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A model for the assessment and analysis of the carbon footprint of residential buildings in Egypt

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A MODEL FOR THE ASSESSMENT AND ANALYSIS OF THE CARBON FOOTPRINT OF RESIDENTIAL BUILDINGS IN EGYPT

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DEDICATION

This thesis is lovingly dedicated to my parents. Their continuous love and encouragement have pushed me forward in my academic career. I will always remember my father's "keep going" advice, and my mother's motivational talks. I can never thank them enough for standing by me every step of the way and owe them any success I achieve in life. I would also like to dedicate this thesis to my husband whose endless support is one of the main reasons I have completed my thesis. I am blessed for having him in my life.

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I will always be thankful to several people without whose help I would have not been able to complete this thesis. Each has had a positive impact in making my dream of a graduate degree come true.

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Finally, I would like to thank my husband for his constant care, support and advice. His presence made it easier for me to move forward and he has been my greatest source of encouragement. I will always be thankful for his sincere efforts to see me grow.

ABSTRACT

Housing contributes substantially to greenhouse gas emissions. This occurs directly through emissions from materials used during construction, and indirectly through energy consumption during the use-phase. Efforts have been exerted across the construction industry to adopt greener, more sustainable practices. However, there have been no established guidelines for tackling such a vital issue in Egypt and other developing countries.

This work examines current practices applied in the design and construction of middle-income housing in the country as a proxy for other building sectors and explores practical solutions that can lead to more sustainable developments. This work also proposes a dynamic model for the assessment and analysis of the carbon footprint of residential buildings in Egypt. The model, naturally, could be challenged, further examined and validated.

This work reveals that efficiencies in construction are responsible for the largest share of potential savings in the earlier years of a building's lifetime when compared to use-phase savings (57-43% by year 1). On the other hand, use-phase savings accumulate as a result of efficiencies in housing elements, contributing 97% of total potential savings by the end of a building's 50-year lifetime. The estimated social cost of potential carbon savings in the Egyptian middle-income housing sector over the past 12 years is found to be LE 10.84 Billion in current monetary terms, implying potential annual savings approaching LE 1 Billion. The savings across other building sectors are multiples more.

This work recommends the following configuration for construction: ready-mix concrete with type F admixtures, steel production through the EAF route, and fly ash bricks as building blocks. This can lead to a reduction of 30% of emissions relative to conventional construction practices. It similarly recommends the following configuration for the use-phase: LEDs instead of incandescent bulbs, Energy Star electrical appliances including electrical water heaters, substitution of single-glazed windows to low-e double-glazed, and shading of all exterior walls. This can lead to a decrease of 49% of emissions relative to conventional use-phase practices.

No incentives are currently present to direct industry stakeholders towards the adoption of sustainable practices. This is noticeably evident in the housing sector where there is a very clear detachment in economic interests between developers and homeowners. Government intervention is desperately needed – through public awareness campaigns, and through the issuance and enforcement of a number of legislations – to accelerate the adoption and implementation of the sustainable practices identified in this work.

KEYWORDS: (Middle-income Housing, Materials, Egypt, Carbon Emissions, Energy Consumption, Sustainability, Use-Phase)

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CHAPTER 1: INTRODUCTION

1.1 Background

Egypt's population has grown drastically over the past decades, reaching almost ninety million in 2014, implying an average increase rate of 1.8% annually (Cement Sustainability Initiative , 2012). At the current growth rate, the population of Egypt is expected to reach 115 million by 2030, which requires extensive resource planning to manage and maintain this population mass – most notably in housing.

Demand for residential buildings is directly proportional to population. As population grows, the need for housing consequently increases. Housing accounts directly (through construction materials) and indirectly (through energy consumption) for the largest share of greenhouse gas (GHG) emissions (carbon dioxide, methane, nitrous oxide, ozone and water vapour) and can therefore be described as one of the major drivers of emissions. As a result of the increase in the demand of residential buildings, there will be an increase in the amount of emissions, and if this growth is not maintained in the most efficient way, the risk of increasing global warming is definite.

A residential building's contribution to GHGs is highly dependent on two variables: (i) the materials used in its construction including concrete, steel, bricks, glass, etc., and (ii) housing elements deployed throughout its lifetime including lighting, appliances, heating/cooling, etc. Both variables will determine the overall energy efficiency and sustainability of a building.

The choice of construction materials during construction is crucial because the production of each consumes differing amounts of energy and hence contributes to differing amounts of emissions. Opting for the right and optimal combination of materials whose production is low in energy-intensity can go a long way in reducing emissions. Design specifications should therefore be produced with this optimization in mind.

Furthermore, ensuring materials have been sourced from energy efficient producers is equally important. For instance, steel can be conventionally produced through the basic oxygen furnace route, which is a relatively energy intensive process; or through the electric arc furnace route, which is more energy-efficient. The same principle applies to almost all other construction materials. Therefore, ensuring that all construction materials are produced in the most energy efficient way would definitely assist in reducing their production emissions.

The contribution of housing elements to emissions is by far determined by the amount of energy they consume. Energy consumption throughout a building's lifetime will therefore be affected by each element's energy consumption rate in addition to the extent of its usage. Design is imperative to ensure that a building can be safely and comfortably operated with reduced lighting and heating/cooling loads e.g. by manipulating exposure to solar light and heat during the day. Furthermore, the sourcing of relatively new sustainable elements low in energy consumption is also important, because by using the most energy efficient housing elements, it can save a lot of emissions due to their continuous usage over the entire lifetime of a residential building.

1.2 Highlights on Egypt's Carbon Emissions

Carbon dioxide emissions in Egypt have increased from 220 million tons of CO_2 equivalent ($MtCO_2e$, the common unit for measuring all greenhouse gas emissions in terms of CO_2) in 2005 to 275 $MtCO_2e$ in 2010, and are expected to double by 2030 reaching 550 $MtCO_2e$. The five major sectors driving emissions are: power generation, cement production, buildings, road transport and agriculture, with 75% driven by the first two (McKinsey, 2010). Of those five, the three sectors most relevant to this study are:

1. Power: it accounted for approximately 61.6 $MtCO_2e$ in 2005 and expected to increase to approximately 210 $MtCO_2e$ by 2030, due to increasing demand for electricity. The overall abatement potential in the power sector is approximately 56%, of which 37% can be through the reduction of electricity demand especially in the building sector (McKinsey, 2010).
2. Cement: accounted for approximately twenty-four $MtCO_2e$ in 2005 and is expected to increase to approximately seventy-one $MtCO_2e$ by 2030, making it the highest contributor of carbon emissions (as shown in Figure 1.1). The overall abatement potential in the cement sector is approximately 14%. Figure 1.1 shows that cement is expected to remain the highest contributor of carbon emissions with approximately 40% of all industry-related emissions, therefore significant attention needs to be given to cement production (McKinsey, 2010).

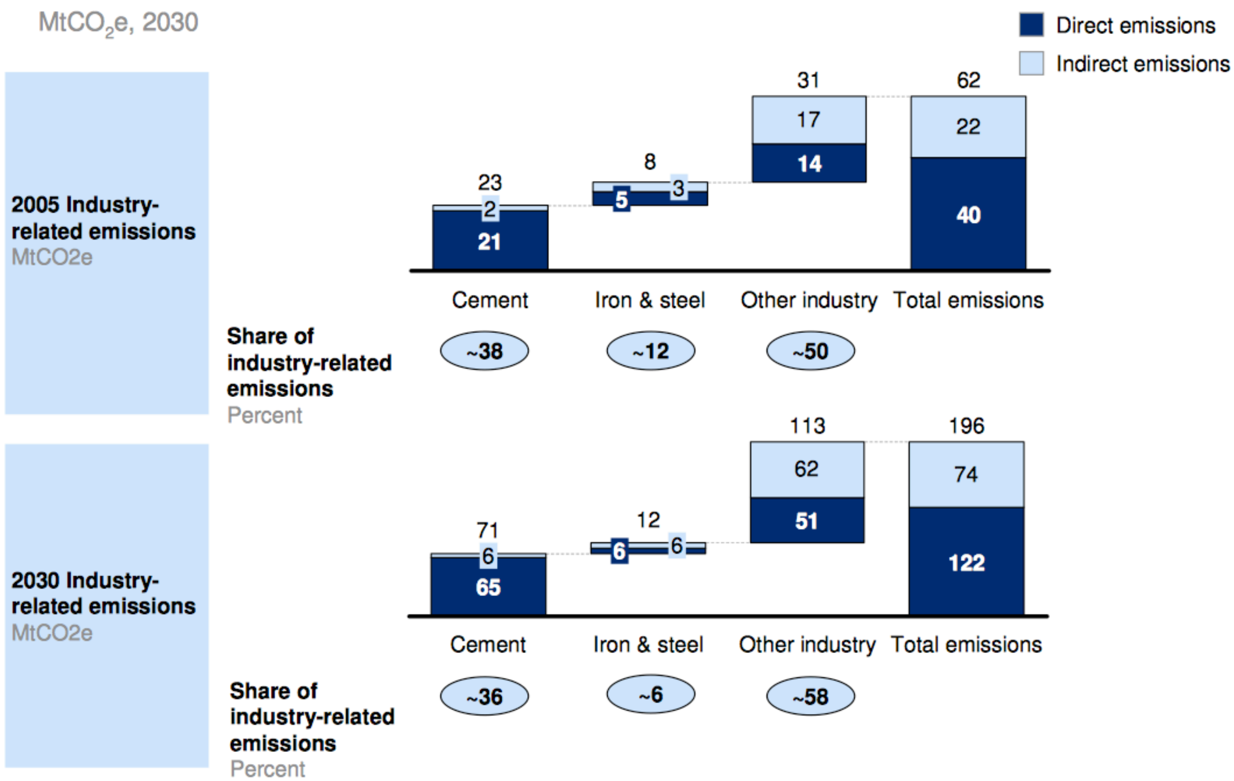

Figure 1.1 Egypt's Industrial Emissions (McKinsey, 2010)

3. <u>Buildings:</u> accounted for approximately sixty-two $MtCO_2e$ in 2005 and expected to increase to approximately 165 $MtCO_2e$ by 2030 mainly due to increasing electricity consumption in residential buildings. The overall abatement potential in the building sector is approximately 24%. As shown in Figure 1.2, most building emissions are due to the use of electricity (also known as indirect emissions and accounting for 65% of total emissions). The building sector is classified as either residential or commercial, the former being responsible for roughly two-thirds of emissions (as shown in Figure 1.3) (McKinsey, 2010).

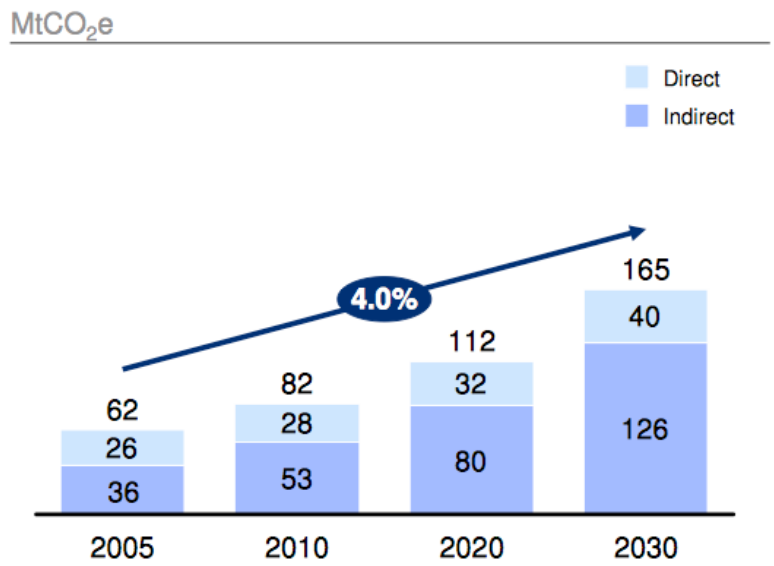

Figure 1.2 Egypt's Building Emissions (McKinsey, 2010)

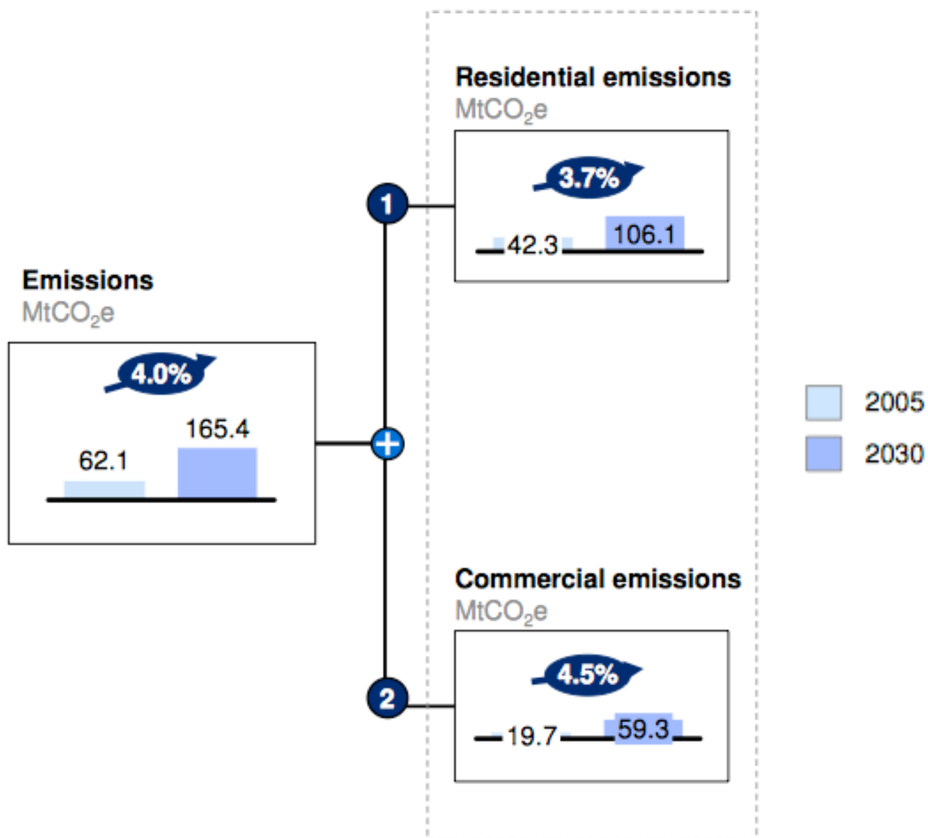

Figure 1.3 Egypt's Residential and Commercial Building's Emissions (McKinsey, 2010)

Focusing on residential emissions, Figure 1.4 reveals that indirect emissions are growing at 4.8% per annum – twice as fast as direct emissions – and are expected to constitute approximately 70% of total emissions by 2030 (McKinsey, 2010).

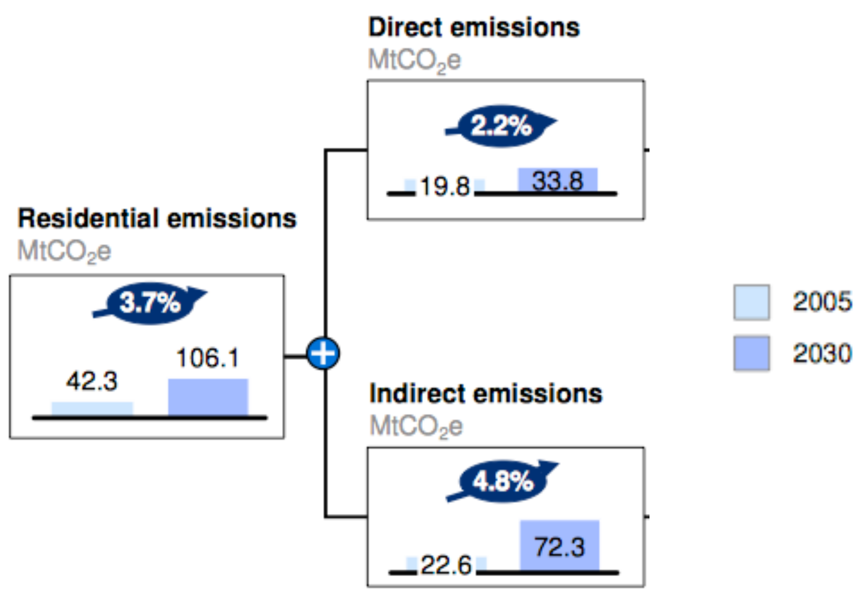

Figure 1.4 Egypt's Residential Emissions (McKinsey, 2010)

All of these expected increases in emissions are due to the increase in population and this study is focused on handling the major contributors of those emissions and finding ways to maximize their reductions in order to save our environment from early extinction.

1.3 Statement of the Problem

Sustainable construction is an increasingly important area of research in both academia and industry. This is driven by a number of mega-trends that are rapidly and incontrovertibly changing Egypt and the world at large including: (i) rapid population growth, (ii) accelerating urbanization, (iii) shortage in resources, and (iv) accelerating carbon emissions and global warming, amongst others.

Egypt is particularly vulnerable – as are other developing nations – to many of these powerful forces shaping its future. Whereas in the developed world, sustainable construction solutions are widely accepted mitigants to the aforementioned mega-trends, they are generally ignored and/or overlooked in the developing world at the expense of short-term cost savings. Lack of awareness both within and outside of government have further worsened the situation.

No incentives – legal, regulatory, or financial – are present to direct the various industry stakeholders towards adopting greener developments. This is noticeably evident in the housing sector where there is a very clear detachment in economic interests between developers and home-owners. The former prioritize fast, cheap and easy construction methods. The latter are left to bear the use-phase consequences of the construction decisions made by developers. Short-termism is also prevalent across all categories of home-owners. Lower-cost housing solutions are also preferred regardless of payback period and/or long-term financial benefits.

In a country facing unprecedented growth rates in population, urbanization and carbon emissions, combined with persistent shortages in electricity leading to black-outs, further analysis is warranted on how alterations to current housing practices can achieve long-term sustainability: meeting the needs of the present without jeopardizing the resources available to future generations.

1.4 The Motivation Behind this Study

This study is particularly needed at this juncture of Egypt's economic development and growth. Economic growth has been substantially rapid in the decade leading up to the 2011 revolution. Following resolution of the current political instability, an even bigger economic boom is expected in the years to come. Economic development coupled with explosive population growth will almost certainly result in an unprecedented boom in housing construction. Serious attention must be directed to minimize the carbon footprint of such a boom to avert a potentially disastrous toll on the country's future generations. Such a toll could most prominently include: (i) an increase in energy shortage leading to a pandemic blackout crisis, (ii) an increase in the cost of living to most Egyptians due to the rise of energy consumption and pricing, and (iii) pronounced adverse health effects due to pollution of most basic resources including air, water, soil and food.

1.5 Work Objectives and Scope

The objective of this study is to examine current practices applied in the design and construction of middle-income housing in Egypt and to explore practical solutions that can lead to more sustainable and more environment-friendly middle-income housing developments in the country. It will seek to identify the major drivers of carbon dioxide emissions related to the construction process, quantify the impact of each, and where applicable propose alternatives to promote more environment-friendly solutions.

This study will accordingly propose a model for the assessment and analysis of the carbon footprint of new building construction in Egypt – focusing on residential buildings – to: (i) serve as a guide for the minimization of carbon dioxide emissions in middle-income housing, and (ii) pave the way for a replication of this analysis across other construction segments and/or other geographies. It will also produce sensitivity analyses to visualize construction carbon footprints assuming different combinations of material – mainly concrete, steel, and bricks.

The analysis in this study focuses on middle-income residential units as a proxy for the housing sector. The choice of middle-income housing is due to a number of reasons. First, middle-income housing is less complex and thus can be used as a base for other models to follow. Second, there is a national interest in expanding into middle-income housing following the Egyptian January 25th Revolution which was led by the middle-class calling for social equality. Third, other housing segments are unrepresentative. Lower-income developments are unregulated and can have very different attributes from one district to the other. Data on this segment is also very scarce. The higher-income segment is equally unrepresentative given its relatively miniscule proportion in the country and its skewed consumption patterns. Finally, this approach allows readers and future users to replicate the research and analysis on other building segments by changing the relevant numerical assumptions highlighted in this study.

This study will encompass aspects of design and construction but will be primarily focused on the selection, sourcing and utilization of greener housing elements to achieve the most GHG reductions on a lifecycle assessment (LCA) basis. It is hoped that designers, developers, contractors and legislators will consider the results of this study in setting new sustainable standards and industry best-practices in Egyptian construction.

An additional objective of this study is to consolidate and provide a comprehensive set of data reflecting the various drivers of emissions during a building's construction and lifetime. Such data is typically scattered across numerous sources and publications making it difficult for industry stakeholders to refer or build upon them. This study intends to bridge this shortcoming and is therefore intentionally dense with its literature review in chapter two.

CHAPTER 2: LITERATURE REVIEW

A disproportionate share of both academic and non-academic literature is being made available to all issues relating to climate change including green and sustainable construction. The topic is now on the top of any political, business and academic agenda due to its increasingly evident and dramatic impact on the livelihoods of many throughout the world.

This section of the study seeks to explore and summarize some of the most common themes and research findings in relation to sustainable construction and climate change. Given the topic's current prevalence and ubiquity, and the abundance of contributions being made to the field from a wide variety of stakeholders and interest groups, this review is not limited to scholarly and academic literature. The review has instead been primarily directed at input from some of the world's leading institutional authorities, think tanks and policy-makers.

A thorough review of the literature identified reveals a number of key findings, which serve as the basis of this work. The initial intention of focusing on the concept of embodied energy was quickly challenged. A more inclusive and comprehensive lifecycle approach is alternatively followed to arrive at more impactful findings and recommendations that can be readily assessed and subsequently applied to the Egyptian building sector – focusing on residential buildings – with long-lasting, sustainable and economically-positive results.

2.1 Mega-Trends Shaping Our World

Roland Berger is a leading global strategy consultancy, which advises major international public, industry and service institutions with fifty offices around the world in the key global economic hubs. The diversity in their geographic coverage and in the assignments and clients they serve, led them to publish a report entitled “The Trend Compodium 2030” to define what the world will look like in the next fifteen to twenty years. They accordingly identified a number of trends, which are slowly and irrevocably changing the world across a number of categories. The ones most relevant to this study relate to "Changing Demographics" and "Scarcity of Resources". In addition, the Department of Economic and Social Affairs of the United Nations Secretariat issued in 2014 a revised version of its report entitled "World Urbanization Prospects". Its purpose is to provide UN member countries with information relating to common problems and prospective policy options. Both documents describe how the world is changing in six ways:

2.1.1 Growing World Population

The world's population is expected to grow by 20% over the next twenty years to reach 8.3 billion by 2030. Most population growth will be occur in developing countries, where population growth rates are seven times what they ate in developed countries. Developing countries' population will jump to seven billion people by 2030 (Roland Berger, 2011).

2.1.2 Rising Carbon Emissions

By 2030, annual carbon emissions from coal, oil and gas combustion will increase by 16%. The concentration of CO_2 in the earth's atmosphere is about 30% higher than atmospheric CO_2 levels were before the Industrial Revolution (Roland Berger, 2011). The Joint Sciences Academies' Statement issued by the head of the national science academies of Brazil, Canada, China, France, Germany, India, Italy, Japan, Russia, the UK and the USA stated that CO_2 levels have increased from 280 parts per million (ppm) in 1750 to over 375 ppm in 2005 – higher than any previous levels in the last 420,000 years (National Academies, 2005). Figure 2.1 shows the trend of carbon emissions over time.

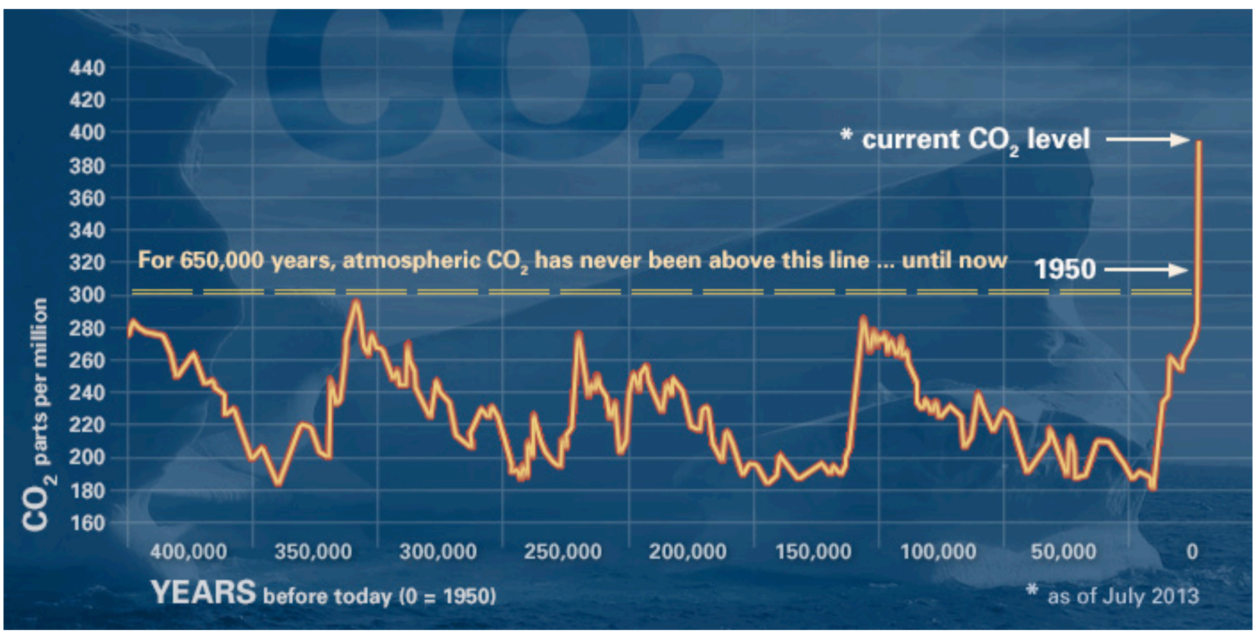

Figure 2.1 Trend of Atmospheric Carbon Dioxide Over Time (NASA, 2013)

2.1.3 Global Warming

The average global temperature will rise 0.5-1.5°C by 2030. This is to be compared with an overall temperature increase of 0.5°C over the past twenty years, with land temperatures rising about twice as fast as ocean temperatures (Roland Berger, 2011). Since the early 1900s, the global air and sea surface temperature has increased by 0.8 °C, of which approximately 0.6% has occurred since 1980 (Committee on America's Climate Choices; Board on Atmospheric Sciences and Climate; Division on Earth and Life Studies; National Research Council, 2011).

Scientists from the Intergovernmental Panel on Climate Change (IPCC) reported they are more than 90% certain that global warming is being caused by larger concentrations of greenhouse gases emitted by human activities (IPCC, 2007). According to the Summary for Policymakers of the Working Group I contribution to the IPCC Fifth Assessment Report of 2013, the largest contributor to global warming is CO_2 emissions from fossil fuel combustion, cement production, and land use changes particularly deforestation given their carbon sink characteristics (IPCC, 2013).

The increase in global temperatures will lead to the following:

- Rise in sea levels and a change in the amount and pattern of rainfall (Lu, Vecchi, & Reichler, 2007);
- Probable expansion of subtropical deserts (Lu, Vecchi, & Reichler, 2007);
- Continuing retreat of glaciers, permafrost and sea ice with warming strongest in the Arctic (Joyce, 2010);
- More common radical weather events (ex: heat waves, droughts and heavy rainfall) (Joyce, 2010);
- Ocean acidification and species extinctions due to warming temperatures (Battisti & Naylor, 2009);
- Threat to human food security from decreasing crop yields, more pronounced in the Southern hemisphere (IPCC, 2014);
- Loss of human habitat from flooding (Battisti & Naylor, 2009) – Figure 2.2 illustrates areas that are exposed to flooding.

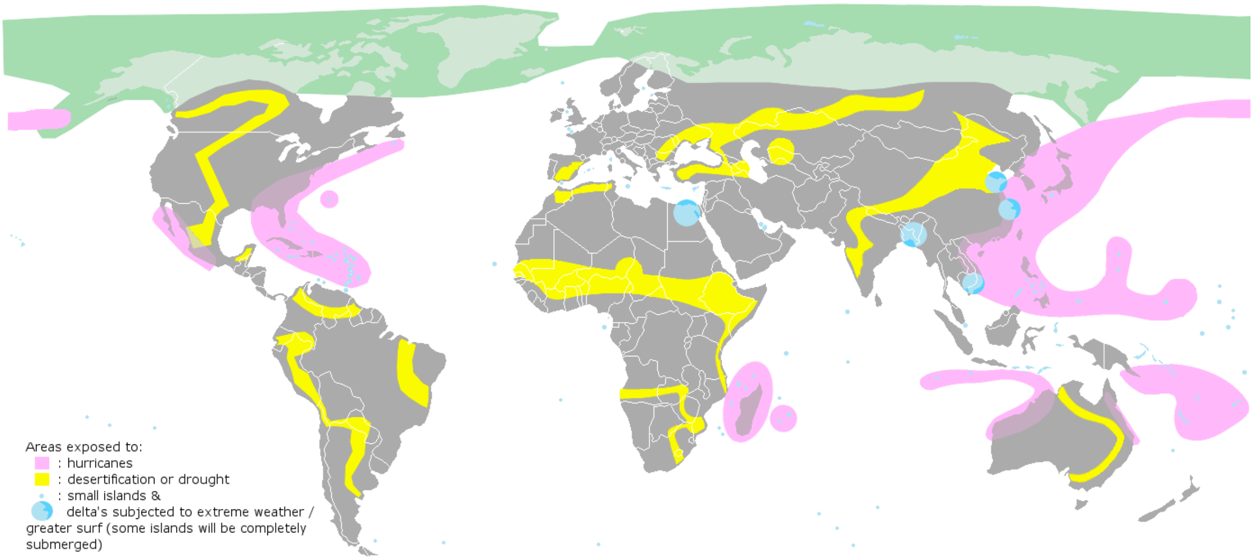

Figure 2.2 Areas of the World Exposed to Flooding (Battisti & Naylor, 2009)

2.1.4 Continued Urbanization

By 2030, 59% of the world's population will live in cities – this figure will be as high as 81% in developed countries compared to 55% in the developing world (Roland Berger, 2011). The most urbanized regions are North America, Latin America and Europe (82%, 80% and 73% respectively), while Africa and Asia are the least (40% and 48% respectively). This continued population growth and urbanization would add 2.5 billion people to urban areas by 2050 with 90% of this increase happening in Asia and Africa (India, China and Nigeria together accounting for 37% of the increase) (United Nations, 2014).

The increase in urbanization will lead to an environmental stress, by:

- A greater production and retention of heat formed by the increased formation of urban and industrial areas. This is a phenomenon often referred to as "urban heat islands". In cities, most of the sun's energy is absorbed by urban structures and asphalt resulting in higher surface temperatures than in rural areas where solar energy is consumed by evaporating water from soil and agriculture. This is in addition to the extra heat generated in cities from vehicles, factories, and industrial/domestic heating and cooling, and as a result of that cities are often 1-3°C warmer (Sanders, 2004). Figure 2.3 shows the trend of growth in the urban population.

- A reduction of soil moisture that will lead to a reduction in the re-uptake of CO_2 emissions (EPA, 2014).
- A 70% increase in the supply of food (according to a July 2013 report by the United Nations Department of Economic and Social Affairs (United Nations, 2013)), thereby straining food resources, especially in countries already facing food insecurity. This is especially true in cities where there will be a noticeable strain to basic sanitation systems and health care, possibly leading to humanitarian and environmental struggles.

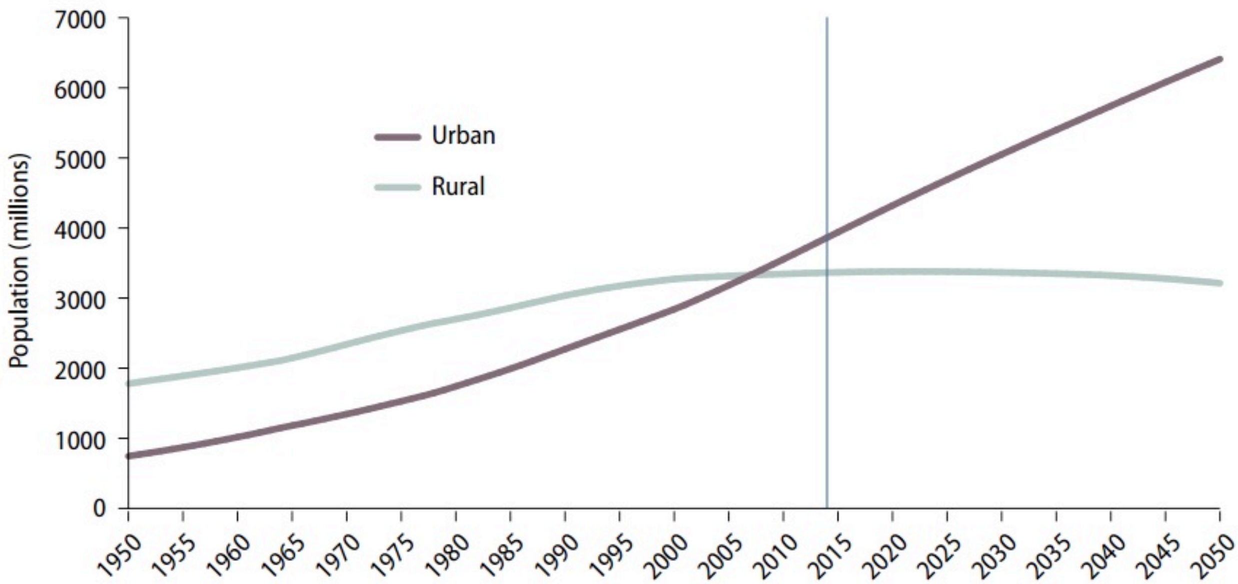

Figure 2.3 Urban & Rural Population of the World (1950-2050) (United Nations, 2014)

2.1.5 Threatening of Ecosystem

The world's biodiversity will be reduced from currently 70% of its original potential (100% some centuries ago) to 65% by 2030 (Roland Berger, 2011).

2.1.6 Ageing World Population

Mainly due to increasing life expectancy, global median age will increase by 5.1 years to thirty-four years in 2030. In developed countries, median age will reach forty-four years. In developing countries, median age will be thirty-two years (Roland Berger, 2011).

2.2 The Building Sector

Building systems contribute to almost 19% (i.e. one fifth) of global carbon emissions of which 6.4% are direct and 12% are indirect in the form of electricity and heat production (IPCC, 2013). This is illustrated in Figure 2.4.

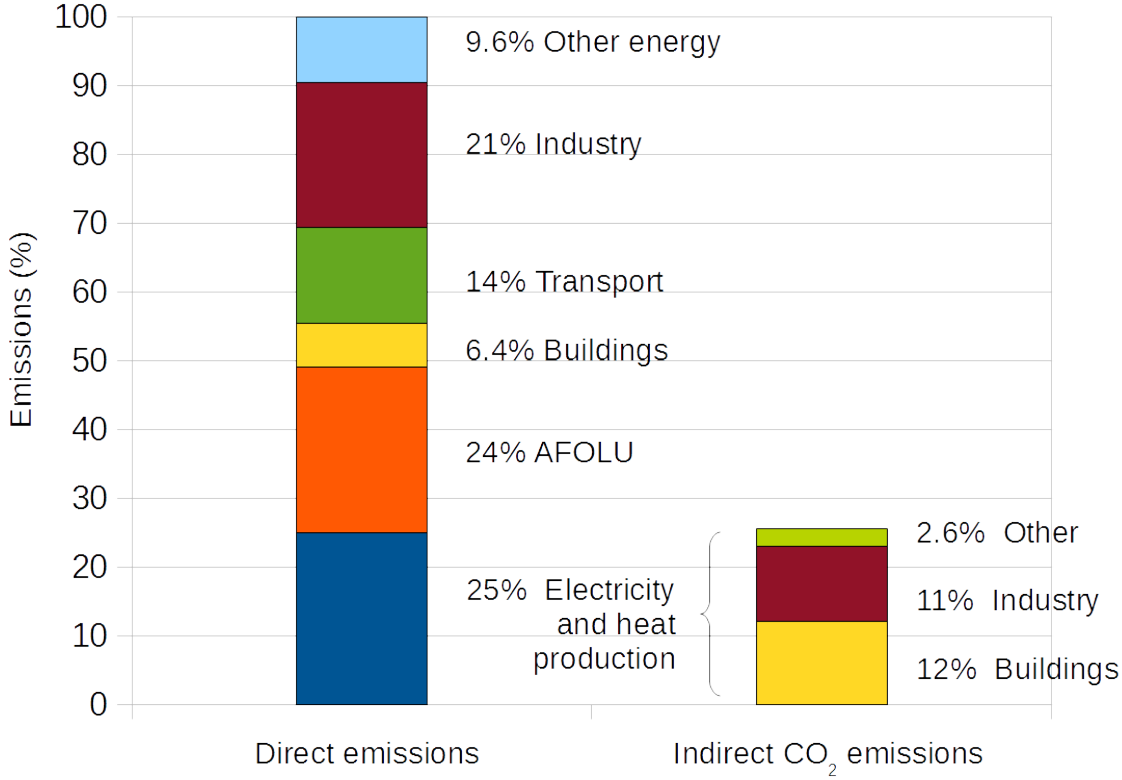

Figure 2.4 Annual Greenhouse Gas Emissions by Sector (IPCC, 2013)

The United Nations Environmental Program (UNEP) found that buildings are responsible for more than 40% of global energy use and one third of global GHG emissions equivalent to 8.6 million metric tons of CO_2 in 2004 (United Nations, 2013).

Moreover, UNEP analyzed the carbon footprint mitigation potential across different sectors and geographies based on data from a 2007 report from the IPCC and found that (i) the potential for carbon reductions to be achieved from buildings far outpaces that from any other category including industry, agriculture and/or energy supply, and (ii) with proven and commercially available technologies, the energy consumption in both new and existing buildings can be cut by an estimated 30-80% with potential net profit during the building's life-span (United Nations, 2013). Figure 2.5 shows that the greatest potential for energy reductions will be from the building sector.

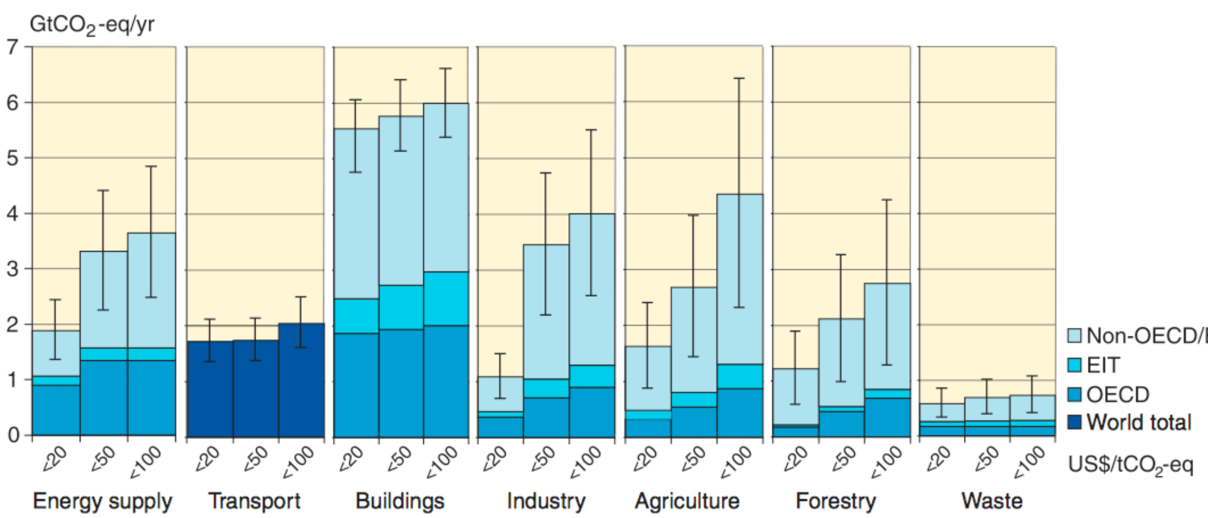

Figure 2.5 Potential Reductions of Carbon Emissions by Sector (IPCC, 2007)

Therefore, UNEP recommends analyzing the carbon footprint of building systems using a life-cycle approach (LCA). Using LCA, it is revealed that over 80% of GHG emissions occur throughout the use-phase of buildings for heating, cooling, ventilation, lighting, appliances, etc. A much smaller proportion, 10-20%, of energy consumed is for capital expenditure purposes (including materials production, transportation, construction, maintenance, renovation and demolition).

This has been also proven in a 2013 report entitled "Life Cycle Assessment of Building Products" for Construction.com, in which author Peter J. Arsenault models the carbon footprint of buildings throughout their lifecycle. He provides a simplified yet powerful illustration of the long-term carbon impact of buildings using an LCA approach and concludes that over 75% of the footprint can be attributed to on-going operations and only 25% can be attributed to building products and construction. This provides a convincing argument for why it is tremendously important to prioritize reduction initiatives directed towards the operational use-phase (Arsenault, FAIA, NCARB, & LEED AP, 2013).

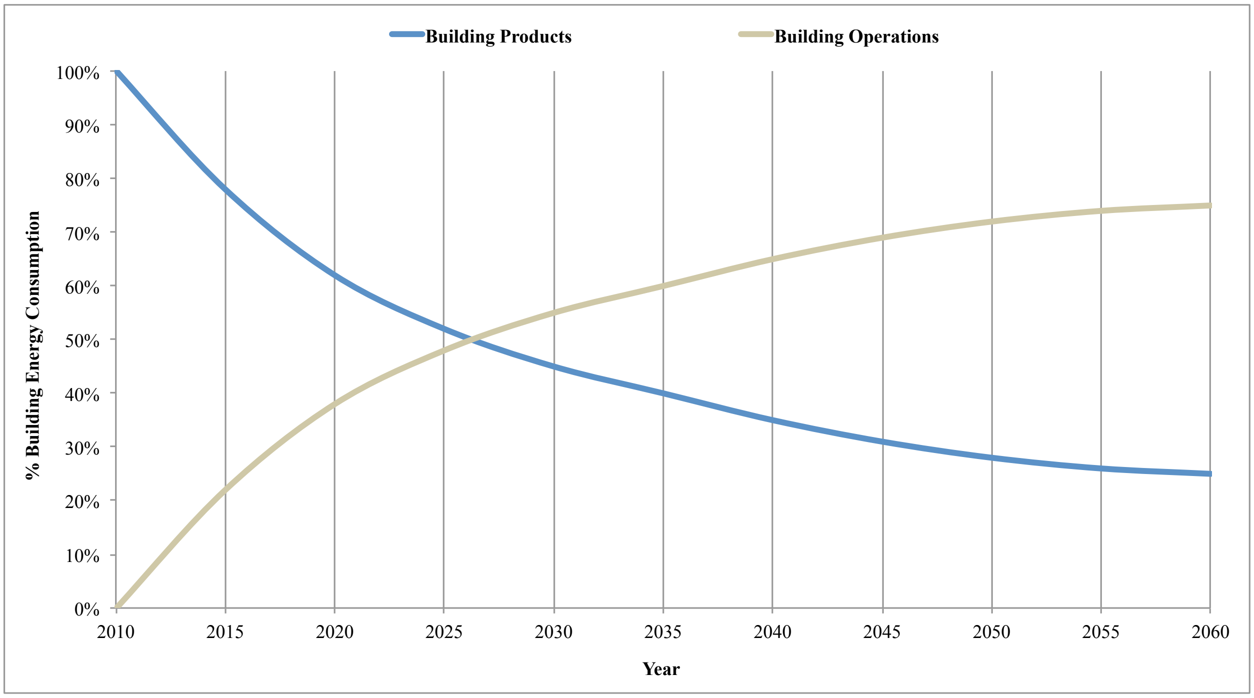

Figure 2.6 Breakdown of a typical Building Energy Consumption Over its Lifecycle (Arsenault, FAIA, NCARB, & LEED AP, 2013)

2.3 Carbon Emissions in Residential Buildings

Carbon emissions in residential buildings are directly due to the materials that are used for their construction and indirectly due to the consumption of electricity of all its housing elements during its entire use-phase.

2.3.1 Drivers of Carbon Emissions during Construction

The drivers of carbon emissions during construction are due to the materials used for constructing a residential building. Their emissions vary depending on each material's production process (energy intensiveness). The major construction elements of any residential building are (i) concrete, (ii) steel, and (iii) bricks.

2.3.1.1 Concrete

Concrete production accounts for approximately 5% of the worldwide GHG emissions. Concrete's main components are cement, water, fine and coarse aggregates. Most of the carbon dioxide emissions in concrete are due to cement production, where its worldwide production accounts for approximately 3% of the annual carbon dioxide emissions (Wimpenny, 2009). The pie chart below shows the contribution of each sector of the concrete industry in its CO_2 emissions.

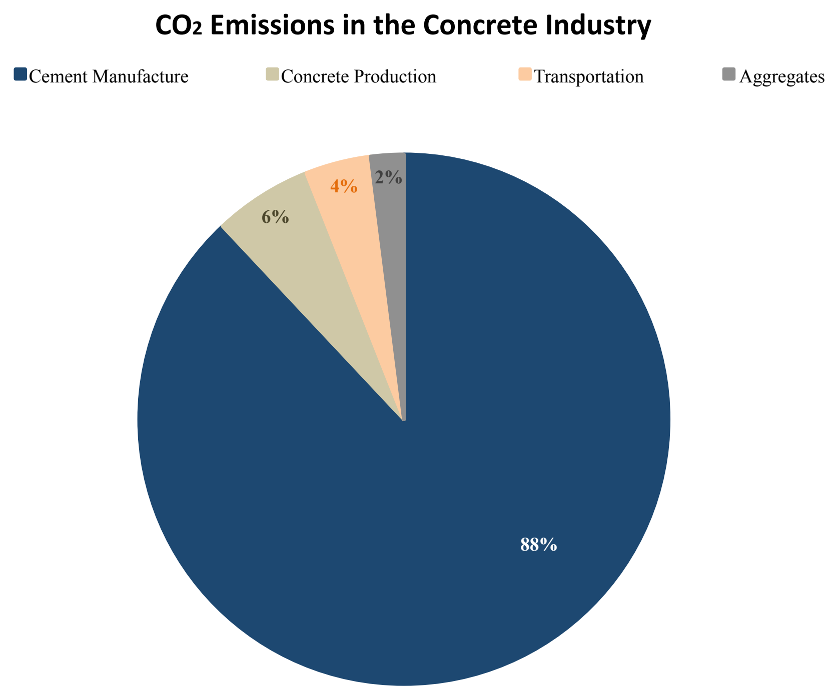

Figure 2.7 Carbon Emissions in the Concrete Industry (Wimpenny, 2009)

As shown in Figure 2.7, cement production is the main contributor of CO_2 emissions because of its highly energy-intensive production process. The water, fine and coarse aggregates, and other ingredients make up 90% of the concrete mix by weight, however, the process of mining the sand and gravel, crushing the stones, combining materials to the concrete plant and transporting it to the construction site will only require small amounts of energy and therefore will emit little amounts of CO_2. Therefore, the amount of embodied CO_2 in concrete is due to the amount of cement (NRMCA, 2012).

Cement Production:

The production of cement is a highly energy-intensive process and is a major source of CO_2 emissions. Each ton of Portland cement produced generates approximately one ton of CO_2. Emissions due to the combustion of fossil fuels and the grinding of cement contribute to 46%, while 54% are due to the calcination of limestone in the raw mix (Malhotra, 2005).

The process involves several stages including, extraction, grinding, heating and finally shipping as described below:

1. Raw Material Preparation – raw materials used are limestone, clay and chalk. The extraction of raw materials and their transportation to the cement plant emits small amounts of CO_2 (NRMCA, 2012).

2. Grinding of Limestone Rocks – limestone is grinded into smaller pieces in primary and secondary crushers (Hegar, 2005).

3. Blending and Fine Grinding – all the raw materials are proportioned in order to produce a uniform cement product. These raw materials are now ready for fine grinding, which is a crucial stage because their fineness and uniformity can help in reducing the amount of heat needed in clinkering (next stage), and thus saving energy with the use of less fuel (Hegar, 2005). Those finely grinded raw materials are known as 'raw meal' (Worrell, Price, Martin, Hendriks, & Meida, 2001).

   Fine grinding can be done using two methods, the wet process where water is added to the raw meal forming slurry, and the dry process with no addition of water (Hegar, 2005).

4. Clinkering – the wet or dry mix is fed into an inclined rotary kiln making the materials slide downwards through hotter zones towards the flame, where temperatures can reach up to 2000°C. The heat causes chemical and physical changes to the raw meal and transforms it into a material called clinker. At the end of the kiln there is a cooler where the clinker is cooled by forced air and the heat recovered from the cooling process is re-circulated back to the kiln or to any preheater (if it is used) in order to save energy (Cement Sustainability Initiative , 2012).

Preheaters are vertical cyclones where the raw meal passes down first before entering the rotary kiln. As they move down the cyclones, they get into contact with the hot kiln exhaust gases and as a result it pre-heats the raw meal before it enters the kiln and thus any necessary chemical reaction will take place faster and more efficient. At the bottom of the preheater there is a combustion chamber called a calciner, which allows for shorter rotary kilns and the use of lower grade alternative fuels (Cement Sustainability Initiative , 2012). Preheaters are added in order to retain energy in the system and making use of it, and as a result saving energy.

The rotary kilns for a wet mix are larger and require more fuel than those used for a dry mix, because more energy is needed to remove the water from the wet raw meal. Wet process kilns are eight meters in diameter, 230 meters long and needs approximately 230 kg of coal to produce 1t of cement, while the dry process kilns (typical sizes) are three to ten meters in diameter, 50-100 meters long and can need less than 120 kg of coal to produce 1t of cement (Kurtis, 2009). This shows that producing cement using the wet process will require more energy and consequently more CO_2 emissions than using the dry process. Therefore, in order to save energy, the production of cement should be done using the dry process.

5. Final Grinding – the cooled clinker is then mixed with gypsum, which is an essential ingredient to control the setting time of concrete. Slag and fly ash can be also added to the mix (Cement Sustainability Initiative , 2012). The final grinding of cement is done using primary and secondary crushers in order to reach the fineness of flour (Hegar, 2005).

6. Packaging/Shipping – all the cement is packed in bags and ready to be transported anywhere.

Figure 2.8 summarizes the efficient production of cement using the dry process technique and preheaters (Cement Sustainability Initiative , 2012).

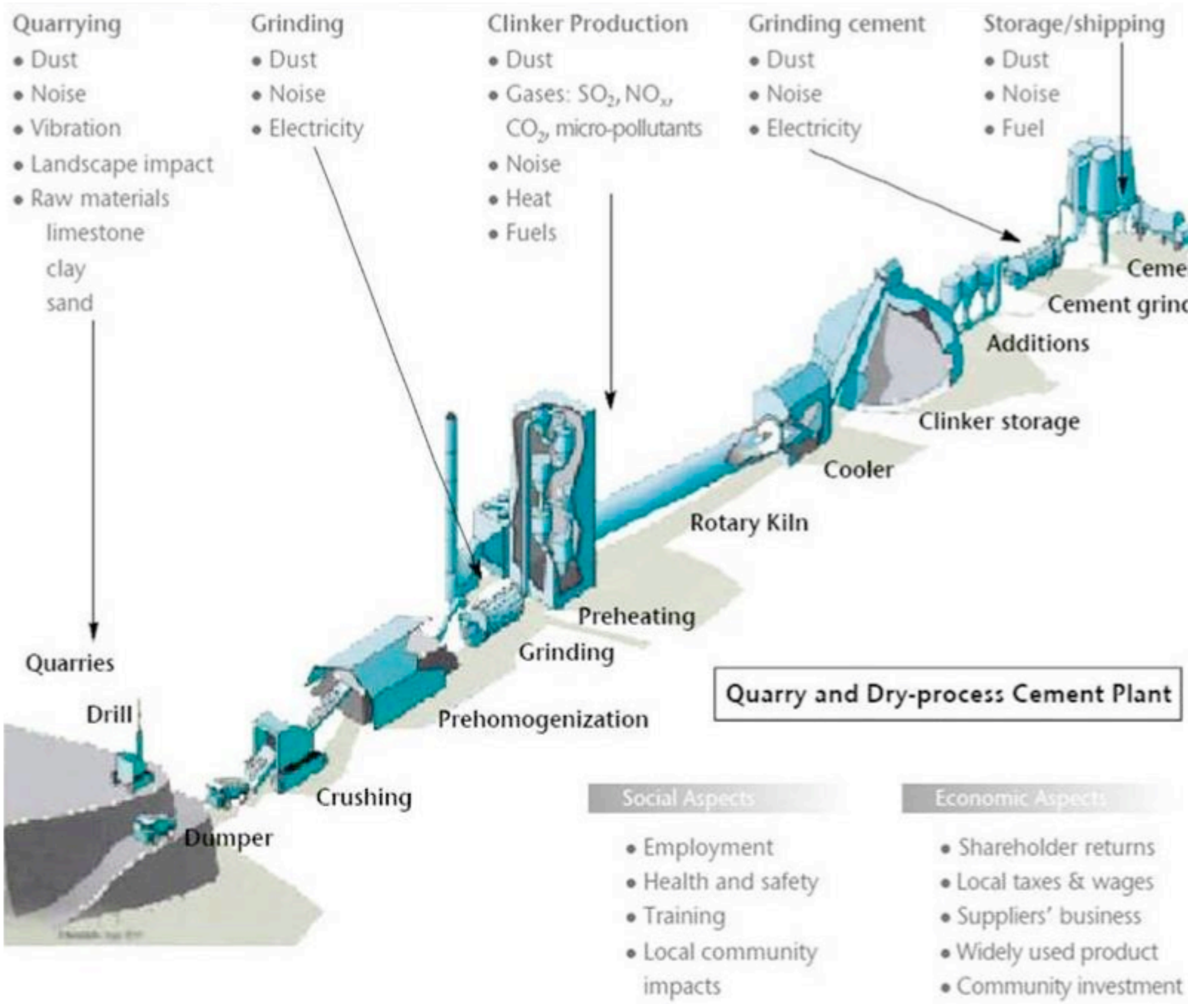

Figure 2.8 Efficient Cement Production Process (Cement Sustainability Initiative , 2012)

<u>Sustainable Concrete:</u>

Making the concrete more environmentally friendly is of major importance because this will help in creating a more sustainable environment. It will require several aspects to be done from the manufacturing of the concrete's components to changes in its mix.

Concrete with lower emissions will need:

- Energy Efficiency Improvements: having an energy-efficient manufacturing process will save a lot of carbon emissions from fuel and electricity use. This will help in reducing the amount of CO_2 emitted from cement production, by choosing the appropriate method and process for manufacturing cement (i.e. using a preheater and the dry process method in the cement manufacturing process). Moreover, using energy-efficient equipment throughout construction processes will make a huge difference (Worrell, Price, Martin, Hendriks, & Meida, 2001).

- High-Carbon Fuel Replacement: using low-carbon fuels will help in reducing the long-cycle carbon emissions (Worrell, Price, Martin, Hendriks, & Meida, 2001). This can be achieved by changing the use of coal to natural gas or by using wastes as fuel for cement plants (used oil, tires and medical wastes) (Concrete Thinking for a Sustainable World, 2009).
- Blended Cements: replacing a portion of the clinker by industrial by-products, like, fly ash, blast furnace slag or pozzolanic materials and blending it with the clinker to produce blended cement. It has a longer setting time and higher ultimate strength than Portland cement (Worrell, Price, Martin, Hendriks, & Meida, 2001). Blended cements will require less clinker and thus reducing carbon emissions.
- Cement Replacement: replacing a portion of cement from the concrete mix by slag, fly ash, silica fume or admixtures. Therefore, reducing the amount of cement needed in a mix and consequently the demand for its manufacture.
    - Using water-reducing admixtures in a concrete mix can reduce the amount of cement by up to 10% for the same concrete strength (Wimpenny, 2009).
    - Silica fume is a by-product of the manufacture of silicon or ferrosilicon alloys, where the fume is condensed at the exit of the escaping gases by filters during the manufacturing process. It has a high content of silicon dioxide and it's added to concrete to react with free lime in order to improve the concrete's performance. Egypt produces more than 12,000 tons of silica fume annually (Khedr & Abou-Zeid, 2014).
    - Fly ash is a by-product of burning pulverized coal in electrical power plants, it's the unburned residue that is carried away by the flue gases and collected by electrostatic separators. The heavier unburned residue is known as bottom ash, which remains at the bottom of the furnace. Fly ash is a pozzolanic material that is made of finely divided alumino-silicates with different amounts of calcium, which when mixed with cement and water, will react with calcium hydroxide that is released from the hydration of cement to produce calcium-silicate hydrates (C-S-H) and calcium-aluminate hydrates. These pozzolanic reactions are beneficial to concrete because it

improves its long-term strength and reduces its permeability. Therefore, ending up with more durable concrete (Thomas, 2007).

- New Cement: geopolymer concrete emits around 9% less carbon emissions than concrete using Ordinary Portland cement. It's made of alumino-silicates instead of calcium oxide in Portland cement, where the silicates come from industrial waste materials. It can be combined with steel or plastic fibers, where fiber-reinforced geopolymer concrete is more resistant to acids, sulphates, fire and corrosion (Turner & Collins, 2013).
- Innovative Aggregates: using crushed concrete as aggregates for concrete in new buildings (Concrete Thinking for a Sustainable World, 2009).
- Carbon Dioxide Removal: separating CO_2 during or after the production process of cement and storing or disposing it outside the atmosphere (Worrell, Price, Martin, Hendriks, & Meida, 2001).

2.3.1.2 Steel

Steel is a major component used in construction and it's the element of strength in any structural building. It has a high strength-to-weight ratio, which means that the weight of steel required for a certain application is usually lower than other material alternatives without jeopardizing the strength (Tata Steel, 2014). It is also stiff allowing larger spans and more flexible designs than other materials (World Steel Association, 2012).

The construction industry is the largest consumer of steel with approximately 50% of the total world steel consumption (as shown in Figure 2.9) (World Steel Association, 2012). However, the steel industry is a highly energy intensive industry and accounts for approximately 6.7% of the total global CO_2 emissions. Due to the expected increase in population and consequently in the demand of steel, the amount of CO_2 emitted will be a major concern. It has been estimated that the use of steel will increase 1.5 times by 2050 and as a result increase the carbon emissions with the same amount (World Steel Association, 2012).

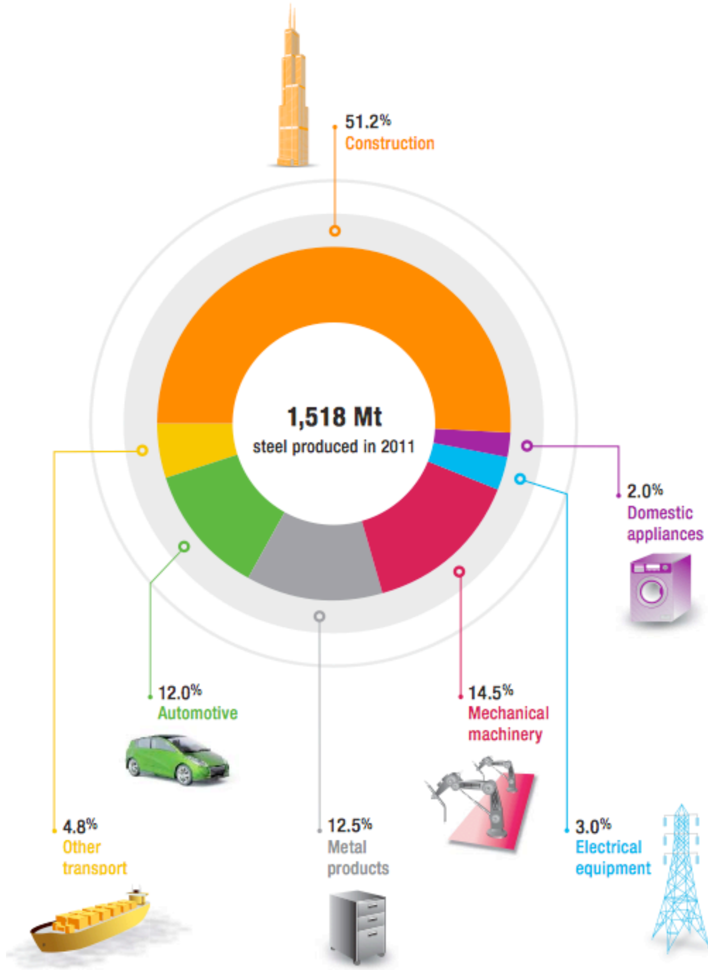

Figure 2.9 Uses of Steel (World Steel Association, 2012)

<u>Steel Production:</u>

There are two different production routes for steel, however, the average CO_2 emissions for every ton of steel produced is 1.8 tons (World Steel Association, 2012). The two production routes are:

1. Blast Furnace-Basic Oxygen Furnace Route (BF-BOF): the pig iron is produced in a blast furnace using iron ore and coke, followed by the production of steel in a basic oxygen furnace where oxygen is injected through the hot metal (IETD, 2012a). It requires 1400 kg of iron ore, 800 kg of coal, 300 kg of limestone and 120 kg of recycled steel, to produce one ton of crude steel (World Steel Association, 2012). Figure 2.10 illustrates the process.

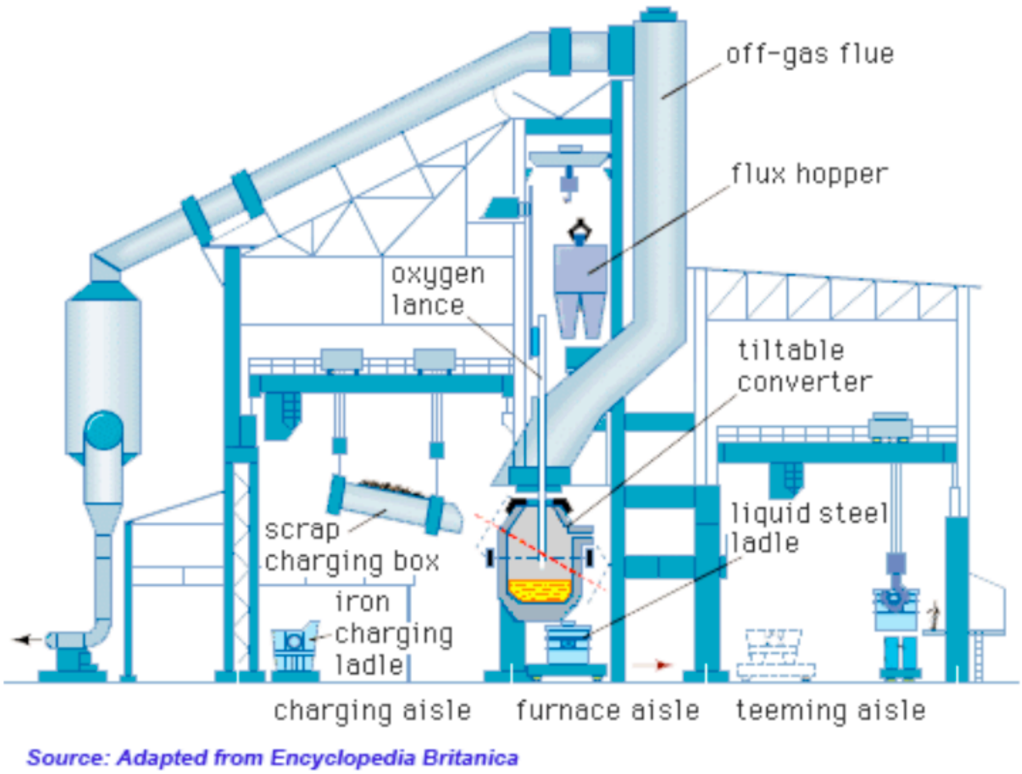

Figure 2.10 Basic Oxygen Furnace Process (IETD, 2012a)

2. Electric Arc Furnace Route (EAF): the iron produced is melted and converted into steel by high-power electric arcs formed between a cathode and an anode. The iron can be produced either from scrap or direct reduced iron (iron ore reduced in its solid state) (IETD, 2012c). This route usually requires sixteen kilograms of coal, sixty-four kilograms of limestone and 880 kg of recycled steel, to produce one ton of crude steel (World Steel Association, 2012). The actual electricity use ranges between 300 to 550 kWh/t, however 350 kWh is the preferred consumption rate, which will lead to annual energy savings (IETD, 2012b). Figure 2.11 shows a section and plan view of an electric arc furnace (IETD, 2012b).

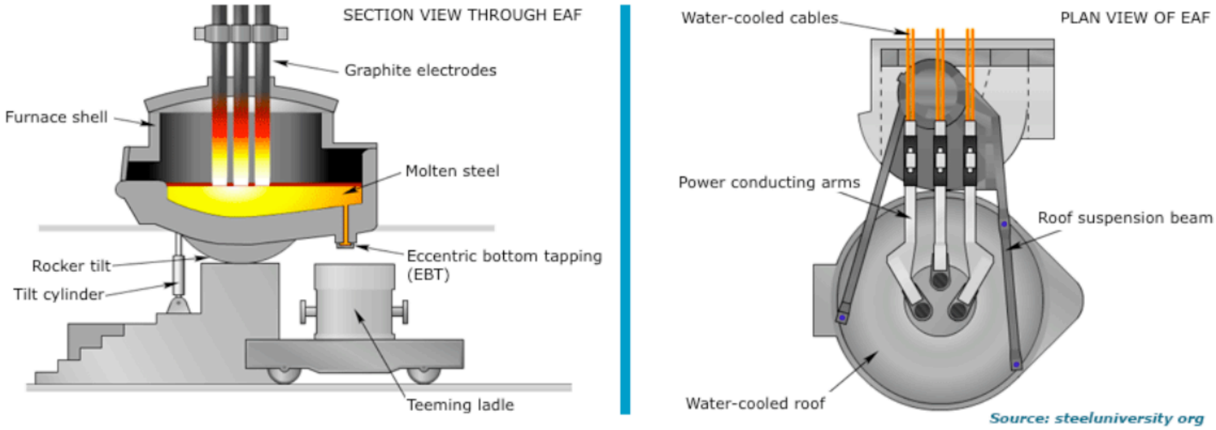

Figure 2.11 Electric Arc Furnace Components (IETD, 2012b)

Carbon dioxide emissions are directly produced from the extraction of the metal from iron ore through a process called 'reduction' that occurs in the blast furnace or indirectly by the consumption of electricity in an electric arc furnace (ULCOS, 2015). Figure 2.12 summarizes both production routes.

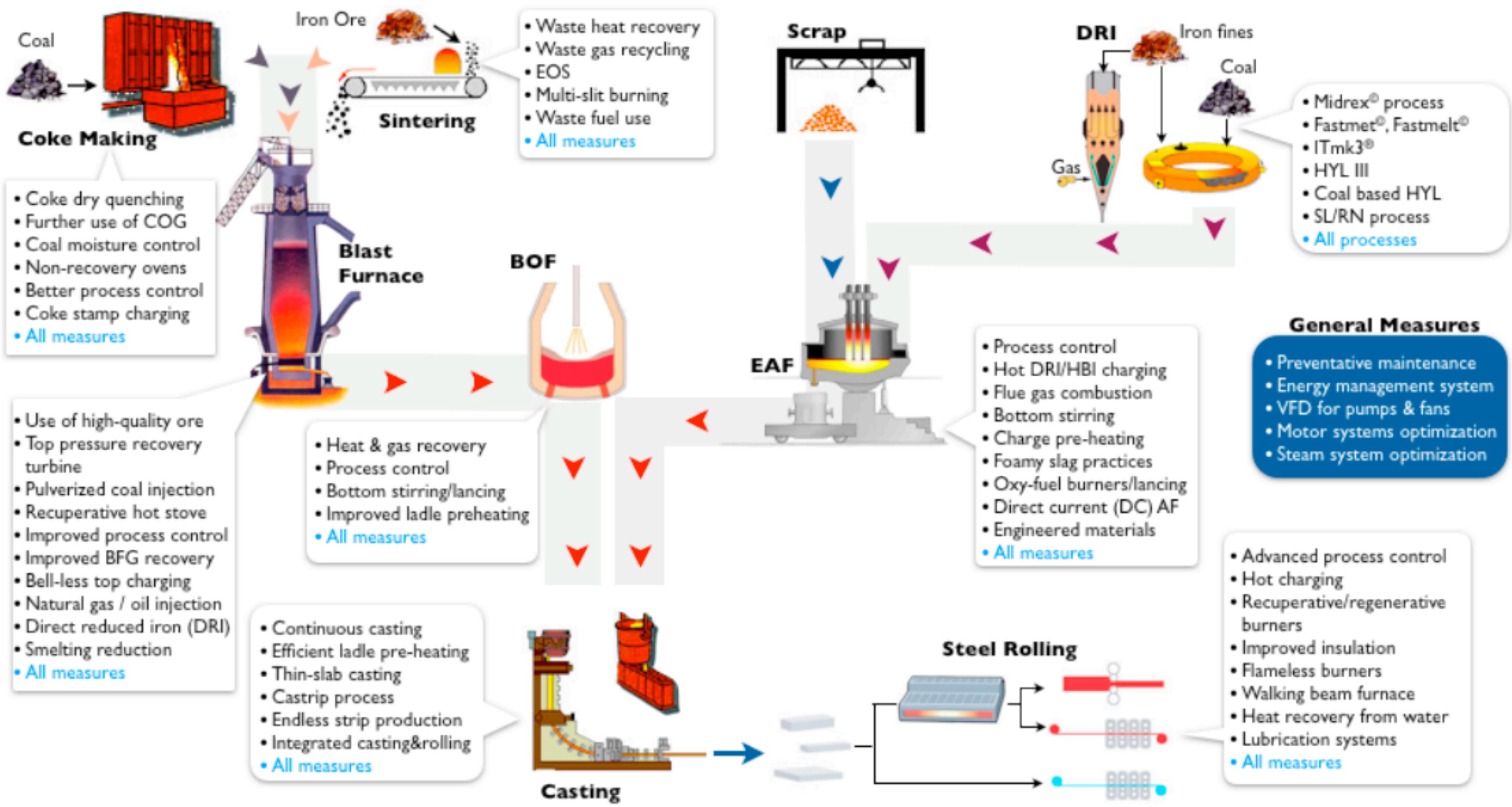

Figure 2.12 Steel Production Routes (IETD, 2012c)

Sustainable Steel:

Producing steel in a more sustainable way will help save our environment and therefore thinking of new ways and implementing them is very important.

Steel with lower emissions will need:

- Energy Efficiency Improvement: having an energy-efficient production process will save tremendous amounts of carbon emissions (World Steel Association, 2012).
- Higher Recycling and Reuse Rates of Steel: Steel can be recycled and reused endlessly without damaging its properties. The CO_2 emission savings from building reuse is approximately 1-1.5 kg CO_2/kg steel (World Steel Association, 2012). Figure 2.13 shows the endless lifecycle of steel.

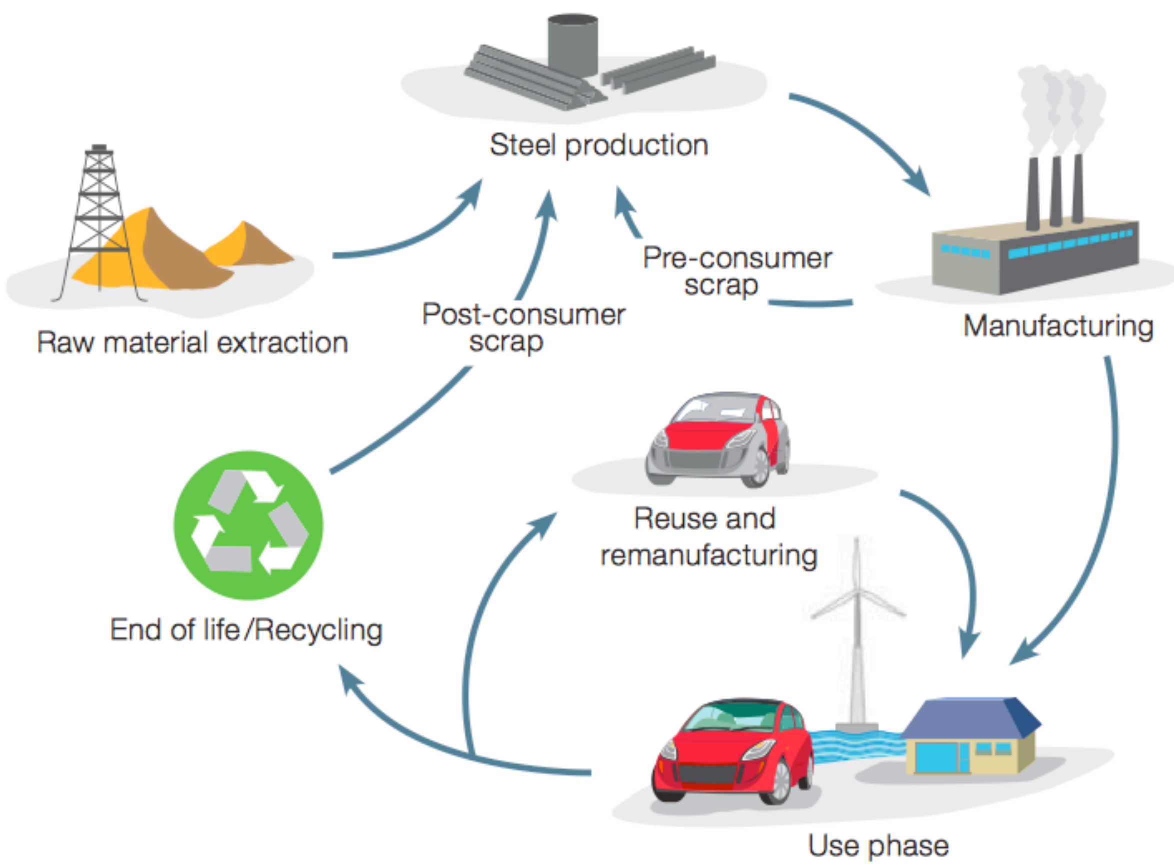

Figure 2.13 Steel's Cycle (World Steel Association, 2012)

- Higher Recycling and Utilization of Steel's By-Products: the by-products can be recycled during the steel making process or it can be sold to other industries, and therefore, preventing landfill wastes, reducing CO_2 emissions and helping preserve natural resources. The main by-products are: slag, process gasses, dust and sludge.
  - Slag can be used to bring down the cost of cement (World Steel Association, 2012). There are two types of slags: (i) air-cooled, which is hard and dense making it suitable to be used as a construction aggregate, or in ready-mixed concrete, road bases and surfaces, roofing and mineral wool (as insulation), and (ii) granulated, which are sand-sized particles of glass and is used to make cementitious material (World Steel Association, 2012).
  - The gasses produced can be used internally in order to reduce the demand for externally produced electricity (World Steel Association, 2012).
  - The dust and sludge removed from gasses contain iron and can be used again in steelmaking (World Steel Association, 2012).

2.3.1.3 Bricks

Bricks are a versatile and durable building material that has an excellent life cycle performance. They require low maintenance and are recyclable which adds up to its energy efficient characteristic (Brick Development Association, 2012).

Clay bricks are the traditional and mostly used type, however they are the most energy intensive with the highest embodied energy and carbon dioxide emissions (Chusid, RA, FCSI, Miller, CSI, & Rapoport, 2009). Therefore, trying to reach sustainable solutions in the brick industry has led to the creation of new bricks in addition to changes in the production of current bricks being used in the construction industry.

Bricks are classified into two groups, the fired and non-fired ones. Clay bricks are classified under fired bricks, while concrete and fly ash bricks are the non-fired ones. The problem with the fired bricks is in the firing process itself, the burning kilns combust tremendous amounts of fuel which is the main contributor of CO_2 emissions and these kilns are always operating even if they are not at full capacity (Chusid, RA, FCSI, Miller, CSI, & Rapoport, 2009). There are several sustainable techniques that can be done to make the traditional clay bricks more sustainable, and this includes the following:

- Alternative Fuels – natural gas (captured from landfills) or petroleum coke (by-product of oil refining) can be used, however both emit almost the same amount of CO_2 and therefore the emissions will still remain high (Chusid, RA, FCSI, Miller, CSI, & Rapoport, 2009).

- Recycled Materials – even though recycling is a huge advantage, but it will not have a major influence on the energy consumption and CO_2 emissions (Chusid, RA, FCSI, Miller, CSI, & Rapoport, 2009).
- Reduced Materials – reducing the amount of clay per brick by coring or deep frogs. Coring are holes through the section that reduce the surface area by 25% and frogs are recessed panels in the bearing surface area of the brick. However, deep frogs require more mortar and therefore compromising their environmental benefit. Moreover, these bricks will still take the same space in the kiln as solid bricks and therefore the number of bricks produced compared to the fuel consumed will stay the same (Chusid, RA, FCSI, Miller, CSI, & Rapoport, 2009).
- Innovative Non-Clay Bricks – They are 100% recycled bricks and they consist of; processed sewage wastes, recycled iron oxides, recycled glass and ceramic scrap. These bricks are fired in normal clay brick plants and even though they are recycled material, but their embodied energy and carbon footprint are similar to conventional fired clay bricks. Their kiln temperature and firing time are approximately lower than normal clay bricks by 33% and 5% respectively (Chusid, RA, FCSI, Miller, CSI, & Rapoport, 2009).

Non-fired bricks eliminate the firing problem and thus reducing all the emissions resulting from it, and therefore creating bricks with far less CO_2 emissions and embodied energy. The concrete bricks have the same components of normal concrete and they have the similar strength and density to that of fired clay bricks, however the problem with this type of brick is in the production of cement, which contributes to most of the CO_2 emissions. The fly ash bricks are made of recycled material and fly ash (recycled from coal-fired power plants) and have achieved 15-20% of the emissions of fired clay bricks (Chusid, RA, FCSI, Miller, CSI, & Rapoport, 2009). Table 2.1 compares the traditional fired clay bricks with non-fired concrete and fly ash bricks.

	Clay Brick	Concrete Brick	Fly Ash Brick
Standard	ASTM C 216	ASTM C 1634	Meets or exceeds performance of ASTM C 216 for SW Clay Brick
Embodied Energy	9.3 MJ (8800 Btus)	1.3 MJ (1240 Btus)	0.89–1.31 MJ (850–1250 Btus)
CO_2 Footprint	0.59 kg (1.3 lb)	0.34 kg (0.75 lb)	0.11 kg (0.25 lb)
Recycled Material	0–6%	Not typical	35–99%
Shrinkage/Expansion	Expands 0.08%	Shrinkage 0.065%	Shrinkage 0.065%
Dimensional Consistency	Can vary due to firing and warpage	Very consistent if cured to ASTM C 55 before shipping	Projected to be very consistent due to manufacturing process
Initial Rate of Absorption/ Ability to Absorb Mortar	2–30	≥ 25	1–14
Pigmentation	Mineral oxides in clay plus natural and synthesized mineral oxide pigments	Natural and synthesized mineral oxide pigments	Natural and synthesized mineral oxide pigments

Table 2.1 Comparing Brick Types (Chusid, RA, FCSI, Miller, CSI, & Rapoport, 2009)

2.3.2 Drivers of Carbon Emissions during the Use-Phase

Carbon emissions during the use-phase of a residential building – as mentioned earlier – are primarily derived from the extensive use of electricity. Most electricity used in homes is for heating, cooling, lighting, and to power other electrical appliances. Therefore, efficiently consuming electricity can save great amounts of energy and consequently millions of tons of carbon emissions.

In this section the major drivers of carbon emissions are highlighted and discussed in more detail along with possible reductions in their emissions. The drivers can be summarized as follows: (i) lighting, (ii) electrical appliances (air conditioners, water heaters, refrigerators and washers), and (iii) building envelope modifications.

2.3.2.1 Lighting

Lighting accounts for approximately 6% of global CO_2 emissions, which is equivalent to 1,900 million tons of CO_2 ($MtCO_2$) per year (Climate Group, 2012). Light is measured in lumens (lm), which is the measure of the total amount of visible light emitted by a source; and its efficiency is described in terms of luminous efficacy, which is expressed in lumens per watt (lm/W) (Merriam-Webster, 2015).

Choosing the most efficient kind of lighting is vital because it will determine the amount of emissions generated along its entire lifetime, and maximizing the reductions as much as possible would definitely contribute to making a home more energy efficient. The three types of light bulbs used are (i) incandescent, (ii) compact fluorescent, and (iii) light-emitting diodes (LEDs). However, by using LED lamps and smart controls, carbon emissions can be reduced by 50-70% (Climate Group, 2012).

2.3.2.1.1 Incandescent Light

An incandescent light is light produced when a filament glows by being heated at very high temperatures when an electric current passes through it. This hot filament is coated inside a glass or quartz bulb that is filled with an inert gas to prevent it from oxidation. These types of bulbs are the least efficient amongst other types of electrical lighting because they only convert 5% of the electricity going through it into visible light and the rest is converted into heat. Its luminous efficacy is sixteen lumens per watt. Its inefficiency is not only in the amount of electricity used, but also in its lifetime duration. Incandescent lighting has the shortest lifetime compared to other types of lighting, which is around 1,000 hours for home light bulbs. It has a low initial cost compared to the cost of energy over its lifetime (Keefe, 2007). Figure 2.14 shows a typical incandescent light bulb.

Figure 2.14 Incandescent Light Bulb (Energy Star, n.d.c)

2.3.2.1.2 Compact Fluorescent Light (CFL)

A fluorescent lamp is a low-pressure, mercury-vapor, gas-discharge lamp that uses fluorescence to produce visible light. Light is produced when an electric current excites the mercury vapor producing ultraviolet light, which then causes a phosphor coating that glows (Energy Star, n.d.b). CFL is more efficient than incandescent lighting having a luminous efficacy of sixty lumens per watt, and a lifetime of 10,000 hours (Keefe, 2007). They are more expensive than incandescent lights, however they use less energy for the same amount of light and that is why it lives longer and thus offsets its higher initial cost (Energy Star, n.d.b). Figure 2.15 shows a typical fluorescent light bulb.

Figure 2.15 Compact Fluorescent Light Bulb (Energy Star, n.d.c)

2.3.2.1.3 Light-Emitting Diode (LED)

A light-emitting diode is a two-lead semiconductor light source. When voltage is applied to the lead it releases energy in the form of light (The American Heritage Science Dictionary, 2005). It has the highest efficiency amongst all types of electrical lighting with a luminous efficacy of 100 lm/W (Carole, 2014) and a lifetime of 30,000 hours (Keefe, 2007). They are the most expensive type of lighting, however its long-life and efficient use of electricity counteracts this cost. Figure 2.16 shows a typical LED bulb.

Figure 2.16 LED Light Bulb (Energy Star, n.d.c)

Out of the three types of lighting, the LEDs are the most efficient and it will be the evolving lighting technology of the future. Figure 2.17 shows that by 2020, the LEDs (solid state) will take over the market and cause the elimination of both the incandescent (GLS – General Lighting Service) and compact fluorescent (CFL) light bulbs (Curtis, 2009).

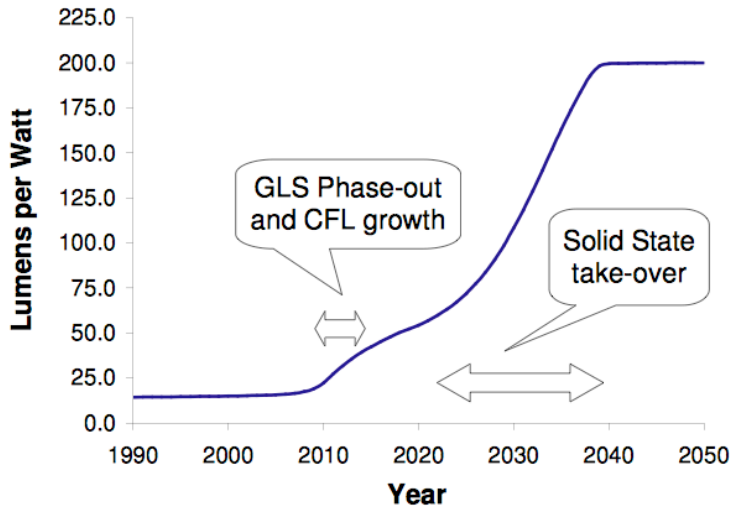

Figure 2.17 The Evolution of Light Bulbs (Curtis, 2009)

2.3.2.2 Electrical Appliances

2.3.2.2.1 Refrigerators and Air Conditioners

Refrigerator: The refrigeration cycle is a liquid - known as a refrigerant – that evaporates by absorbing heat from the outside and re-condenses as it passes through a compressor releasing heat and thus the cycle continues (UNFCCC, n.d.). The U.S. Department of Energy stated that refrigerators use up to 14% of electricity used in homes. However, by the end of its lifetime it should be replaced because it becomes a greater consumer of electricity and can use double or triple its amount of energy (Ariskan, 2009).

Air Conditioner: An air conditioner is composed of three parts; an evaporator (cooling part), a condenser (hot coil) and a compressor pump. The evaporator transmits cooler air inside a room, while the condenser releases warm air outside. The compressor pump's role is to move the refrigerant between the evaporator and condenser changing it from a liquid to a gas to move the cooler and warmer air (Long, n.d).

Figure 2.18 illustrates the refrigerant cycle for both, refrigerators and air conditioners.

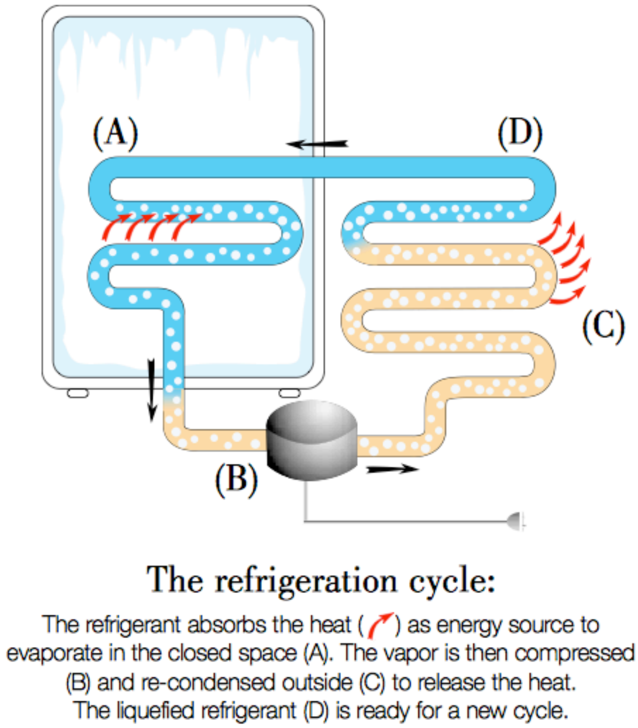

Figure 2.18 A Typical Refrigerant Cycle (UNFCCC, n.d.)

The choice of a refrigerant can either harm or protect our environment. Carefully selecting a refrigerant is very important because it can cause ozone depletion and global warming (Emerson Climate, 2008).

The ozone layer is a reactive form of oxygen fifteen miles above the Earth's surface and it is necessary for planetary life because it prevents the penetration of harmful ultraviolet rays from the sun from reaching Earth. Therefore, its depletion can disturb the quality of human, animal, plant and marine life. Chlorine from refrigerants has been proven to contribute with the depletion of the ozone layer, much of this has come from chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) and thus chlorine-free refrigerants should be used as an alternative to prevent further damages, such as hydrofluorocarbons (HFCs) (Emerson Climate, 2008).

Global warming is a result of an accumulation of GHGs due to human activities; refrigerants are one of those gases that can contribute to an increased warming effect. It has been estimated that by 2050, HFCs will only contribute by no more than 3% of the GHG emissions (Emerson Climate, 2008).

Calculating the total equivalent warming impact (TEWI) depends on both the direct and indirect emissions of a refrigerator and air conditioner:

- Direct Emissions: the Global Warming Potential (GWP) measures the direct impact of a refrigerant as it escapes to the atmosphere. This will occur if refrigerants are improperly installed in refrigerant units causing leakages, or not recycling the refrigerant fluids at the end of their lifetime. Both of these situations will lead to refrigerant emissions, which contribute to a total of 20% of the total emissions (UNFCCC, n.d.). Early leak detections can help in reducing the amount of emissions to the atmosphere (Emerson Climate, 2008).
- Indirect Emissions: it depends on the efficiency of a piece of equipment; it takes into account its energy efficiency and power source. The lower the efficiency of equipment, the more the electricity it will use, and thus leading to more CO_2 emissions (Emerson Climate, 2008). These emissions contribute to a total of 80% of the total emissions (UNFCCC, n.d.).

Due to the indirect emissions higher contribution to emissions, the main objective is to focus on the quality of refrigeration systems. Figure 2.19 shows the percentage contributions of these emissions.

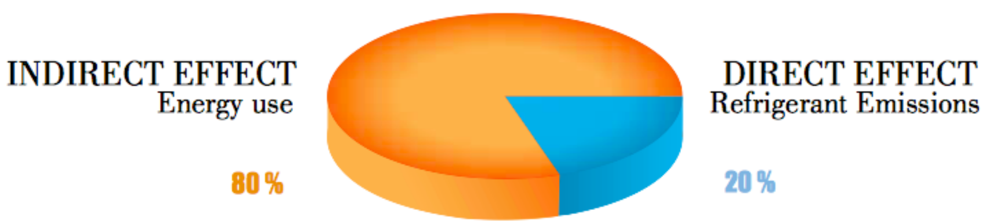

Figure 2.19 Direct and Indirect Emissions of a Refrigerator and AC (UNFCCC, n.d.)

On deciding between different refrigerant alternatives, the TEWI should be calculated, which is the sum of the direct (refrigerant), and indirect (energy) emissions of a refrigerant and thus taking into account refrigerant emissions and system power consumption/efficiency. This comparison would assess the impact on climate change fairly. HFCs were identified as the best option for refrigerants, due to its low GWP and CO_2 emissions compared to CFC and HCFC refrigerants. In addition to the TEWI, a refrigerant should also be: (i) environmentally acceptable, (ii) chemically stable, (iii) non-flammable, and (iv) non-toxic (Emerson Climate, 2008).

Using refrigerants responsibly is by enclosing it in a well-designed system, making sure that the equipment is highly efficient, and recovering, reclaiming and recycling them at the end of their lifetime (Emerson Climate, 2008).

2.3.2.2.2 Washers

Energy Star stated that around 90% of the energy used in washing machines is for heating the water. Therefore, if cold water is used instead this can save a lot of energy, and this means shifting to cold-water detergents (available at Procter and Gamble – P&G) (Alliance, 2011).

The following can be done to save energy from washing machines:

- Dry clothes on a washing line instead of drier.
- Spin off the water as much as possible instead of taking more time in driers.
- Efficiently use the washing machine – efficiently add loads and avoid over-washing clothes (Alliance, 2011).
- Wash clothes using cold water - reduces CO_2 emissions by 0.5 to 6.8 kilograms per laundry load depending on the washing machine type, hot water temperature, and electricity source (Center for Sustainable Systems, 2014).

2.3.2.2.3 Water Heaters

The two most common types of water heaters are:

Storage Water Heaters: they consist of a container where water is kept hot and ready for use at any time. Hot water is released from the top of the storage tank when the hot tap is turned on, and cold water enters the bottom of the tank to make sure the storage tank is always full. Domestic heaters vary in size, but are usually 50-300 liters in size and can use electricity or natural gas as their energy source. Storage water heaters are considered relatively inefficient due to the constant heating of water in their tanks causing a waste of energy at times when hot water is not needed (ex. overnight) (Energy, 2012b). A new alternative in recent years that mitigates this inefficiency has been solar energy, which harnesses the power of the sun in concentrated solar collectors to keep water hot in storage water heaters.

Tankless Water Heaters: they instantly heat water as they flow through the heater and this allows for unlimited and continuous flow of heated water. They are stored in many different places in a house. When hot water is needed, cold water moves through a pipe into a gas burner or an electric unit that heats the water and they provide water at a rate of seven to sixteen liters per minute (gas-fired types provide higher flow rates than electric ones). However, gas-fired heaters cannot provide hot water to simultaneous uses in a household and to overcome this problem several tank-less water heaters should be connected in parallel or installed separately for different appliances (Energy, 2012c).

Homes that use a maximum of 155 liters of hot water per day can save 24-34% of energy if tank-less heaters are used instead of conventional storage water heaters. However, 27-50% savings can be achieved if they are installed at each hot water outlet. The initial cost of tank-less water heaters are higher than that of conventional storage water heaters, but due to its longer life and lower operating and energy costs it offsets its higher purchase price. The life expectancy of tank-less water heaters is usually twenty years or more, as compared to the ten to fifteen years lifespan of a storage water heater (Energy, 2012c).

2.3.2.3 Building Envelope Modifications

The building envelope is the main component responsible for protecting a building's indoor environment from external environmental impacts. The roof, external walls, floors, windows and doors are the components forming the envelope. They control the solar, thermal and moisture flow in and out of a building, and thus controlling its indoor air quality. It protects the building from wind, rain, solar radiation, temperature difference, vapour pressure difference, industrial pollution and soil temperature (as shown in the Figure 2.20 below) (Iwaro & Mwasha, 2013). Figure 2.20 illustrates the building envelope components and shows the possible protections it may achieve.

The heat transfer in a multi-storey building is 40% from exterior walls, 30% from windows, 17% from air leaks, 7% from roofs and 6% from basement slab (i.e. floor) (Basarir, Diri, & Diri, 2012). Figure 2.21 shows a thermal image of heat losses and gains in a household.

This heat can be transferred in three ways; by (a) conduction: the heat flow through materials, (b) convection: the heat flow through liquids and gases where the lighter and warmer air rises while the denser and cooler air sinks into space, or (c) thermal radiation: the heat emitted by objects, where the warmer it is the more radiation it will emit (Energy, 2012a).

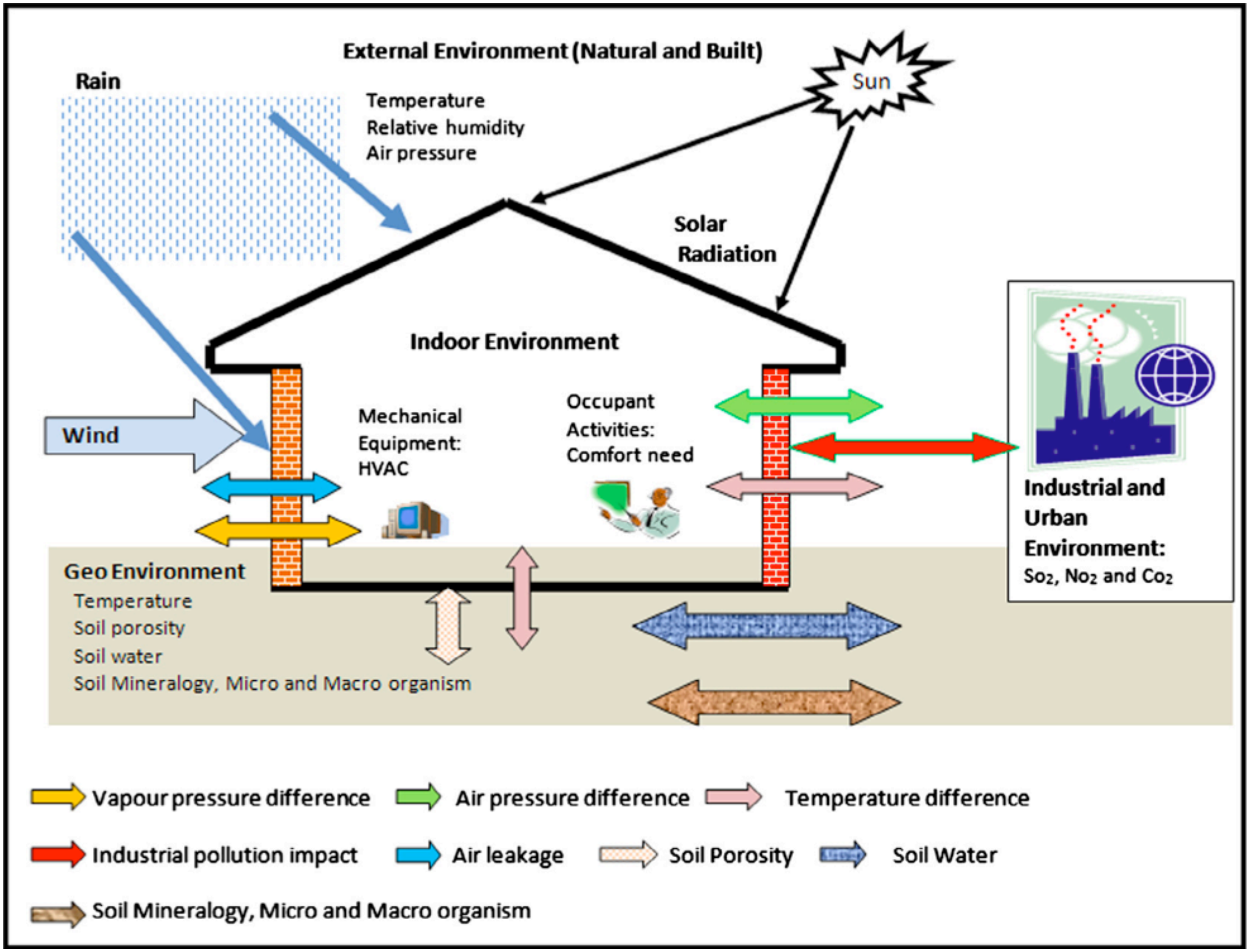

Figure 2.20 Building Envelope Components (Iwaro & Mwasha, 2013)

Figure 2.21 Thermal Image of Heat Loss/Gain in a Household (Rehau, 2011)

The design and construction of a building envelope will affect the energy use of buildings by 20-60% because it will play a major role in determining the amount of natural lighting, ventilation, and most importantly the energy needed for heating and cooling (IEA, 2013). According to Energy Star, publications issued by the American Environmental Protection Industry and the Department of Energy, the energy use in a household is divided as follows: 29% heating, 17% cooling, 14% water heaters, 13% electrical appliances, 12% lighting, 4% electronics and 11% any other electrical units (Energy Star, n.d.d). This shows that heating and cooling are the major consumers of energy, however by having a sustainable envelope it can reduce their need by 60% (IEA, 2013).

Having a sustainable envelope will require several modifications to its five components (roof, floor, windows, doors and walls). Modifications to each of these components are considered hereunder but it is important to note that they will be invariably dependent on climate.

2.3.2.3.1 Roof

- Insulation – glass wool, mineral wool, EPS (extruded polystyrene), XPS and polyurethane – they can be applied over the roof slab or between roof rafters (Basarir, Diri, & Diri, 2012).
- Painting Roof Surface – in a light colour to reflect unwanted heat or a dark colour to absorb needed heat (Basarir, Diri, & Diri, 2012).
- Using Renewable Energy Sources – like, photovoltaic panels, thin-filmed photovoltaic roofing materials or solar collectors (Basarir, Diri, & Diri, 2012).

2.3.2.3.2 Floor

Insulating them with glass wool, mineral wool, EPS (extruded polystyrene), XPS and polyurethane (Basarir, Diri, & Diri, 2012).

2.3.2.3.3 Windows and Doors

The main characteristics for windows and doors are their U-Values, and Solar Heat Gain Coefficients (SHGC), which are described below.

U-Value – the measure of the total heat flow through a window or door, it takes into account all types of heat transfer. It measures the heat flow per hour through each square foot of a window or door for a one degree Fahrenheit temperature difference between the indoor and outdoor air temperature (Window Technologies, 2014b). For residential buildings, low U-values are preferred (not more than 0.4 for windows) (Ander, Windows and Glazing, 2014). Figure 2.22 shows the heat transfer in windows.

The u-value is expressed in two different ways; (a) the u-value of an entire window or door (insulating value of the glazing glass and materials used are taken into consideration) and/or (b) the u-value of the center-of-glass (only shows the insulating values of the glazing glass) (Window Technologies, 2014b).

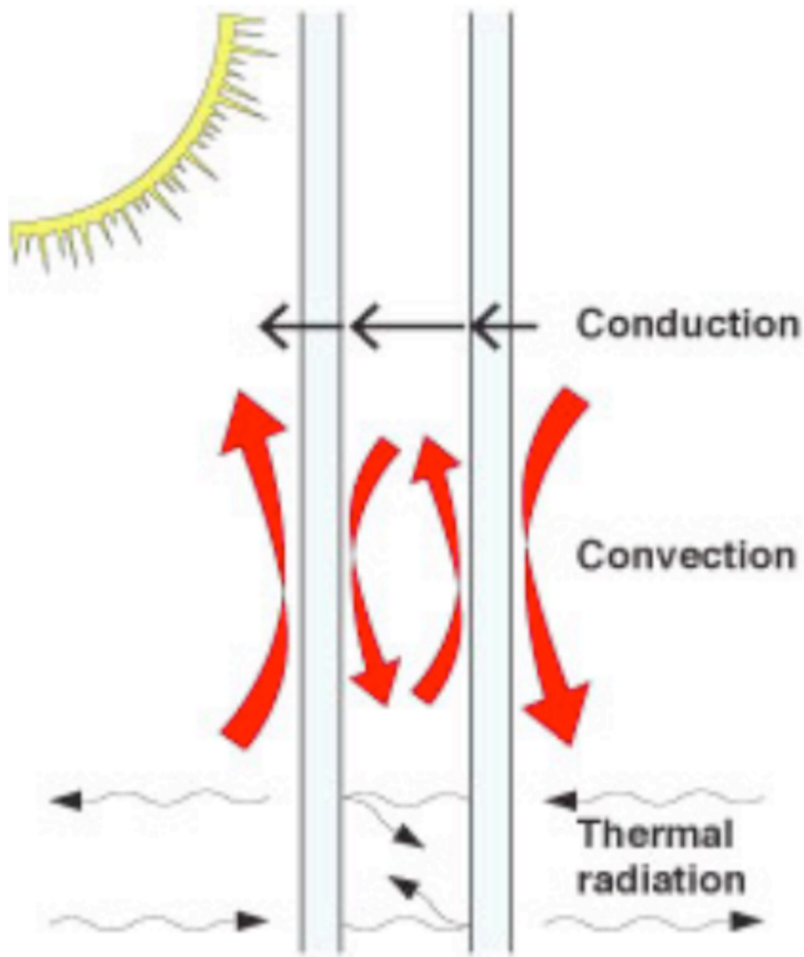

Figure 2.22 Heat Transfer in windows
(Window Technologies, 2014b)

Solar Heat Gain Coefficient (SHGC) – the amount of solar radiation that actually enters a building through the entire window or door assembly as heat gain. Solar heat gain includes the direct transmission of solar heat and indirect transmission by absorbed solar heat that is reradiated, convected or conducted into a building. It is expressed in a dimensionless number from zero to one, where the higher the coefficient the higher the heat gain (Window Technologies, 2014a). Low SHGC windows on the south, east and especially west facades will reduce the cooling loads (U.S Department of Energy, 2013). Figure 2.23 illustrates the solar heat gain in windows and illustrating how the heat is transferred within the window.

The glazing type, number of panes and glass coatings will affect the u-value and SHGC of a window or door. Figure 2.24 illustrates the effect of glazing and coating on u-values and SHGC (Window Technologies, 2014a).

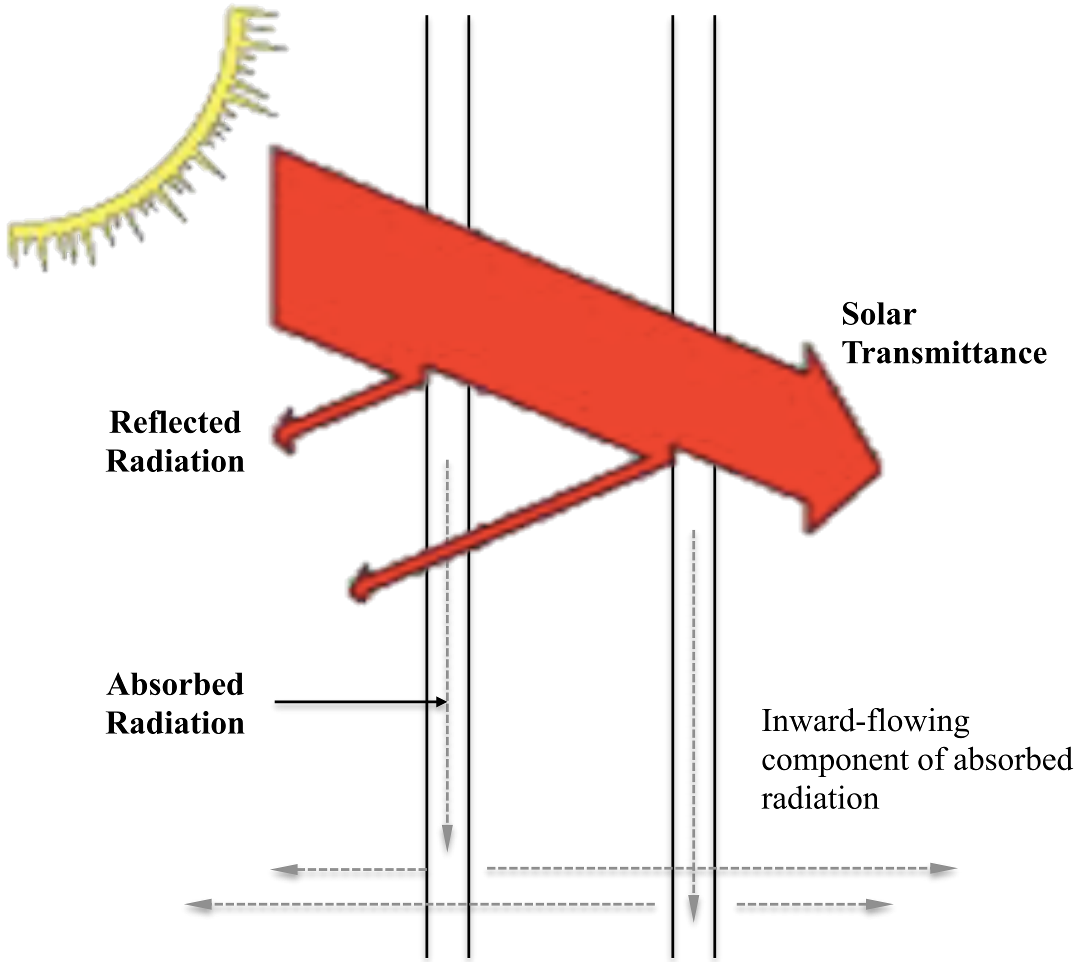

Figure 2.23 Solar Heat Gain in Windows (Window Technologies, 2014a)

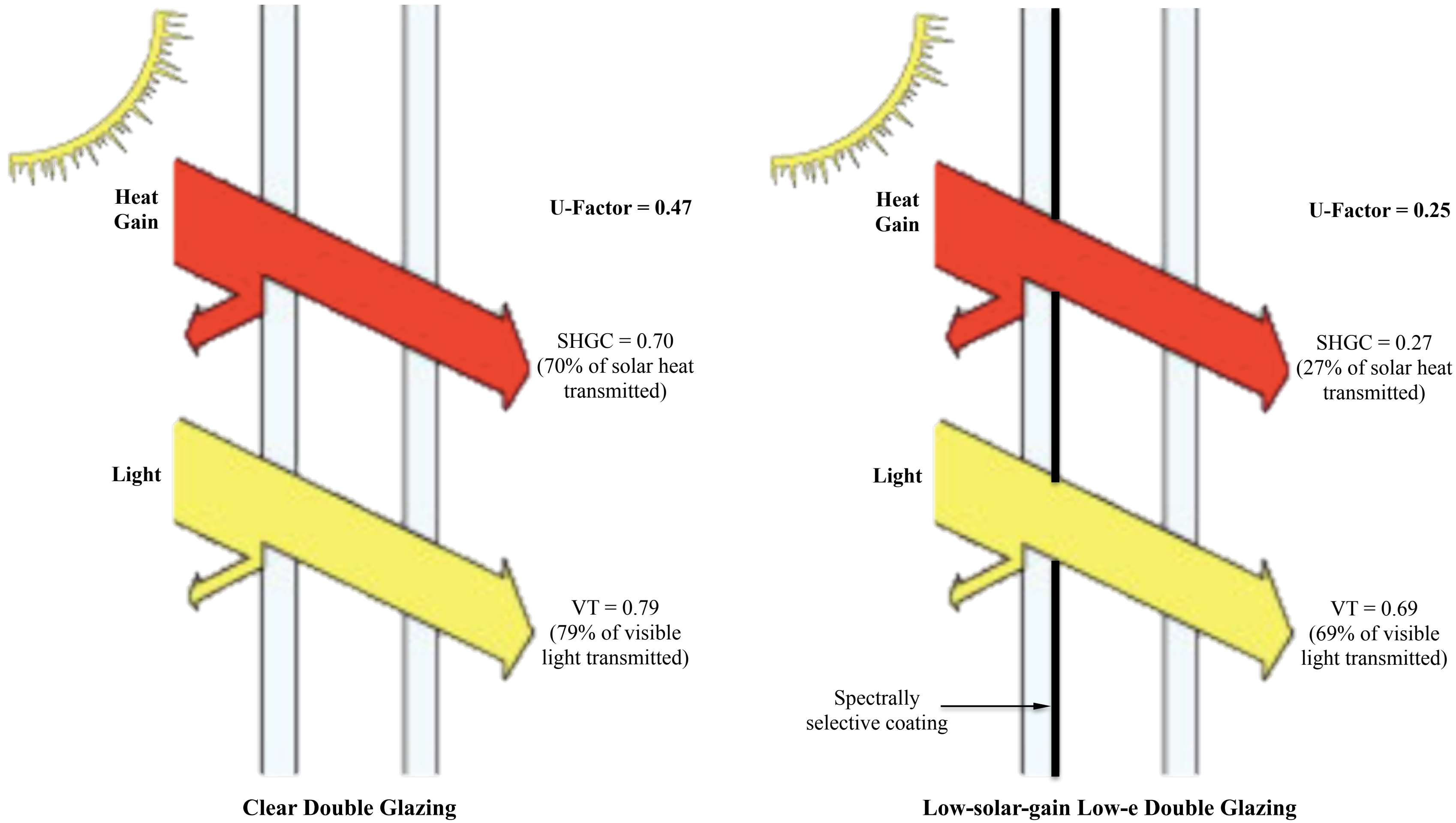

Figure 2.24 Effect of Glazing and Coating on U-Values and SHGC
(Window Technologies, 2014a)

Windows:

Windows are composed of a frame and glass. Frames occupy 10-30% of the window area and that is why its design needs to be taken into consideration. They have U-values four to ten times higher than any other building envelope component making it responsible for most of the heat losses in a building (Basarir, Diri, & Diri, 2012). Having more sustainable windows will require three things:

1. Choosing the most suitable frame material – they are either: aluminum, wood or vinyl. Aluminum is the least recommended due to its high heat transfer coefficient, wood is the preferred type due to its high insulation characteristics and vinyl is rarely used (Basarir, Diri, & Diri, 2012).
2. Using Energy Efficient Glass – this is achieved by:
    - Coating with a low-emittance (low-e) material – a transparent coating that helps to reflect heat back to the building and prevents heat transfer from a warm place (inside a building) to cooler places (outside of a building), therefore reducing heat loss through windows and consequently the need for heating. In addition, the coating allows for free solar energy to enter a building and thus heating it passively (Glass for Europe, 2012). Figure 2.25 shows double and triple glazing windows with one and two low-e coatings respectively.

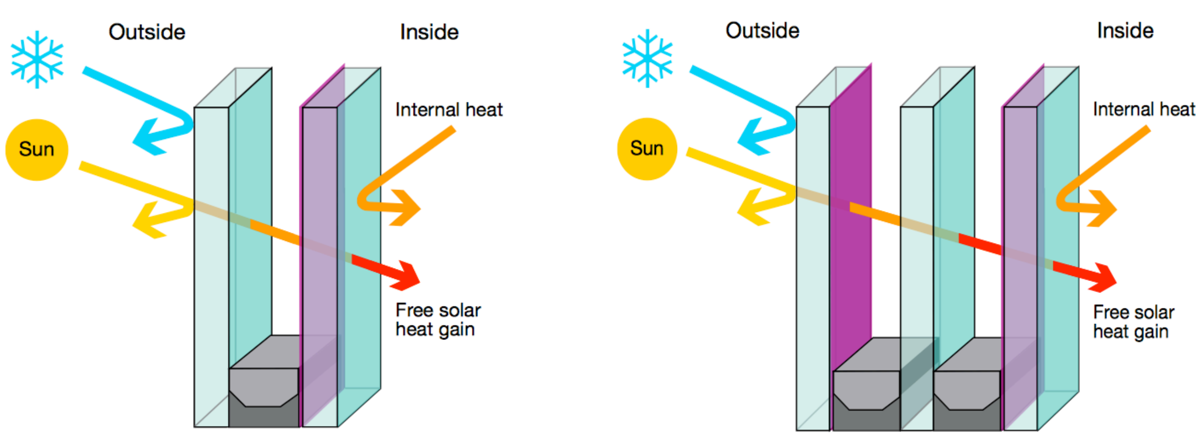

Figure 2.25 Low-e Coating in Double & Triple Glazed Windows
(Glass for Europe, 2009)

- Coating with reflective material or using coloured glass – only used for commercial buildings (Glass for Europe, 2012).
- Having a Solar Control Glass – it is a high performance coated product that reflects a large amount of the sun's heat while allowing daylight into a building. This allows for a bright and cool indoor space and thus reducing the need for cooling (Glass for Europe, 2012). Figure 2.26 illustrates a solar control glass.
- Glazing – all glazing types can have glass insulation and low-e coatings. The gasses used for insulation are argon or krypton (Basarir, Diri, & Diri, 2012). Glazing types are: (i) single-glazed, which are the least efficient, (ii) double-glazing, they are very efficient and their insulation with argon or krypton gas can increase the window's performance by 11% or 22% respectively, or (iii) triple-glazed, which are the most efficient types, but are the most expensive (Basarir, Diri, & Diri, 2012). Figure 2.27 illustrates the benefits of glazing.

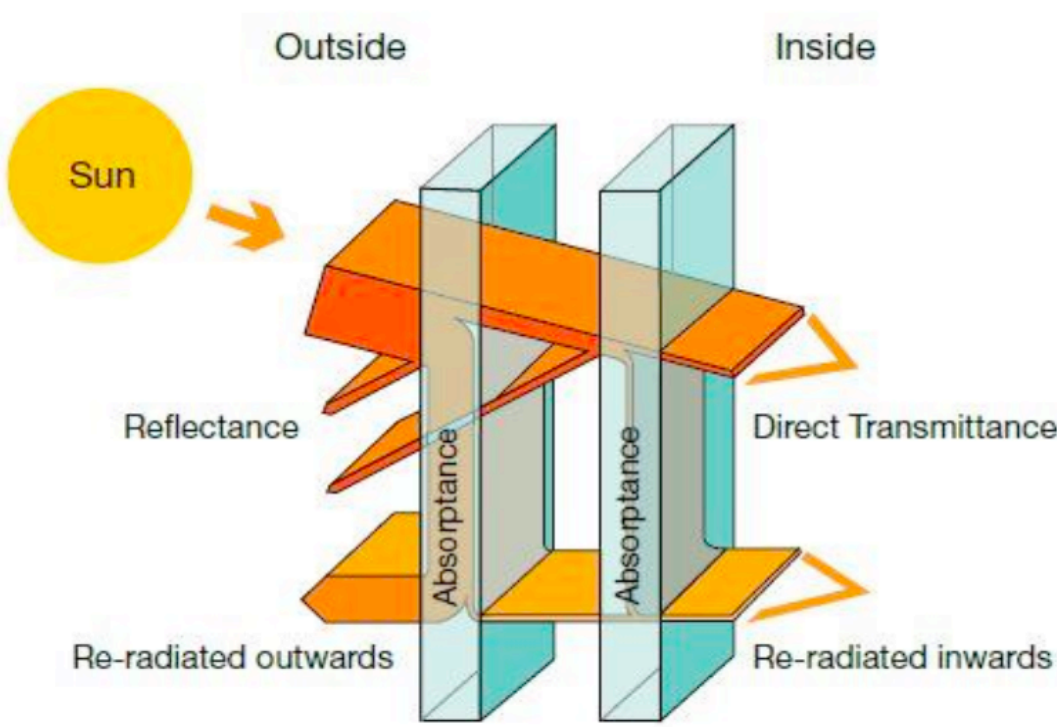

Figure 2.26 Solar Control Glass (Glass for Europe, 2012)

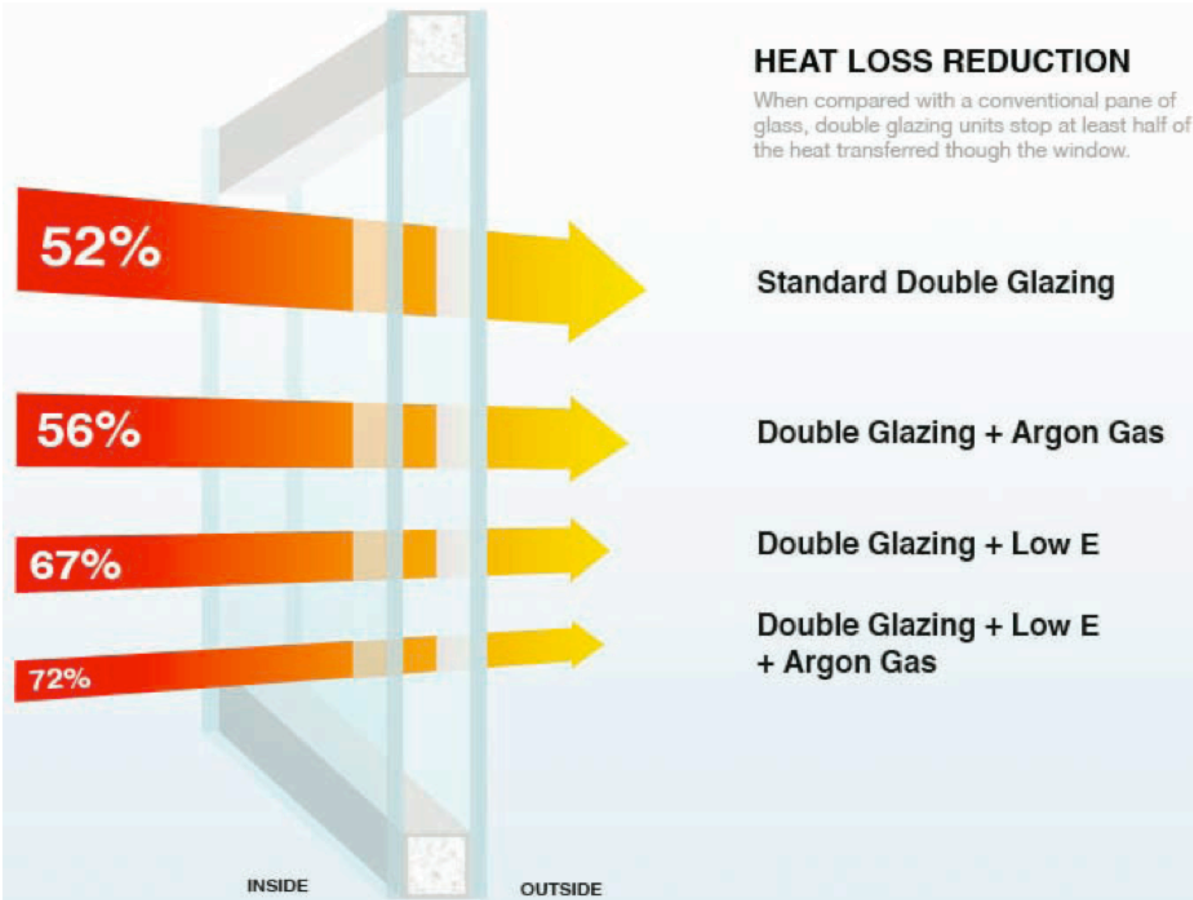

Figure 2.27 Benefits of Glazing (Rehau, 2011)

3. Enabling Natural Lighting as much as possible – this will maximize the benefits of sunlight by reducing heating and lighting needs (IEA, 2013). This can be achieved by maximizing the amount of daylight from the north and south facades of a building and minimizing its exposure from the east and west facades. However, shading devices are needed to reduce the glare or any heat gains or losses (Ander, Daylighting, 2014). The savings from reduced electrical lighting can directly reduce the building's cooling demand by 10-20% (Ander, Daylighting, 2014). Figure 2.28 shows the effect of daylight on electrical lighting (U.S Department of Energy, 2013). The taller a window is the more the daylight penetration will be (depth of daylight = 2.5 times the distance between the top of the window and the sill) (Ander, Daylighting, 2014).

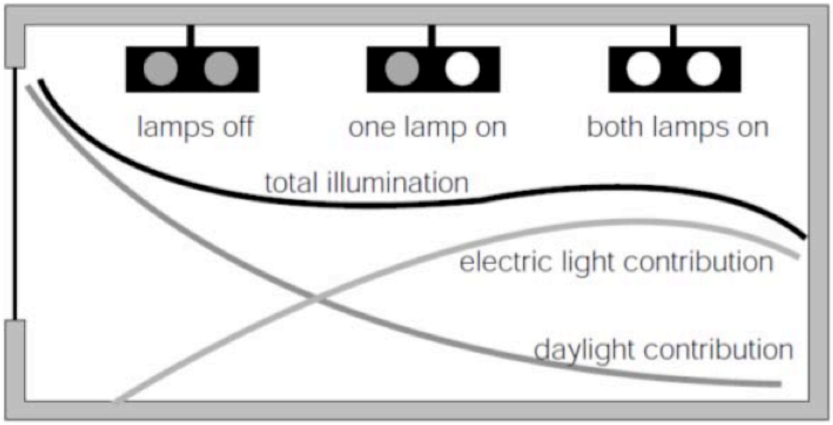

Figure 2.28 The Effect of Natural Lighting on Electrical Lighting
(U.S Department of Energy, 2013)

All windows should be properly sized, located and glazed to balance the flows of heat and natural lighting (IEA, 2013). Having sufficient amount of glass surface area in a household is important yet deceiving at the same time, because having a lot of glass can cause overheating in summer and unnecessary heat loss in winter. Figure 2.29 shows an energy efficient window.

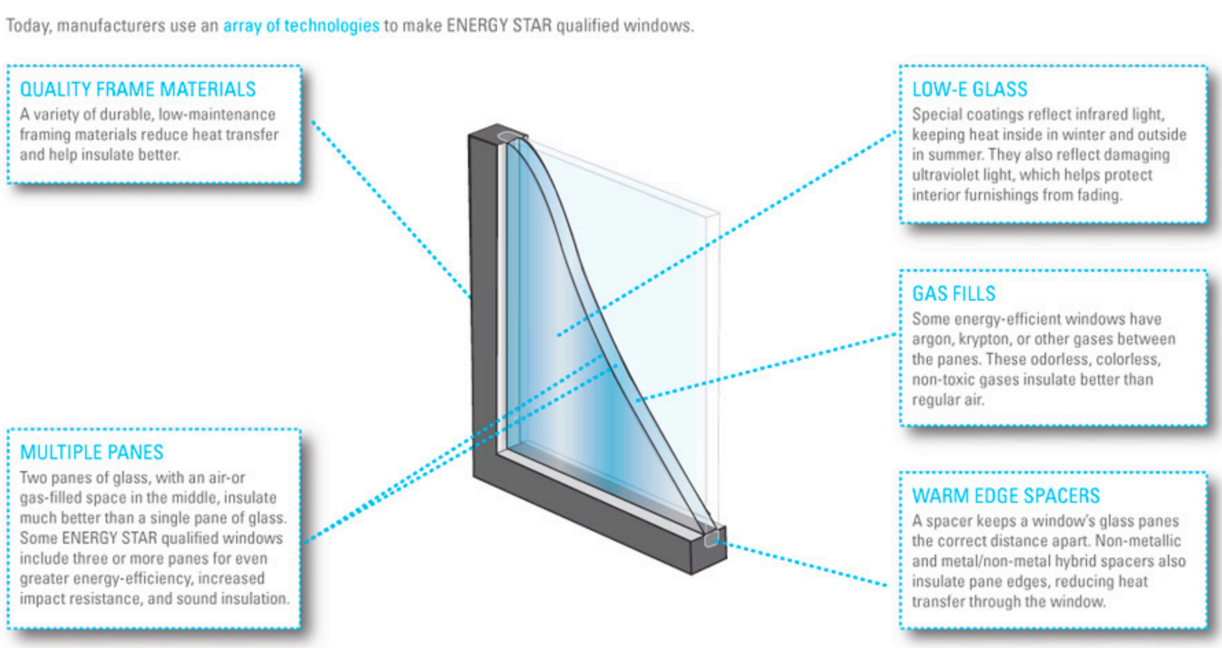

Figure 2.29 Energy Efficient Window (Energy Star, n.d.e)

Doors

Most doors do not have any glass, however even with doors with a lot of glass they will still have a lower glass-to-frame ratio making them better insulators than windows. An energy efficient door should have the following characteristics: (a) air tight seal, (b) energy efficient core material, and (c) double or triple glass panes (if glass is available) (Energy Star, n.d.e) (as shown in Figure 2.30).

The accepted Energy Star rating of an energy efficient residential door is shown Figure 2.31. Doors are recognized as being either opaque or lite, where opaque doors are unglazed. Lite doors are either glazed by a maximum of 30% (≤ ½-lite) or more (> ½-lite) (Energy Star, 2009).

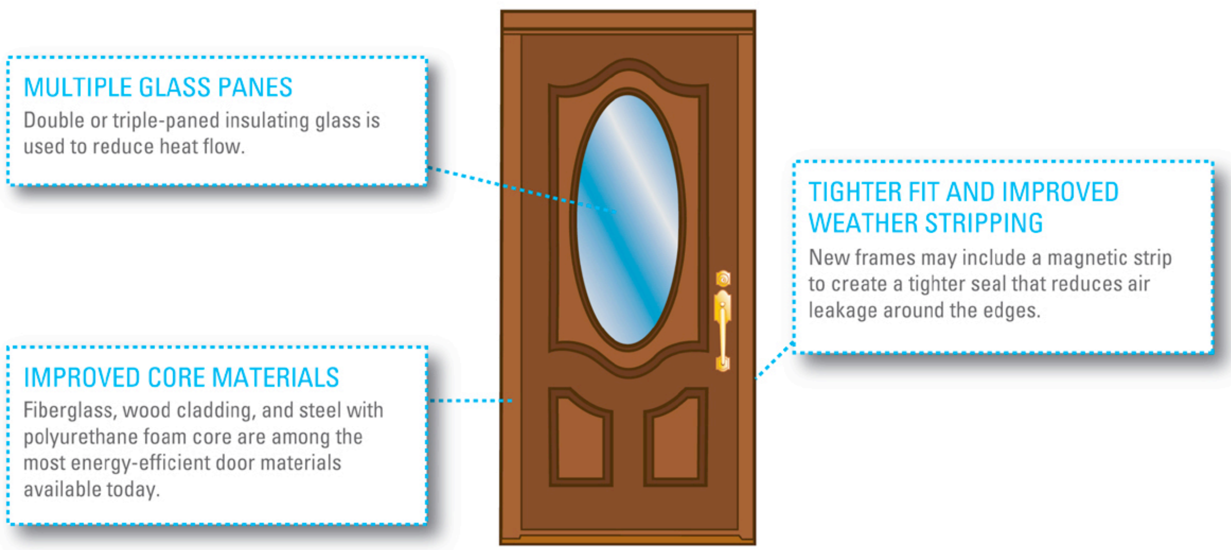

Figure 2.30 Energy Efficient Door (Energy Star, n.d.e)

Having energy efficient doors will also have its benefits, however they are not the major sources of energy loss in Egyptian housings since the majority of all housing doors are fully made of wood making them the least contributors of heat loss or gain.

Glazing Level	U-Factor[1]	SHGC[2]
Opaque	≤ 0.21	No Rating
≤ ½-Lite	≤ 0.27	≤ 0.30
> ½-Lite	≤ 0.32	≤ 0.30

Figure 2.31 Energy Star Rating for Residential Doors
(Energy Star, n.d.e)

2.3.2.3.4 Walls

Walls are the mostly exposed elements of a building envelope. Making them sustainable can be done in four ways:

1. Insulation – glass wool, mineral wool, EPS (extruded polystyrene), XPS and polyurethane. They are either internally or externally installed, however external insulation is preferred to avoid condensation problems in the inner surface of the wall (as a result of high temperatures) (Basarir, Diri, & Diri, 2012).
2. Shading Elements – this can reduce heat gain and thus reducing the annual cooling loads by 5% (Anilkumar, 2013). Moreover, it is essential for the visual comfort of the building occupants (Basarir, Diri, & Diri, 2012).
   - Exterior Shading: either attached to the building skin or an extension of the skin itself. They are the most effective shades for blocking solar heat gains. Light coloured shades are used for diffusing daylight transmittance, while dark coloured ones are used to completely reduce light and heat gain. They can either be horizontal forms (as shown in Figure 2.32) for south windows (which should take a shading priority), or vertical forms (as shown in Figure 2.33) for east and west windows (west windows should take priority) (U.S Department of Energy, 2013).

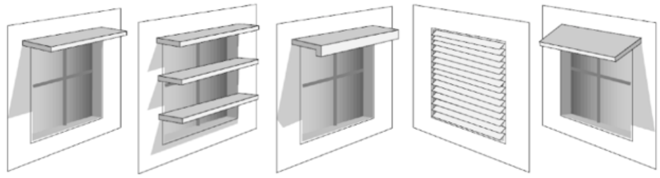

Figure 2.32 Horizontal Wall Shading (U.S Department of Energy, 2013)

Figure 2.33 Vertical Wall Shading (U.S Department of Energy, 2013)

- Interior Shading: like shades, blinds and draperies. However, they do not really control solar gains and are best used for glare control and backup shading (U.S Department of Energy, 2013). Figure 2.34 illustrates interior shading.

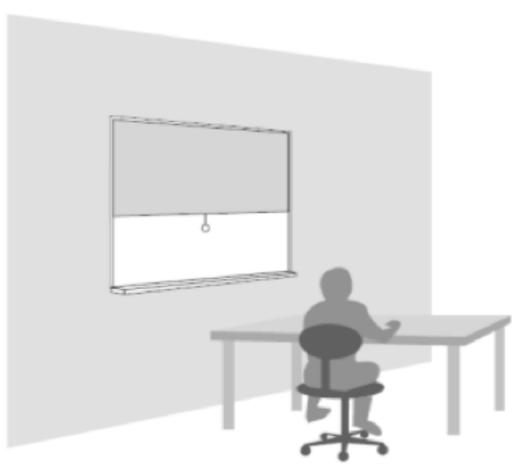

Figure 2.34 Interior Shades (U.S Department of Energy, 2013)

- Window Pane Shading: using exterior shade screens (U.S Department of Energy, 2013). Figure 2.35 illustrates exterior shade screens.

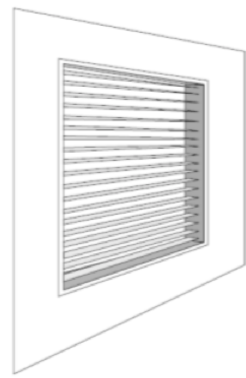

Figure 2.35 Exterior Shade Screens (U.S Department of Energy, 2013)

3. Photovoltaic Panels - adding onto the façade of the building to take advantage of solar energy (IEA, 2013).
4. Reflective Surfaces (IEA, 2013).

Analyzing a building envelope will differ from one place to another because of the global diversity of building materials, climates and economies (developed vs. developing). Figure 2.36 summarizes the differences for each type/geography. Of particular relevance to this study, are the findings on hot climates in the developing world – a category to which Egypt belongs. It has been found that shading, window alterations, and passive design strategies that make use of natural lighting and ventilation, are the three preferred routes to reduce emissions and improve sustainability.

Type of economy	Climate	Technology	
		New construction	Retrofit
		Insulation, air sealing and double-glazed low-e windows for all buildings*	
Developed	Hot climate	• Architectural shading • Very low-SHGC windows (or dynamic shades/windows) • Reflective walls/roofs • Advanced roofs (integrated design/BIPV) • Optimised natural/mechanical ventilation.	• Exterior window shading and dynamic glass/shading • Reflective roofing materials and coatings • Reflective wall coatings • Window film with lower SHGC • New low-SHGC windows.
	Cold climate	• Highly insulated windows • Passive heating gain (architectural feature /dynamic glass/shades) • Passivhaus-equivalent performance based on LCC limitations.	• Highly insulated windows • Low-e storm or interior panels • Insulated shades and other insulating attachments (low-e films) • Exterior insulating wall systems • Interior high-performance insulation.
Developing	Hot climate	• Exterior shading and architectural features • Low-SHGC windows • Reflective roofs and wall coatings • Optimised natural/mechanical ventilation.	• Exterior shading • Reflective coatings (roof and wall) • Low-cost window films • Natural ventilation.
	Cold climate	• Highly insulated windows (possibly double-glazed with low-e storm panel) • Passive heating gain (architectural feature) • Optimised low-cost insulation and air sealing.	• Low-e storm or interior panels • Insulated shades and other insulating attachments (low-e films) • Exterior insulating wall systems • Cavity insulation, lower-cost (e.g. expanded polystyrene) interior insulation.

Notes: BIPV = building-integrated photovoltaic. Passivhaus, an advanced residential building programme that calls for very high levels of building envelope performance, has gained significant momentum in Europe and is active globally (see www.passiv.de/en/index.php).

* The IEA recommends a minimum performance for all new windows globally to meet the performance of double glaze low-e with low-conductive frames and climate-optimised SHGC. Air sealing is needed for any building that will have heating and cooling provided. Insulation is needed for all applications, renovation is more challenging but possible, especially for roofs in all climates.

Figure 2.36 Analyzing Building Modifications (IEA, 2013)

Having a sustainable building envelope will not only reduce the environmental impacts on the building, but the building's impact on the environment as well. However, in addition to having a sustainable envelope, the orientation of a building is also very important in determining the effectiveness of this envelope, because a 30-40% reduction in energy consumption can be achieved if a building is sustainably oriented (EcoWho, 2015).

A sustainable orientation should take advantage of the sun's heat and light without the risk of overheating, therefore knowing the sun's path and prevailing wind direction is necessary because it can help with correctly identifying places of walls, windows, doors or even trees surrounding the building (Anilkumar, 2013). Figure 2.37 shows the sun's path during the summer and winter times.

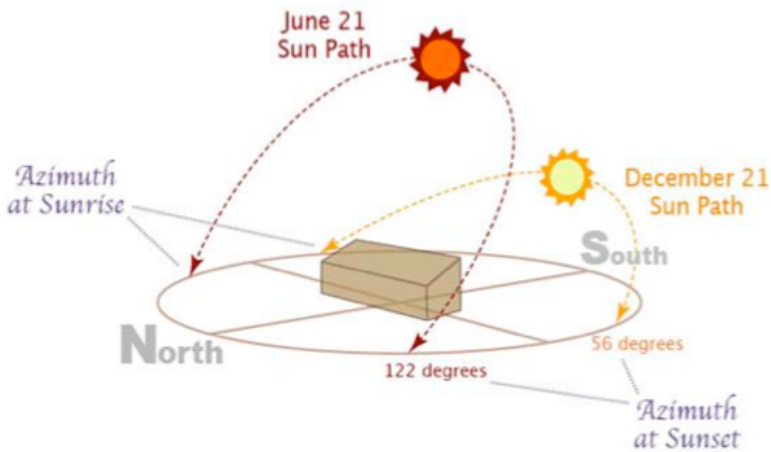

Figure 2.37 Sun's Path (Anilkumar, 2013)

Due to the sun's lower altitude in winter, a building should be oriented in a way that captures its energy in winter and reflects it in summer (EcoWho, 2015). Therefore, having longer walls on the East-West direction is preferable to reduce any heat gains from the walls (Anilkumar, 2013). Figure 2.38 illustrates an ideal building orientation, where most windows are located in the North-South direction with the least heat penetration from the sun (EcoWho, 2015).

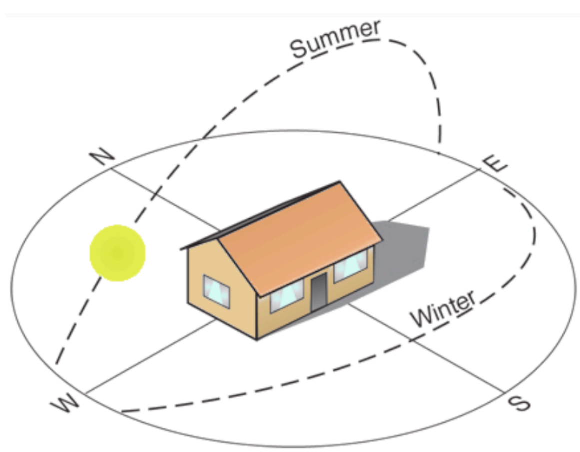

Figure 2.38 Sun's Path with Building Orientation (EcoWho, 2015)

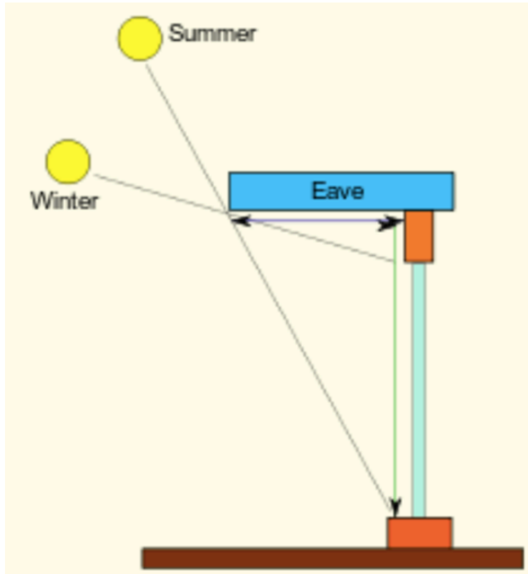

Figure 2.39 Sun's Location and Shading
(EcoWho, 2015)

2.4 Building Sustainability

2.4.1 Evaluation

A number of building codes and sustainable certification systems are now in place around the world in support of sustainable construction of which LEED, BREEAM and Pearl are most commonly known. These continue to evolve and are subject to annual updates and reviews from their issuing bodies and organizations as more research and findings in sustainable construction are made public. Colorado College has used those as the basis for the development of its "Facility Life Cycle Design Guidelines for Sustainability" issued in 2010. The guidelines that are of most relevance to this study can be summarized as follows (Colorado College, 2010):

1. Energy Use
   - Utilize free energy sources such as solar energy, daylight, wind, etc.
   - Select a building envelope, which would allow for the control & utilization of solar heat gain, day-lighting of interior spaces, high performance windows/glazing, energy efficient window coverings, optimized insulation values, reduced air infiltration.
   - Select mechanical systems with: high efficiency equipment, Direct Digital Control System for air conditioning, occupancy sensors/CO_2 monitoring, occupancy sensors,

heat recovery systems, economizer cycle cooling, zoning of air conditioning systems based on building orientations & loads, variable speed drives on motors and fans, low-flow plumbing fixtures, time of day scheduling, individual space controls, etc.

- Select electrical systems featuring: high efficiency lighting fixtures, occupancy sensors, daylight sensors, separate ambient and task lighting, lighting dimmers.
- Implement Energy Metering with sub meters monitoring energy use. Where possible high energy consuming operations within buildings or facilities should be sub-metered locally to identify, monitor, and control energy use.
- CFC/HCFC Reduction: Avoid their use in refrigerants and fire suppression systems.

2. Selection of Building Materials
    - Recycled Content Materials: Use materials with post-consumer or post-industrial recycled content where feasible. Common products with recycled content include structural steel, aluminum windows, gypsum board, acoustical ceiling tiles, rubber floor tiles, carpeting, and toilet partitions.
    - Durable & Flexible Materials: Utilize components and systems, which are durable and easy to maintain. Where feasible, use materials, which provide flexibility for future changes and modifications to occur.
    - Renewable Materials: Consider use of products that are comprised of raw materials that are in abundant supply or come from renewable sources. When feasible, obtain wood products from suppliers certified as utilizing sustainable harvesting methods.
    - Local Materials: Use products produced regionally where possible.

2.4.2 Challenges

Failure to adopt and implement sustainable construction practices on a large-scale to date is evident around the world, and particularly so in developing countries. This can be attributed to a number of barriers (UNEP, 2009):

- Extreme fragmentation as the carbon reduction potential of any single development is negligible and reductions can only be felt on an aggregate level.
- Lack of ownership with decision-making lying with different stakeholders at different phases of a project's lifecycle including developers, contractors, etc.
- High cost of implementing sustainable construction practices with the economic incentives too weak to induce owners and or tenants towards energy savings.

- Lack of awareness about the importance and potential impact of sustainability in construction.
- Lack of indicators to measure energy savings in buildings making it very difficult for stakeholders to actively engage in the process.

2.5 GaBi Software

A useful software program developed in Germany and known as GaBi has been garnering attention by practitioners in the field for its assessment of product life-cycle emissions. The processes supported by GaBi software conform to the SETAC Global Guidance Principles for Life Cycle Assessment Databases (UNEP, 2011). GaBi models every element of a product's manufacturing from a life cycle perspective, empowering businesses to make informed decisions relating to the sustainability of their product design and manufacturing. The software is a powerful and flexible platform, which can be used to analyze the emissions associated with the manufacturing of any product ranging from a matchstick to an airport. It also provides an easily accessible content database detailing the energy and environmental impact of sourcing and refining every raw or processed element of a manufactured item. In addition, it looks at the impact on the environment and presents alternative options for manufacturing, distribution, recyclability, pollution and sustainability (GaBi, 2011).

2.6 Hypotheses

The literature review conducted in this study has suggested a number of hypotheses all of which have served as the basis for the development of our new model:

- A number of megatrends are slowly and irrevocably changing the world
- Increasing urbanization will lead to more pronounced environmental stress
- Combating global warming should be a top priority to avert potential disaster
- Altering building systems has the potential to substantially limit global warming
- Building systems have a much larger environmental impact during the use phase
- Numerous obstacles challenge the uptake of sustainable construction practices
- There are many possibilities for reducing the carbon lifecycle footprint of buildings
- Building sustainability is the key driver for reducing Egypt's GHGs
- The production process for cement is the main driver of carbon dioxide emissions related to building materials.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This study adopts a top-down approach for the development of a model for the assessment and analysis of the carbon footprint of new residential buildings in Egypt. The model is driven by the findings derived in Section 2.6. The model is further supplemented by a number of editable quantitative inputs - highlighted in detail in Section 3.4 – to incorporate and account for recent trends in the construction of middle-income residential buildings in the country.

The model analyzes carbon footprint during both the construction phase and the use-phase of a building. However, substantial attention has been given to the latter given its drastically larger contribution to emissions.

The model's methodology has primarily focused on middle-income housing units in Egypt but can be extended to other construction segments in other geographical context. Such a replication would require adjustments to the quantitative assumptions relevant to the sector and geography being analyzed.

3.2 Model Design

The model's design was crafted around the findings of the literature reviewed in Chapter 2 of this work – following a top-down approach. It is divided into two main parts: (i) construction emission savings, and (ii) use-phase emissions savings. Figure 3.1 illustrates the design of the model, which is explained in more detail in the following sub-sections below (3.2.1 and 3.2.2).

Once the framework for the model had been conceptualized, its further development necessitated the quantification and refinement of the numerical factors assigned to each category of emissions. Needless to say, such an exercise is inherently difficult due to the scarcity and unavailability of construction research data in Egypt. A work-around that proved to be invaluable was to rely instead on data from the United States – which is fortunately abundant on the Internet – limited only to southern states whose climates are relatively similar to Egypt's.

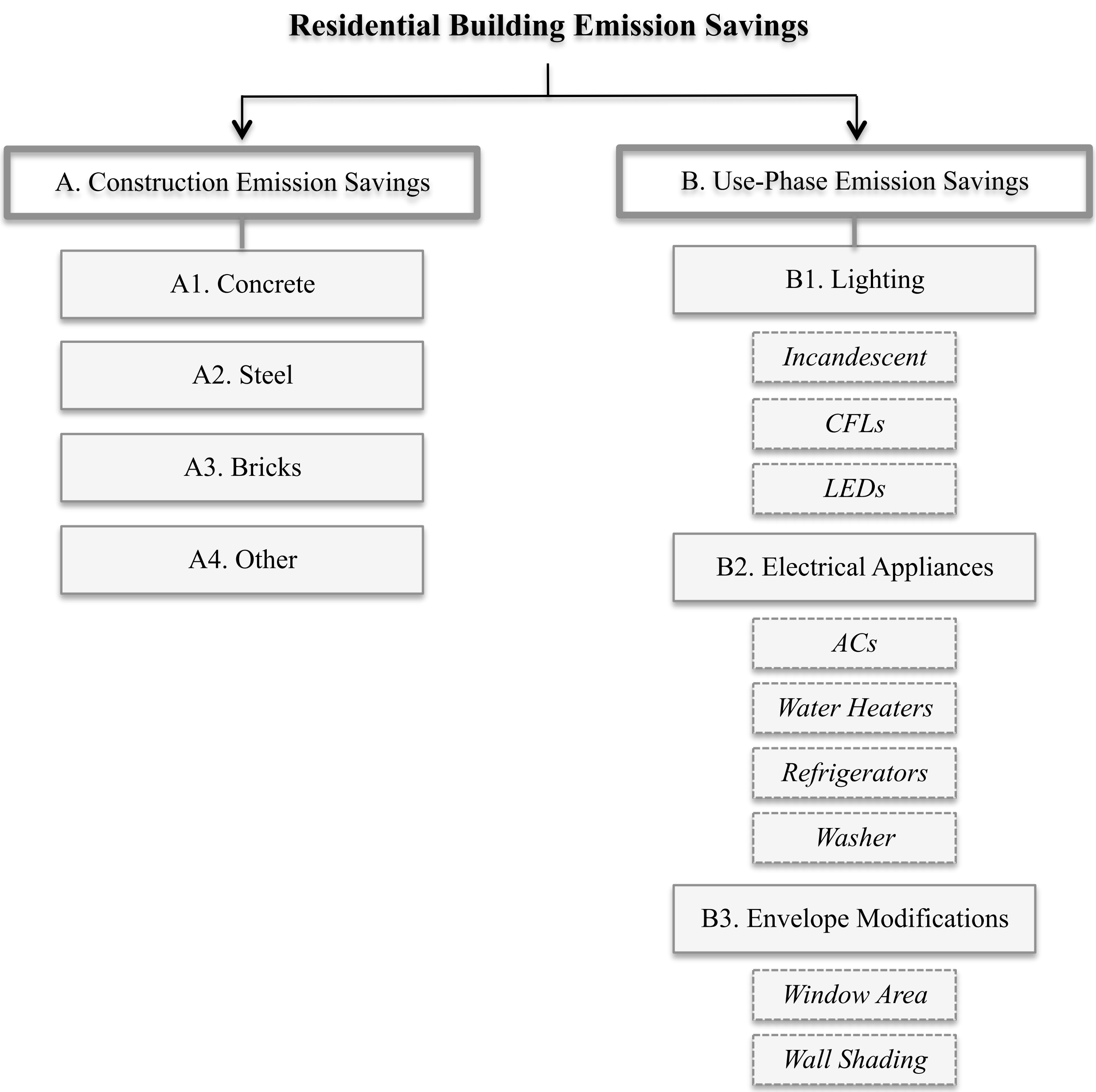

Figure 3.1 Model Design

3.2.1 Construction Phase Design

In relation to the construction phase of the model, the sourcing, selection and management of building materials served as the primary sources of carbon emissions being measured and analyzed – comparing conventional and sustainable practices. The materials considered for detailed calculations were concrete, steel and bricks given their prevalence in Egyptian construction. However, the emissions from other construction materials were also considered in their entirety as a ratio to the emissions from concrete, steel and bricks. For each material its production and transportation emissions were calculated, which served as the total amount of emissions they contribute in construction, and the emissions saved were computed as the difference between sustainable and conventional emissions.

The methodology for calculating each material's emissions and carbon savings depended on current construction practices in Egypt and ways to make those practices more sustainable. The sustainable practices proposed differed from one material to the other and is anticipated for potential energy and emissions savings.

In concrete calculations, the concrete strength used for this model was 25 MPa since it is a typical strength commonly used for middle-income housings in Egypt (The Egyptian Ministry of Housing, 2014), and therefore the sustainable practices considered for this concrete strength were the addition of two different types of chemical admixtures: (i) plasticizer (type A), and (ii) super-plasticizer (type F). Their additions would ultimately reduce the amount of cement in a concrete mix – which is the largest driver of emissions. However, mineral admixtures such as silica fume, fly ash and slag could have also lowered the cement content in a concrete mix, but these were not considered due to their limited use in higher strength concrete. In addition to potential savings from admixtures, the type of concrete used was also observed and therefore the transportation emissions coming from concrete mixed on-site and ready-mixed were calculated.

As for steel calculations, the blast furnace-basic oxygen furnace and the electric arc furnace routes were examined in terms of their energy use in producing a ton of steel. The amount of energy used was converted to carbon emissions revealing the most energy efficient process. In addition to that, the transportation emissions of all the rebars needed for construction was calculated for a typical middle-income housing in Egypt.

As for brick calculations, three types of bricks were considered: (i) clay, (ii) concrete, and (iii) fly ash. Clay bricks are the most commonly used in Egypt, and therefore used as the conventional type in the model. Concrete and fly ash bricks were considered its substitutes and thus the emissions of each were calculated and the one with the least emissions is identified as the most sustainable. In addition to that, the transportation of all bricks needed for construction was calculated for a typical middle-income housing in Egypt.

In summary, the sum of all carbon savings from all materials were added to come up with the total amount of savings from all construction materials in the construction phase of a middle-income residential building in Egypt. These savings were also monetized to arrive at a financial value that can be more easily grasped and interpreted in layman's term.

3.2.2 Use-Phase Design

In relation to the use-phase of the model, three major housing elements were considered: (i) lighting, (ii) main electrical appliances, and (iii) envelope modifications. All are widely regarded as the primary sources of use-phase energy consumption, and hence indirect carbon emissions. For all lighting and electrical appliances the amount of emissions were calculated for all conventional products and their equivalent sustainable ones, and the savings were the difference of both emissions. However, any additional savings to a residential building were calculated from any envelope modifications that can be applied.

The methodology for calculating the amount emissions and carbon savings depended on comparing conventional products with more energy efficient ones to see the effect if more sustainable products are used. The additional energy savings from envelope modifications will depend on whether the house owner would want to apply them.

In the lighting calculations, three types of bulbs were assessed; (i) incandescent, (ii) compact fluorescent (CFL), and (iii) light-emitting diodes (LEDs). Incandescent bulbs are the most commonly used type in all middle-income residential buildings in Egypt and are considered the conventional type. CFLs and LEDs are the proposed substitutes and their emissions were calculated and compared to incandescent ones to come up with an alternative with the least emissions (most carbon savings).

In the electrical appliance calculations, four major residential appliances were assessed; (i) air conditioners (AC), (ii) water heaters (gas and electric), (iii) refrigerators, and (iv) washers. In each of those appliances a conventional type was compared to a more energy efficient one to find out the potential carbon savings they can acquire.

In the envelope modification calculations, two major changes were considered; (i) window glazing, and (ii) exterior wall shadings. The amount of carbon savings from converting a single-glazed window to a low-emittance double-glazed one and applying exterior shades were calculated.

To summarize all calculations, the carbon savings from each housing element were added to come up with the total amount of savings from all housing products in the use-phase of a middle-income residential building in Egypt. These savings were also monetized to arrive at a financial value that can be more easily grasped and interpreted in layman's term.

3.2.3 Comparison against GaBi Software

The model proposed in this work provides different functionality than what is featured and provided for by the GaBi software platform. GaBi allows for the computation and calculation of emissions for any manufactured product on a life-cycle basis. It is very detailed and customizable allowing product designers and manufacturers to evaluate the sustainability of their products and associated manufacturing processes. Unfortunately this flexibility comes at the expense of user-friendliness. Meaningful use of the platform requires substantial training. Only qualified professionals are sufficiently empowered to use and benefit from the software. Further, the program only evaluates sustainability as it relates to the inputs of a manufactured product. Use-phase implications are not considered. For example, GaBi makes it possible to assess the sustainability of producing a light bulb, but will not be able to assess the impact of using this light bulb and of the associated consumption of energy.

This work has attempted to avoid those specific shortcomings of GaBi. The model as proposed requires little training and has been designed and formatted to allow users from various backgrounds to use it. More importantly, the model permits for a detailed assessment of use-phase sustainability specifically as it relates to residential buildings. This feature – as evidenced by the literature reviewed under Chapter 2 – is critical and accounts for a majority of emissions yet it is noticeably absent from GaBi.

3.3 Data Collection

The data acquired for this work was acquired from various sources. This was further supplemented by proprietary data from leading industry participants. Additionally, data was also gathered from public resources made available by industry associations and interest groups. Data concerning the number of housing units in Egypt was obtained from the Ministry of Housing and is summarized in Table 3.1.

Table 3.1 Number of Housing Units in Egypt in the Past 12 Years
(Ministry of Housing, 2014)

New Residential Buildings in the past 12 years in Egypt					
Year	**Low**	**Low/ Medium**	**Medium**	**Medium/ High**	**High**
2003/2004	11,343	985	1,372	1,245	0
2004/2005	11,289	4,473	590	1,088	0
2005/2006	8,901	3,869	589	753	24
2006/2007	11,357	2,820	1,624	742	24
2007/2008	7,563	15,040	2,330	664	177
2008/2009	3,383	29,222	1,299	0	0
2009/2010	1,358	50,264	1,939	0	0
2010/2011	2,602	67,008	683	0	0
2011/2012	1,254	71,696	5,579	0	0
2012/2013	466	28,688	1,321	0	98
*2013/2014	5,952	27,407	1,733	449	32
Total	**65,468**	**301,472**	**19,059**	**4,941**	**355**

* Number of housing units assumed as an average of previous years

3.3.1 Construction Phase Data

With regards to the construction phase, an abundance of data was found on the emissions of concrete, steel and bricks. The production processes of those three core-building materials are to a large extent identical regardless of geography or end-purpose. This made it possible to rely upon data from authors from around the world. Calculating their amounts in a typical middle-income housing was estimated based on several assumptions and data collected from the

Ministry of Housing, which will be identified in the following section (Methodological Assumptions). Data on savings were obtained as follows:

1. Concrete: a previous study in 2014 done by a group of students at the American University in Cairo on green concrete. Several tests were performed on different concrete mix designs showing the effect of chemical admixtures on the amount of cement used.
2. Steel: a study commissioned by Industrial Efficiency Technology Database, which is established and managed by the Institute of Industrial Productivity based in Washington DC. It showed different production routes of steel and how each are different in the amount of energy they use.
3. Bricks: a study published by Chusid Associates, a consulting firm specializing in technical and marketing services for advanced construction products and materials. It introduced more sustainable bricks to be used in construction.

3.3.2 Use-Phase Data

With regards to the use-phase, this report has relied extensively on the Energy Star publications issued by the American Environmental Protection Industry and the Department of Energy. Many previous researches were available on lighting and electrical appliances across all fifty United States. This work focused on those southern states whose average temperatures are most similar to Egypt's (i.e. Florida and Southern California). On envelope modifications – limited to windows and wall shading in this work – data was collected from Glass for Europe, a trade association for Europe's manufacturers of building, automotive and transport glass, and from an ISO certified International Journal of Emerging Technology and Advanced Engineering respectively.

3.4 Methodological Assumptions

A number of assumptions were made for the creation of this model. The assumptions are intended to allow for a realistic calculation of outputs, yet readers of this model are encouraged to further explore how those assumptions can be challenged, refined and/or validated, particularly when prevailing conditions are different from those associated with this work.

3.4.1 Construction Phase Assumptions

A number of assumptions were made in relation to the configuration of a typical middle-income housing unit. The purpose of these assumptions was to allow for the quantification of the amount of materials used – specifically concrete, steel and bricks, and their transportation to a construction site.

A typical middle-income residential building is composed of:

- Four stories
- Two apartments per floor, each apartment is sixty-four square meters.
- Staircase surface area is ten square meters
- Floor surface area is $138m^2$ (sum of two apartments and the staircase)
- Columns are every three meters (dimensions: 0.25 X 0.5m) - total of sixteen columns
- Square footings (P.C and R.C) – total of sixteen footings
- Slab thickness is twelve centimeters
- Exterior wall height is 2.5 meters
- Concrete strength 25MPa
- Aggregate's density is 1750 kilograms per cubic meter
- A brick is 25 x 12 x 6 centimeters in size, with a weight of 2.5 kilograms.
- Truck loads for carrying: (i) aggregates is ten cubic meters, (ii) ready mix concrete is nine cubic meters, (iii) steel is twenty tons, (iv) bricks is ten cubic meters, and (v) cement is fifty tons.

The above assumptions were all assumed according to typical design dimensions of a middle-income residential building in Egypt (The Egyptian Ministry of Housing, 2014). By using those assumptions it was estimated that in a residential building there are: (i) 185 m^3 of concrete (ii) fifteen tons of steel, and (iii) 60,000 bricks.

The multiplier of "other emissions": it was assumed that since the majority of the materials used for construction are concrete, steel and bricks, therefore they would contribute to 75% of the emissions and the remaining 25% would be due to any other emissions; like glass, aluminum, paint, ceramics, marble etc. A schematic of a typical middle-income residential floor plan and side elevation is illustrated in Figure 3.2 and Figure 3.3 respectively.

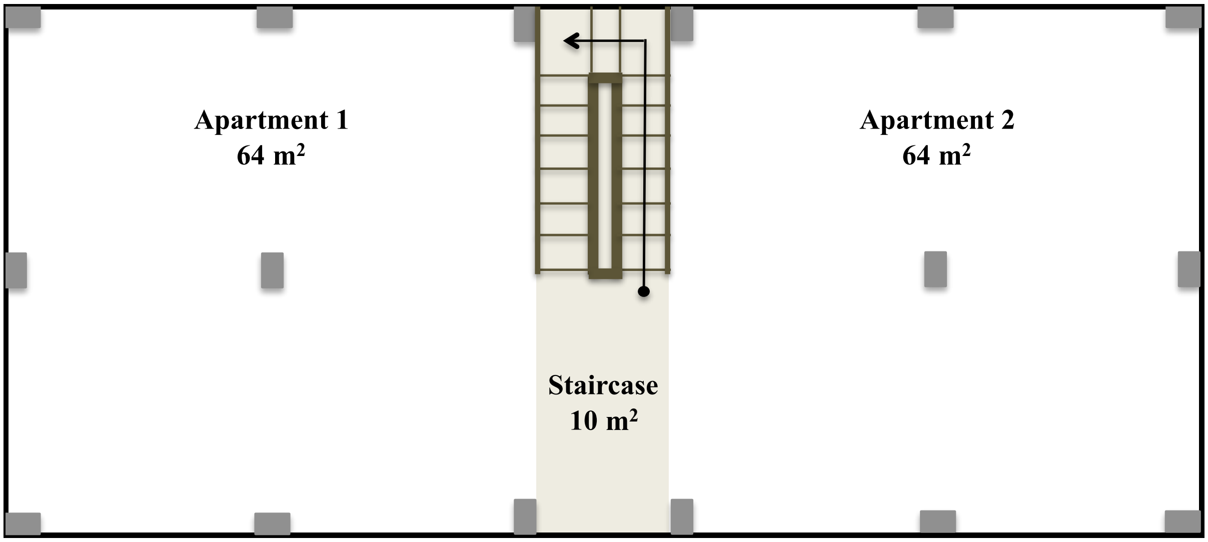

Figure 3.2 A Schematic of a Typical Middle-Income Residential Floor Plan ($138m^2$) in Egypt

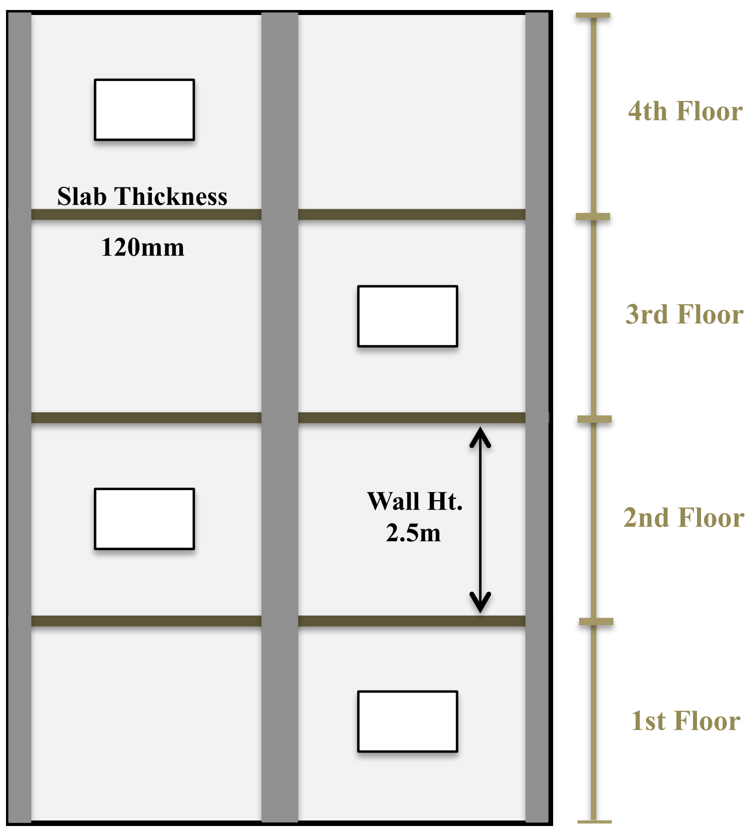

Figure 3.3 A Schematic of a Side Elevation of a Typical Middle-Income Residential Building in Egypt

3.4.2 Use-Phase Assumptions

The assumptions here are for assuming the number of housing elements in a residential building. It was assumed that:

- Window surface are in an apartment is approximately twelve square meters
- The lifetime of a residential building is fifty years.
- Weather Assumptions: in all Energy Star's energy consumptions, it was assumed that all lighting and electrical appliances were used in southern states, like Florida and Southern California.
- Lighting and Electrical Appliances – in one middle-income residential building:
    - Light Bulbs = 20
    - Air Conditioners = 2
    - Water Heaters = 1
    - Refrigerators = 1
    - Washer = 1
- Emissions from water heaters are eliminated in the case of using solar water heaters.

3.4.3 Monetization Assumptions

The purpose of this work has been to quantify the potential for carbon savings in terms of tons of carbon dioxide. This quantification is nevertheless abstract and difficult to comprehend unless a corresponding monetary value can be assigned to it. The concept of "Social Cost of Carbon" or "SCC" can be adopted to address this shortcoming. SCC is defined as the estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year including changes in net agricultural productivity, human health, property damages from increased flood risk, etc. (Department of Energy, 2010). The SCC for carbon is commonly accepted to be thirty-three dollars per ton in 2007 terms, increasing at 2.4% per annum (Department of Energy, 2010). This accounts for a cost of LE 304.4 per ton of CO_2 in current terms in 2015.

3.5 Calculations

The model is constructed to allow the comparison of the carbon footprint of middle-income housing unit assuming two different configurations: conventional and sustainable practices. All calculations were based on the aforementioned assumptions (Methodological Assumptions).

3.5.1 Construction Phase Calculations

With regards to the construction phase, the model calculates emissions for concrete, steel, and bricks as well as emissions from all other materials combined. The calculations for each are arrived at as follows. The calculations for each are arrived at as follows, noting that all are based on the same set of assumptions previously described under Methodological Assumptions.

1. Concrete Emissions:
    a. Input concrete mix design for each of the model's two configurations: (i) conventional, and (ii) sustainable.
    b. Input the total volume of concrete in a residential building. This determines the total amount of each of the concrete's components (cement, water, fine and coarse aggregates).
    c. Input the average round-trip distance travelled by a truck carrying all concrete components to a construction site.
    d. The model subsequently calculates production emissions of both mix design configurations using data from (a) and (b) above. Production emissions are assumed to be driven by cement only because emissions from water, fine and coarse aggregates are negligible. Cement emissions are calculated by multiplying the total quantity of cement required, by the emission factor of cement obtained from literature.
    e. Similarly, the model calculates transportation emissions under both mix design configurations. The first step in calculating transportation emissions is to determine the number of truckloads required to transport the quantities of concrete components identified in (b) above (by dividing the quantity of materials carried by the truck capacity). The second step is to derive the emissions of these truckloads by multiplying the following factors: distance travelled from (c) above, number of

truckloads, diesel consumption per truck load as obtained from literature, and the emission factor of diesel consumption also obtained from literature.

f. Step (e) above is repeated for the sustainable configuration assuming the use of ready mix concrete.

g. Finally the model compares the aforementioned emissions from both configurations to arrive at the potential savings that can be achieved by switching from current conventional practices to more sustainable methods as proposed. The comparison is carried out for a single residential building, and again for the middle-income housing sector as a whole. This is achieved by multiplying the emissions from a single building by the total number of middle-income buildings in Egypt as provided for by the Ministry of Housing.

The process above is illustrated in Figure 3.4.

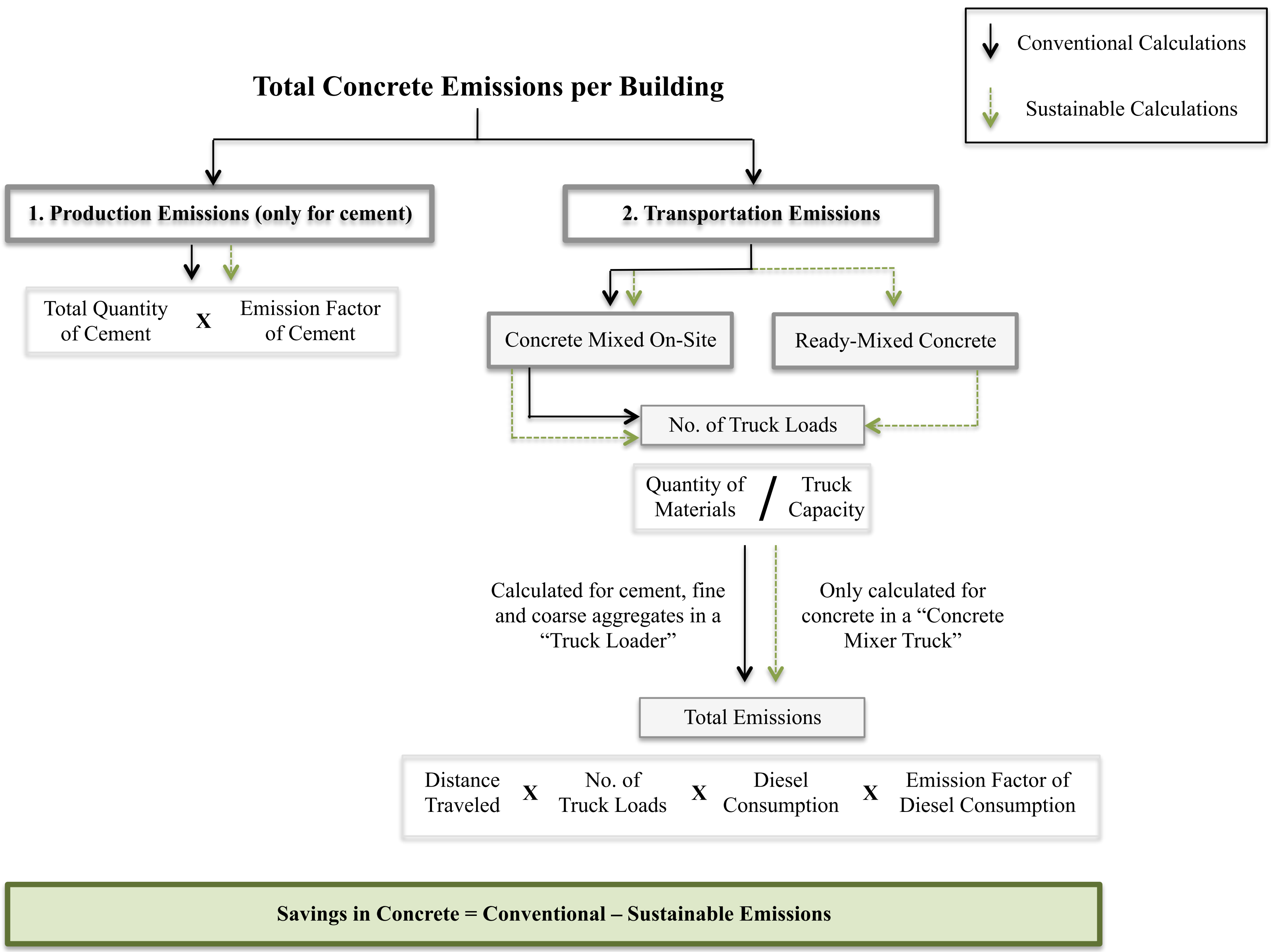

Figure 3.4 Description of Model's Calculations for Concrete Emissions

2. Steel Emissions:
   a. Input weight of steel required for the construction of a single residential building.
   b. Input the average round-trip distance travelled by a truck carrying steel to a construction site.
   c. The model subsequently calculates steel production emissions of both production routes as obtained from literature. These are: (i) Blast Furnace-Basic Oxygen Furnace, and (ii) Electric Arc Furnace. Production emissions are calculated by multiplying the energy consumption of each route by its emission factor and the quantity of steel inputted in (a) above.
   d. Similarly, the model calculates transportation emissions. Unlike concrete, transportation emissions for steel are identical under both model configurations. Sustainability is achieved by changing the production route only and not by modifying transportation volume and/or method. The first step in calculating transportation emissions is to determine the number of truckloads required to transport the quantities of steel required as identified in (a) above (by dividing the quantity of steel carried by the truck capacity). The second step is to derive the emissions of these truckloads by multiplying the following factors: distance travelled from (b) above, number of truckloads, diesel consumption per truck load as obtained from literature, and the emission factor of diesel consumption also obtained from literature.
   e. Finally the model compares the aforementioned emissions from both configurations to arrive at the potential savings that can be achieved by switching from current conventional practices to more sustainable methods as proposed. The comparison is carried out for a single residential building, and again for the middle-income housing sector as a whole. This is achieved by multiplying the emissions from a single building by the total number of middle-income buildings in Egypt as provided for by the Ministry of Housing.

The process above is illustrated in Figure 3.5.

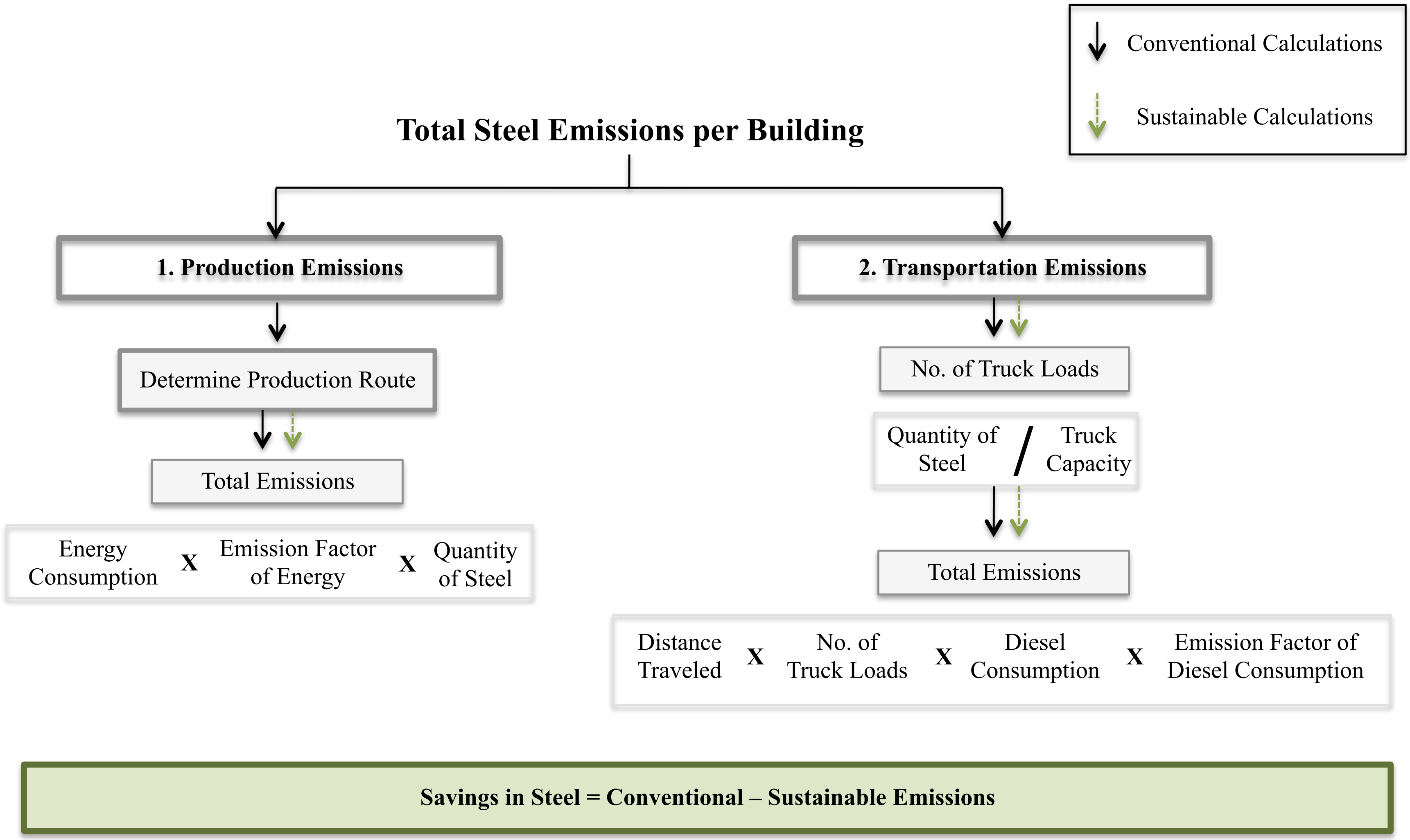

Figure 3.5 Description of Model's Calculations for Steel Emissions

3. Bricks Emissions:
    a. Input number of bricks required for the construction of a single residential building.
    b. Input the average round-trip distance travelled by a truck carrying bricks to a construction site.
    c. Input the brick type used in the sustainable configuration, which is either concrete or fly ash. The conventional configuration assumes the use of clay bricks.
    d. The model subsequently calculates brick production emissions of both configurations. Production emissions are calculated by multiplying the emission factor of each brick type as obtained from literature by the quantity of bricks inputted in (a) above.
    e. Similarly, the model calculates transportation emissions. Unlike concrete, transportation emissions for bricks are identical under both model configurations. Sustainability is achieved by changing the brick type only and not by modifying transportation volume and/or method. The first step in calculating transportation emissions is to determine the number of truckloads required to transport the quantities of bricks required as identified in (a) above (by dividing the quantity of bricks carried by the truck capacity). The second step is to derive the emissions of these truckloads by multiplying the following factors: distance travelled from (b) above, number of truckloads, diesel consumption per truck load as obtained from literature, and the emission factor of diesel consumption also obtained from literature.
    f. Finally the model compares the aforementioned emissions from both configurations to arrive at the potential savings that can be achieved by switching from current conventional practices to more sustainable methods as proposed. The comparison is carried out for a single residential building, and again for the middle-income housing sector as a whole. This is achieved by multiplying the emissions from a single building by the total number of middle-income buildings in Egypt as provided for by the Ministry of Housing.

The process is illustrated in Figure 3.6.

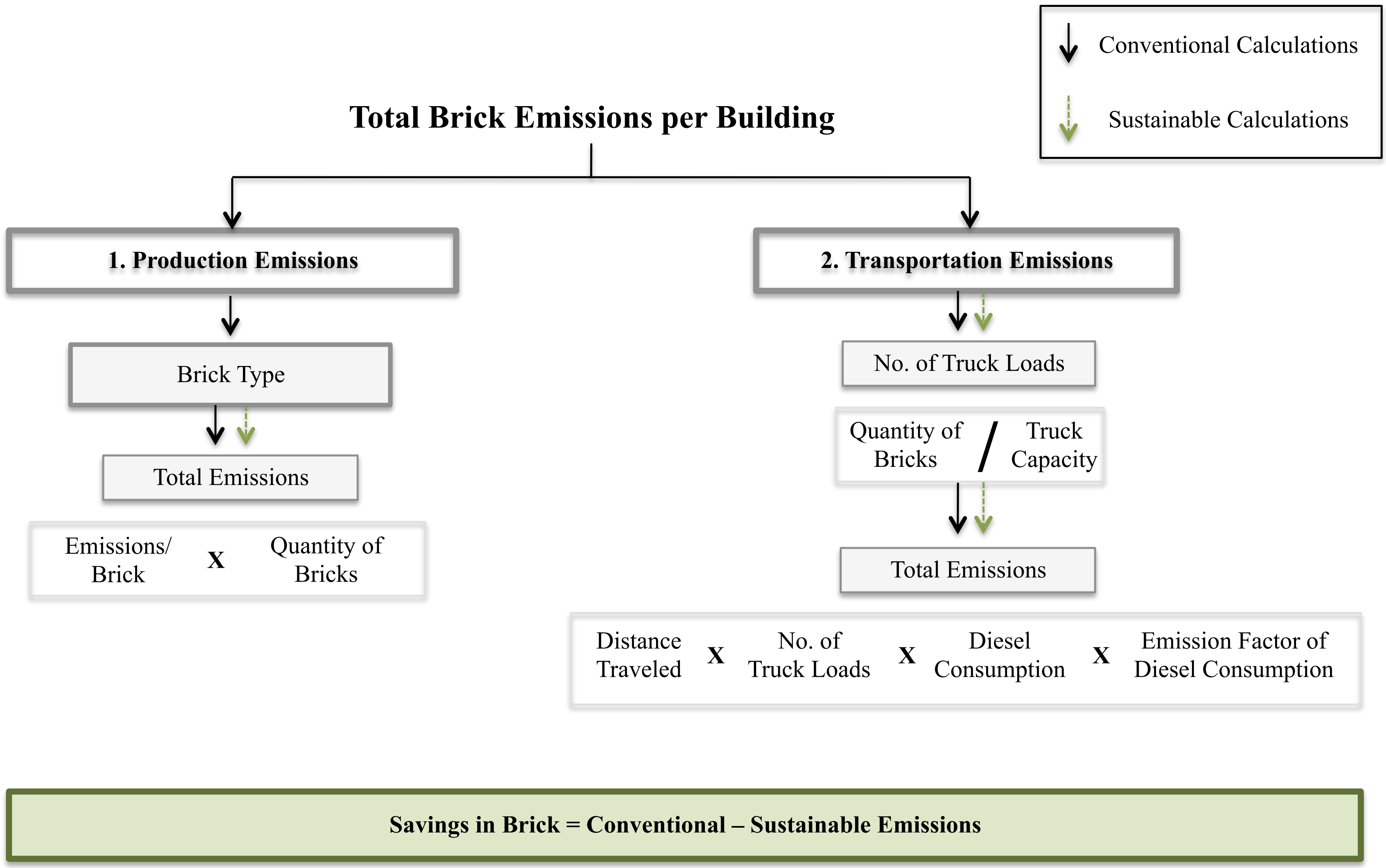

Figure 3.6 Description of Model's Calculations for Brick Emissions

4. Other Emissions: These are assumed to constitute 25% of the total production emissions for a single building. Twenty-five percent is an arbitrary assumption deduced from literature but can be modified by model users. Emissions from other materials are accordingly calculated by multiplying the total emissions from concrete, steel and bricks combined under then conventional configuration, by an appropriate factor. The amount of emissions for other materials under the sustainable configuration is assumed to remain as-is in the absence of any clear justifications or reduction proposals in relation to those other materials.

3.5.2 Use-Phase Calculations

With regards to the use phase, the model calculates emissions driven by lighting, electrical appliances, and envelope modifications (specifically window glazing and window shading). The calculations for each are arrived at as follows, noting that all are based on the same set of assumptions previously described under Methodological Assumptions.

1. Lighting Emissions:
   a. Input the lighting type used in the sustainable configuration, which is either compact fluorescent (CFL) or light-emitting diodes (LEDs). The conventional configuration assumes the use of incandescent bulbs.
   b. Input the number of light bulbs needed in a middle-income residential apartment.
   c. Select the average wattage used per light bulb.
   d. The model subsequently calculates the emissions of both configurations. These emissions are calculated by multiplying the annual energy consumption of each bulb as obtained from literature by the energy emission factor and the number of light bulbs inputted in (b) above.
   e. Finally the model compares the aforementioned emissions from both configurations to arrive at the potential savings that can be achieved by switching from current conventional products to more sustainable ones as proposed. The comparison is carried out for a: (i) single middle-income residential apartment, (ii) a whole building (by multiplying by the total number of apartments in a residential building which are assumed to be eight for the purposes of this model), and (iii) the middle-income housing sector as a whole (by multiplying by the total number of middle-income buildings in Egypt as provided for by the Ministry of Housing). The comparison is

first carried out for a single year of use, and also for the lifetime of a building assumed to be fifty years as previously assumed in under Methodological Assumptions.

The process if illustrated in Figure 3.7.

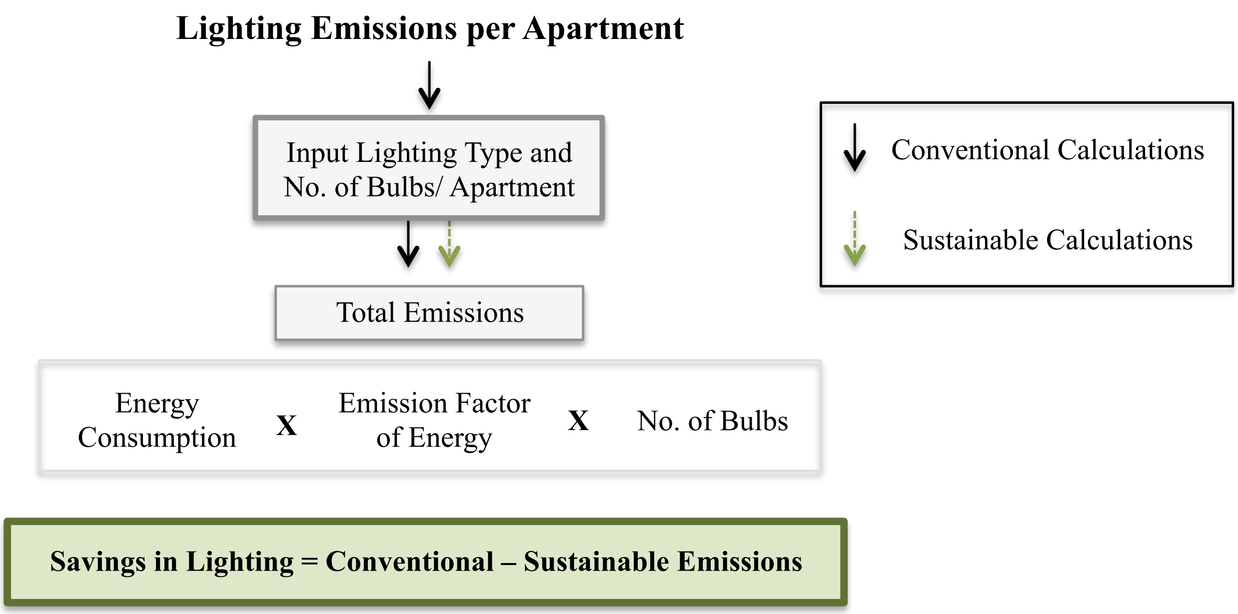

Figure 3.7 Description of Model's Calculations for Lighting Emissions

2. Electrical Appliances:
    a. Input the number of units for each appliance type. The appliances used are: (i) air conditioners, (ii) water heaters (gas and electric), (iii) refrigerators, and (iv) washers. For each appliance, the energy consumption for a conventional and sustainable unit is obtained from literature.
    b. The model subsequently calculates the emissions of both configurations. These emissions are calculated by multiplying the annual energy consumption of each appliance type as obtained from literature by the energy emission factor and the number of units inputted in (a) above.
    c. Finally the model compares the aforementioned emissions from both configurations to arrive at the potential savings that can be achieved by switching from current conventional products to more sustainable ones as proposed. The comparison is

carried out for a: (i) single middle-income residential apartment, (ii) a whole building (by multiplying by the total number of apartments in a residential building which are assumed to be eight for the purposes of this model), and (iii) the middle-income housing sector as a whole (by multiplying by the total number of middle-income buildings in Egypt as provided for by the Ministry of Housing). The comparison is first carried out for a single year of use, and also for the lifetime of a building assumed to be fifty years as previously assumed under Methodological Assumptions.

The process is illustrated in Figure 3.8.

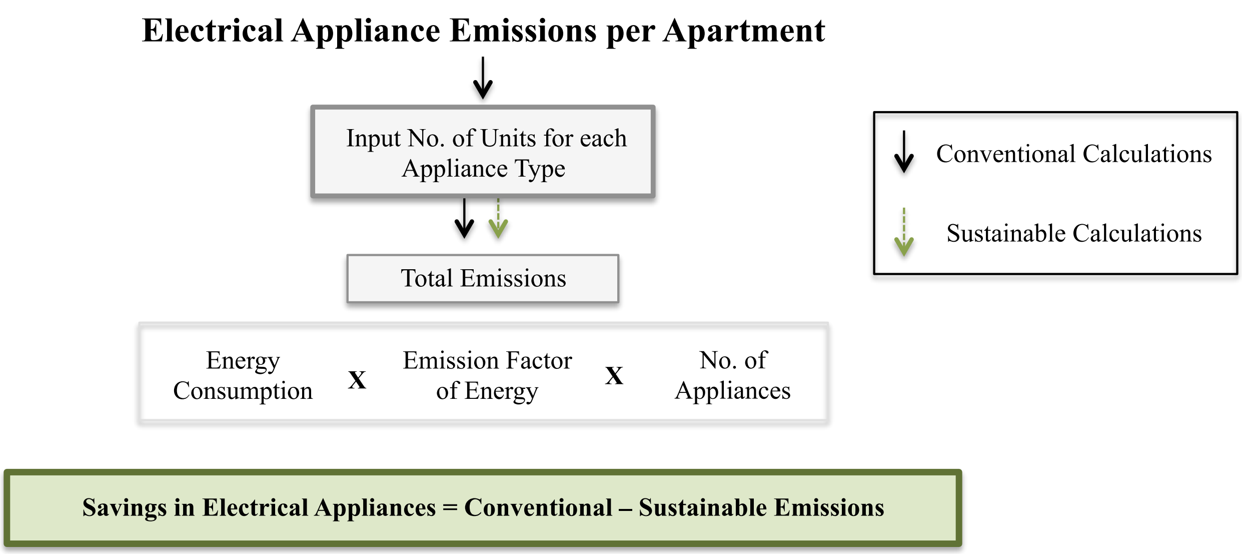

Figure 3.8 Description of Model's Calculations for Electrical Appliance Emissions

3. Envelope Modifications:
   a. For Window Glazing: replacing single-glazed windows with low-e double-glazed.
      i. Input an assumed window area in an apartment.
      ii. Input percentage of windows to be replaced with low-e double-glazed.
      iii. In the conventional configuration, all windows are assumed to be single-glazed and therefore no further reductions are realized. In the sustainable configuration, savings are calculated as outlined in (iv) and (v) below.
      iv. The model subsequently calculates the carbon savings by multiplying the window replacement area by the savings factor of glazing per apartment.

v. The savings calculations are carried out for a: (i) single middle-income residential apartment, (ii) a whole building (by multiplying by the total number of apartments in a residential building which are assumed to be eight for the purposes of this model), and (iii) the middle-income housing sector as a whole (by multiplying by the total number of middle-income buildings in Egypt as provided for by the Ministry of Housing). The calculations are first carried out for a single year of use, and also for the lifetime of a building assumed to be fifty years as previously assumed under Methodological Assumptions.

The process is illustrated in Figure 3.9.

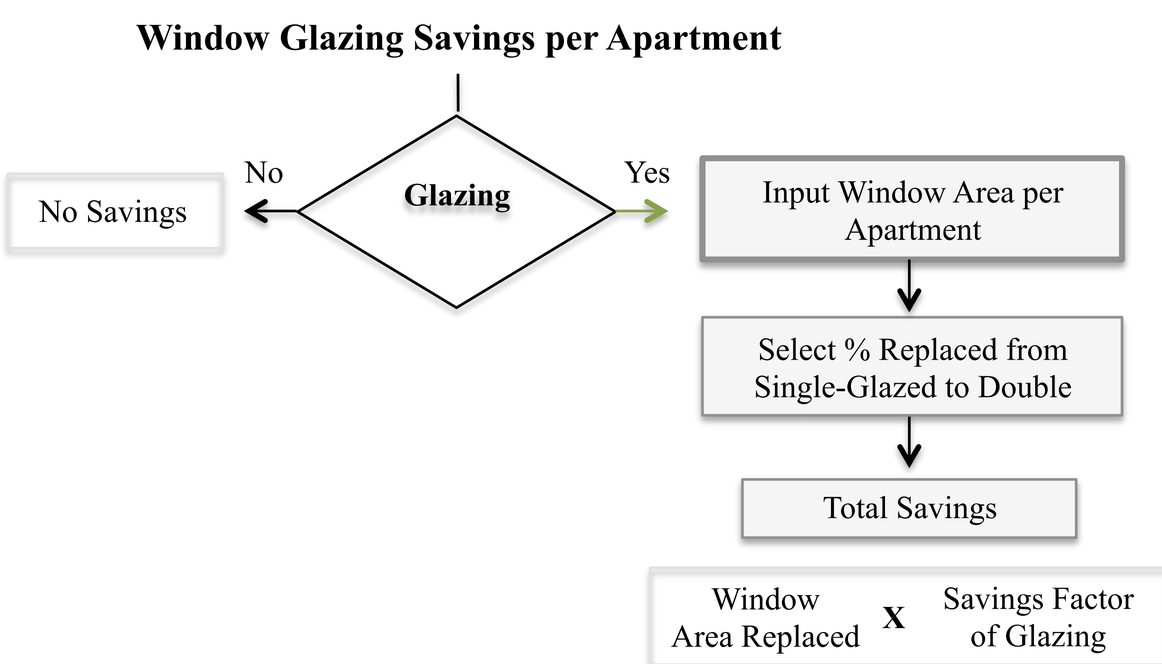

Figure 3.9 Description of Model's Calculations for Window Glazing Savings

b. For Wall Shading:

   i. The sole input in the model is whether wall shading is applied.

   ii. In the conventional configuration wall shading is omitted and therefore no further savings are realized. In the sustainable configuration, wall shading is assumed to lead to a reduction of five percent of required cooling loads in each apartment as obtained from literature. This leads to energy savings calculated by multiplying the following three factors; energy reductions per AC unit, energy emission factor and the number of AC units in an apartment.

   iii. The savings calculations are carried out for a: (i) single middle-income residential apartment, (ii) a whole building (by multiplying by the total number of apartments in a residential building which are assumed to be eight for the purposes of this model), and (iii) the middle-income housing sector as a whole (by multiplying by the total number of middle-income buildings in Egypt as provided for by the Ministry of Housing). The calculations are first carried out for a single year of use, and also for the lifetime of a building assumed to be fifty years as previously assumed under Methodological Assumptions.

The process is illustrated in Figure 3.10.

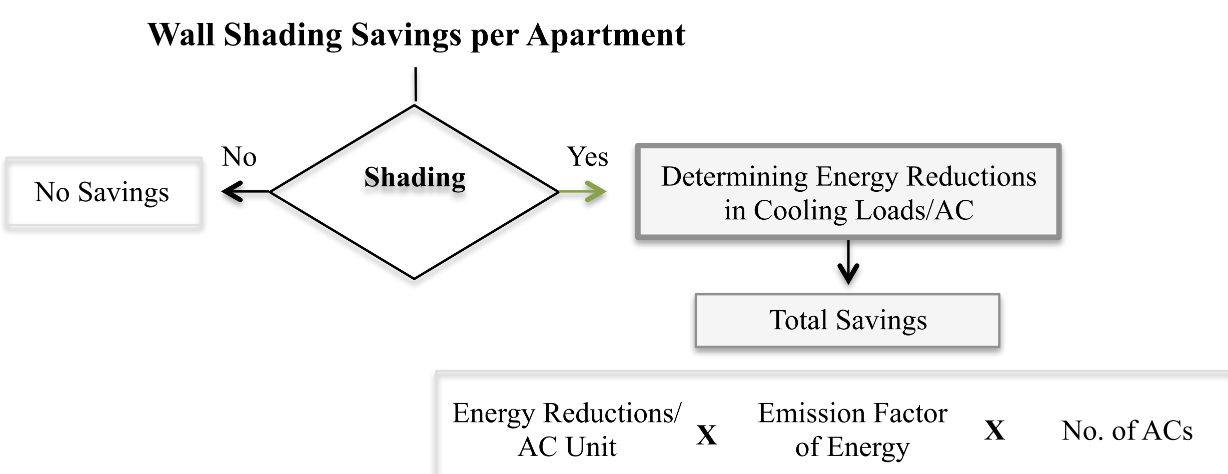

Figure 3.10 Description of Model's Calculations for Wall Shading Savings

3.5.3 Monetization Calculations

With regards to the monetization calculations, the model monetizes the carbon savings for both the construction phase and use-phase. The calculations for each are arrived at as follows, noting that all are based on the same set of assumptions previously described under Methodological Assumptions.

The sum of savings from the constriction phase and use-phase is multiplied by the cost of one ton of carbon dioxide to reveal a financial value that interprets the emission savings evolving from each.

CHAPTER 4: RESULTS AND ANALYSIS

The model has revealed a number of key findings on the profile of emission savings that can be realized by opting for more sustainable construction practices. This section of the work is meant to summarize findings to highlight those that are most impactful. Caution must be exercised in interpreting the quantitative figures provided as those are based on a number of assumptions that may require further adjustment. As previously indicated, the purpose of this model is to provide a framework to be challenged and refined by practitioners in the field across various industry segments and geographies.

It should also be emphasized that the quantitative findings in this model are all based on the emissions of all middle-income residential buildings constructed in Egypt over the past 12 years. These figures can be used as a proxy for the potential savings that can be realized in future construction if the sustainable practices identified in this work are adopted.

4.1 Carbon Savings during the Construction Phase

Construction phase emissions were calculated for the main construction materials used in all residential buildings, namely concrete, steel and bricks, in addition to emissions from all other materials combined. For each material, production and transportation emissions were calculated assuming adoption of sustainable practices, and compared against the material's base case emissions. Potential carbon savings were correspondingly calculated as the difference between both.

Table 4.1 shows a summary of all material emissions from middle-income residential buildings in Egypt in the past 12 years (since 2003) and the potential savings that could have been achieved.

4.1.1 Concrete

The emissions of a conventional concrete mix, type A sustainable concrete mix – once assuming concrete mixing on-site and a second time assuming ready-mixing, and type F sustainable concrete mix – once assuming concrete mixing on-site and a second time assuming ready-mixing, are listed in tables Table 4.2, Table 4.3, Table 4.4, Table 4.5, and Table 4.6 respectively. The emissions of each and their potential savings are summarized in Figure 4.1.

Table 4.1 Construction Phase Emissions and Savings in Middle-Income Residential Buildings in Egypt in the Past 12 years

All Material Emissions and Savings										
	Concrete					Steel		Bricks		
	Conventional	Using Type A		Using Type F						
	Mixed on-site	Mixed on-site	Ready-mix	Mixed on-site	Ready-mix	BF-BOF	EAF	Clay	Concrete	Fly Ash
Emissions in all Residential Buildings (t)	1,456,592	1,390,446	1,185,165	1,319,300	1,097,614	88,788	80,783	755,756	469,877	206,869
Savings (t)		66,146	271,427	137,292	358,977		8,005		285,879	548,887
		5%	19%	9%	25%		9%		38%	73%

Table 4.2 Conventional Concrete Emissions

Conventional Concrete (Strength: 25 MPa)								
					Carbon Emissions/R.Bldg			
Concrete Components	Qty/m3 (kg)	Vol/R.Bldg (m3)	Roundtrip Distance (km)	Truck Loads	Production (kg)	Transportation On-Site (kg)	Total in each Component (kg)	Carbon Emissions in all Residential Bldgs (t)
1. Cement	350	185	50	2	64,750	334	65,084	**1,456,592**
2. Water	175			0	0	0	0	
3. Fine Aggregates	715			8	0	2,728	2,728	
4. Coarse Aggregates	1290			14	0	8,615	8,615	

Table 4.3 Sustainable Concrete Emissions (Type A – mixed on-site)

Sustainable Concrete (Strength: 25 MPa)									
Additions to the Concrete Mix		**Qty**		**Unit**	**Concrete Type**			Mixed on-site	
Adm. Type A		2		L					
					Carbon Emissions/R.Bldg				
Concrete Components	**Qty/m3 (kg)**	**Vol/R.Bldg (m3)**	**Roundtrip Distance (km)**	**Truck Loads**	**Production (kg)**	**Transportation On-Site (kg)**	**Transportation Ready-Mix (kg)**	**Total in each Component (kg)**	**Carbon Emissions in all Residential Bldgs (t)**
1. Cement	325	185	50	2	60,125	310		60,435	**1,390,446**
2. Water	146			0	0	0		0	
3. Fine Aggregates	750			8	0	2,862		2,862	
4.Coarse Aggregates	1350			15	0	9,659		9,659	

Table 4.4 Sustainable Concrete Emissions (Type A – ready-mixed)

Sustainable Concrete (Strength: 25 MPa)									
Additions to the Concrete Mix		**Qty**		**Unit**	**Concrete Type**			Ready-mix	
Adm. Type A		2		L					
					Carbon Emissions/R.Bldg				
Concrete Components	**Qty/m3 (kg)**	**Vol/R.Bldg (m3)**	**Roundtrip Distance (km)**	**Truck Loads**	**Production (kg)**	**Transportation On-Site (kg)**	**Transportation Ready-Mix (kg)**	**Total in each Component (kg)**	**Carbon Emissions in all Residential Bldgs (t)**
1. Cement	325	185	50	2	60,125		515	60,640	**1,185,165**
2. Water	146			0	0			515	
3. Fine Aggregates	750			8	0			515	
4.Coarse Aggregates	1350			15	0			515	

Table 4.5 Sustainable Concrete Emissions (Type F – mixed on-site)

Sustainable Concrete (Strength: 25 MPa)									
Additions to the Concrete Mix		**Qty**		**Unit**	**Concrete Type**			Mixed on-site	
Adm. Type F		4		L					
					Carbon Emissions/R.Bldg				
Concrete Components	**Qty/m3 (kg)**	**Vol/R.Bldg (m3)**	**Roundtrip Distance (km)**	**Truck Loads**	**Production (kg)**	**Transportation On-Site (kg)**	**Transportation Ready-Mix (kg)**	**Total in each Component (kg)**	**Carbon Emissions in all Residential Bldgs (t)**
1. Cement	300	185	50	2	55,500	286		55,786	**1,319,300**
2. Water	120			0	0	0		0	
3. Fine Aggregates	780			9	0	3,349		3,349	
4.Coarse Aggregates	1410			15	0	10,089		10,089	

Table 4.6 Sustainable Concrete Emissions (Type F – ready-mixed)

Sustainable Concrete (Strength: 25 MPa)									
Additions to the Concrete Mix		**Qty**		**Unit**	**Concrete Type**			Ready-mix	
Adm. Type F		4		L					
					Carbon Emissions/R.Bldg				
Concrete Components	**Qty/m3 (kg)**	**Vol/R.Bldg (m3)**	**Roundtrip Distance (km)**	**Truck Loads**	**Production (kg)**	**Transportation On-Site (kg)**	**Transportation Ready-Mix (kg)**	**Total in each Component (kg)**	**Carbon Emissions in all Residential Bldgs (t)**
1. Cement	300	185	50	2	55,500		523	56,023	**1,097,614**
2. Water	120			0	0			523	
3. Fine Aggregates	780			9	0			523	
4.Coarse Aggregates	1410			15	0			523	

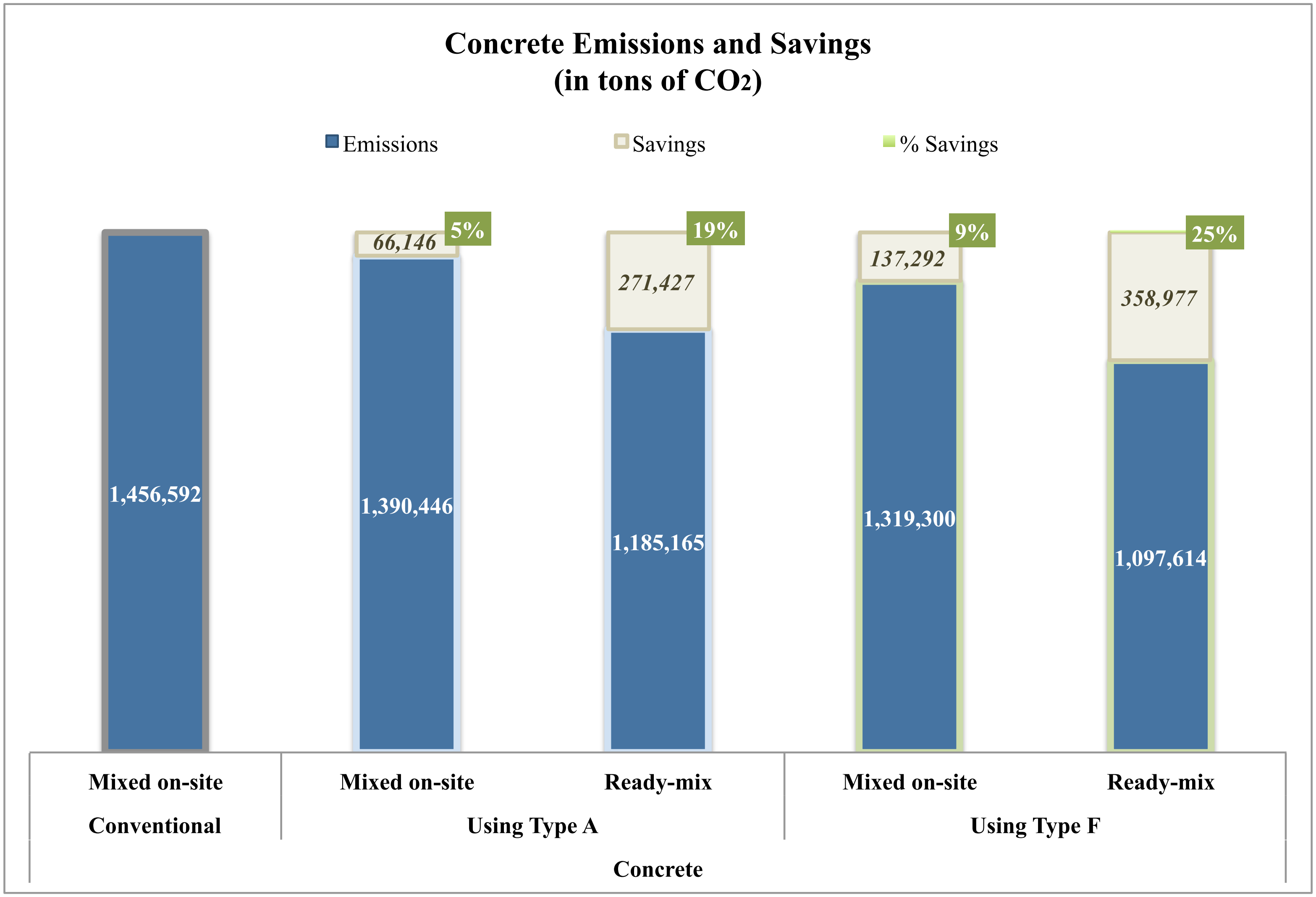

Figure 4.1 Concrete Carbon Emissions and Savings in Residential Buildings

The model analyzed five different concrete production configurations:

- The first is the conventional concrete mixed on-site, which is used as the base case. It results in emissions of approximately 1.5 million tons of CO_2 ($MtCO_2$), which is equivalent to the carbon dioxide emissions from the energy use of 124,158 homes annually.
- The second is a concrete configuration using type A admixture and assuming on-site mixing. It leads to a 7% decrease in cement content and a 5% decrease in CO_2 emissions relative to the base case, which is approximately 67 thousand tons of CO_2 ($KtCO_2$) – equivalent to avoiding the carbon dioxide emissions from the energy use of 6,546 homes annually.
- The third is a concrete configuration using type A admixture and assuming ready-mixed concrete. It leads to an additional 14% decrease in CO_2 emissions due to savings in transportation, relative to the second configuration (implying a 19% reduction relative to the base case).
- The fourth is a concrete configuration using type F admixture and assuming on-site mixing. It leads to a 14% decrease in cement content and a 9% decrease in CO_2 emissions relative to the base case, which is approximately 138 $KtCO_2$ – equivalent to avoiding the carbon dioxide emissions from the energy use of 11,423 homes annually.
- The fifth is a concrete configuration using type F admixture and assuming ready-mixed concrete. It leads to an additional 16% decrease in CO_2 emissions due to savings in transportation, relative to the fourth configuration (implying a 25% reduction relative to the base case).

It is important to note that the analysis of type A and type F admixtures in this work was due to their prevalence in the Egyptian housing market. Other admixtures however are available and can be similarly analyzed. The addition of cementitious materials can also be considered and their impact assessed, however those are only applicable for high-strength concrete, which is uncommon in middle-income residential buildings (The Egyptian Ministry of Housing, 2014). Calculations above are exclusive of transportation emissions of each concrete component to the point of mixing in a batch plant, which would have reduced the potential savings from ready-mixed concrete. This work's findings on concrete deserve consideration by lawmakers in the country to restrict use of concrete to energy-efficient mixtures with lower cement content.

Moreover, the use of recycled aggregates and mobile batch plants should be considered for further carbon reductions.

4.1.2 Steel

Steel emissions are dependent on the production route; Table 4.7 lists the emissions of the two common routes from all middle-income residential buildings in the past 12 years, and Figure 4.2 illustrates those emissions along with the potential savings that could have been achieved if a more sustainable production route had been followed.

The EAF route can save 9%, which is approximately 8 thousand tons of CO_2 ($KtCO_2$) due to its lower energy consumption, which is equivalent to avoiding the carbon dioxide emissions from the energy use of 662 homes annually. Transportation emissions are negligible relative to production emissions and account for less than 1% of total steel emissions.

The findings of this work on steel highlight the importance of value engineering and sustainable design to minimize the amount of steel used in any building without compromising on structural safety.

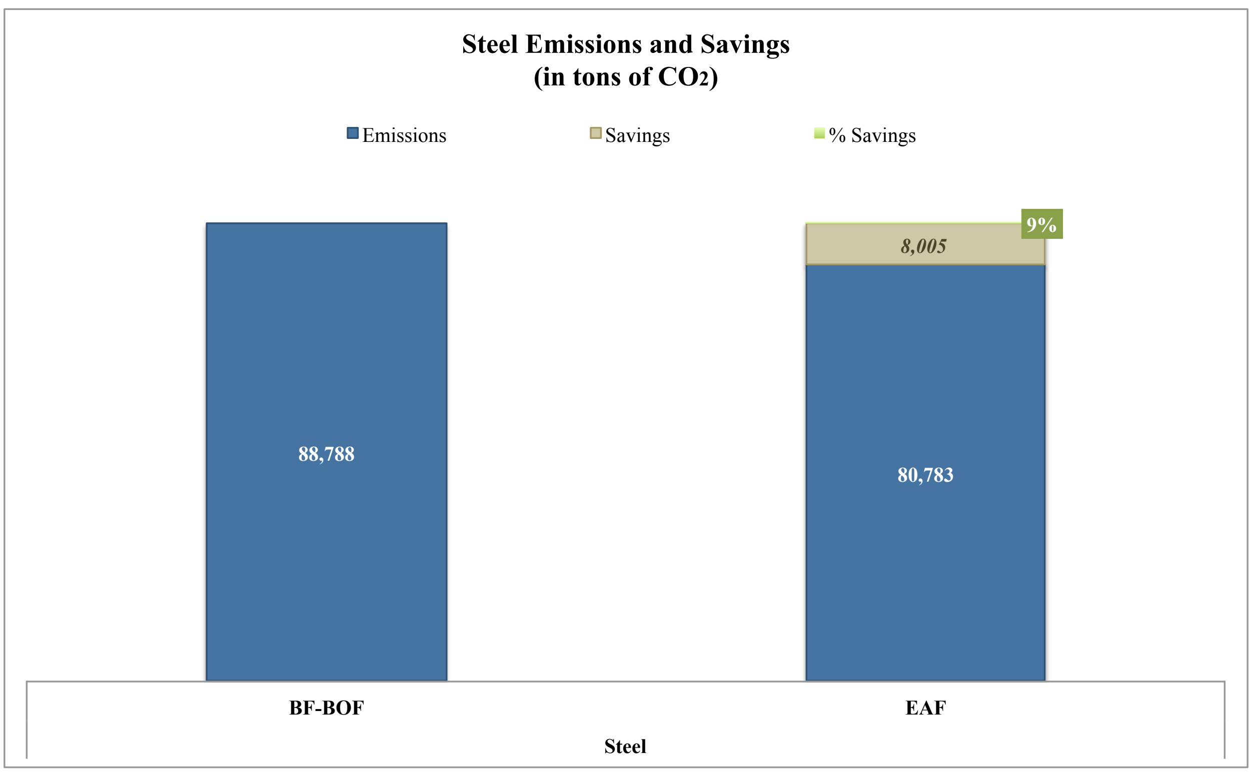

Figure 4.2 Steel Carbon Emissions and Savings in Residential Buildings

Table 4.7 Steel Emissions in Residential Buildings

Steel									
						Carbon Emissions/R.Bldg		
Type of Construction	Production Route	Energy/t (kwh)	Wt. of Steel/R.Bldg (t)	Roundtrip Distance (km)	Truck Loads	Production (t)	Transportation (t)	Carbon Emissions in all Residential Bldgs (t)
Conventional	Basic Oxygen Furnace (BOF)	440	15	50	1	4.62	0.039	**88,788**
Sustainable	Electric Arc Furnace (EAF)	400				4.20		**80,783**
	Steel Savings (t)					**8,005**		**9%**

4.1.3 Bricks

Brick emissions were calculated for three different types bricks: (i) clay, (ii) concrete, and (iii) fly ash. The clay brick was considered as the conventional type, while concrete and fly ash bricks were considered as its sustainable alternatives. Table 4.8 and Table 4.9 show the emission savings that can be achieved by switching from conventional clay bricks to concrete and fly ash bricks, respectively. These savings are illustrated in Figure 4.3.

It is found that concrete bricks lead to savings of 38% (approximately 286 $KtCO_2$, which is equivalent to avoiding the carbon dioxide emissions from the energy use of 23,673 homes annually) relative to the conventional clay brick base case. The equivalent savings from fly ash bricks are found to be 73% (approximately 550 $KtCO_2$, which is equivalent to avoiding the carbon dioxide emissions from the energy use of 45,525 homes annually). These savings are due to the substitution of the energy-intensive firing process required in a conventional clay brick, by a chemical process in a concrete or fly ash brick where no firing is needed. Fly ash bricks lead to substantially greater reductions than concrete bricks primarily because they do not contain any cement content. Switching brick types does not result in any transportation emission reductions, which are equivalent for all three brick types and are estimated at 5 tons of CO_2 per residential building.

The findings of this work on bricks call for exploring the use of fly ash bricks as an alternative to conventional clay bricks prevalent in the Egyptian construction industry. This can be accomplished by offering tax breaks and incentives to efficient manufacturers. Since the use of fly ash bricks is not common in Egypt, other brick types can also be considered including earth-compressed blocks and blended bricks containing 10-20% cement dust.

4.1.4 Other Materials

To calculate total emissions in the construction phase, other construction material emissions were assumed to be 25% of the combined emissions of concrete, steel and brick in the conventional scenario. The resulting volume is assumed to be unchanged across all sustainable scenarios.

Table 4.8 Brick Emissions in Residential Buildings (Clay vs. Concrete Bricks)

Bricks								
						Carbon Emissions/R.Bldg		
Type of Construction	Type of Bricks	Emissions/ Brick (kg)	No. of Bricks/R.Bldg	Roundtrip Distance (km)	Truck Loads	Production (t)	Transportation (t)	Carbon Emissions in all Residential Bldgs (t)
Conventional	Clay	0.59	60,000	50	11	35	4.25	**755,756**
Sustainable	Concrete	0.34				20		**469,877**
		Brick Savings (t)				**285,879**		**38%**

Table 4.9 Brick Emissions in Residential Buildings (Clay vs. Fly Ash Bricks)

Bricks								
						Carbon Emissions/R.Bldg		
Type of Construction	Type of Bricks	Emissions/ Brick (kg)	No. of Bricks/R.Bldg	Roundtrip Distance (km)	Truck Loads	Production (t)	Transportation (t)	Carbon Emissions in all Residential Bldgs (t)
Conventional	Clay	0.59	60,000	50	11	35	4.25	**755,756**
Sustainable	Fly Ash	0.11				7		**206,869**
		Brick Savings (t)				**548,888**		**73%**

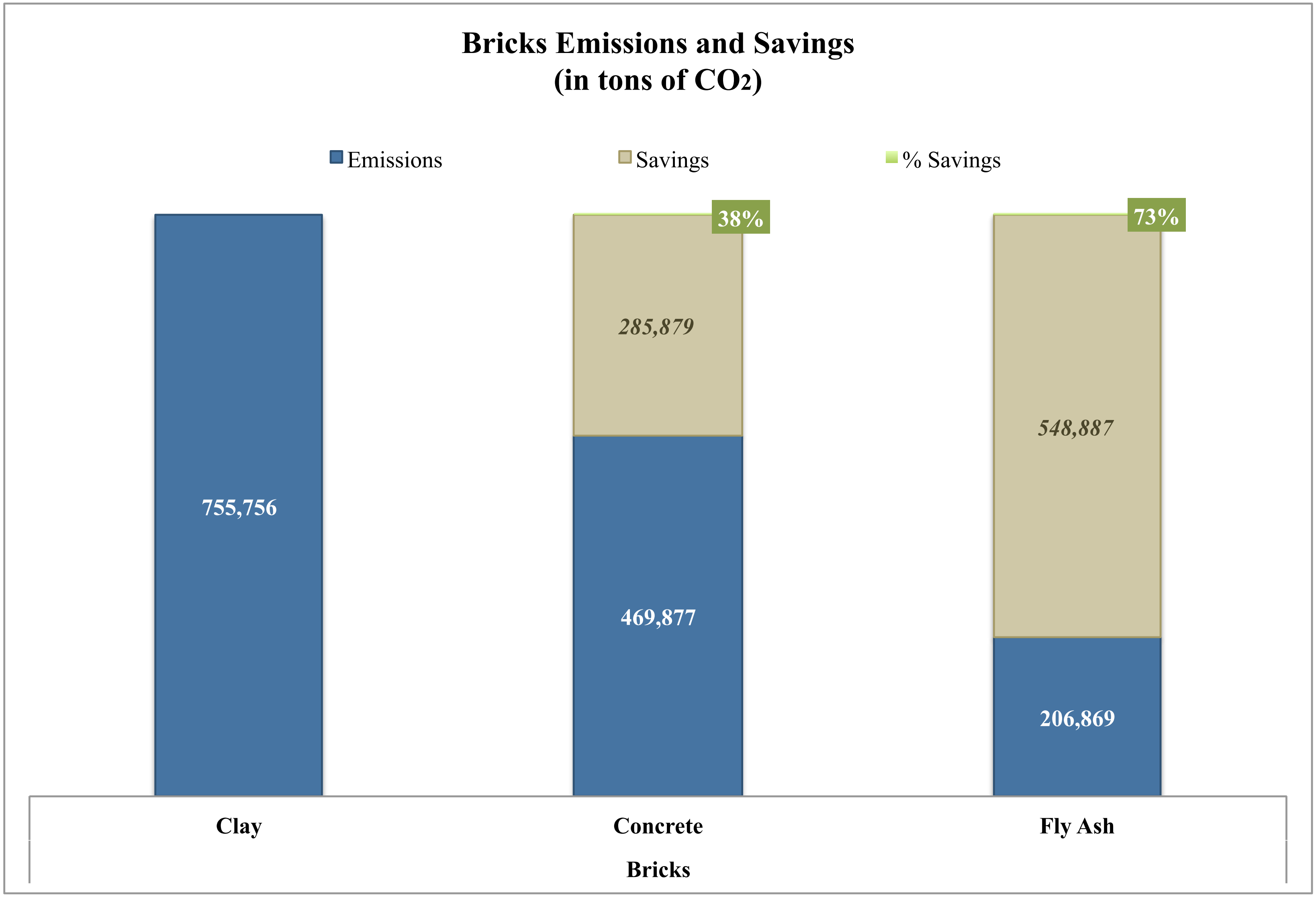

Figure 4.3 Bricks Carbon Emissions and Savings in Residential Buildings

4.1.5 Summary

In summary, Table 4.10 provides a summarized sensitivity analysis of the amount of savings that can be achieved in the construction phase of a residential building assuming the use of nine different combinations of materials. This analysis reveals that most carbon savings can be achieved in “Sustainable Case 1” which assumes the following: type F admixtures are used in concrete, concrete is ready-mixed, the EAF route is used for the production of steel, and fly ash bricks are used as building blocks. If all four conditions are met, the total savings from all residential buildings is approximately 916 $KtCO_2$, which constitutes a 30% reduction to emissions relative to the conventional base case. This is equivalent to avoiding the carbon dioxide emissions from the energy use of 75,819 homes annually. The least efficient combination of materials is “Sustainable Case 8” which assumes the following: type A admixtures in concrete, concrete mixed on-site, the EAF route for the production of steel, and concrete bricks as building blocks. It achieves savings of approximately 360 $KtCO_2$, corresponding to a 12% reduction in emissions relative to the conventional base case. This is equivalent to avoiding the carbon dioxide emissions from the energy use of 29,798 homes annually. All other intermediate scenarios (“Sustainable Cases 2 – 7” in Table 4.10) assume different combinations of chemical admixtures, concrete type, and brick type, but all assume the EAF route for the production of steel is maintained.

A more detailed analysis of savings can also be obtained by considering more construction materials including but not limited to: other brick types (like earth-compressed bricks and blended bricks), wood, ceramics, marble, paint, glass, etc. Such an analysis may also be broadened by considering the cost and payback period consequences of each alternate construction material to assess practicality and financial feasibility.

Table 4.10 Carbon Savings for Various Combinations of Construction Materials

Base Case	Sustainable Case 1	Sustainable Case 2
Conventional Concrete	Concrete - Type F (ready-mix)	Concrete - Type A (ready-mix)
BF-BOF Steel Production	EAF Steel Production	EAF Steel Production
Clay Bricks	Fly Ash Bricks	Fly Ash Bricks
No Savings	**30%**	**27%**
	~ 916 $KtCO_2$	**~ 829 $KtCO_2$**

Sustainable Case 3	Sustainable Case 4	Sustainable Case 5
Concrete - Type F (mixed on-site)	Concrete - Type F (ready-mix)	Concrete - Type A (mixed on-site)
EAF Steel Production	EAF Steel Production	EAF Steel Production
Fly Ash Bricks	Concrete Bricks	Fly Ash Bricks
23%	**21%**	**20%**
~ 695 $KtCO_2$	**~ 653 $KtCO_2$**	**~ 624 KtCO2**

Sustainable Case 6	Sustainable Case 7	Sustainable Case 8
Concrete - Type A (mixed on-site)	Concrete - Type F (mixed on-site)	Concrete - Type A (mixed on-site)
EAF Steel Production	EAF Steel Production	EAF Steel Production
Concrete Bricks	Concrete Bricks	Concrete Bricks
18%	**14%**	**12%**
~ 566 $KtCO_2$	**~ 432 $KtCO_2$**	**~ 360 KtCO2**

4.2 Carbon Savings during the Use-Phase

Use-phase emissions were calculated for the main determinants of emissions in all residential buildings, namely lighting, electrical appliances and envelope modifications.

In analyzing lighting and electrical appliances, indirect carbon emissions (due to their use of electricity) were calculated assuming adoption of sustainable practices, and compared against base-case emissions. Potential carbon savings were correspondingly calculated as the difference between both.

In analyzing envelope modifications, the additional carbon savings as a result of changes to a building's envelope was calculated, specifically extent of window glazing and wall shading.

4.2.1 Lighting

Lighting emissions were calculated for three different types of light bulbs: (i) incandescent, (ii) compact fluorescent (CFL), and (iii) light-emitting diodes (LED). The incandescent bulb was considered as the conventional type, while CFL and LED bulbs were considered as its sustainable alternatives. Table 4.11 summarizes the wattage, energy consumption, and carbon emissions for the three types of bulbs, in addition to the carbon savings relative to the conventional incandescent bulb. These calculations were for all middle-income residential buildings in Egypt in the past 12 years. Figure 4.4 illustrates the carbon emissions and savings that could have been achieved for each type of bulb per year.

The difference between each bulb is in its energy consumption; this is due to the different wattage consumed for the same amount of light emitted. Figure 4.5 illustrates the equivalent wattages of incandescent, CFL and LED light bulbs, and it shows how CFLs and LEDs are more energy efficient due to their average decrease of watts consumed relative to an equivalent incandescent bulb by 75% and 85% respectively.

The results of the model can be summarized as follows:

- The use of CFLs can cause a reduction of approximately 77% in energy consumption and carbon emissions relative to conventional incandescent bulbs. This is equivalent to approximately 73 $KtCO_2$ to 179 $KtCO_2$ in savings per year depending on the wattage used. This is equivalent to avoiding the carbon dioxide emissions from the energy use of 6,042 to 14,816 homes annually.

- The use of LEDs can cause a reduction of approximately 83% in energy consumption and carbon emissions relative to conventional incandescent bulbs. This is equivalent to approximately 80 $KtCO_2$ to 195 $KtCO_2$ per year depending on the wattage used. This is equivalent to avoiding the carbon dioxide emissions from the energy use of 6,622 to 16,141 homes annually.

It can therefore be concluded that LEDs are the more sustainable alternative to incandescent light bulbs, due to their efficient use of electricity. This finding should be considered by Egyptian lawmakers in banning the importation and production of incandescent bulbs in an attempt to promote and replace them with more efficient ones (specifically CFLs and LEDs). Moreover, passive use of daylight should be considered, since it can reduce the amount of lighting emissions and therefore increase carbon savings.

Table 4.11 Lighting Emissions and Savings in Middle-Income Residential Buildings in Egypt in the Past 12 Years

Lighting Emissions and Savings													
		40W			**60W**			**75W**			**100W**		
		Incandescent	**CFL**	**LED**	**Incandescent**	**CFL**	**LED**	**Incandescent**	**CFL**	**LED**	**Incandescent**	**CFL**	**LED**
Equivalent Wattages (W)		40	9	6	60	13	10	75	18	13	100	23	16
Energy Consumption/Bulb (kWh)		44	10	7	65	14	11	82	20	14	109	25	18
No. of Bulbs/Apt		**20**											
No. of Middle-Income Residential Buildings		**19,059**											
Annual Calculations	**Energy Consumption (kWh)**	134,172,544	30,493,760	21,345,632	198,209,440	42,691,264	33,543,136	250,048,832	60,987,520	42,691,264	332,381,984	76,234,400	54,888,768
	Energy Savings (kWh)		103,678,784	112,826,912		155,518,176	164,666,304		189,061,312	207,357,568		256,147,584	277,493,216
	Carbon Emissions (t)	93,921	21,346	14,942	138,747	29,884	23,480	175,034	42,691	29,884	232,667	53,364	38,422
	Carbon Savings (t)		72,575	78,979		108,863	115,266		132,343	145,150		179,303	194,245
Lifetime		**50**											
Use-Phase Calculations	**Carbon Emissions (t)**	4,696,039	1,067,282	747,097	6,937,330	1,494,194	1,174,010	8,751,709	2,134,563	1,494,194	11,633,369	2,668,204	1,921,107
	Carbon Savings (t)		3,628,757	3,948,942		5,443,136	5,763,321		6,617,146	7,257,515		8,965,165	9,712,263
Savings (%)			**77%**	**84%**		**78%**	**83%**		**76%**	**83%**		**77%**	**83%**

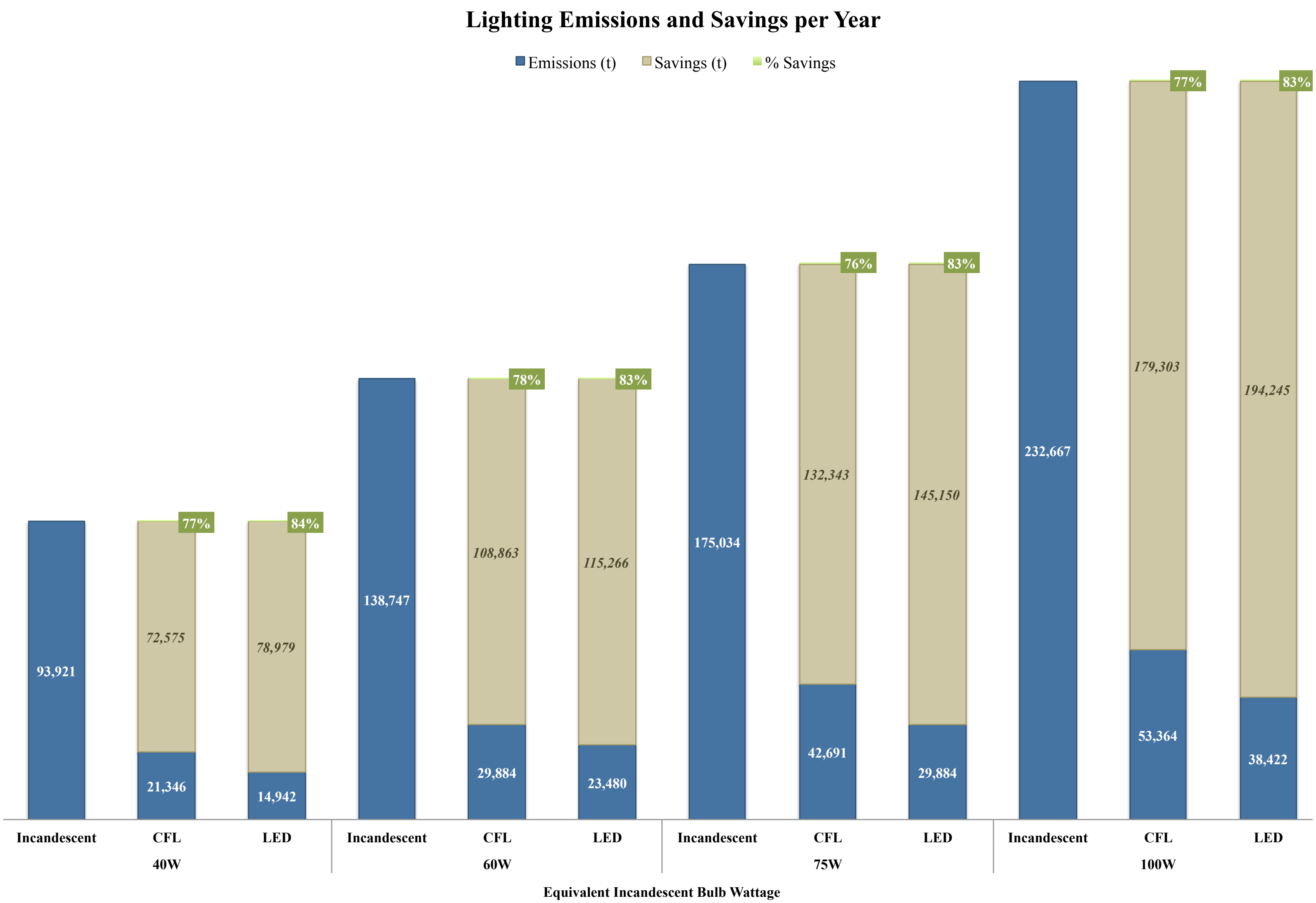

Figure 4.4 Lighting Emissions and Savings in Residential Buildings per Year

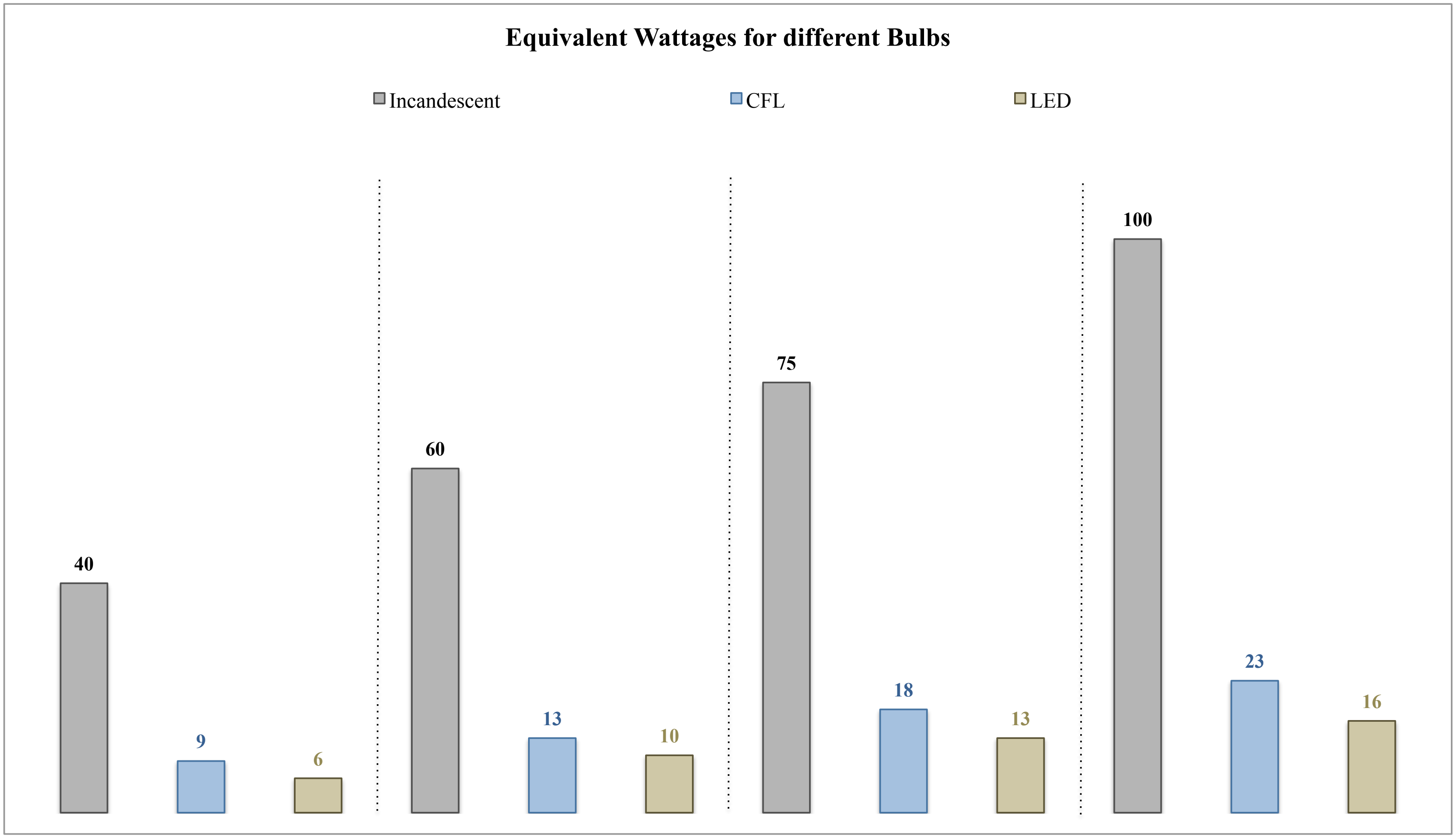

Figure 4.5 Equivalent Wattages of Different Light Bulbs

4.2.2 Electrical Appliances

The four electrical appliances considered in this model were: (i) air conditioners, (ii) water heaters (gas and electric), (iii) refrigerators, and (iv) washers. For each appliance type, a conventional unit was compared to sustainable models to determine its potential energy and carbon savings. Table 4.12 summarizes the energy consumption, and carbon emissions of each appliance type, in addition to its carbon savings relative to a conventional unit. These calculations were for all middle-income residential buildings in Egypt in the past 12 years. Figures Figure 4.6,Figure 4.7,Figure 4.8 and Figure 4.9 illustrates the carbon emissions and savings for all four appliance types – air conditioners, water heaters, refrigerators, and washers, respectively. The calculations assume that a typical residential unit comprises 2 air conditioners, 1 water heater, 1 refrigerator and 1 washer as previously described under Methodological Assumptions.

The results of the model can be summarized as follows:

- Air Conditioners: an Energy Star unit can save approximately 30 $KtCO_2$ per year (which is approximately 1.5 $MtCO_2$ over the 50-year use-phase of a building – this is equivalent to avoiding the carbon dioxide emissions from the energy use of 124,158 homes annually). Figure 4.6 illustrates the emissions and potential savings for all middle-income residential buildings per year of switching to Energy Star units. It shows that two Energy Star units can save 9% of carbon emissions as compared to a conventional unit.
- Water Heaters: gas heaters emit more carbon emissions than electric ones even with the use of Energy Star units. However, the savings from an Energy Star electric heater is higher, with a total amount of approximately 14 $MtCO_2$ (this is equivalent to avoiding the carbon dioxide emissions from the energy use of 1,158,813 homes annually) as compared to approximately 12 $MtCO_2$ from gas heaters (this is equivalent to avoiding the carbon dioxide emissions from the energy use of 993,268 homes annually) over 50 years. These contribute to 55% and 30% savings respectively. Figure 4.7 illustrates the emissions and potential savings for all middle-income residential buildings per year. However, the use of solar water heaters can add an additional 11.8 and 28.6 $MtCO_2$ savings if they replace energy star electric and gas heaters respectively.
- Refrigerators: an Energy Star unit can save 11 $KtCO_2$ per year (which is approximately 520 $KtCO_2$ over 50 years – this is equivalent to avoiding the carbon dioxide emissions

from the energy use of 43,042 homes annually). Figure 4.8 illustrates the emissions and potential savings for all middle-income residential buildings per year. It shows that an Energy Star unit can save 20% of the carbon emissions as compared to a conventional unit.

- Washers: an Energy Star unit can save approximately 31 $KtCO_2$ per year (which is approximately 1.5 $MtCO_2$ over 50 years – this is equivalent to avoiding the carbon dioxide emissions from the energy use of 124,158 homes annually). Figure 4.9 illustrates the emissions and potential savings for all middle-income residential buildings per year. It shows that an Energy Star unit can save 37% of the carbon emissions as compared to a conventional unit.

Water heating units are the main contributors of carbon emissions over the entire 50-year use-phase of a residential building due to the continuous need of hot water all year round. Generally, gas heaters emit higher quantities of carbon emissions than electric heaters even if Energy Star units are used, however the savings attributed to Energy Star electric heaters are 14% more. It can therefore be concluded from this work that Egyptian legislators should consider legal alternatives for the promotion of efficient electric heaters over conventional gas heaters by increasing the price of gas supplies to homes and by the application of hefty sales tax and customs on the sale of gas heaters.

Table 4.12 Electrical Appliances Emissions and Savings in Middle-Income Residential Buildings in the Past 12 Years

Electrical Appliances Emissions and Savings											
		Air Conditioner		**Gas Water Heater**		**Electric Water Heater**		**Refrigerator**		**Washer**	
		Conventional	**Energy Star**	**Conventional**	**Energy Star**	**Conventional**	**Energy Star**	**Conventional**	**Energy Star**	**Conventional**	**Energy Star**
Energy Consumption/Unit (kWh)		2,974	2,699	7,647	5,362	4,857	2,195	486	389	768	484
No. of Unit/Apt		**2**		**1**		**1**		**1**		**1**	
No. of Middle-Income Reseidential Building		**19,059**									
Annual Calculations	**Energy Consumption (kWh)**	906,884,422	823,026,582	1,165,928,914	817,537,706	740,540,962	334,669,016	74,099,837	59,310,363	117,096,038	73,794,899
	Energy Savings (kWh)	83,857,840		348,391,208		405,871,946		14,789,474		43,301,139	
	Carbon Emissions (t)	634,819	576,119	816,150	572,276	518,379	234,268	51,870	41,517	81,967	51,656
	Carbon Savings (t)	58,700		243,874		284,110		10,353		30,311	
Lifetime		**50**									
Use-Phase Calculations	**Carbon Emissions (t)**	31,740,955	28,805,930	40,807,512	28,613,820	25,918,934	11,713,416	2,593,494	2,075,863	4,098,361	2,582,821
	Carbon Savings (t)	2,935,024		12,193,692		14,205,518		517,632		1,515,540	
Savings (%)		**9%**		**30%**		**55%**		**20%**		**37%**	

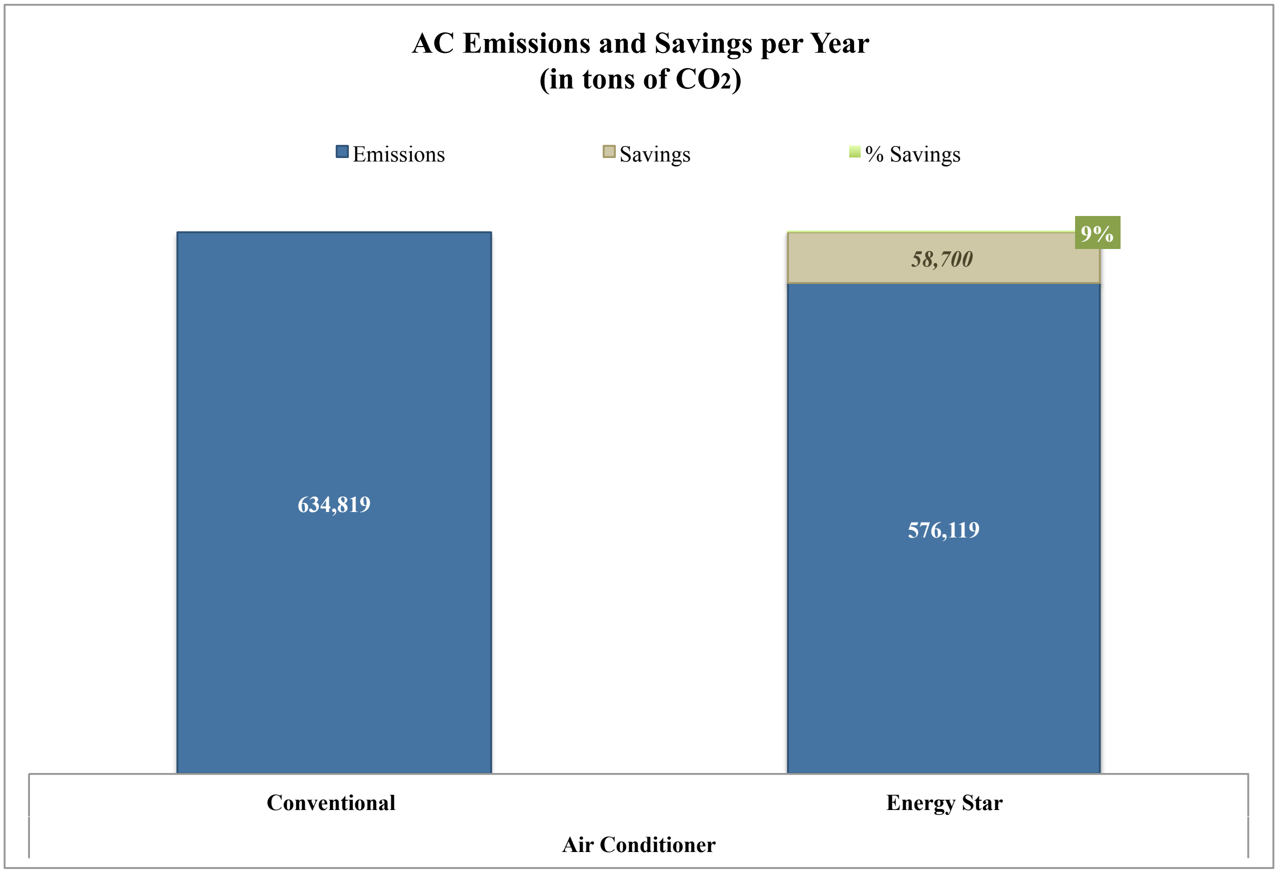

Figure 4.6 AC Emissions and Savings in Residential Buildings per Year

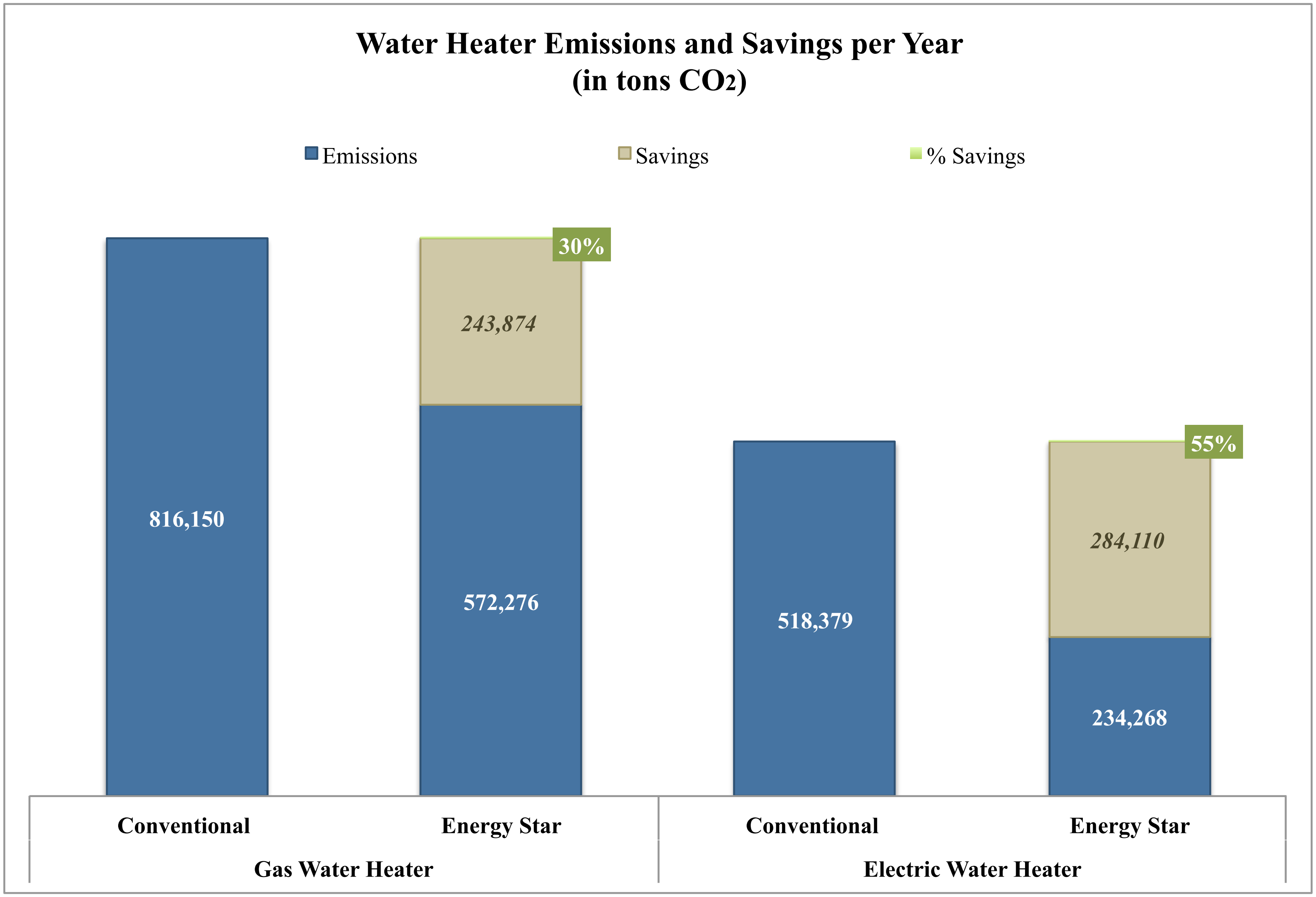

Figure 4.7 Water Heater Emissions and Savings in Residential Buildings per Year

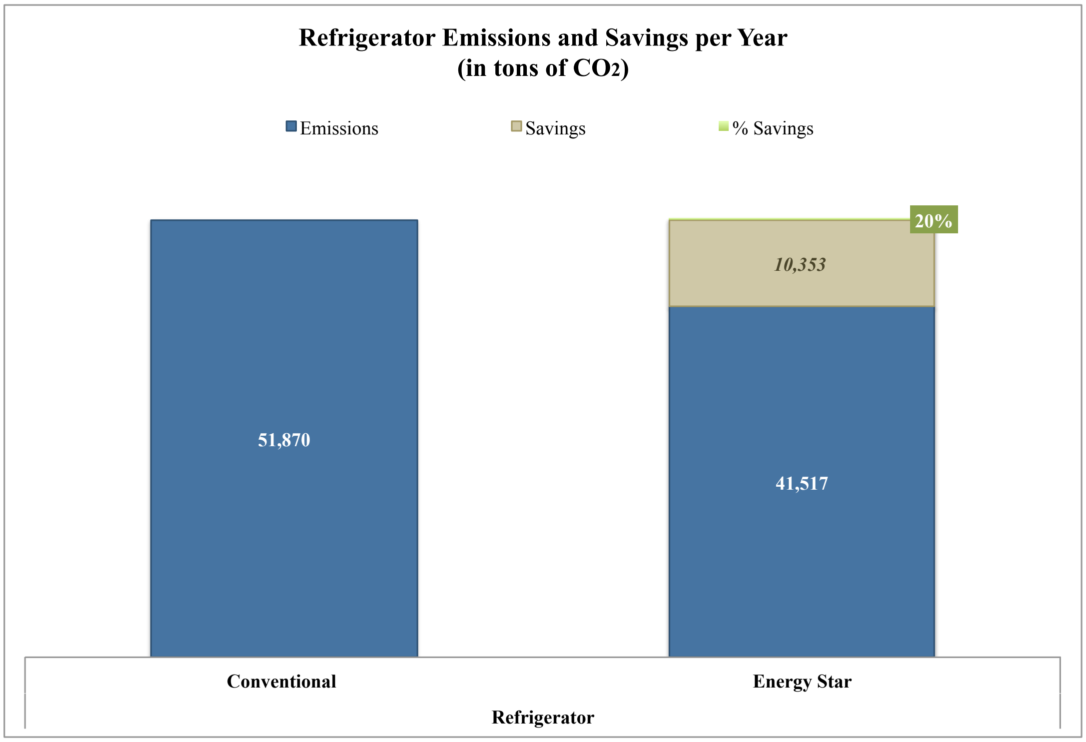

Figure 4.8 Refrigerator Emissions and Savings in Residential Buildings per Year

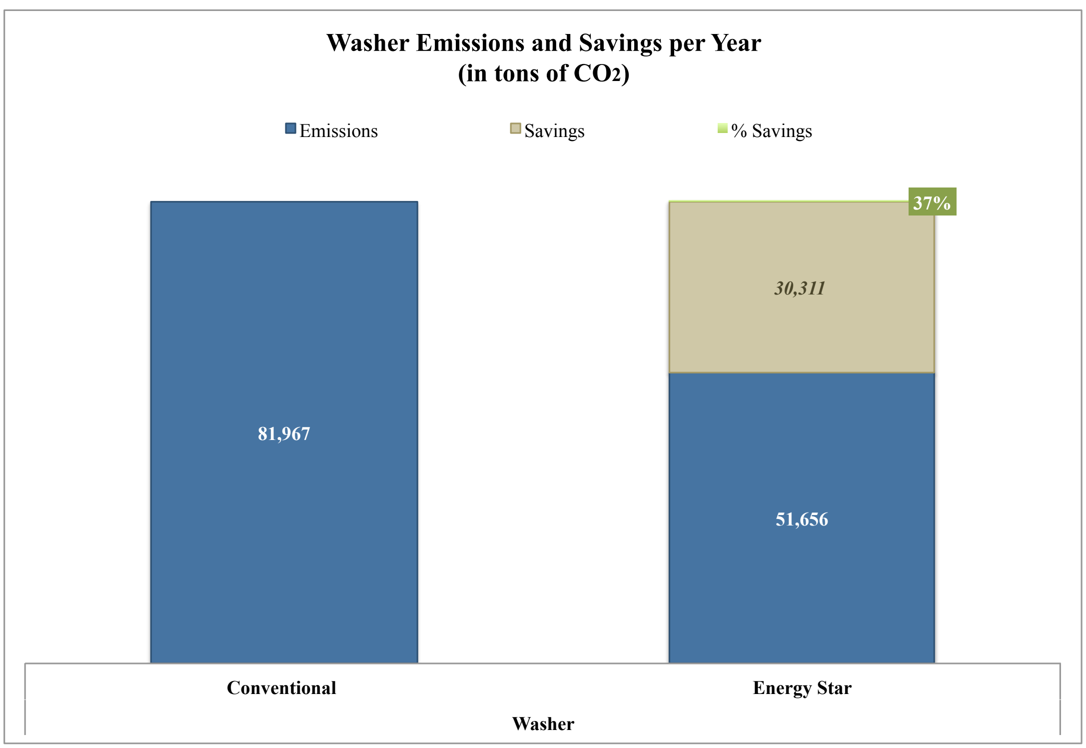

Figure 4.9 Washer Emissions and Savings in Residential Buildings per Year

4.2.3 Envelope Modifications

The impact of envelope modifications was considered in this study given the extensive reference to the topic in literature. There are many types of modifications to building envelopes, which can yield energy savings. In this study, the analysis was limited to the two that are most relevant to Egypt: window glazing and wall shading.

Window Glazing: fully replacing single-glazed windows with low-e double-glazed, can reduce emissions by approximately 170 $KtCO_2$ per year from all middle-income residential buildings in the past 12 years. This is equivalent to avoiding the carbon dioxide emissions from the energy use of 14,071 homes annually. Figure 4.10 illustrates the carbon savings by replacing single-glazed windows to low-e double-glazed. It is therefore strongly recommended to push developers and contractors to commit to the glazing of all windows as a pre-condition to the issuance of building permits.

Wall Shading: adding exterior horizontal shading in south-facing windows and vertical shades in east and west facing-windows can reduce cooling loads by 5%, which is equivalent to approximately 29 $KtCO_2$ per year from all middle-income residential buildings in the past 12 years. This is equivalent to avoiding the carbon dioxide emissions from the energy use of 2,400 homes annually. It is therefore strongly recommended to shade all windows with the most solar exposure in any building or constructing walls using hollow block bricks to act as insulators in reducing cooling loads.

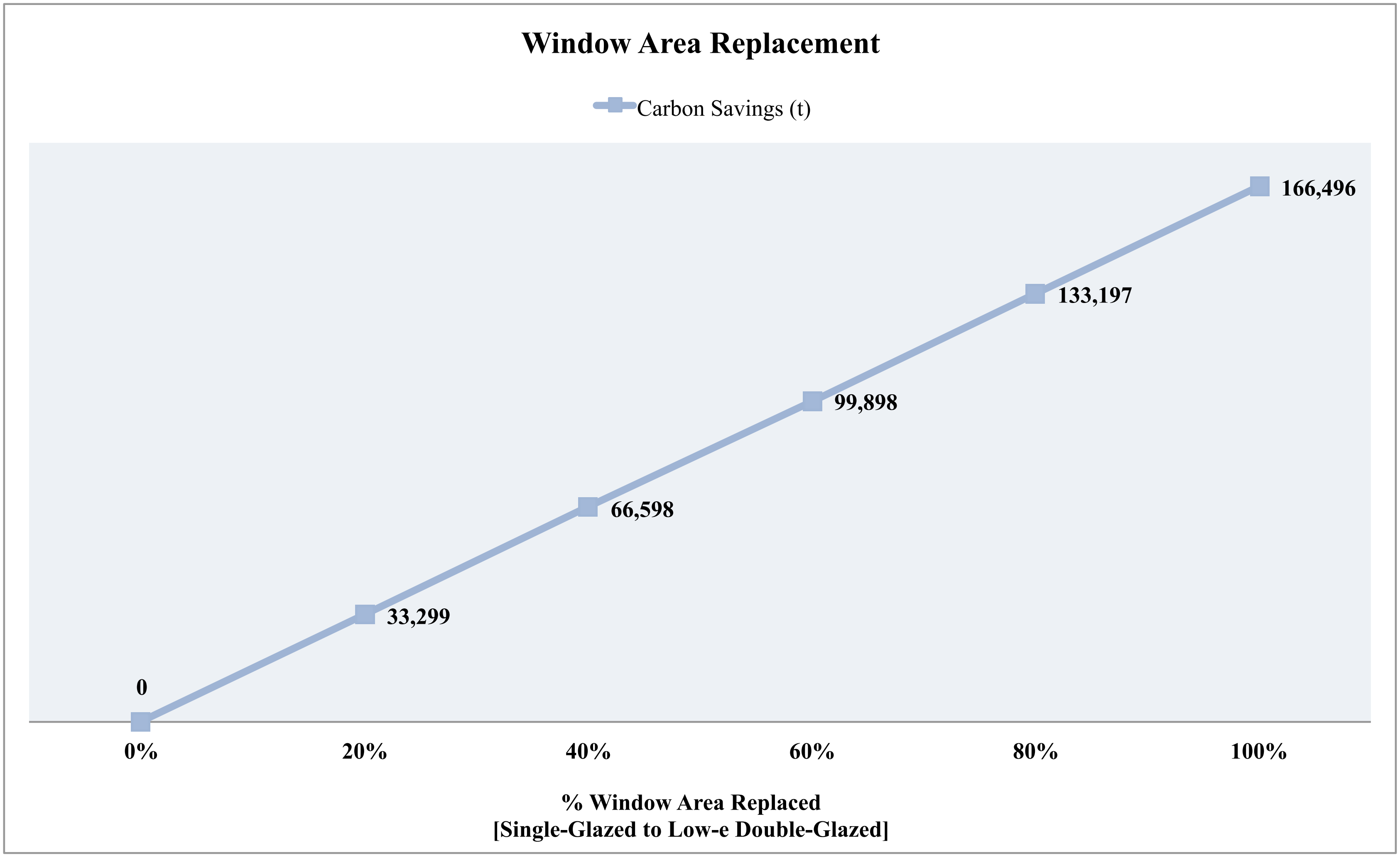

Figure 4.10 Carbon Savings due to Double-Glaze Conversion per Year

4.2.4 Summary

Table 4.13 provides a summarized sensitivity analysis of the amount of savings that can be achieved in the use-phase of a residential building assuming two scenarios: (i) maximum, and (ii) minimum savings over the use-phase of a middle-income residential building.

It can be concluded that most savings are attributed to the use of LEDs instead of conventional incandescent bulbs (an equivalent to a 60W bulb was used in this calculation, due to its frequent use), Energy Star electrical appliances (electrical heaters instead of gas), complete substitution of single-glazed windows to low-e double-glazed, and adding shades to all exterior walls. This can save up to approximately 35 $MtCO_{2,}$ which constitutes a 49% reduction to emissions relative to the conventional base case over 50 years. This is equivalent to avoiding the carbon dioxide emissions from the energy use of 2,897,031 homes annually. The least savings are attributed to the use of CFLs instead of LEDs, Energy Star gas heaters instead of electrical heaters, only 20% of the windows are low-e double-glazed, and the addition of shades to all exterior walls. This can save up to approximately 26 $MtCO_{2,}$ which constitutes a 30% reduction to emissions relative to the conventional base case over 50 years. This is equivalent to avoiding the carbon dioxide emissions from the energy use of 2,152,080 homes annually. A more detailed analysis of savings can also be obtained by considering more use-phase housing elements including but not limited to: heating, insulation, doors and other appliances. This analysis may also be broadened by considering the cost and payback consequences of each element.

Finally, the importance of promoting passive design strategies in the design and construction of middle-income homes cannot be overestimated. Sustainable passive strategies can deliver substantial emission savings at no expense to homeowners by reducing lifetime cooling and lighting loads.

Table 4.13 Carbon Savings for Various Combinations of Housing Elements

Conventional Case	Most Savings in 50 years	Least Savings in 50 years
Using Incandescent Bulbs	Using LEDs	Using CFLs
No Energy Star Units	Electrical appliances (with the use of electric heaters)	Electrical appliances (with the use of gas heaters)
Single-Glazed Windows	All windows are Low-e Double-Glazed	Low-e Double-Glazed are only 20%
No Shading	Wall Shading	Wall Shading
No Savings	**49%** **~ 35 $MtCO_2$**	**30%** **~ 26 $MtCO_2$**

4.3 Total Carbon Savings

Due to the many alterations that can be introduced to the model in combining different construction materials and housing elements; this section will focus on means to attain maximum savings within the construction industry by revealing the amount of emissions with their potential maximum savings. Table 4.14 reveals the amount of conventional and sustainable emissions of all middle-income residential buildings in the past 12 years and shows that the emissions per square meter can be reduced by 31% if sustainable measures are applied to materials and housing elements. Additional savings can be realized if savings from envelope modifications are added.

Table 4.14 Total Residential Emissions per Year in Egypt

Total Residential Emissions / Year						
	Emissions from all Residential Buildings (t)		Emissions per Residential Building (t)		Emissions/sqm (t)	
	Conventional	Sustainable	Conventional	Sustainable	Conventional	Sustainable
Construction Materials	3,068,181	2,152,311	160.99	112.93	0.29	0.20
*Housing Elements	1,425,781	927,041	74.81	48.64	0.14	0.09
Total Emissions (t)	4,493,962	3,079,352	235.80	161.57	**0.43**	**0.29**

* Sustainable calculations are without additional savings from enevelope modifications (window glazing and shading)

4.3.1 Construction Carbon Savings

As previously outlined in Table 4.10 ("Sustainable Case 1"), the combination of materials with the most carbon savings is: (i) ready-mixed concrete with type F admixtures, (ii) EAF route for the production of steel, and (iii) fly ash bricks as building blocks. The savings from each material is summarized in Table 4.15 and illustrated in Figure 4.11 assuming that concrete, steel and bricks contribute to 75% of emissions and all other materials combined contribute 25%.

Table 4.15 Total Construction Carbon Savings in Residential Buildings

A. Construction Carbon Emissions and Savings						
					Carbon Savings	
Materials		Details	Conventional Emissions (t)	Sustainable Emissions (t)	in tons	%
A1	**Concrete**	Adm. Type F Ready-mix	1,456,592	1,097,614	358,977	25%
A2	**Steel**	EAF Route	88,788	80,783	8,005	9%
A3	**Bricks**	Fly Ash	755,756	206,869	548,888	73%
A4	**Other**	-	767,045	767,045	0	0%
Total (t)			**3,068,181**	**2,152,311**	**915,870**	**30%**

The results show that the potential savings in construction-phase emissions from middle-income residential buildings in Egypt is approximately 916 $KtCO_2$, which constitutes a 30% reduction to emissions relative to the base-case. This amount is substantial and is equivalent to avoiding the carbon dioxide emissions from the energy use of 75,819 homes annually. Most potential savings can be attributed to the use of fly ash bricks, which delivers 549 $KtCO_2$ in emissions savings equivalent to a massive 60% of the total. This is equivalent to avoiding the carbon dioxide emissions from the energy use of 45,442 homes annually. Sustainable concrete comes in second place and delivers 359 $KtCO_2$ equivalent to 39% of savings, which is equivalent to avoiding the carbon dioxide emissions from the energy use of 29,715 homes annually. Savings from applying the EAF route to steel production are negligible and amount to just 8 $KtCO_2$ equivalent to under 1% of the total savings.

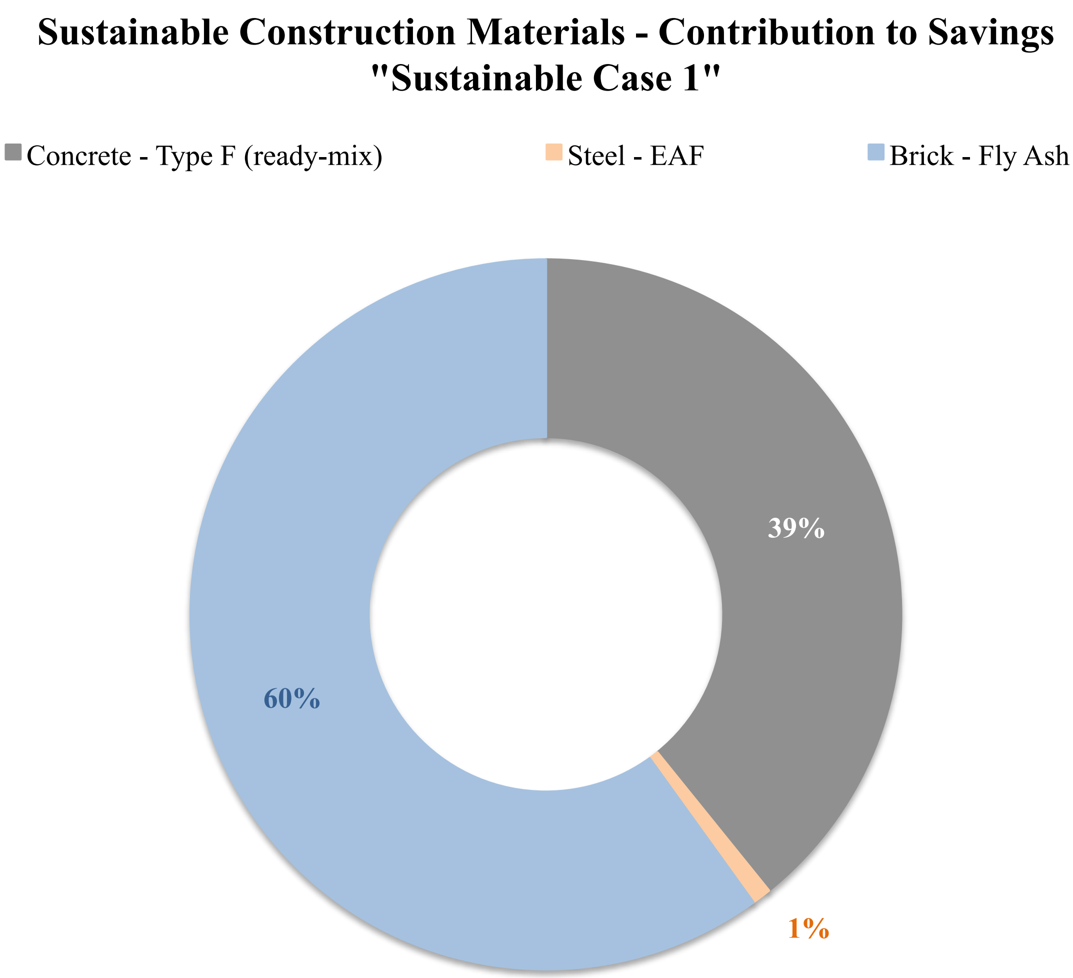

Figure 4.11 Construction Materials Contribution to Savings in Residential Buildings

4.3.2 Use-Phase Carbon Savings

As previously outlined in the middle scenario of Table 4.13 ("Most Savings in 50 years"), the combination of housing elements with most carbon savings is: (i) using LEDs for all lighting fixtures, (ii) using all Energy Star electrical appliances, including electric heaters rather than gas, (iii) replacing all single-glazed windows with low-e double glazed, and (iv) applying shading to all exterior walls with direct sunlight exposure. The savings from each element is summarized in Table 4.16, and illustrated in Figure 4.12.

Results reveal that potential carbon savings over the 50-year use-phase of middle-income residential buildings in Egypt amount to approximately 35 $MtCO_2$, equivalent to a 49% reduction to emissions relative to the conventional base case. This is equivalent to avoiding the carbon dioxide emissions from the energy use of 2,897,031 homes annually. Most savings can be delivered through the use of Energy Star electric water heaters, which achieve a 41% reduction in emissions relative to the use of conventional water heaters. Full window glazing (100% of all single-glazed windows) come second and promise 8.3 $MtCO_2$ in savings, equivalent to 24% of the total. This is equivalent to avoiding the carbon dioxide emissions from the energy use of 687,010 homes annually. Switching to LED lighting comes in third place with a promising reduction of 5.8 $MtCO_2$ equivalent to 17% of the total. This is equivalent to avoiding the carbon dioxide emissions from the energy use of 480,079 homes annually.

Table 4.16 Total Use-Phase Carbon Savings in Residential Buildings

B. Use Phase Carbon Savings			
	Carbon Savings		
Components	**in tons**	**%**	**Comments**
B1 Lighting			
a From CFLs			*- No CFLs are used*
b From LEDs	5,763,321	17%	
B2 Electrical Appliances			
a Air Conditioner	2,935,024	8%	
b Water Heaters			
i. Gas			*- No gas heaters are used*
ii. Electric	14,205,518	41%	
c Refrigerator	517,632	1%	
d Washer	1,515,540	4%	
B3 Envelope Modifications			
a Window Glazing			
100%	8,324,796	24%	*- Single glazed windows will be replaced by low-e double glazed*
b Wall Shading	1,440,297	4%	
Total Carbon Savings (t)	**34,702,128**		**in 50 years**

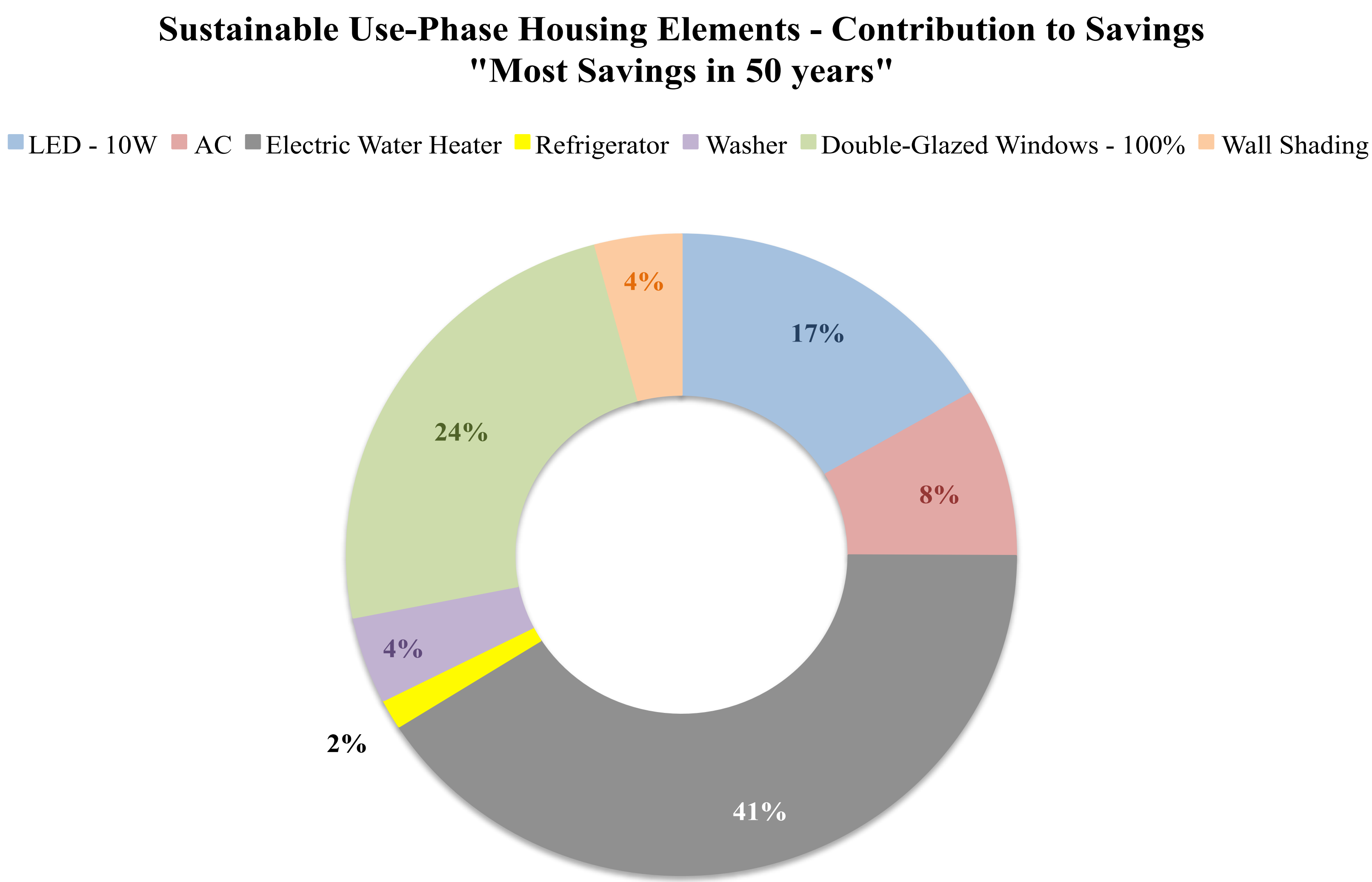

Figure 4.12 Housing Elements Contribution to Savings over the 50-year Use-Phase of Residential Buildings

4.3.3 Construction Versus Use-Phase Carbon Savings

The maximum amount of savings in both the construction phase and use-phase during a residential building's lifetime is summarized in Table 4.17 and illustrated in Figure 4.13. In the earlier years of a building's lifetime, efficiencies in construction are responsible for the largest share of potential emissions as compared to use-phase savings (57% to 43% in year 1). This ratio skews to the opposite direction as the building gets put to use. One-off savings due to construction remain unchanged since calculations do not include emissions from maintenance, refurbishments and demolition (which are assumed to be negligible for the purposes of this model). Use-phase savings continue to accumulate year after year as efficiencies from housing elements (lighting, appliances and envelope modifications) persist. By the end of a building's 50-year lifetime, use-phase savings can account for over 97% of total potential savings. For that reason, it can be safely concluded that the choice of housing elements is more crucial in determining the sustainability of a residential building as compared to construction materials.

Table 4.17 Construction and Use-Phase Contribution to Savings Over a Residential Building's Lifetime

Year	Construction Savings	Use-Phase Savings	Construction Contribution	Use-Phase Contribution
0	0	0	0%	0%
1	915,870	694,043	57%	43%
2	915,870	1,388,085	40%	60%
5	915,870	3,470,213	21%	79%
10	915,870	6,940,426	12%	88%
15	915,870	10,410,638	8%	92%
20	915,870	13,880,851	6%	94%
25	915,870	17,351,064	5%	95%
30	915,870	20,821,277	4%	96%
35	915,870	24,291,489	4%	96%
40	915,870	27,761,702	3%	97%
45	915,870	31,231,915	3%	97%
50	915,870	34,702,128	3%	97%

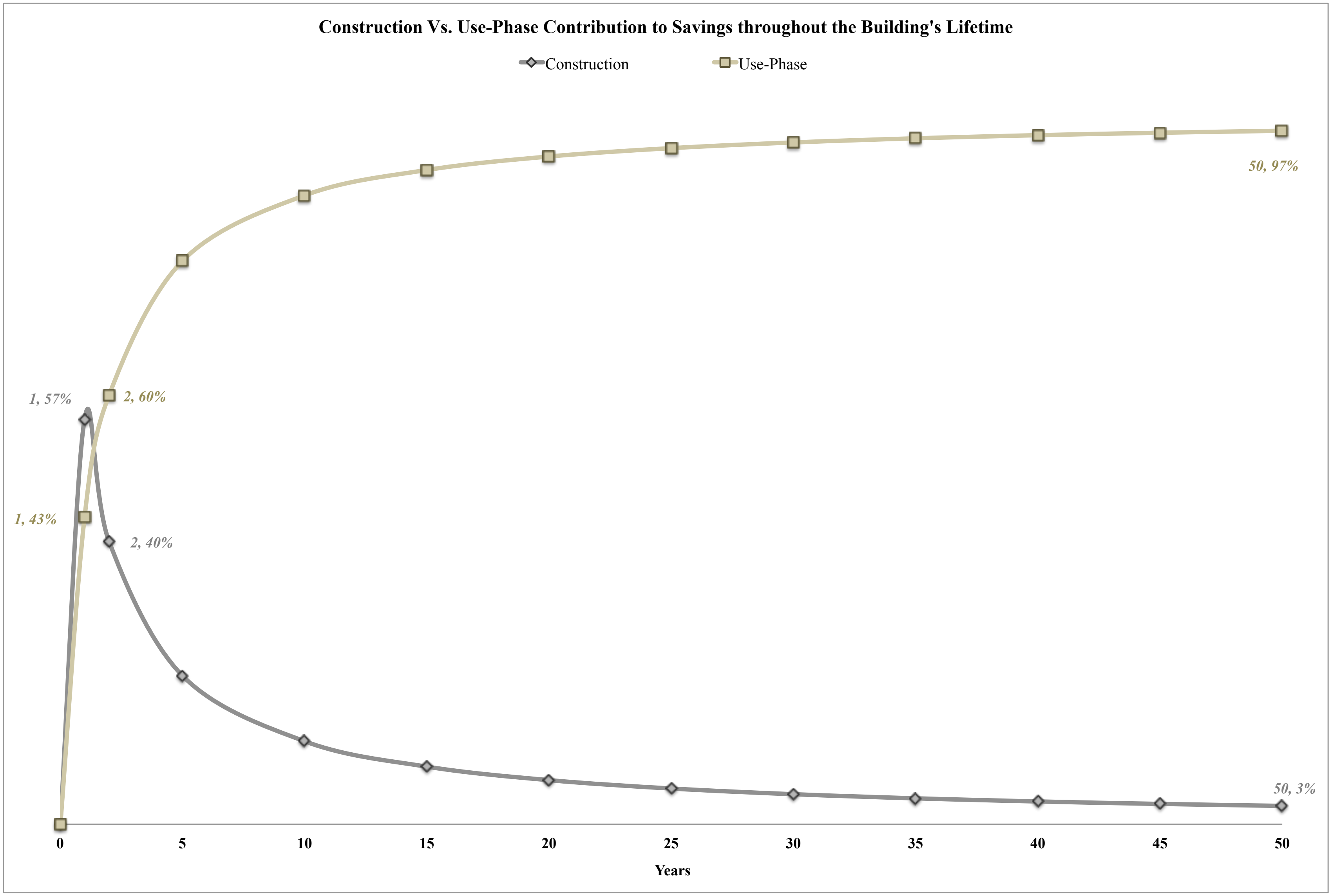

Figure 4.13 Construction and Use-Phase Contribution to Savings over a Residential Building's Lifetime

4.4 Monetization of Potential Carbon Savings

The estimated social cost of carbon in current terms (2015) as previously stated in section 3.4.3 is LE 304.4 per ton of CO_2. Applying this benchmark to the model's emission savings as summarized in Table 4.15 and Table 4.16 reveals a dramatic potential for financial savings equivalent to LE 10.84 Billion (of which LE 0.28 Billion can be attributed to the construction phase and LE 10.56 Billion can be attributed to the use-phase). These savings correspond to the middle-income housing sector only, and are limited to the past 12 years implying annual savings of LE 0.9 Billion. It can be safely assumed that corresponding savings across all building sectors are multiples more.

Reduction in CO_2 emissions can not only spare our environment from undesired side-effects, but can also play a major role in alleviating the corresponding costs to society. Table 4.18 summarizes the savings in tons and monetary values for both the construction phase and use-phase over the 50-year lifespan of a typical middle-income residential building in Egypt.

Table 4.18 Summary of Potential Savings in the Social Cost of Carbon in Middle-Income Residential Buildings in Egypt in the Past 12 Years

Savings Summary			
Construction Savings		**Use-Phase Savings**	
Tons	**EGP**	**Tons**	**EGP**
915,870	278,786,505	34,702,128	10,563,169,121
Total Carbon Savings			
Tons		**EGP**	
35,617,997		10,841,955,627	
Year(s)		50	
Construction Contribution		**Use-Phase Contribution**	
2.57%		**97.43%**	

Financial savings from carbon reductions are not limited to reduced social costs, but also to a reduction in the energy bills of customers and accordingly in the overall subsidy bill to government. This aspect of energy savings was not investigated in this study, but can be further examined in the future by reference to the Levelized Cost of Electricity (the economic assessment of the average cost per kilowatt-hour to build and operate a power plant) and the Marginal Cost of Electricity (an economic assessment of the cost of increasing electricity generation from one source versus others) in Egypt.

CHAPTER 5:
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In light of the methodology followed, data collected and other parameters associated with this study, the following can be concluded to all middle-income residential buildings in Egypt:

- Concrete is the largest driver of carbon emissions amongst all construction materials.
- The addition of chemical admixtures can reduce the amount of cement in a concrete mix by approximately 14% (if type F admixtures are added) and 7% (if type A admixtures are added).
- The addition of type A admixtures can reduce concrete emissions by 5%.
- The addition of type F admixtures can reduce concrete emissions by 9%.
- Ready-mixed concrete can reduce concrete emissions by an average of 15%. This is due to the elimination of the need to transport each individual concrete component to site.
- The EAF production route of steel consumes less energy than BF-BOF route and thus reduces carbon emissions by 9%.
- Bricks have the highest potential to save energy amongst all construction materials, as they are responsible for over half of potential savings.
- Non-fired bricks (concrete and fly ash) lead to lower emissions than fired ones (clay).
- Fly ash bricks are the most sustainable type of brick as compared to clay and concrete bricks. They can save up to 73% of carbon emissions as compared to conventional clay bricks.
- Concrete bricks can save up to 38% of carbon emissions as compared to conventional clay bricks.
- LEDs are the most sustainable types of light bulbs and have the highest potential of carbon and energy savings.
- Water heaters and air conditioners are the biggest drivers of carbon emissions amongst all other electrical appliances, and they can also contribute to most of the savings.
- Electric heaters have more potential in carbon savings than gas heaters.
- The use of solar water heaters can add an additional 11.8 and 28.6 $MtCO_2$ savings if they replace energy star electric and gas heaters respectively over their 50-year use-phase.

- Double-glazed windows can add additional carbon savings to a building.
- Wall shading can reduce cooling loads and consequently save a lot of carbon emissions.
- Emissions per square meter of a residential building can be reduced by ~31% if sustainable practices are adopted.
- Most carbon savings are attributable to the use-phase of a residential building.
- Annual savings of LE ~0.9 Billion can be realized in the social cost of carbon if sustainable practices are adopted in middle-income residential buildings in Egypt. Multiples more of this figure can be realized if all other building segments are considered.
- The potential savings identified in this work in relation to middle-income residential buildings erected in the past 12 years are still achievable. This is evidenced by the fact that most savings are driven by use-phase energy consumption patterns due to lighting, electrical appliances and envelope modifications. Immediate implementation of the energy efficient practices recommended in this work can still allow for the realization of a large share of these potential savings.

5.2 Recommendations for Future Work

There are several recommendations that can be followed during future work. They can be summarized as follows:

- Conducting this analysis with the incorporation of more construction materials to get a more detailed understanding of each material's contribution to carbon emissions and savings (ex: wood, ceramics, marble, paint)
- Considering carbon emission reductions from concrete with the use of recycled aggregates and mobile batch plants.
- Exploring more brick types (earth-compressed blocks and blended bricks with cement dust) to be used as alternatives to conventional clay bricks.
- Performing this analysis with more housing elements to get a more detailed analysis (e.g. heating, insulation, doors, day lighting).
- Re-applying this model for other building types by changing or adding any relevant numerical assumptions.
- Applying a similar model for the analysis of other construction segments, like roads where there remains a large potential for improvements.

- Calculating costs for each sustainable alternative with its payback period.

It is also important to consider renewable energy in all future work. The government of Egypt has embarked on an ambitious program of renewable energy development with the ultimate objective of generating 20% of the country's electricity from renewable energy resources. This has included passing legislation for private sector participation, the issuance of a unified feed-in tariff for developers, the tendering of large-scale wind and solar projects, amongst others. Public awareness is also growing towards energy conservation and the use of solar-powered appliances in homes where possible. These developments should have a positive impact on the country's carbon emissions, particularly as they relate to the construction and operation of residential buildings. This impact can be easily quantified using this work's model in two ways:

- The conversion factor of kWh to equivalent CO_2 emissions – adopted as 0.7 kg – can be dropped by up to 20% thereby allowing for a computation of emissions following completion of the government's plans for renewable energy.
- The emissions for water heating appliances – as an example – can be reduced in the model by the same ratio of homes using solar-heating panels. This adds to other justifications for the implementation of renewable energy appliances in housing.

Upon adoption, modification and maturity of the model developed in this work, a more sophisticated and target oriented software can be developed to produce more accurate assessments for carbon dioxide emissions in Egypt.

5.3 Recommendations for the Construction Industry

In light of the conclusions arrived at in this study, a number of recommendations for the construction industry has emerged. These are summarized in two categories. The first set comprises those that can be referred to as low-hanging fruits – meaning practices that can deliver immediate savings despite being easily and inexpensively adopted. The second set comprises practices that are more challenging and more time consuming to rollout across the industry.

Recommendations for Immediate Savings:

- Optimizing the concrete mix in any project to minimize the cement content, as this is the primary driver of emissions in concrete. This can be easily accomplished by enforcing legislation that forces local concrete manufacturers to restrict their production to energy-efficient mixtures.

- Conversion of all lighting fixtures to compact fluorescent given its huge potential for savings and its relative affordability. This can be easily accomplished by banning the importation and/or local production of incandescent light fixtures.
- Using electrical water heaters where possible as opposed to gas water heaters. This can be easily accomplished by an increase in the pricing of gas supplies to homes, the application of hefty customs and taxes on the sale of gas heaters.
- Shading of all windows to minimize heat gain and hence cooling requirements. This can be accomplished through a public awareness campaign across media and television to increase awareness of this issue and the potential for savings that homeowners can achieve through shading.
- Doing any necessary design changes that can reduce the amount of steel without compromising safety.

<u>Recommendations Requiring More Time for Adoption:</u>

- Forcing brick manufacturers to explore the fly ash alternative. This can be accomplished by offering tax breaks and incentives to those manufacturers.
- Conversion of all lighting fixtures to LEDs. This can be prioritized as a follow-up step to the CFL conversion also through similar government legislation.
- Conversion of all windows to low-e double-glazed units. This can be accomplished by forcing all developers and new homeowners to utilize these windows as a pre-condition to reducing building licensing fees.
- Institutionalizing sustainable architecture across the field to promote passive design strategies that can reduce use-phase electrical loads. This can be accelerated by testing architects for sustainable construction practices.

The application of the aforementioned recommendations can save tremendous amounts of energy in the construction industry and thus reduce carbon dioxide emissions. In addition to environmental benefits, sustainable practices are also economically positive and can substantially reduce energy bills in Egyptian homes.

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