature swing. In general, a large thermal mass of a building can have a positive effect on the indoor conditions during summer period and offer better indoor thermal comfort [210]. This research investigates the time constant of each dwelling envelope materials based on Eq. 9.4. The thermophysical characteristics of the concrete hollow brick and the adobe brick portrayed in Table 9.4 were considered in order to calculate the time constant of the two type of bricks that have been investigated during the field study. Based on these data, the time constant was estimated at 10 hours for the concrete hollow brick and 370.7 hours for the adobe brick. This shows that the adobe brick time constant is 37 times higher than the concrete hollow brick one. The results confirm the field study result portrayed in Figs.9.8 – 9.10 which indicate that indoor temperature swings are significantly reduced in the adobe house.
Table 9-4 Thermophysical characteristics for different wall materials

<table>
<thead>
<tr>
<th>Wall brick type</th>
<th>Material</th>
<th>Thickness m</th>
<th>Conductivity W/(m.K)</th>
<th>Density kg/m³</th>
<th>Specific heat capacity</th>
<th>U value W/m².K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brickwork</td>
<td></td>
<td>0.13</td>
<td>0.84</td>
<td>1700</td>
<td></td>
<td>800</td>
</tr>
<tr>
<td>Plastering</td>
<td></td>
<td>0.015</td>
<td>0.42</td>
<td>1200</td>
<td></td>
<td>837</td>
</tr>
<tr>
<td>Concrete hollow</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.34</td>
</tr>
<tr>
<td>Adobe</td>
<td></td>
<td>0.6</td>
<td>0.2</td>
<td>1700</td>
<td>800</td>
<td></td>
</tr>
<tr>
<td>Plastering</td>
<td></td>
<td>0.015</td>
<td>0.42</td>
<td>1200</td>
<td>837</td>
<td></td>
</tr>
</tbody>
</table>

The heat flux through the wall causes the variations of the indoor temperature. Between the three types of dwelling chosen for this study the adobe thick walls (40cm x 20cm x 10cm brick dimensions) with low rate of thermal conductivity has shown advantageous results with temperate indoor temperature throughout the all field study period. The thermal performance of adobe house has been found to be satisfactory in hot climate conditions characterised by the Ouagadougou weather. The results suggest that adobe dwelling may attain thermal comfort without the use of mechanical means and thus have energy saving potential just by applying passive cooling techniques. This naturally comfortable adobe house is one of the solutions for global warming adaptation in the built environment not only for Burkina Faso but also for other like countries for both rural and urban population.

9.6 Adobe performance

9.6.1 Advantages

Adobe construction presents several attractive characteristics. The field study results have shown that the adobe indoor temperature remains temperate and relatively stable throughout.
the 10 months study period. Adobe construction relies mainly on locally available unprocessed earth as its basic building material and is readily available in large quantities. That makes it affordable for construction. In addition to these advantages, it has great cultural and architectural importance. Adobe construction has the uniqueness of manifesting the cultural heritage of the country and the continued use of the material helps to maintain and preserve the expertise and cultural values embedded in earth building.

One of the main advantages of the adobe construction is that it is cheap. Study has shown that in urban area, 80m² house made of cement would cost around 12,000$ at least, but a mud one with local materials cost just 2,000$ [211]. This is an 83% saving, a huge amount especially for modest income household. According to Mani et al (2007, p154), adobe is always reusable and can be recycled an indefinite number of times over an extremely long period [212]. So it never becomes a waste material that harms the environment. Therefore, it has a minimal impact on the environment. In addition, adobe construction materials have the potential to reduce energy used in the production stage. Investigations by Adam et al. (2001) prove that the energy needed to manufacture and process one cubic metre of adobe is about 36 MJ (10 kWh), while that required for the manufacture of the same volume of concrete is about 3000 MJ (833 kWh). This is 83 times the energy needed to manufacture the adobe [213].

Table 9-5 Energy consumption and CO₂ emissions for construction materials

<table>
<thead>
<tr>
<th></th>
<th>Gypsum</th>
<th>Cement</th>
<th>Adobe</th>
<th>Fired bricks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy required (in MJ/kg)</td>
<td>1</td>
<td>4.8</td>
<td>0.028</td>
<td>3.16</td>
</tr>
<tr>
<td>CO₂ emission in kg CO₂/kg material</td>
<td>0.01</td>
<td>1.25</td>
<td>0</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Source: Vroomen, 2007
As it can be seen from Table 9.5 that the emission of CO$_2$ zero in the case of adobe production while 1kg of cement results in a 1.25kg release of CO$_2$. It is notable from Table 9.5 that adobe construction is environmentally sustainable compared to the conventional concrete bricks and would be appropriate in the case of urban house construction. It is therefore worthy to promote and adopt adobe as alternative urban house construction material. It could significantly help in achieving sustainability with less energy demand for cooling.

### 9.6.2 Limitations

Adobe construction has proven to be advantageous in many areas, but there are some drawbacks of adobe techniques and technology which makes it sometime unpopular amongst professionals, clients, and decision makers. According to Dunlap (1993), a significant problem associated with the construction of adobe building is the lack of standard criteria to evaluate it. It therefore, discourages investors from investing money in this type of construction when they have no guarantee about it lifetime [215].

Moreover, adobe construction has a very high shrinkage and swelling ratio resulting in major structural cracks when exposed to different weather conditions. Thus, it is eroded easily by water, which makes its use difficult in areas with high rainfall or possibilities of flooding. A study by Blondet et al (2007), shows that most vernacular adobe houses are built without professional intervention. That results in poor construction quality, making the adobe extremely vulnerable in event of earthquake [216]. Beside the above weakness, it is worth mentioning that in many regions, adobe constructions are viewed as building materials for the poor. These stigmas make the urban population feel ashamed of living in adobe houses.

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Most of the above weaknesses can be overcome by suitable improvements in design and technology, such as soil stabilisation, appropriate architecture, and improvement in structural techniques as well as suitable sheltering of the wall from rain with suitable overhang of the roof. This adds to the solar shading as well.

9.7 Conclusion

This field study provides real insight into the actual thermal performances of a sample of adobe houses in Burkina Faso. Critical analyses of arguments in favour of adobe construction in urban area have been conducted. It shows that adobe construction has a better thermal performance with a 9 hours time lag and 0.13 for the decrement factor. In addition the adobe brick time constant was estimated to be 37 times higher than the concrete hollow brick one. These factors result in a stable, temperate indoor temperature for the adobe dwelling while the concrete hollow brick dwelling is experiencing huge indoor temperature swings. However, some unfavourable drawbacks such as structural limitations, shrinkage cracks, need of high maintenance, water erosion and behave poorly in event of earthquake have been found. It is notable that the limitations of earth construction can be addressed and solved through solutions that have been developed in contemporary adobe construction research and innovation. The solutions range from filling cracks, solution to water erosion, enhancement of binding force and increasing compressive strength to increasing thermal insulation of adobe building material. These solutions could help significantly address the drawbacks of earth construction and overcome the disadvantages of adobe construction.
Chapter 10 The potential of renewable energy

10.1 Introduction

In developing strategies and scenarios for mitigation and adaptation in order to avoid the potential consequences of climate change, many researchers suggest a strong role for energy efficiency, fuel switching, and the development of renewable energy [217]. Burkina Faso is experiencing one of the highest costs of electricity in the world because its electricity production is mainly based on fossil fuel which is imported. This chapter investigates to which extent renewable energy could help increase electricity coverage in Burkina Faso. In addition, climate change will have a significant impact on cooling load in the built environment. The current electricity production is mainly based on fossil fuel. This chapter outlines how optimum energy production systems could be achieved. It compares different configurations based on the economic viability, net present cost, payback time and environmental impact based on a designed micro grid. The results of this research are currently under review for publication.

10.2 Case study specification

Data from a 100% fossil fuel electricity generation plant (diesel motor) which is partly funded by government subsidies was considered. The data provided by the national electricity production company SONABEL shows that the total electricity generated in this plant in 2004 was about 5404 MWh [230]. The research will determine the appropriate power production configuration using extensive financial cost analysis.
10.3 Power optimization simulation tools

Various optimization techniques for hybrid energy system sizing have been developed in different literature. These models use stochastic algorithms, which incorporate uncertainties in demand, component failure and weather behaviour in order to estimate renewable energy potential [218-219]. Different software programs such as Hybrid Power System Simulation Model (HYBRID2) [220], General Algebraic Modelling System (GAMS) [221], Optimization of Renewable Intermittent Energies with Hydrogen for Autonomous Electrification (ORIENTE) [222] can also be downloaded from various websites. However, among all these programs, one of the most appropriate sizing tools for hybrid energy system is HOMER (Hybrid Optimization Model for Electric Renewables) developed by US National Renewable Energy Laboratory (NREL). HOMER has been extensively used in previous renewable energy supply case studies [223-225] and in validation tests [226-228]. Jose et al (2006) described HOMER as the best tool available for power optimization design [229]. In addition, its operation is simple and straightforward. For all these reasons, HOMER has been used as energy optimization tool for this research.

10.4 HOMER

HOMER is an optimisation software package which simulates many system configurations and scales them on the basis of Net Present Cost (NPC) [225]. It has an energy production component, like photovoltaics, wind turbines, hydro, batteries, diesel and other fuel generators, electrolysis units, fuel cells, etc. HOMER needs information on natural resources (wind and solar), electrical loads, economic constraints, current and future equipment cost, and control strategies in order to perform an analysis [226]. It first estimates if the system is
technically feasible, that means the energy supply system is able to supply enough electricity for the thermal loads. Secondly, it estimates the system NPC, which is the total cost of installing and operating the system over its lifetime [226].

10.4.1 System configuration

Fig 10.1 illustrates a large-scale hybrid configuration system that will be used as the basis of electricity production for this case study simulation. Hybrid energy systems generally consist of renewable sources of energy working in parallel with standby non-renewable modules and storage units. Wind turbines over 10kW usually produce AC, therefore need to be connected to the AC bus. However, the main advantage of this configuration is that the power can be directly supplied without being diverted through the DC bus and storage components. This helps to save a lot of energy. PV and battery modules are connected to the DC bus, and a converter links both AC and DC buses.
10.4.2 Data inputs

10.4.2.1 Load

A typical 24 hour daily energy consumption profile for each month of the year has been obtained from the national Electricity provider SONABEL [230]. The data has been loaded into the HOMER, which used its randomising algorithms and correlation functions to simulate a full-year load profile. A full year of hourly uncorrupted field data input would have given the most representative results, however this data was not available for this case study. Fig.10.2 illustrates the annual load profile derived from the hourly load obtained from SONABEL. Peak energy consumption is reached in April and May which are the warmest months in Burkina Faso and the minimum in the winter between November and February. During the warm period, energy demand for air conditioning and fan energy needed to provide mechanical ventilation further contributes to significantly increase energy demand.
10.4.2.2 Environmental inputs

Hourly solar radiation measurements for the year 2010 (8760 points) have been obtained from the NASA satellite website [231]. The solar data in Fig.10.3 shows an average daily radiation of 5.89kWh/m²/d and a clearness index of 0.6. As can be seen in Table 10.1 the daily radiation is well above the average comparison for most cities around the world [232]. Therefore, solar energy clearly represents a significant potential for Burkina Faso. Fig.10.4 illustrates the monthly average wind speed data for the year 2010 and was provided by Burkina Faso meteorology office. It indicates that average wind speed is about 2.28 m/s. This is well below the average comparison in several cities around the world as can be seen in Table 10.2 [232-234].
Figure 10-3  Solar radiation profile

Figure 10-4  Wind speed profile
Table 10-1 Sample of world solar irradiance values

<table>
<thead>
<tr>
<th>Country</th>
<th>Solar insolation (kWh/m²/day)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sydney</td>
<td>4.1-4.8</td>
<td></td>
</tr>
<tr>
<td>Brisbane</td>
<td>4.8-5.2</td>
<td></td>
</tr>
<tr>
<td>Townsville</td>
<td>5.4-6.2</td>
<td></td>
</tr>
<tr>
<td>Alice Springs</td>
<td>&gt;6.2</td>
<td>Trainer, T. Can solar sources meet Australia’s electricity demand?</td>
</tr>
<tr>
<td>New York</td>
<td>3.5</td>
<td>insolation_levels_usa.htm</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
<td>Hawaii</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Oregon</td>
<td>4.1</td>
<td></td>
</tr>
<tr>
<td>Spain (Zaragosa)</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>Arabia</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
<td>Newfoundland</td>
<td>3.04</td>
<td></td>
</tr>
</tbody>
</table>
Table 10-2 Sample of global wind speed values

<table>
<thead>
<tr>
<th>Country</th>
<th>Wind speed m/s</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brisbane</td>
<td>3.2</td>
<td><a href="http://www.brisbane-australia.com/brisbane-weather">http://www.brisbane-australia.com/brisbane-weather</a></td>
</tr>
<tr>
<td>Gold Coast</td>
<td>6.1</td>
<td><a href="http://www.windfinder.com/windstats/windstatistic">http://www.windfinder.com/windstats/windstatistic</a></td>
</tr>
<tr>
<td>Sydney</td>
<td>4.6</td>
<td>gold_coast_seaway.htm.</td>
</tr>
<tr>
<td>Melbourne</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>Perth</td>
<td>5.6</td>
<td></td>
</tr>
<tr>
<td>Townsville</td>
<td>5.5-6</td>
<td><a href="http://www.soe-townsville.org/strandwindproject/wind_power.html">www.soe-townsville.org/strandwindproject/wind_power.html</a></td>
</tr>
<tr>
<td>Germany</td>
<td>3.5 - 4.5</td>
<td>BoyleG. Renewable Energy. Oxford; New York. 2004</td>
</tr>
<tr>
<td>UK</td>
<td>5 6</td>
<td><a href="http://www.dti.gov.uk/energy/sources/renewables/renewables-explained/wind-energy/page27708.html">http://www.dti.gov.uk/energy/sources/renewables/renewables-explained/wind-energy/page27708.html</a></td>
</tr>
<tr>
<td>Ireland</td>
<td>&gt;6</td>
<td><a href="http://www.met.ie/climate/wind.asp">http://www.met.ie/climate/wind.asp</a></td>
</tr>
</tbody>
</table>

10.4.3 Hybrid system components

The hybrid energy system is schematically presented in Fig.10.1 and is composed of a diesel generator, PV module, wind turbine, battery, and a power converter. To find the optimum energy production level of the system, HOMER needs the capital cost, replacement and operating costs, number of units to be used, operating hours, etc. of each piece of equipment to be specified. A description of these components is given in the following sections.

10.4.3.1 Diesel generator

The cost of a diesel generator may vary between $250 and $600/kW [235]. For larger units, the cost of the kW is lower than smaller unit ones. For this case study a relatively large unit (about 1000kW) is required. Therefore, the initial capital cost is assumed to be about $500/kW corresponding to a total capital cost of $500,000. Replacement and operational costs are assumed to be respectively about $450/kW and $0.150/h with operating lifetime of
Based on field observation in Burkina Faso, the diesel price is currently about 1$/l, due to oil price increase on the international market and because fossil fuel is imported from neighbouring countries. In addition, the continuous increase of the crude oil price and transportation costs further increase the diesel price. Therefore, higher diesel prices will also be considered to assess the impact of increase fuel prices.

### 10.4.3.2 Photovoltaic

The installation cost of photovoltaic array ranges from $6,000 to $10,000/kW [235]. However with improvements in technology and a steady reduction in PV prices the price is projected to decline to between $6,000 and $7,000/kW. In this present case study, an actual photovoltaic cost of $7,000/kW was used, resulting in a capital cost of $17,500,000. PV operation and maintenance (O&M) costs are considered to be almost zero and their lifetime is about 30 years.

### 10.4.3.3 Wind energy

Average wind speed for this case study is about 2.3 m/s and suggests that energy availability from the wind turbine might be low. A Fuhrlaender 250 with a capacity of 250kW was considered [236]. The cost is about $1.98/W and therefore the total cost of one unit is $495,000. The replacement and Operation&Maintenance costs are respectively about $300,000 and $2500/year. The life time of a turbine is taken to be 25 years.

### 10.4.3.4 Battery

Battery cost is important, because the initial cost is high and it has to be replaced several times during the project lifetime. For this particular case study, Rolls/Surrette Battery
Surrettee 4KS25P models 4 V, 1900 Ah, and a lifetime over 10569 kWh are considered in the scheme [237]. The cost of one battery is $250 with a replacement cost of $150.

10.4.3.5 Power converter

An AC/DC power converter unit has to be installed in order to maintain the flow of energy between the AC and the DC components in the system. The power converter unit capital cost is around $600–800 per kW [238]. A price of $670 per kW was chosen for the current case study. A lifetime of 17 years was assumed with an efficiency of 95%.

10.4.3.6 Economics

For this project, the lifetime is considered to be 25 years, with an annual real interest rate assumed to be about 6%. No subsidy is available from the Burkina Faso government so it has not been considered in this study.

10.4.4 Limitations

All figures about prices of different materials are market prices which are subject to constant changes. Therefore, the estimates are for indicative purposes in order to help figure out what would be the best configuration of energy production system.

10.4.5 Assessment criteria

10.4.5.1 Net Present Cost (NPC)

To assess the optimum system configuration, HOMER uses total Net Present Cost (NPC) to represent the life cycle cost of the system. It includes all costs and revenues that occur within
the project lifetime. The NPC includes the Initial Cost (IC) of the system components, their replacements cost, maintenance cost and fuel cost only for the diesel motor for the project lifetime. The total net present cost is HOMER's main economic output. HOMER ranks all systems according to NPC. The NPC is calculated according to the following equation:

\[
NPC = \frac{TAC}{CRF} \quad \text{Eq. 10.1}
\]

where TAC is the total annualised cost (which is the sum of the annualised costs of each system component). The capital recovery factor (CRF) is given by the formula

\[
CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \quad \text{Eq. 10.2}
\]

where \( N \) is the lifetime of the project (number of years) and \( i \) is the annual interest rate. Moreover, NPC also takes into account any salvage costs, which is the remaining value of a component at the end of the project lifetime. HOMER assumes a linear depreciation of each component, meaning that the salvage value of a component is directly proportional to its remaining life. The salvage cost is calculated as follow:

\[
S = C_{\text{rep}} \frac{R_{\text{rem}}}{R_{\text{comp}}} \quad \text{Eq. 10.3}
\]

where \( C_{\text{rep}} \) is the replacement cost of the component, \( R_{\text{rem}} \) is the remaining life of the component and \( R_{\text{comp}} \) is the lifetime of the component.
10.4.5.2 Renewable Factor

The renewable fraction (RF) is the portion of the system’s total annual electrical production originating from renewable. The RF is calculated by dividing the total annual renewable power production (the energy produced by the PV array, wind turbines) by the total energy production.

10.4.5.3 Payback time

The general definition of payback time is the number of years it takes to recover an investment. A certain amount of money is invested first, then income is earned from that investment, and the payback is the number of years it takes for the cumulative income to equal the value of the initial investment [287]. However, for this study, money is spent up front to build the power system and the system keeps spending money each year to operate. The concept of payback has meaning only if we compare one system to another. Therefore, for this research, the payback is the number of years when the cumulative cash flow of the difference between the hybrid system and the diesel motor standalone system switches from negative to positive [287]. The payback is an indication of how long it would take to recover the difference in investment costs between the hybrid system and the diesel motor standalone system. The payback is reach when the nominal cash flow difference line crosses zero line.

10.5 Simulation results

10.5.1 Optimum result

The power production system (Fig. 10.1) was simulated in order to find the most suitable system type (combination of technologies) and system configuration (size and numbers of
each component). The search space was widened by introducing various alternatives listed in Table 10.3. A feasible system is defined as standalone or hybrid system configuration that is capable of meeting the load. HOMER eliminates all infeasible combinations and ranks the feasible systems according to increasing NPC in order to identify an optimal system type.

<table>
<thead>
<tr>
<th>PV array size (kW)</th>
<th>Wind turbine (Quantity)</th>
<th>Diesel Generator size (kW)</th>
<th>Converter size (kW)</th>
<th>Battery (Quantity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>1000</td>
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</tr>
<tr>
<td>1500</td>
<td>2</td>
<td>1500</td>
<td>1500</td>
<td>4000</td>
</tr>
<tr>
<td>2500</td>
<td>3</td>
<td>2000</td>
<td>5000</td>
<td>6000</td>
</tr>
</tbody>
</table>

HOMER simulation aims at finding the most cost effective system with to the lowest energy cost. Table 10.4 illustrates different configurations. These combinations are listed from (top to bottom) the most cost-effective to least cost-effective. The cost-effectiveness of a system configuration is based on its net present cost. For this present case study, HOMER optimisation predicts that a hybrid energy production system with a 2500kW of PV array, 1000kW back up diesel motor, 1500kW converter and 6000 batteries produces the lowest Total Net Present Cost (NPC) of $33.1M over the 25 years of the project lifetime, which is 30% less than using the diesel generator alone (as currently used) which has a NPC is about $43.1M (Fig.10.6). The worst system is the diesel generator – wind turbine configuration with an estimated $43.3M NCP which 31% higher than the most cost efficient energy production system (Table 10.4 and Fig. 10.5). Moreover, as can be seen in Table 10.4, the Operation and Management (O&M) costs for diesel generator standalone configuration is
estimated to be about $3.3M over the life span of the project, three times higher than the most cost efficient system.

Table 10-4 System configuration

<table>
<thead>
<tr>
<th>PV size (kW)</th>
<th>Wind turbine (Quantity)</th>
<th>Diesel Generator size (kW)</th>
<th>Converter size (kW)</th>
<th>Battery (Quantity)</th>
<th>Initial Capital ($M)</th>
<th>Total NCP ($M)</th>
<th>Operating cost ($M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2500</td>
<td></td>
<td>1000</td>
<td>1500</td>
<td>6000</td>
<td>19.5</td>
<td>33.17</td>
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<td>1000</td>
<td>6000</td>
<td>20</td>
<td>33.5</td>
<td>1.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>1000</td>
<td>4500</td>
<td>1.63</td>
<td>43.1</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1000</td>
<td>4500</td>
<td>2.12</td>
<td>43.3</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>1</td>
<td>1500</td>
<td>1000</td>
<td></td>
<td>8.25</td>
<td>67.9</td>
<td>4.7</td>
</tr>
</tbody>
</table>

Figure 10-6 Total net present cost and initial investment cost for each system
The average annual electricity produced by the optimal configuration illustrated in Fig.10.7 is estimated to be about 7.12 million kWh/yr. with a Renewable Factor (RF) of about 73% (Fig 10.7). The optimal system configuration CO₂ GHG emissions are about 1.6 million kg/year while the base scenario diesel generator only configuration yields GHG emissions of about 5 million kg/year. The base case scenario has 3.13 times more emissions than the optimal system configuration (Fig.10.8). This research has also shown that at the moment a 100% renewable energy configuration is not technically and economically a viable solution against conventional fossil fuel based stand-alone power system which is currently the only production system available in the country. However, PV coupled with a backup diesel generator configuration wins over all other type of configurations. Clearly the feasibility of a hybrid PV/wind energy system depends on the solar radiation and wind energy potential available at the site. Our results demonstrate that wind energy is not cost-competitive due to the lack of wind power in Burkina Faso.

One of the major obstacles is the initial capital cost of the renewable energy system. All results related to cost and system configurations are summarised in Table 10.4. As it can be seen from Table 10.4 and Fig.10.6, the most cost effective system hybrid PV – diesel generator (RF 74%) has the second highest initial investment cost of $19.5 million while the diesel generator stand-alone system held the lowest investment cost approximately about $1.63 million. Nevertheless, in the long term, the diesel generator stand-alone system is the most expensive configuration with the highest NPC.
10.5.2 Potential of carbon abatement

The results portrayed and examined in Figs. 10.6 – 10.8 clearly demonstrate that hybrid systems which are defined as a combination of renewable and back up units or conventional energy sources represent a viable solution to the challenges that face Burkina Faso in providing enough electricity to its population. The results have shown that a PV – diesel generator is the best configuration for the present study and thus would be an excellent choice that will meet the growing energy demand for air conditioning in the built environment. However the high initial capital cost of renewable energy sources represents a significant barrier that needs to be overcome.
It has been shown in this research that the optimum energy production system allows a huge abatement of carbon emission. The base case scenario (diesel generator only) emissions are 3.13 times higher than the optimal configuration one. This represents a reduction of emission from 5million kg/year to 1.6million kg/year. The estimate of expected emission reductions from the business-as-usual baseline scenario have shown that there is a huge potential for Burkina Faso to reduce its carbon emissions and get involved in carbon trading. Additional, funding obtained from carbon trading could help alleviate the main barrier for investment in renewable which is the high initial capital cost. Carbon trading will provide the initial funding that the country needs to get started.
10.5.3 Payback period

The techno-economic analyses of all configurations that derived from simulations demonstrate that the hybrid PV – diesel generator system (2500kW of PV array, 1000kW diesel generator, 1500kW converter and 6000 batteries) is the most cost efficient configuration. Therefore, this system will be considered as the basis for comparison to conventional energy production technologies, namely a diesel generator – only configuration in order to evaluate how long it would take to get back the difference in investment costs between the hybrid PV – diesel generator system (Initial Capital cost of $19.5M) and the diesel motor stand-alone system (Initial Capital cost of $1.63M). As illustrated in Fig.10.9, it only takes 8.39 years for the cumulative cash flow of the difference between the hybrid system and the diesel motor stand-alone system to switch from negative to positive.

It is estimated that the difference in investment of about $18M between the two systems would be paid back within 8.39 years with a healthy Return on Investment (RI) of 12.4%. Therefore, the optimal PV – diesel generator system is clearly both technically feasible and economically viable.
10.6 Sensitivity analysis

Three sensitivity variables: PV capital multiplier, solar irradiation and diesel price are considered in this analysis. The system types (combination of technologies) and system configurations (size and numbers of each component), for the search space remain as illustrated in Table 10.3. A total of 12 sensitivity cases (PV capital multiplier (2), solar irradiation (2) and diesel price (3)) were tested with each system configurations. In total 204 systems were simulated for 960 cases.

10.6.1 Fuel price
Fig.10.10 portrays the trend of crude oil from 1987 to 2012. It shows that oil prices are continuously increasing over the past decades. Therefore, for the sensitivity analysis, diesel prices were estimated to increase up to $1.5 and $2 per litre.

Figure 10-10  Crude oil price
The results presented in Fig. 10.11 indicate that an increase of fuel price would lead to an increase of NPC for all configurations. This increase is due to the fact that more financial resources will be required for diesel which is now experiencing higher prices. However, the PV – diesel generator configuration still remains the optimal system with the lowest NPC while the diesel generator standalone system has the highest NPC. The impact of the diesel price increase on the payback time is examined in Fig. 10.12. The results have shown that when diesel prices increase up to $1.5 and $2 per litre, the payback time drops to 6.38 and 5.32 years respectively. This represents a reduction of 2 and 3 years respectively when compared to the base case scenario (Fig. 10.9) with a diesel price of $1/l. Higher diesel prices make hybrid PV-Diesel generator a more attractive configuration.

Figure 10-12  Payback time for different diesel price scenarios
Currently, the average solar irradiation is about 5.89kWh/m²/day in Burkina Faso. However, it has been shown in this research that climate change will lead to an increase of temperature and more solar irradiation in the country. As a result a higher solar irradiation value (7kWh/m²/d) has been considered for the present sensitivity analysis. The estimated results show that the PV – diesel generator configuration is again the most cost efficient system with NPC of $30.1M with a Renewable Factor of 79%. This represents a 10 % NPC decrease compared to the PV – diesel generator configuration with a solar radiation of 5.89kWh/m²/d. Likely increases in Burkina Faso solar radiation for the coming years will result in NPC reduction for PV systems.

### 10.6.3 PV capital multiplier
The major obstacle in using solar panels is the high initial capital cost. However, the evolution of PV module prices illustrated in Fig.10.13 indicates that the cost of PV is decreasing, because of new developments in PV technology. Therefore, a PV capital cost multiplier of 0.8 was considered for the sensitivity analysis.

Figure 10-13  PV module price

The estimated result shown in Fig.10.13 suggests that multiplying the PV capital by 0.8 results in a decrease of the NPC for the optimal configuration. The result shows that when a 0.8 PV capital multiplier is applied, the NPC drops from $33.17million (NPC for base case
scenario) to 29.67 million. This is an 11% decrease for the optimum PV – diesel generator configuration. In addition, the payback period drops from 8.39 to 6 years when compared to the diesel generator stand-alone configuration.

Figure 10-14 NPC for different PV Capital multiplier
This result clearly shows that technological development in solar photovoltaic batteries technology is a breakthrough that will make electrification in remote areas more promising and attractive. This could help Burkina Faso increase its electricity coverage and meet the growing demand of electricity for air conditioning due to climate change.

10.6.4 Combined Solar, PV capital multiplier and fuel price

The optimum configuration remains the PV – diesel generator system with a RF of 79% if fuel price increases to about 1.5 per litre, solar irradiation is set to about 7kWh/m²/d with a capital multiplier is 0.8. The optimisation analysis comparing hybrid PV – diesel generator to diesel generator stand-alone system showed that a diesel generator stand-alone configuration results in the highest NCP. The diesel generator only system has an NCP of about $67.5M while the hybrid PV – diesel generator configuration has a NCP of $33.5M. That’s a difference of 100% between the two configurations and it requires only 4 years for the payback.

10.7 Renewable energy barriers

The economic analysis has shown that options with high levels of renewable energy have the lowest net present cost. However, if the most common barriers such as the lack of access to investment capital, the lack of technical capacity, the limited awareness remains, it will be very difficult to implement such cost-effective projects in Burkina Faso. In addition, as indicated in the above results, the fact that the projects are so cost effective and still remain unimplemented show that it is difficult to remove the barriers and implement renewable energy project.
10.8 Conclusion

This case study base on a group of office buildings in the capital has proven that Burkina Faso has all the potentials to solve its energy problems if appropriate infrastructural support can be provided to use its widely available renewable (especially solar) resources. Hybrid PV – Diesel generator has proven to be the optimal configuration for energy supply. It has a healthy 8.39 years payback time when compared to the business as usual base case scenario (Diesel generator only). It also allows significant abatement of carbon emission because the diesel only configuration has a 213% higher carbon emission than the optimal energy production system. This constitutes an opportunity for the country to get additional investment through carbon trading. This will bring down the cost of electricity and increase its coverage. Therefore, it will make electricity affordable to the majority of the population.

The mentioned hybrid systems can use as stand-alone or in grid-parallel. Grid-parallel renewable energy systems are mostly utilized in urban areas where grid system already exists. The excess of renewable energy could be sold to the grid. However, stand-alone hybrid systems are alternative solutions for remote rural areas where electrical grid is unavailable and the significantly high connection cost-due to large distances and irregular topography lead to higher cost. This represents the most promising way to handle the electrification requirements of these regions.
Chapter 11 Recommendations

11.1 Future building regulations

Building regulations that aim at energy consumption reduction do not exist in Burkina Faso. This research therefore outlines the main recommendations that could lead to future building regulations. Economic progress is the key to implementing regulation therefore the current recommendations are not overly ambitious but simply based on the main points of the research in this thesis and a consideration of the use of electricity in the built environment.

11.2 Window to wall ratio (WWR)

This research has shown that significant cooling load reduction can be achieved with lower window to wall ration. However, the current architecture design for office building is mainly
based on large glazed window buildings. It has been shown in this research that a reduction of up to 84% in cooling load could be achieved by reducing WWR from 50% to 12%. Therefore, it is suggested that a building regulation be implanted to set a limit for the WWR of new buildings or renovations. That will lead to significant energy consumption reduction and the implantation of sustainable building styles.

11.3 Shading devices

Climate change will have an important impact on the cooling load of the Burkina Faso built environment. It has been shown in this research that a reduction of energy for air conditioning consumption can be achieved by applying a shading device to a currently unshaded window. It was observed that the external shutter is the most efficient shading device with an average energy consumption reduction of 53%. Therefore, it is suggested that a building regulation be implemented. That will require that new and possibly existing buildings with large glazed windows that exceed the conditions outline in section 11.1.1 to be equipped with shading devices.

11.4 Smart electricity meters

To establish more detail of electricity consumption (especially of air-conditioning systems) it is recommended that smart (communicating) electricity meters be installed in new and possibly existing buildings. For large buildings these meters are to be of the maximum demand type so that half hourly demand can also be measured and monitored as well as the overall consumption. This will allow a database to be built up to aid energy conservation work and to provide the basis for future research activity. Also the introduction of a maximum demand tariff will encourage energy conservation.
11.5 Renewable energy

This research has shown that renewable energy is a viable solution financial solution. Hybrid PV – Diesel generator has proven to be the optimal energy supply configuration with 8.39 years payback time compared to the business as usual base case scenario (Diesel generator only). This configuration will bring down the cost of electricity and increase its coverage, making electricity more affordable to the majority of the population. Therefore, this research suggest that more investigation be done to assess the technical, socio-economic and environmental feasibility of electricity production by hybrid solar PV/diesel plant for rural and peri-urban areas in Africa.

11.6 Adobe dwellings

It has been shown in this research that adobe construction has a better thermal performance with a 9hours time lag and 0.13 for the decrement factor. In addition the adobe brick time constant was estimated to be 37 times higher than the concrete hollow brick one. These factors result in a stable, temperate indoor temperature for the adobe dwelling while the concrete hollow brick dwelling is experiencing huge indoor temperature swings. Base on the performance of the adobe dwellings, this research suggest that more investment be done in adobe houses and that more investigation should be carried out to improve their design and strength so that multiple storey buildings could be done.

11.7 Steel based roofs
Steel based roofs have proven to have the worst thermal performance even if they are widespread in urban areas. This research suggests that government should on the one hand implement restrictions in steel based roofs importation by enforcing higher taxes and on the other hand promote the development of alternative materials for roofs.

11.8 Climate change impact on future energy consumption

This research has shown that average temperature will increase by 2°C between 1990 and 2050 with significant impact on future energy demand for cooling in the built environment. For a typical office building current energy consumption for cooling will increase by up to 36% by 2060. Therefore, policy makers should considered the above recommendations (11.1-11.7) in order to adapt to the projected future increase in energy demand.

Chapter 12 Conclusion

The objectives of this research, outlined in Chapter 1, were to:

- Examine current and future climate data for Burkina Faso
- Assess Burkina Faso’s rapid population growth and its impact on energy consumption
- Estimate energy consumption and CO₂ emissions for selected domestic and public buildings now and for the future
- Estimate the optimum energy production configuration by looking at the Net Present Cost and Pay Back time of each system.
- Outline recommendations for Burkina Faso future building regulations

12.1 Temperature increases due to climate change
This research has developed different Test Reference Years (TRYs) which represent a typical year selected from 20 years data. Based on the TRYs, the projected future weather data (HadCM3 TRY2050-2069) was compared to the historical data (Observed TRY1990-2009) and the control period. It was found that average temperature will increase by 2°C between the period of TRY1990-2009 and TRY2050-2069. In addition average maximum temperature will increase from 37°C to 39°C for the same period. The TRY of weather parameters has been used to simulate future energy consumption.

12.2 The impact population growth on energy consumption

This research investigated the drivers of energy consumption in Burkina Faso. It was found base on the STIRPAT model that population is the most important driver of both CO₂ emissions and electricity consumption in Burkina Faso. A 1% increases in population results in a 1.38 and 2.03% increase in CO₂ emissions (from primary energy consumption) and electricity consumption, respectively. Additionally, the forecast of Burkina Faso future electricity demand has been investigated. It shows based on 2011 electricity consumption and population growth that electricity demand will double by 2025 under medium growth scenario.

12.3 The impact of climate change on energy consumption in the built environment.

IES VE building energy simulation program and projected future weather parameter TRYs has been used to estimate future energy consumption. It was found that climate change will result in major consumption increase for cooling load in office buildings and domestic dwellings. For a typical office building current energy consumption for cooling will increase
by 15%, 36% and 100% respectively for the period TRY (2020 – 2039), TRY (2040 – 2059) and TRY (2070 – 2089). For domestic household, the simulation prediction based on TRY2000-2019 climatic conditions shows that energy consumption for air conditioning will increase by 14% and 45% for the period TRY2020-2039 and TRY2040-2059 respectively.

12.4 Climate adaptation measures for thermal comfort in the built environment.

It has been shown in this research that adequate building design could help tackle the projected increase of cooling load consumption due to global warming. The results of the analysis have shown that window to wall ratio (WWR) and the orientation of the glazed windows has an impact on solar gains. Irrespective of the storey level, South West and South East facing window’s rooms are experiencing the highest cooling load demand. It has also been found that large WWR has a significant effect on cooling load. If the WWR is increased from 12% to 25, 37.5 and 50%, it results in an increase of cooling load of 25%, 49% and 84% respectively. Thus, the current trend in Burkina Faso which consists of designing large glazed window building should be reversed because these types of buildings are energy inefficient and lead to huge energy waste. In addition, it has been shown that shutters have the potential of reducing cooling load considerably. External shutters have been shown to be the most efficient shading device with an average of 53% cooling load reduction. Curtain and balcony additions achieved an average cooling load reduction of 38% and 19% respectively.

In urban areas in Burkina Faso 89% of domestic dwellings have steel based roof. This research has investigated different roof styles relevant for the country and their respective impacts on cooling load. The research provides a novel set of results to better understand the relative effectiveness of building adaptations for improving thermal comfort and cooling load
demand. It has been found that all alternative roofs to the steel based roof are effective in cutting on average 25% off the cooling energy consumption. Concrete roofs with ventilated cavity and concrete false ceilings have shown to be the optimal roof design. This particular type of roof leads to a decrease of the annual cooling load by 36% compared to the reference steel roof dwelling. The corresponding decrease in the cooling load is 27%, 21.2% respectively for the clay tile roof with cavity and wood false ceiling; concrete roof with cavity and wood false ceiling dwelling. It has also been found that thermal insulation has the potential of reducing the average cooling load by 25%. When located indoor, thermal insulation is optimal and results in a 26% decrease in cooling load demand. The decrease is respectively of 25% and 23% when placed outdoor and in the middle of the wall slab. Furthermore, between 0cm and 2cm of thickness it is possible to achieve up to 26% cooling load reduction while the reduction is about 4% when the thermal insulation thickness is increased from 4cm to 7cm. As a result, the use of thermal insulation thicker than 4cm might not be economically an attractive solution because it results in small reduction of the yearly cooling demand.

Finally, it has been shown that significant yearly energy consumption savings could be achieve by adjusting the thermostat setting from 25°C (which the current cooling setting point or even lower) to 26, 27, 28 and 29°C. This research suggests that cooling setting point should be between 27°C and 29°C because the population in warmer countries is likely to be more comfortable in warmer indoor conditions. That could result in energy consumption saving for cooling between 29% and 56%. In addition, the results have shown that cooling load is decreased with glazing U-value. It was found that double glazing yields an 11% cooling load reduction when compared to the single glazed window domestic dwelling.
Field work findings have shown that traditional adobe construction has a better thermal performance with very stable indoor temperature compared to modern dwellings. It represents a cheap viable solution for climate change adaptation in the built environment with abundant locally available raw materials. Although developed in the context of Burkina Faso, these findings are likely to be relevant for other sub-Saharan countries in the wider climate zone with similar building stock characteristics.

12.5 Optimum energy production configurations

In 2010 only 13.7% of the population had access to electricity. This research has shown that population rapid growth and climate change will exacerbate the need for energy especially in the built environment. The country relies heavily on subsidised fossil fuel (70%) energy production system. This research has shown that Burkina Faso has the potentials to solve its energy supply problems if appropriate infrastructural support can be provided for harnessing its abundant renewable (especially solar) resources. Hybrid PV – Diesel generator has proven to be the optimal configuration for energy supply with 8.39 years payback time compared to the business as usual base case scenario (Diesel generator only). This configuration will bring down the cost of electricity and increase its coverage. Therefore, electricity will be affordable to the majority of the population.

The next focus of new analysis for this research should be on how to remove the barriers that are making renewable energy projects unattractive for policy makers. The results suggest that access to the initial capital for investment may in fact be the key barrier for renewable energy projects. Thus, it is very hard to implement such renewable energy production project without addressing this difficulty of investment and access to loan for the initial capital. Another key barrier is the lack of required infrastructure, including maintenance and operating equipment,
and transportation facilities. Finally, private companies must be willing to support the high initial investment cost associated with renewable energy.

### 12.6 Research implication for future building regulations

This research outlined some recommendations for future building regulations. It was suggested that legislative law be taken to enforce a threshold for WWR. Buildings with higher WWR should be equipped with shading divers in order to reduce the overall energy consumption for cooling load.

### 12.7 Combined effects

With the population increasing there will be an increased demand for electricity and air-conditioning. The simulation work has shown that better design can reduce the rate of increase due to air-conditioning and the optimisation of the micro grids has shown that significant savings can be made by using renewable energy systems. The combination of the good building design and optimal electricity micro grids will further enhance the reduction in the rate of increase of carbon emissions. The micro grids will be particularly utilised in outlying, rural areas but the use of renewables can be used in urban and suburban areas (especially PV panels) for the buildings or to be directly connected to the main grid. There is a project to link PV cells just south of the Sahara to the capital to supplement the main grid electricity.
12.8 Limitations and future work

The results of this work have some limitations that could be dealt with in future researches. The combined effects, discussed above, have not been analysed in detail but this could benefit from future work analysing the interactions. The current research addresses many unknowns in the context of Burkina Faso and is multi-disciplinary in scope. However, there are inevitable limitations and potential improvements which need to be considered, and which future work could address in order to improve the overall results and recommendations of this research. Therefore, this work constitutes a starting point for future work. Future work might include an analysis of the disaggregated energy use (how much electricity is used for instance for refrigeration compressors, fans, pumps and lighting etc.) that will consider more assumptions to forecast future electricity consumption. In addition, future research could also rely on different forecast of energy consumption drivers. That should hopefully help avoid the policy mistakes of the past.

Regarding building energy simulation, high resolution climate change weather data downscaled with a resolution of 8km is now available for Burkina Faso and includes the capital city Ouagadougou. These data were not available within the timescale of the current research, but it is suggested that these data developed by the Council for Scientific and Industrial Research (CSIR) in South Africa [285] for the Climate Change and Urban Vulnerability in Africa (CLUVA) project might be used as the basis for alternative simulations of future energy consumption in the built environment. Furthermore, it recommended that more building design scenarios and measures be used for future simulations. WWR and shading devices have shown excellent result in this research. Therefore, future research should put more emphasis on these adaptation measures. In addition, for future work, careful material selection with high thermal diffusivity and high
surface reflectivity combined with the concrete based roof would be beneficial because it could help minimize heat absorption therefore, reducing the cooling load.

Finally, energy production optimization has shown that renewable energy could help increase electricity coverage and reduce the high cost of the kWh. Therefore, lifting the high investment cost could be a viable and sustainable solution of providing energy to the majority of the population.

A more detailed examination of the potential building regulations should aim at considering the economics and the potential political/bureaucratic barriers.

Appendix A
Papers and presentation

Journal papers


Seminars and Conference papers


Bachir Ismael Ouedraogo (2010), Financial impact of renewable energy and energy efficiency in the building sector. *Sustainable future* (Seminar at University of Birmingham)

Bachir Ismael Ouedraogo (2010), Biomasse et énergies renouvelables dans le contexte des changements climatiques au Burkina Faso, *Réseau des OSC d'environnement du Burkina Faso*

Bachir Ismael Ouedraogo (2009 and 2011) Climate change impact on energy consumption in Burkina Faso built environment. *COP 15 in Copenhagen and COP 16 in Durban (South Africa)* with Burkina Faso government official delegation

Appendix B

The following graphs represent the observed temperature for Dori in the north, Ouagadougou the capital city located in the centre and Bobo Dioulasso the economical capital which is located in the south of Burkina Faso.
The above figures from historical data suggest that the temperature is increasing when you go from the south to the north and during March to October. However, from November to February, the north is experiencing almost the same temperature as the south and centre and even reaching sometimes lower temperature than the rest of the country. Finally the graphs reveal that the south is experiencing the lowest temperature when compared to the centre and the North, and the North is reaching the highest temperatures of the country.

Furthermore, the observations from the historical data which suggest that March April and May are the hottest months in Burkina Faso and the months of December and January are experiencing relatively cold temperatures. We also noticed a significant drop in temperature during the raining season from June to September.
Appendix C

My research in the Press

This research has got some coverage in the press. The following article has been published in the University of Manchester School of Mechanical Aerospace and Civil Engineering Newsletter

http://www.mace.manchester.ac.uk/research/newsletter/Research_Newsletter_Issue2.pdf
OPEN Education

I founded a NGO named OPEN Education which is promoting free quality education and sustainability in my country. My NGO have got a large coverage in the press and a couple of articles are highlighted in the following sections.

The following articles have been published in the University of Manchester Newsletter Unilife:

http://documents.manchester.ac.uk/display.aspx?DocID=12931
The following articles have been published in Burkina Faso newspaper:

http://www.lefaso.net/spip.php?article45546
The following articles have been published in Burkina Faso newspaper:

http://www.lefaso.net/spip.php?article48617
En collaboration avec ses partenaires néerlandais, Ismaël Bachir Ouédraogo, doctorant en Énergies renouvelables à Manchester, en Angleterre, président fondateur de OPEN Burkina, est en train de mettre en place un logiciel au service des besoins des apprenants du monde rural.

« Il est inconcevable qu’en ce 21ème siècle, nous ne puissions pas nourrir pleinement des TIC pour développer notre capital humain. (...) L’éducation est un puissant instrument pour réduire la pauvreté et les inégalités, améliorer la santé et le bien-être social, et poser les bases d’une croissance économique durable. Les TIC représentent une des meilleures solutions pour poursuivre une éducation de qualité pour tous », déclare Ismaël Bachir Ouédraogo. À en croire celui-ci, par le biais de l’Internet par exemple, on est en mesure, de nos jours, de mettre à la disposition de tout élève ou de tout étudiant, où qu’il se trouve, une documentation de qualité.

En plus, les vidéos en ligne sur les expérimentations, difficilement accessibles dans nos pays de par les coûts qu’elles engendrent, sont une excellente opportunité pour rendre les cours des meilleurs enseignants accessibles.

« Les élèves ne se contenteront plus seulement des cours dispensés à l’école, mais développeront un appétit d’information qui les propulsera vers des recherches plus avancées. »

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