Towards Displacing Domestic Air Conditioning in KSA

An Assessment of Hybrid Cooling Strategies Integrated with 'Fabric First' Passive Design Measures

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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2018

Declaration of Authenticity and Author's Rights

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.'

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List of Publications and Awards

- Hijazi, J., Howieson, S. (2017). *Displacing AC use in KSA: An Evaluation of 'Fabric First' Design Measures Integrated with Hybrid Night Radiant Cooling and Ground Pipe Supply Ventilation*. Published in Building Services Engineering Research and Technology (BSERT) in conjunction with the Chartered Institute of Building Services Engineers (CIBSE)**.**
- Hijazi, J., Howieson, S. (2017). *Efficiency Validation of Hybrid Cooling Application in Hot and Humid Climate Houses of K.S.A*. World Academy of Science, Engineering and Technology, International Scientific Index, Architectural and Environmental Engineering, *11* (8), 1062.
- Best paper presentation award, granted by the Scientific Committee of the International Scientific Research and Experimental Development for conference paper entitled "*Efficiency Validation of Hybrid Cooling Application in Hot and Humid Climate Houses of K.S.A"* submitted to the 19th International Conference on Modern Building Design Strategies and Planning, ICMBDSP 2017, London, UK

Acknowledgements

From the bottom of my heart, I thank Allah for enlightening my heart and granting me with the strength to be able to complete this PhD degree enjoying every moment of it. I am grateful to my supervisor, Dr Stirling Howieson, whose encouragement, guidance and support enabled me to present this work. Distinguished appreciation goes to the Department of Architecture at King Abdulaziz University in KSA for sponsoring me throughout the study. I gratefully thank my parents, my wife, and my children, to whom this work is dedicated, for their love, patience, and support.

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List of Abbreviations

AC	Air-Conditioning
ACH	Air Change per Hour
AHU	Air Handling Unit
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning
BP	British Petroleum
Btu	British thermal unit
CAD	Computer Aided Design
CAV	Constant Air Volume
CDSI	Central Department of Static and Information
CFD	Computational Fluid Dynamics
CFM	Cubic Feet per Minute
CIBSE	Chartered Institution of Building Services Engineers
CO_2	Carbon dioxide
COP	Coefficient of Performance
CPU	Central Processing Unit
CSO	Central Energy Statistics
CV	Control Volume
DOE	Department of Energy
DX	Direct Expansion
EER	Energy Efficiency Ratio
EIA	Energy Information Administration
EU	European Union
GAMEP	General Authority of Meteorology and Environmental Protection
GAS	General Authority of Static
GCC	Gulf Cooperation Council
GPCS	Ground Pipe Cooling Strategy
GSHP	Ground Source Heat Pump
GW	Giga-Watt
HCS	Hybrid Cooling System
HDPE	High-Density Polyethylene
HRCS	Hydronic Radiant Cooling System
HVAC	Heating, Ventilation, and Air-Conditioning

IAQ	Indoor Air Quality
IEA	International Energy Agency
JRCC	Jeddah Regional Centre for Climate
KACST	King Abdul-Aziz City for Science and Technology
Kg	Kilogram
KSA	Kingdom of Saudi Arabia
kW	Kilo-Watt
kWh	Kilo-Watt-hour
LCA	Life Cycle Assessment
LED	Light Emitting Diode
LEED	Leadership in Energy and Environmental Design
MEW	Ministry of Electricity and Water
MFGSHP	Multi-Function Ground Source Heat Pump
MOW	Map of the World
Mt	Mega-tonnes
mtoe	million tonnes of oil equivalent
MWh	Mega-Watt-hour
PCMs	Phase Change Materials
PCS	Passive Cooling Strategy
PDMs	Passive Design and Measures
PMV	Protected Mean Vote
PV	Photovoltaic
SEEC	Saudi Energy Efficiency Centre
SEC	Saudi Electricity Company
Sc	Shading Coefficients
TRNSYS	Transient System Simulation Program
TWh	Tera-Watt-hour
UAE	United Arab Emirates
UK	United Kingdom
UN	United Nations
USA	United States of America
VAV	Variable Air Volume
W	Watt
WBCSD	World Business Council for Sustainable Development
WEC	World Energy Council

Nomenclature

A	Area [m^2]
cp	Specific heat capacity at constant pressure [J/kg·K]
°C	Temperature degree celsius
COP	Coefficient of Performance [-]
D	Diameter [m]
h	Enthalpy [kJ/kg]
hc	Convective heat transfer coefficient [$W/m^2 \cdot K$]
H	Height [m]
k	Thermal conductivity [W/m·K]
L	Length [m]
ppm	Parts Per Million
R	Thermal resistance [m^2K/W]
RH	Relative humidity [%]
T	Temperature [°C]
U	Overall heat transfer coefficient [$W/m^2.K$]
V	Velocity [m/s]
w	Width [m]
V	Volume of the receiver tank [cu ft]
t	Time for the receiver to go from upper to lower pressure limits [min]
C	Free air needed [cfm]
Pa	Atmosphere pressure [14.7 psia]

Greek Symbols

ω	Humidity ratio [kg/ (kg dry air)]
ρ	Density [kg/m^3]
α	Thermal diffusivity [m^2/s]
f	Friction factor [-]
Δ	Change [-]
η	Fan efficiency [-]

Subscripts

a	Air
ama	annual mean ambient

amb	Ambient air
clo	Clothing thermal effect value
comf	Comfort temperature
dp	Dew-point
db	Dry-bulb
e	Moist air entering the cooling coil
ind	Indoor
inlt	Pipe inlet air temperature
L	Latent
optv	Operative temperature
out	Outlet air pipe
Pd	Partial Pressure
rad	Radiant temperature
S	Sensible
soil	Soil temperature
surf	Surface temperature
v	Ventilation
wb	Wet-bulb

Abstract

Reducing energy use and CO_2 emissions to curb global warming and climate change are the greatest challenges now facing mankind. The vast majority of energy generated from fossil fuels is burned to run vehicles, fuel power stations and cool or heat homes. Saudi Arabia, the world's largest producer and exporter of petroleum, currently consumes almost three times higher than the world average energy use and hence; ranked ninth among nations for CO_2 emissions. Among all fossil energy consumers, residential buildings use almost half of the Saudi's prime energy sources and are responsible for almost 50% of the emitted CO_2. In such a hot climate region, air conditioning (AC) of dwellings is by far the major consumer representing 69% of domestic energy use and drives peak loading. Future projections predict a continuous increase in energy use as the majority of existing buildings are poorly designed for the prevailing climate, leading to excessive use of mechanical AC. Therefore, it is crucial for Saudi Arabia to consider a horizon where hydrocarbons are not the dominant energy resource. The adoption of energy efficiency measures and low carbon cooling strategies may have the potential to displace a substantial percentage of oil currently used to run conventional AC plants.

Therefore, the current study investigates the viability of 'fabric first' intelligent architectural design measures, in combination with hybrid ground cooling pipes integrated with black-body radiant night cooling systems, with a specific purpose to displace AC systems and decrease the carbon footprint while sustaining year-round thermal comfort.

The interrogation of this hypothesis was addressed in three stages. The first stage was to generate a baseline analysis of the thermo-physical and energy performance of a typical residential block in Jeddah. The second stage involved developing an alternative low energy cooling approach that could handle high ambient temperatures. The task involved designing ground pipe ventilation integrated with high emissivity blackbody radiator to displace AC systems. The design of such 'hybrid' system required a parametric analysis combined with testing prototypes in field trials to establish actual ground temperatures at various depths and black body emissivity ranges under different sky conditions. This hybrid system became the subject of numerical modelling and simulation using DesignBuilder software in conjunction with EnergyPlus simulation engine. The third stage was to assess the simulation results and validate the cooling efficiency and cost-effectiveness of the hybrid system compared to the baseline.

The preliminary results of prototype thermal simulation and field trials suggest that 'fabric first' passive designs and measures (PDMs), combined with night hydronic radiant

cooling (HRCS) and supply ventilation via ground pipes (GPCS), can negate the necessity for a standard AC system by displacing over 80% of cooling demand and lower the carbon footprint of a typical housing block by over 75%. Such passive and hybrid system applications also have a remarkably short payback period with energy savings offsetting the capital costs associated with building thermo-physical enhancement.

1 CHAPTER | Introduction

1.1 General Context

1.1.1 Energy Trend: Global Issues

Reducing energy use and CO_2 emissions to inhibit global warming and climate change are probably the greatest challenges now facing humanity (World Bank, 2013). Due to population growth and industrialisation in developing nations, humanity's consumption of primary energy has reached unprecedented levels (CSO, 2017). Almost half of this energy being generated from fossil fuels extracted from 'deep earth' (BP, 2016). According to a recent report by the World Energy Council (WEC), since the beginning of commercial oil drilling circa 1850, more than 135 billion tonnes of crude oil has been burned to run cars, fuel power stations and cool or heat homes and our use continues to increase on an almost daily basis (WEC, 2015). An investigation carried out by the US Energy Information Administration (EIA) estimates that global consumption of energy will grow by around 70% by 2030 (EIA, 2015).

The World Energy Council has reported that among all fossil energy consumers, the building industry is considered as one of the main users (WEC, 2015). Construction uses almost 40% of the world's prime energy sources and is responsible for almost 70% of emitted oxides of Sulphur and 50% of emitted CO_2 (WEC, 2015).

An investigation conducted by US Energy Information Administration in 2014 (EIA) has stated that Saudi Arabia is the world's largest producer and exporter of petroleum produces an average of 11.6 million barrels per day, exporting an estimated 8.6 million (Figure 1.1)(EIA, 2014). According to (EIA), Saudi Arabia produces more than three times as much oil as the next largest member of the organisation of the petroleum exporting countries (OPEC), and as much as the rest of the Arab Middle East put together (EIA, 2014).

The latest report of EIA indicated that, in 2014, Saudi Arabia consumed approximately 3 million barrels of oil per day (272 billion kWh compares with 309 billion kWh for the UK with more than double the population)(EIA, 2014). The primary energy consumption per capita was 7.9 tons of oil which is 3.6 times higher than the world average, at 1.9 tons (Figure 1.2) (EIA, 2014).

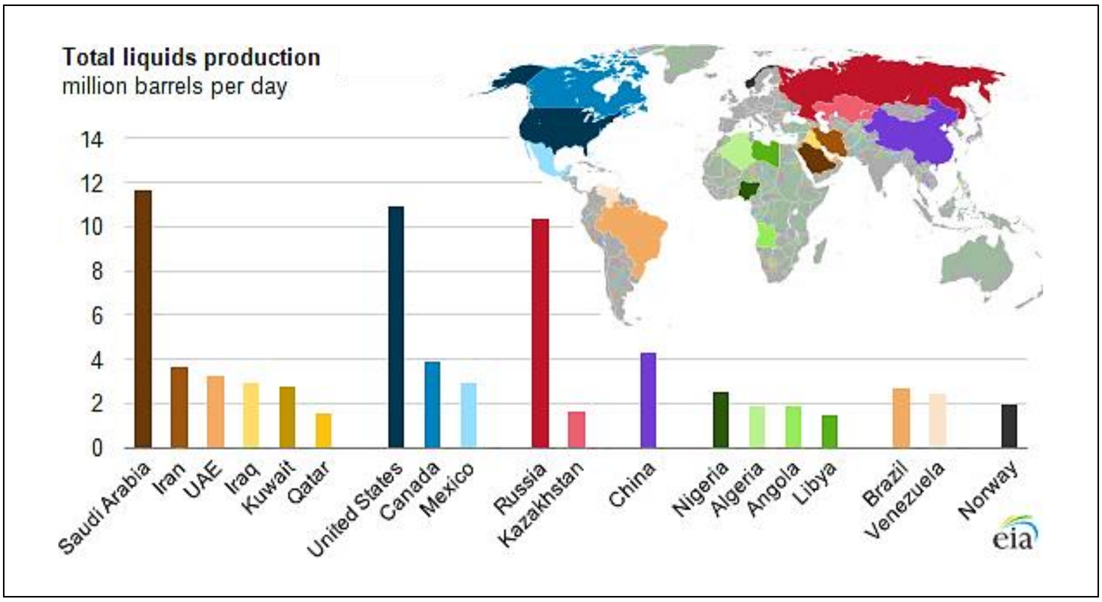


Figure 1.1: Statistics show the total liquid (oil) production per million barrels by country (EIA, 2014).

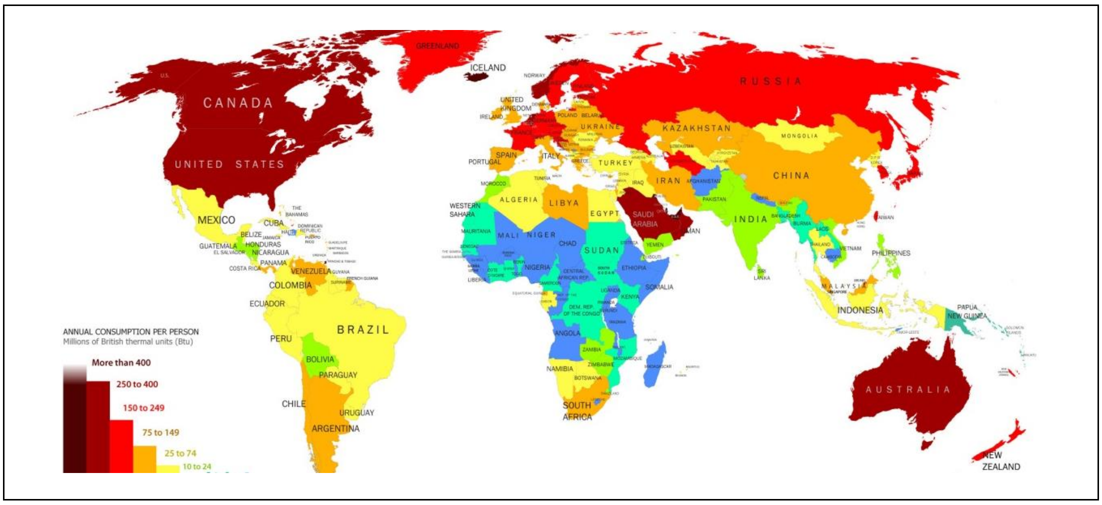


Figure 1.2: Statistics show the energy consumption per person by country (EIA, 2014).

In Saudi Arabia, the consumption of petroleum products represents the bulk of the countrie's fossil-fuel CO_2 emissions (EIA, 2014). In 2014, Saudi Arabia ranked ninth among nations for CO_2 emissions (494,000 metric tons of carbon equating to16.8 metric tons per capita), that represented 1.38% of the total global CO_2 emissions and almost double the European average CO_2 emission at 7.9 metric tons per capita (Figure 1.3) (EU, 2016). Given that oil is a finite resource and climate change agreements may limit future exploitation, it is crucial for Saudi Arabia to consider the adoption of energy efficiency measures and low-carbon cooling strategies.

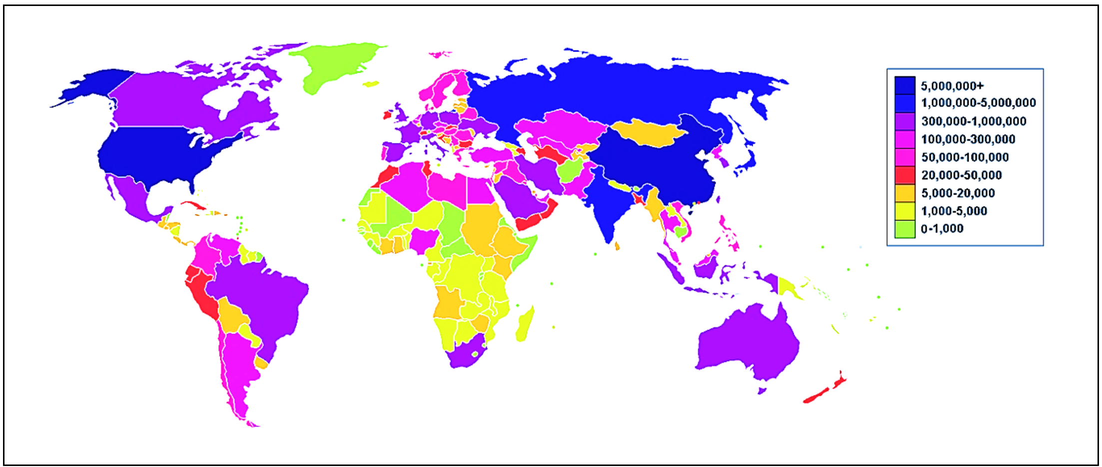


Figure 1.3: Countries carbon dioxide emissions in thousands of tons per annum (World Bank, 2013).

1.1.2 Domestic Energy Use and Cooling Demand

According to the annual report conducted by Saudi Electricity Company (SEC), electricity generation represents 34% of Saudi Arabia's internal oil consumption. The demand for electricity has doubled since 2004 (Figure 1.5) and is expected to continue its rapid growth as a result of economic development, population growth and the absence of energy conservation measures (SEC, 2015)

Buildings sector form almost 77% of the total electrical energy consumption while residential buildings consume more than half of the total building energy use. Air conditioning of dwellings is by far the largest user representing 69% of domestic energy use and responsible for driving peak loading that presently demands additional capacity (Figure 1.4)(SEC, 2015).

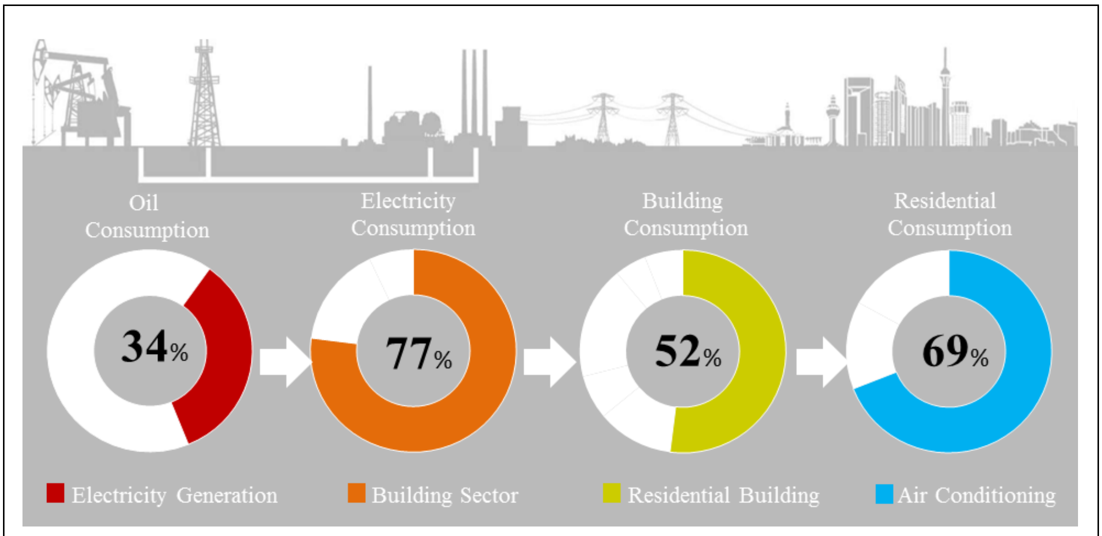


Figure 1.4: Percentage of Saudi energy use per sector (SEC, 2015).

Electricity consumption has increased dramatically in the last two decades from 1152200 GWh in 2004 to 275863 GWh in 2014 (Figure 1.5)(SEC, 2015). In 2014, the energy use in the residential sector was almost 144627 GWh (52% of the total energy for all sectors) and demand is increasing annually by 6.4% (SEC, 2015). As one barrel of oil is required to generate 1628 kWh, an annual consumption of 144627 GWh of electricity requires approximately 88 million barrels of oil (SEC, 2015).

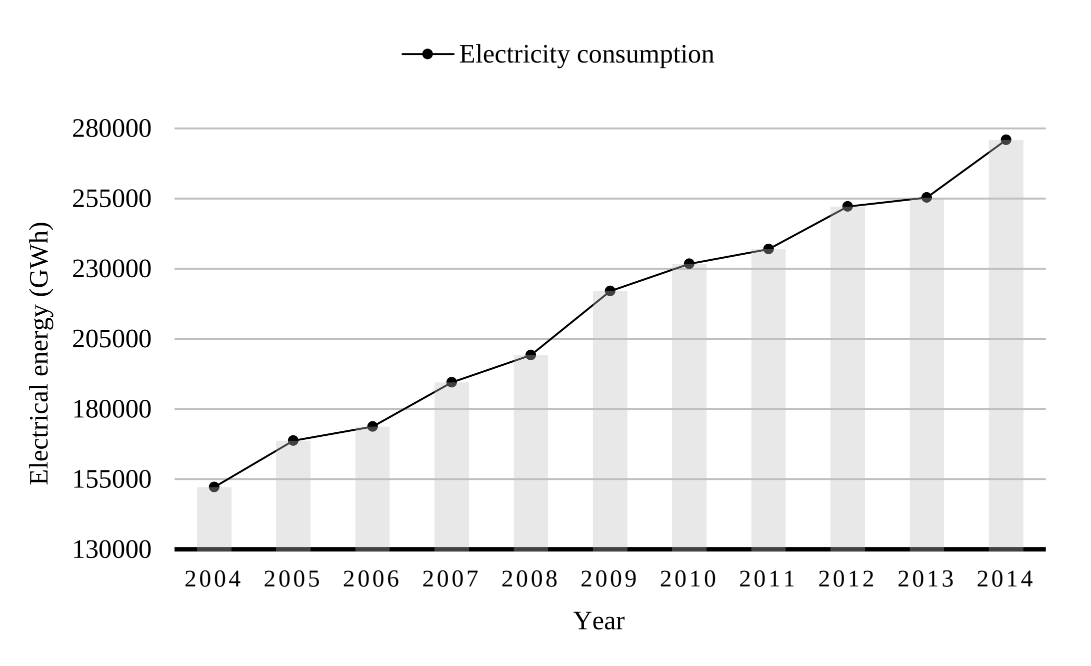


Figure 1.5: Electricity consumed in Saudi Arabia from 2004 to 2014 (SEC, 2015).

In July 2014, Saudi Arabia burned an average of 0.9 million barrels per day of crude oil, the highest ever recorded by Joint Organisations Data Initiative (JODI) data for the month of July and the highest overall since August 2010 (JODI, 2015). According to the Saudi Electricity Company (SEC), the peak electricity load hit its highest demand during that particularly hot summer, with peak demand rising by 10.2% to 62,260 megawatts (MW) from 56,547 MW a year earlier (SEC, 2015). The state-run company electricity supplier was prompted to commission 4,516 MW of additional power generation capacity, by building 22 new power transfer units and facilities. This represents an annual growth somewhere between 6 to 8% (SEC, 2015). SEC currently spends 40 billion (Saudi Riyal) to 60 billion SARs a year to meet such demand (SEC, 2015). The monthly total electricity consumption in the KSA reflects the demand for air conditioning in the summer months when electricity demand is double of that in the winter (Figure 1.6) (SEC, 2015).

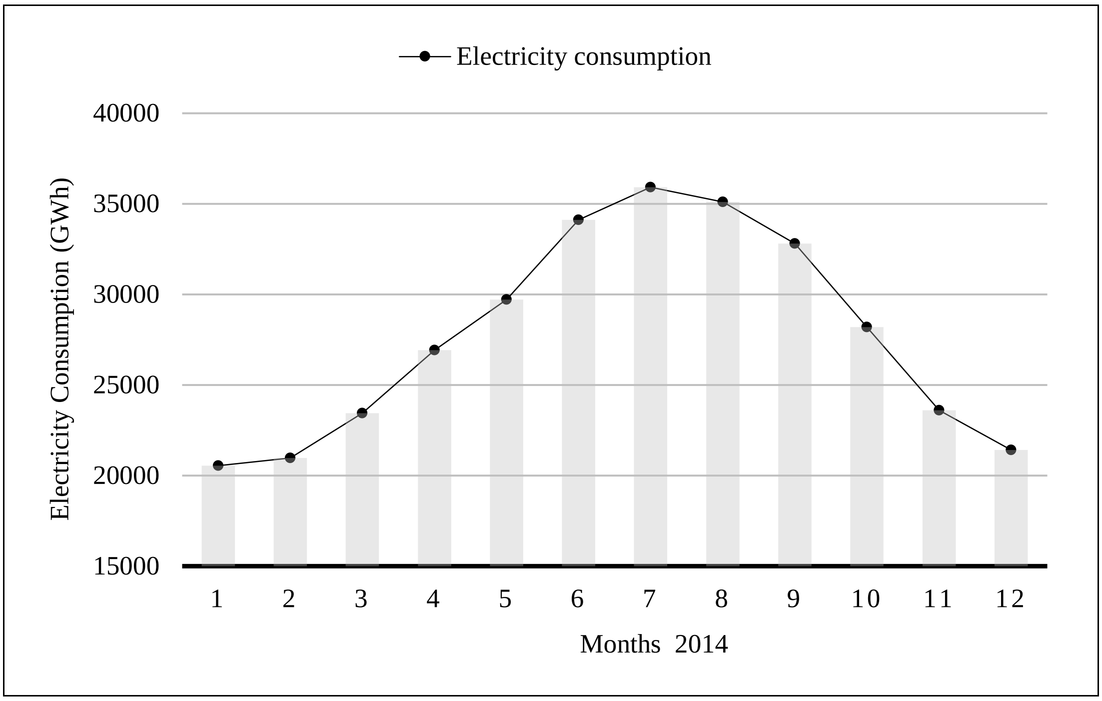


Figure 1.6: Average monthly electricity consumption of KSA (SEC, 2015)

According to the Saudi Central Department of Statistics and Information (CDSI), the population of Saudi Arabia reached 29,994,272 in 2013 and is likely to reach 37,610,985 by 2025 (CDSI, 2015). This has required a major response from the building industry to provide new homes. Therefore, the Saudi Ministry of Housing (SMH) has set a target of 214,433 residential units per year and one million new homes by 2020 to meet the needs of the growing population (SCRIBD, 2015). Such rapid growth will result in further energy demands for air condition new dwellings, with a consequential economic and environmental cost.

Saudi Energy Efficiency Centre (SEEC) has attributed the current excessive domestic energy use and cooling demand to poor building standards with almost 70% of the current dwellings having no thermal insulation (SEEC, 2015). The absence of such energy efficiency standards in the construction industry has led to an assortment of low-quality buildings (SEEC, 2015). The relatively low cost of electricity (0.17 SR/kWh or 0.034 GBP/kWh) does not provide any incentive to apply energy efficiency measures or increase the capital cost of construction (SEEC, 2015). Prices are however starting to rise above the rate of inflation and this will allow such measures to have a shorter pay-back.

1.1.3 Cooling Energy Saving Potential

The rapid expansion of AC usage in the building industry has several disadvantages in addition to excessive energy consumption and growth in peak electricity demand, including environmental issues such as CO_2 emissions, global warming, ozone depletion and indoor air quality (Alshehry & Belloumi, 2015). Alternative solutions have to be developed to move from active cooling systems to passive or hybrid techniques that can reduce prime energy usage while maintaining internal thermal comfort. Vernacular architecture has historically produced several strategies for cooling buildings in hot climates such as the use of clay to provide thermal inertia, small windows openings to increase shading and where possible the use of internal courtyards and ponds - sometimes in conjunction with stack ventilation (wind towers) to induce air movement – to produce evaporative cooling.

Modern techniques have built upon these vernacular strategies to control solar gain and minimise internal heat build-ups by retrofitting the building fabric (over-cladding) or utilising renewable energy sources (solar or wind) in combination with heat sinks such as black body radiant emissivity to a clear night sky or to soil or water (Givoni, 1983).

Most of the developed countries have reacted to this energy imperative by developing sustainable energy codes and have established legislation and building regulations based on local climate and dwelling typology (Al-Ajlan et.al, 2006). In 2010, the Government of KSA established the Saudi Energy Efficiency Centre (SEEC), and energy efficiency has now been identified as a 'national priority'(SEEC, 2015). One of the main objectives of the SEEC is to produce a national energy efficiency plan in order to rationalise and reduce energy usage in the country (SEEC, 2015). Saudi Arabia has moved to develop and implement energy efficiency standards and mandates in key sectors and educate end users to potential savings. These standards are focused on high-value actions in the building sector (SEEC, 2015). New buildings are now required to be insulated to a 'basic level'. Improving the efficiency of air conditioning units is a priority as they have the highest usage (Atalay, Biermann, & Kalfagianni, 2016).

KSA is now attempting to take a lead in the region's emerging trend towards the adoption of alternative and renewable sources of energy for cooling purposes (Abd, Ali, Al-Sulaihi, & Al-Gahtani, 2013). With almost 3245 hours of sun per year (equating to 2300 kWh/m^2), KSA has the potential to exploit existing solar energy systems. The total installed capacity of solar photovoltaic (PV) is currently 4.4 MW and another 10 MW is under construction (SEEC, 2015). A study on the wind characteristics in the Eastern Province has indicated the potential and economic viability of wind for electricity generation. (SEEC, 2015). The authority is considering grid-connected wind farms and wind-diesel hybrid systems (SEEC, 2015).

According to Frost & Sullivan's recent study on 'Energy Efficiency in KSA', a critical challenge to the development of the Saudi Arabian energy-efficiency market is a lack of awareness amongst end users. KSA needs to incentivise the adoption of new technology to reduce energy consumption, provide more autonomy for energy related organisations and create awareness about the need to conserve energy as well as educating the end user with respect to the proposed increase in real energy prices (Taleb, 2014). As on-going industrial development in the Kingdom is expected to raise the energy demand further (Lahn & Stevens, 2011) Frost & Sullivan have recommended implementation of a transparent building model, showcasing periodic reduction in operational costs for both new as well as existing buildings, to support architectural and environmental solutions that reduce energy demand. They have also produced a range of guidelines for the design of sustainable low-energy dwellings (Frost & Sullivan, 2012).

1.2 Problem Statement and Research Questions

In KSA, the annual demand for electricity and CO_2 emissions have increased over the last two decades due to population growth and low electricity tariffs. Residential buildings consume a significant proportion of electrical energy especially during the summer where almost 70 % of the prime energy is attributed to air conditioning (EIA, 2014). The hot climate in the region and the corresponding operation of air conditioning systems accounts for exceptionally high levels of energy consumption and CO_2 emissions per capita. Future projections show energy consumption continuing to increase as almost all existing buildings are poorly designed for the prevailing climate, leading to the almost continuous use of mechanical air conditioning (SEEC, 2015). Therefore, these critical problems are giving an explicit indication of the significance of this study and raise several pertinent questions:

a) What strategies and/or systems can be adopted to minimise the energy use in the domestic sector?
b) To what extent can passive strategies be applied to existing house typologies and will their performance be able to provide the desired thermal condition for its occupants particularly in peak summer?

c) What is the possibility of hybridizing passive techniques with low energy active cooling system to perform a viable mixed mode or Hybrid Cooling System (HCS) to substitute the current employment of AC towards limiting cooling energy usage while ensuring a degree of thermal 'safety'?

d) To what extent can HCS be integrated with the current thermo-physical performance of building's fabric and envelope and what additional measures are required to be taken to ensure that such strategies are both efficient and cost-effective?

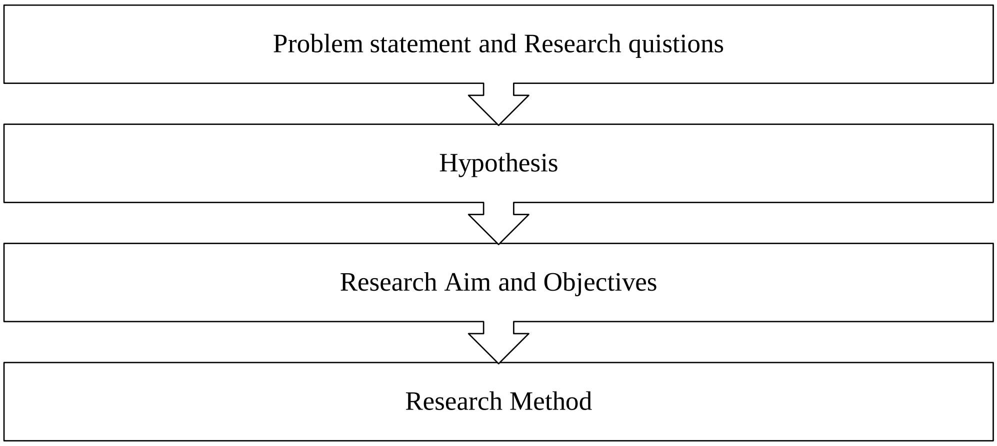


Figure 1.7: Flowchart of the logical sequence of research process.

1.3 Research Hypothesis and Study Context

The demand for cooling in any building is related directly to the environmental and climatic conditions. The challenge is therefore to develop design paradigms integrated with low energy passive and active cooling systems (possibly in synergistic combination) that can displace the existing AC systems. Although a 'fabric first' approach may be sufficient in moderate climatic conditions it is unlikely to perform in the KSA where summer temperatures can be excess of 45ºC. Passive Design Measures (PDMs) including the optimisation of a building's thermo-physical performance and fabric, such as window shading and insulated glazing systems, wall and floor insulation and increased thermal mass, may be required in order to sustain and enhance the cooling efficiency of any applied passive or hybrid cooling approach. The task is therefore to assess whether such an approach can be cost-effective. How quickly can potential energy savings pay back the additional costs of novel hybrid systems that are integrated with 'fabric first' passive design measures?

1.4 Research Aim and Objectives

This research aims to present an investigation into the viability of 'fabric first' intelligent architectural design measures, in combination with passive and active cooling systems operating in hybrid combination. The specific aim is to displace air conditioning and reduce carbon emissions, while maintaining year-round thermal comfort, in a typical urban housing block in Saudi Arabia. The specific objectives of the research are:

a) To assess the current energy use and mechanical cooling approaches in existing dwelling typologies.
b) To identify the reasons for the high cooling energy demand in current dwellings.
c) To determine the actual thermo-physical performance of a housing block's envelope and fabric in current house typologies in Saudi Arabia.
d) To investigate the potential implementation of a range of viable passive design measures aimed at reducing heat gain and cooling load.
e) To develop HCS combined with passive measures and test their influence on reducing cooling energy consumption, CO_2 emissions while ensuring indoor comfort is maintained throughout the year.
f) To estimate the capital and life cycle running cost of the applied PDMs and HCS and calculate the payback timeframe.

1.5 Research Uniqueness and Contributions

There is a lack of awareness and consideration of the potential integration of cooling systems with the architectural design strategy (building fabric and layout). This research therefore aims to bridge the gap between building designers and building physicists, by developing an integrated mixed mode "hybrid" cooling system, combining passive cooling strategies with low energy active cooling technologies. The contributions of the present research to the body of knowledge are summarised as follows:

a) To develop innovative hybrid low energy cooling systems and explore techniques to integrate this approach with the building layout and fabric, to create a dwelling typology for KSA that is 'sustainable'. The design framework will address such aspects as architectural design and the thermo-physical performance to enhance the efficiency of any proposed cooling system with the aim of encouraging building professionals to design low energy buildings in Saudi Arabia. Such an ambition will not be exclusive to KSA as many aspects will be applicable in countries with similar climates, such as the other GCC countries.

b) To promote public awareness and create a more positive consumer attitude towards energy efficiency by establishing new standards.

c) To define a new benchmark for energy efficiency in the domestic sector in Saudi Arabia. Targets need to be set for building performance in terms of heat loss/heat gain parameters (cost per kWh/m^2 p.a. to maintain an agreed indoor temperature regime) that can drive the necessary changes that will require to be enshrined in mandatory building codes.

d) To develop hybrid systems that can be cost-effectively retrofitted into the existing stock. The relatively poor performance of the existing stock will require to be addressed if current targets and timescales are to be achieved. The solution may, therefore, be found in a dual approach, ensuring new building meet much higher standards while simultaneously retrofitting the existing stock using techniques and systems that are both practical and cost-effective.

e) To support and enhance the developing energy efficiency program in KSA. This body of research aims to produce a cost-effective low energy building typology that will not compromise human comfort.

1.6 Research Challenges and Limitations

a) ***Climate*****:** Saudi Arabia is a country with considerable climatic diversity; hot and arid, hot and humid and mountainous. Each climatic type requires separate analysis. The challenge is to ensure that any new approach is applicable to all areas/climate.

b) ***Available statistical information***: It proved problematic to obtain accurate statistics on residential electricity consumption and indoor temperatures due to such factors as the diversity of houses sizes, construction, and the mechanical cooling systems; system types such as split, through the wall (window) and/or central air conditioning. Problems were also encountered calculating fluctuating electricity tariffs and actual consumption in terms of real costs over specific timeframes.

c) ***Literature review:*** There is a relative paucity of information on how to employ passive or hybrid cooling systems in such climatic conditions. This was viewed as an opportunity to start developing appropriate systems and techniques to model and trial.

d) ***Computer simulation:*** Before implementing any strategy, computer simulations are required to test a range of potential options. Most of the available energy simulation software packages are limited in their ability to model such novel passive and active hybrid cooling strategies, particularly in hybrid combination. The only viable method was to use a combination of system modelling and simulation with mathematical equations supported by testing prototypes in field trials that could at least quantify the margin of error.

e) ***Barriers:*** The implementation of such research faces a range of human factors; the difficulty in imposing a new style and pattern of building especially in the presence of traditional construction systems and the absence of any building codes that are climate specific. The ease of use and simplicity of existing control mechanisms in combination with what is effective, a heavily subsidised electricity tariff has historically provided no significant financial incentives. There is also an apparent a lack of awareness about climate change and its potential catastrophic side effects.

1.7 Research Structure

a) ***Chapter 1** | Introduction*:

An introduction to the background and an overview of the research field, explaining the context and outlining energy profiles for cooling in Saudi houses. In addition, this chapter presented the hypothesis, the aims and objectives and the specific research questions. It also purports to outline the novel contributions to the body of knowledge, alongside a description of the challenges and limitations encountered.

b) ***Chapter 2** | Literature Review:*

This chapter reviews relevant studies of cooling strategies in hot humid climates and discusses the recent contributions of other researchers in this field. The review covers the current residential cooling system that is typical of existing Saudi typologies. This review also contains a focused review conducted to investigate the main principles and essence of some viable Passive Cooling Strategies (PCS) that have been utilised in hot humid climates. Finally, the review discusses the potential benefits that can accrue from adopting HCS as an alternative cooling strategy in KSA.

c) ***Chapter 3*** *| Research Methodology*:

This chapter provides a description and justification of the research paradigm, the specific methods and strategies adopted and an assessment of their applicability and practicality. This chapter aims to clarify and rationalise the selected research approach in response to the research questions. The third section presents the research methods, strategies and instruments to be employed at each stage. The fourth section outlines the key research stages, the process and the conceptual framework.

d) ***Chapter 4*** *| Residential Energy Scenario and Thermal Performance in KSA: Case Study*

This chapter presents the general background study outlining the current residential energy profiles of the main dwelling typologies in Saudi Arabia. This includes a numerical modelling and simulation study of the chosen block design (existing typical flat complex in Jeddah) including the actual thermo-physical and energy performance of the case study building. The analytical study includes specifying the acceptable thermal comfort level based on building energy simulation, the predicted indoor conditions, and the adaptive model of human comfort parameters in this specific region.

e) ***Chapter 5*** *| Developing Low Energy Hybrid Cooling System HCS*

This chapter discusses the principles of a building cooling hierarchy, including some key passive design measures PDMs that can be applied to minimise external and internal heat gain and cooling loads. These strategies involve considering building appropriate orientation and spatial organisation, lighting (natural and artificial), window shading and glazing dimensions, appropriate material selection and the integration of vegetation. This chapter focusses on hybridizing passive cooling strategy to be integrated with low energy active cooling technology towards optimising the overall cooling performance. This section involves designing ground pipe supply ventilation integrated with high emissivity blackbody radiator to displace AC system. The design of such 'hybrid' system includes a parametric analysis combined with testing prototypes in field trials to establish actual ground temperatures at various depths and black body emissivity ranges under different sky conditions.

f) ***Chapter 6** | Numerical Modelling and Simulation of HCS Application.*

This chapter reports on the modelling and parametric simulations of the applied HCS using DesignBuilder software in conjunction with EnergyPlus simulation engine as the chosen simulation tool and based on initial field measurements and system design. This chapter performs a comparison of simulation results between the developed cases with initial baseline obtained in chapter 4. The simulation process aims to measure the actual impact of PDMs and HCS applications on heat gain, cooling energy consumption and indoor temperatures. The results of this simulation are then tested against statistical and mathematical formulas to provide a comparison and first pass validation. This was an attempt to assess the accuracy of the program given the complexity of the input data and boundary conditions. Further validation using physical models and longitudinal thermo-graphic data capture would allow the margin of error to be further quantified.

g) ***Chapter 7** | Efficiency Validation of HCS Application.*

This chapter presents a critical assessment of PDMs and HCS energy efficiency in controlling heat gain and cooling load and estimating the cooling energy saving as a result of the applied cooling system and compares this with the baseline case. It considers the possible improvement in the indoor thermal environment and the potential scale of the reductions in CO_2 emissions. The capital and life cycle running cost of the applied HCS with an estimated payback comparison with the baseline is also included.

h) ***Chapter 8** | Research Conclusion and implication.*

These chapter summaries the key research findings including the impact of HCS applications on the energy performance of existing and new dwellings. It provides answers to the research questions under consideration. The chapter concludes with an outline of suggested future research work and recommendations for researchers, decision-makers, architects, developers and homeowners with the aim of maintaining indoor comfort and utility while significantly reducing cost and carbon emissions.

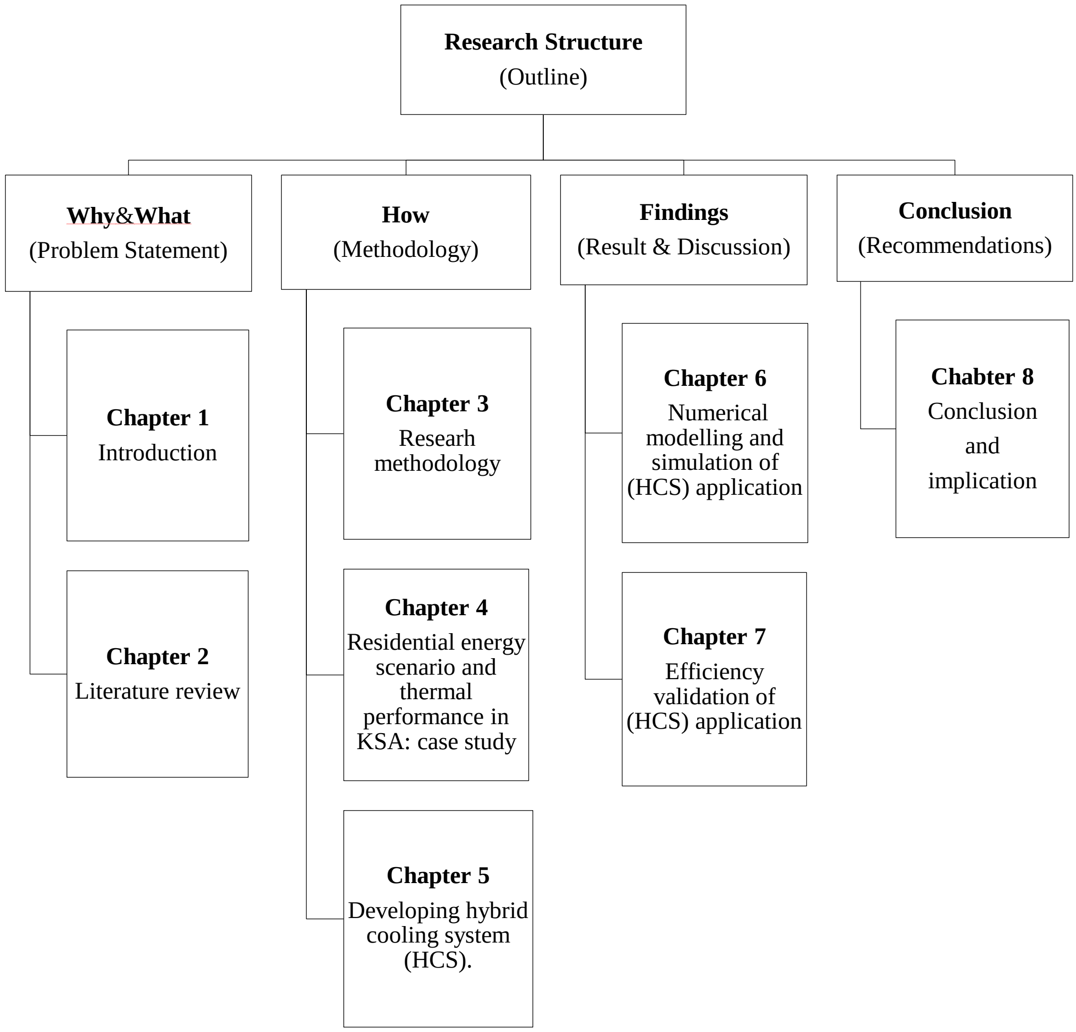


Figure 1.8: Research structure and outline.

2 CHAPTER | Low Energy Cooling Approaches in Hot and Humid Climate: Literature Review

2.1 Introduction

As an introductory section, this chapter starts by presenting the general background of KSA including geographic, location and climatic conditions followed by a review of the typical current approaches to cooling Saudi's buildings. Thermal comfort of building's occupants in hot and humid climate is outlined in this chapter including the key factors that affect thermal comfort. The recent review of literature involves investigating the employed cooling approaches in hot humid climates including the current application of active mechanical AC systems and the potential options for passive and hybrid cooling strategies in hot and humid climates which include: ground pipe ventilation and nocturnal 'black body' radiant cooling strategies and their potential to be used in synergistic hybrid combination.

2.2 KSA Background Study

2.2.1 Location

The Kingdom of Saudi Arabia is located between latitudes 16° and 33° N, and longitudes 34° and 56° E and situated in the Southern-Eastern part of the Asian Continent; Comprises about four-fifths (approximately 80%) of the Arabian Peninsula and about one-fourth the size of the continental United States (Table 2.1) (NationMaster, 2013).

Saudi Arabia has a strategic location as it is situated in heart of the Middle East between the Arabian Gulf and the Red Sea (Figure 2.1) (GAS, 2015). It borders Jordan, Iraq, and Kuwait to the north, Yemen to the south, and Oman, the United Arab Emirates (UAE), and Qatar to the east (GAS, 2015).

The estimated size is around 2,149,690 km^2 as the world's 13th largest area (GAS, 2015). It has 1700 km of Western Coast along the Red Sea and 560 km of Eastern Coast along the Arabian Gulf. The total land boundaries in the South and in the North exceed 2,700 km (GAS, 2015). Geographically, Saudi Arabia is dominated by desert in the south and eastern region. A number of linked deserts includes the 647,500 km^2 "Rub' al Khali" which means (Empty Quarter) in the southern part of the country, the world's largest desert (NationMaster, 2013).

The country, which is divided into 13 provinces, is composed primarily of the desert (Figure 2.1)(GAS, 2015). With a land area of about 2,149,690 km^2, there are numerous cities in Saudi Arabia (NationMaster, 2013). Each of them varies from the other in various aspects such as climate, vegetation, soil, people, culture, infrastructure, trade, etc (NationMaster, 2013). Riyadh is the largest Saudi Arabian city (NationMaster, 2013). The inhabited land area of this capital city of Saudi Arabia exceeds 1600 km while other important cities include Jeddah, which is the second largest city and main seaport in the Red Sea (GAS, 2015). Makkah, one of the two most important pilgrimage centres for Muslims where the holy mosque is located (GAS, 2015). Apart from the above cities in Saudi Arabia, there are many other large cities such as Abha, Hail, Dammam, Najran. (Table 2.1) (GAS, 2015).

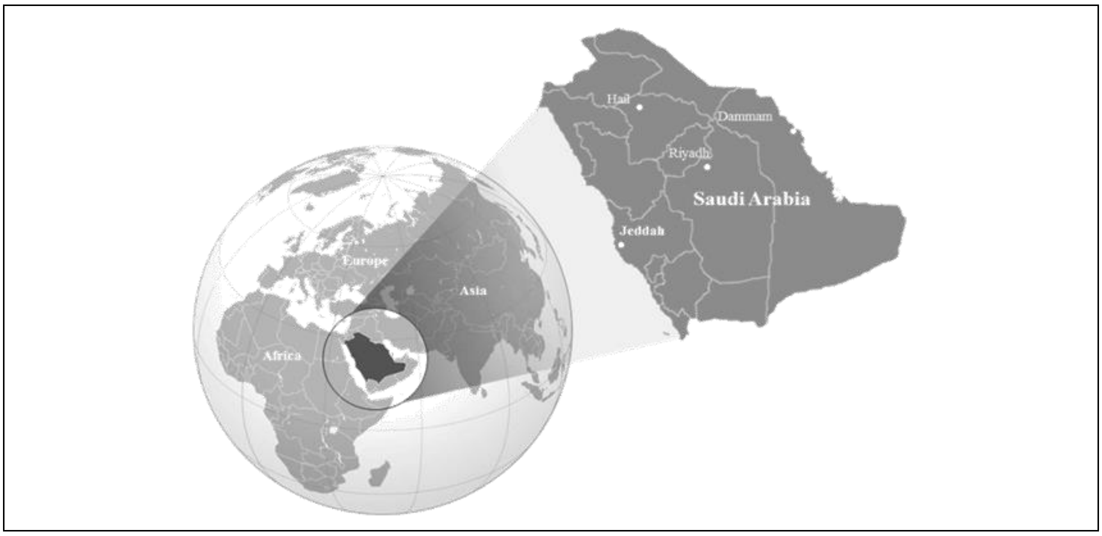


Figure 2.1: Location and province of Saudi Arabia.

Continent	**Southwest - Asia**
Area	2,149,690 km²
Population	30,770,375 (2014 estimate)
Latitude Long	16° and 33° N, and longitudes 34° and 56° E
Capital and main cities	Riyadh – Jeddah – Makkah – AL Dammam - Hail

Table 2.1: Facts and numbers about Saudi Arabia (GAS, 2015)

2.2.2 Climate

Saudi Arabia is characterised by extreme heat during the day, with a sudden drop in temperature at night and very low annual rainfall (GAS, 2015). As a result of a subtropical system, there is a huge variation in temperature and humidity (GAS, 2015). The two main differences in the climate of Saudi Arabia can be felt between the coastal areas and the interior (GAS, 2015). Saudi Arabia is among a few numbers of countries around the world where temperatures reach above 45°C during the summer period (World Bank, 2014). On the other hand, there can be snow or winter frost forming in the mountains of the southern highlands (Figure 2.2) (World Bank, 2014).

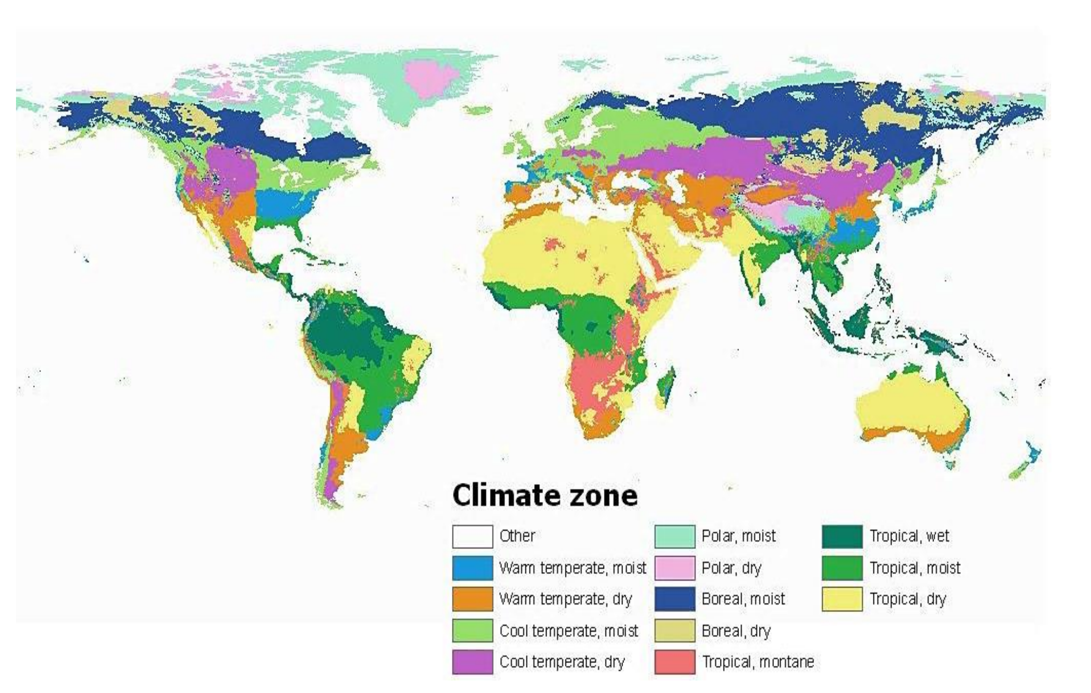


Figure 2.2: Climate zones worldwide (MOW, 2014)

Climatically, Saudi Arabia is classified into five different climatic zones; hot dry with a maritime desert subzone, subtropical with a Mediterranean subzone, cold dry with a desert subzone and hot dry with a desert subzone (NationMaster, 2013). In general, the average temperature varies from 24°C in the Western Province, rising as one descends toward the southwest until it reaches 32°C in Jeddah and 30°C in Jizan (World Bank, 2014). In the northwest, the average temperature is 22°C in Tabouk and 28°C in Madinah in the southwest region, Asir which is 850 meters above the sea level, the average temperature is only 19°C due to the high altitude (World Bank, 2014). The Central Province, which is surrounded by desert, has an average of 25°C for Riyadh, 21°C in Ha'il and 23°C in Al-Qaseem (World Bank, 2014). In Al-Dammam, the Eastern Province, the temperature is an average of 26°C (Figure 2.3) (World Bank, 2014).

During July, the air temperature can reach 49°C (GAS, 2015). Winter is cooler with an average temperature of 23°C in Jeddah and 14°C in Riyadh (GAS, 2015). Between almost mid-October and May, the weather is generally pleasant with sunny days and cool nights (GAS, 2015). Night temperatures in the coastal areas may drop to 16°C (GAS, 2015), however, from April to November the temperatures are extremely high and life would be unpleasant without air-conditioning. During winter the temperature varies between 8°C to 20°C in cities such as Riyadh, while in the city of Jeddah which is located on the coast of the Red Sea, the temperature in winter season varies between 19°C to 29°C (GAS, 2015). The highland mountain areas have the coolest and freshest weather condition thus; this area is the greenest part of Saudi Arabia (Figure 2.3) (World Bank, 2014). In the central and northern regions of the country the temperatures in winter drop below freezing and snow and ice can occur in the southwest (Figure 2.3) (World Bank, 2014)

Saudi Arabia's climate is also influenced by tropical winds that cause monsoons in the west and the southwest (GAMEP, 2016). In the south tropical continental winds blow, particularly in winter and regularly produce sandstorms (GAMEP, 2016). The wind blows for most of the summer months in areas where there is a little ground cover. When coming from a northwesterly direction it invariably whips up strong sandstorms, particularly in the eastern part of the country (Figure 2.4) (GAMEP, 2016).

Saudi Arabia has a fairly high intensity of solar radiation and long hours of sunshine duration (Almasoud & Gandayh, 2015). Saudi Arabia receives each day, an average of more than 5.5 kW/m^2 of global solar radiation on a horizontal surface (Figure 2.5) (Almasoud & Gandayh, 2015). Based on the geographical location of the country, the global solar irradiation is varying between a minimum of 4.493 kW/m^2/day at Tabuk and a maximum of 7.014 kW/m^2/day at Bisha (GAMEP, 2016). As illustrated in Figure 4.4 that higher values of global solar irradiation are observed in the southern region of the Kingdom, while the lower values are found in the northern region. The total mean value of sunshine duration is approximately 8.89 hours each day totalling an average of 3245 hours per annum (Figure 2.5).

Saudi Arabia is one of the driest countries in the world, with rainfall averaging less than 127mm per year (GAMEP, 2016). The climate is principally determined by the southerly shift in wind patterns during the winter months, which brings rain and cool weather (GAMEP, 2016). Other factors, such as latitude, proximity to the sea and altitude, also affect the climate. Due to the monsoon in the southern region the country, Asir Highlands receives 255mm of rainfall per year.

In Riyadh, the Annual average rainfall between the January and May is 100 mm while in Jeddah the average rainfall is only about 54 mm and commonly falls in the month of November until January (Figure 2.6) (GAMEP, 2016).

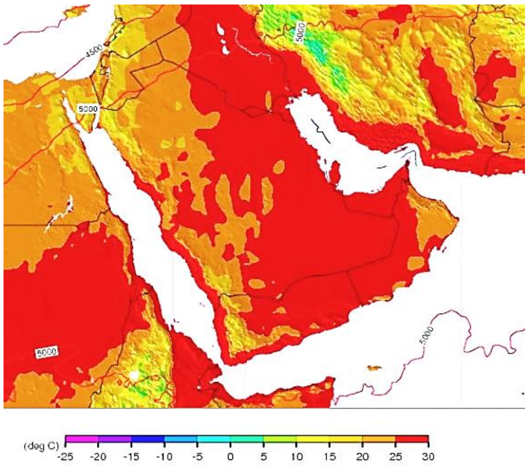


Figure 2.3: The average annual temperature in KSA (GAMEP, 2016)

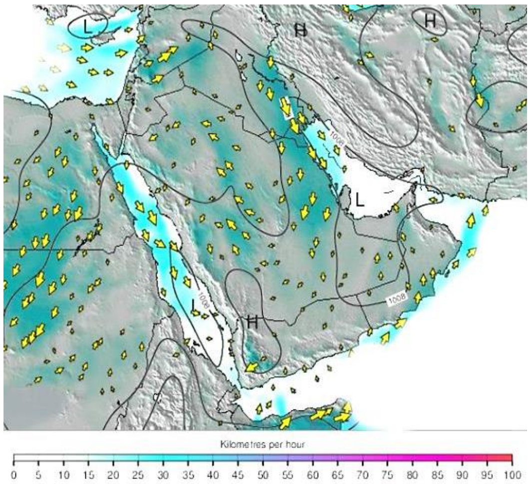


Figure 2.4: The average annual wind speed in KSA (GAMEP, 2016)

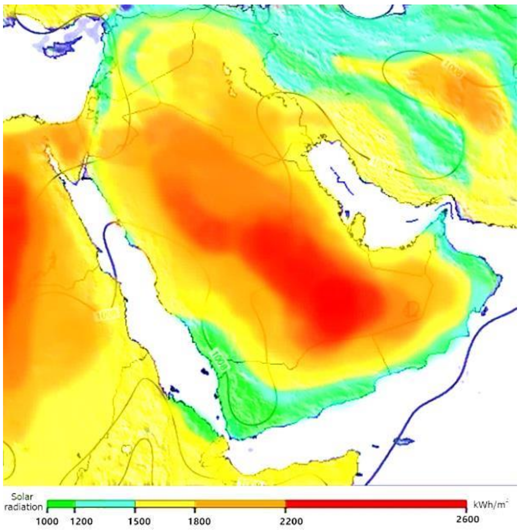


Figure 2.5: The average annual solar radiation in KSA (GAMEP, 2016)

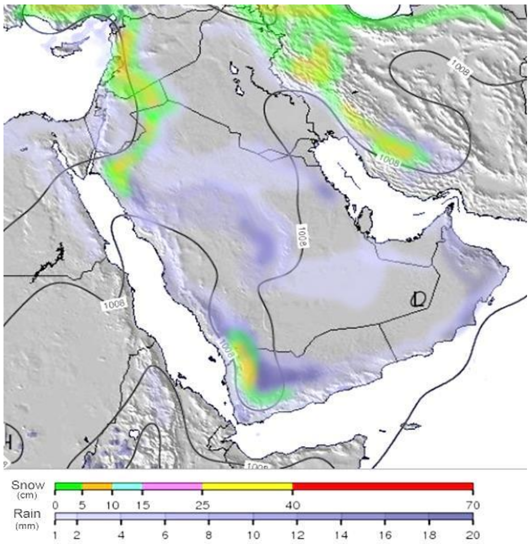


Figure 2.6: The average annual rainfall in KSA (GAMEP, 2016)

2.2.3 Current Residential Cooling Approaches

As a result of climatic analysis of Saudi Arabia that demonstrated the high temperature in the most of the regions especially in the summer season, air conditioners are used to meet the peak summer cooling demand and consequently, a substantial amount of energy (70%) is consumed to run AC systems. Peak loading for cooling systems occurs between 1 and 5 pm during the summer months in the Kingdom (SEC, 2015). It can be necessary to provide cooling to buildings during hot or humid weather, or where there are significant thermal gains such as solar gain, people and equipment. This cooling is sometimes referred to as comfort cooling (Al-Ajlan et al., 2006). There are different cooling approaches adopted in hot and humid climate houses of Saudi Arabia. The market for air conditioning in buildings is dominated by mechanical vapour compression systems, as they have a reliable performance and good controllability (SEEC, 2015). Individual air-conditioners such as conventional window-type AC systems are popular and constitute 54% of the cooling systems employed in the residential sector due mainly to ease of installation and maintenance. This system type is followed by mini-split systems that form (28%) while whole house central systems are typically only used in large residences and commercial buildings (14%) (Figure 2.7).

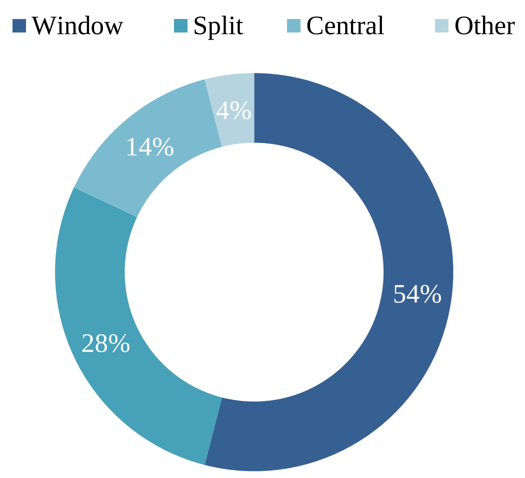


Figure 2.7: Typical air conditioning systems used in Saudi residential buildings (SEC, 2015).

Such active mechanical cooling systems consume a numerous proportion of energy, water, and money. These systems are distinct from ventilation systems in that they physically remove heat from the indoor air. These electric based AC systems generally use the vapour compression cycle as the source of cooling and tend to include all electrically driven systems and components. As a result, significant amounts of energy are consumed with substantial carbon emissions (SEEC, 2015). A detailed description of typical air conditioning systems used in Saudi houses is summarized as the follows :

a) Window AC System

Window air conditioners system is the most extensively used types of air conditioners in Saudi Arabia due to its simplicity and affordability. Window air conditioner consists of the rigid base on which all the parts of the window air conditioner are assembled. The base is accumulated inside the casing which is fitted into the wall or room window. The assembly of the window air conditioner can be divided into two compartments; the room side (cooling side) and the outdoor side (heat expulsion side). Both sides are separated from each other by an insulated partition enclosed inside the window air conditioner assembly (R. Nicholas, 2002).

- ***Indoor side parts*** comprise cooling coil mounted by air filter. This cooling coil is where the heat exchange occurs between the refrigerant in the system and the air inside the room. The air conditioner system includes a centrifugal evaporator blower fan to discharge the cool air to the room. In addition, operation panel is used to control the temperature and speed of the blower fan. A thermostat is also used to sense the return air temperature and monitor the coil temperature. Filter drier is used to remove the moisture from the refrigerant while drain pan is used to contain the water that condensate from the cooling coil (R. Nicholas, 2002).
- ***Outdoor side parts*** include a compressor which is basically used to compress the refrigerant ln addition to condenser coil to reject heat from the refrigeration to the outside air. A propeller fan is used in air-cooled condenser to help move the air molecules over the surface of the condensing coil. Also, a double shaft fan motor is located in this side where the indoor blower and outdoor propeller fan are connected together.

The window air conditioner cooling mechanism starts when the evaporator blower fan sucks the air from the room to be conditioned through the air filter and the cooling coil. Air that has been conditioned is then discharged to deliver the cool and dehumidified air back to the room. This air mixes with the room air to bring down the temperature and humidity level of the room. The introduction of fresh air from outside the room is done through the damper which is then mixed with the return air from the room before passing it through the filter and the cooling coil. The air filter which is mounted in front of the evaporator acts as a filter to keep the cooling coil clean to obtain good heat-transfer from the coil. Window air conditioner units are highly efficient, as all the warm air is pushed outdoors. If properly placed and sized, a window air conditioner unit can cool a space volume up to 125 m^3 (R. Nicholas, 2002).

b) Split System

Individual air conditioners employ one condenser for one evaporator unit. The evaporator unit is usually mounted on the wall inside the building, while the condenser unit is mounted on the external side. Split air conditioners are used for small rooms and halls, usually, in places where window air conditioners cannot be installed, however many people prefer the split air conditioner units. There are two main parts of the split air conditioner used in Saudi houses:

- ***Outdoor unit***: This unit houses important components of the air conditioner like the compressor, condenser coil and also the expansion coil or capillary tubing. This unit is installed outside the room or office space, which is to be, cooled (R. Nicholas, 2002). The compressor is the maximum noise making part of the air conditioner, and since in the split air conditioner, it is located outside the room, the major source of noise is eliminated (R. Nicholas, 2002). In the outdoor unit, a fan blows air over the condenser thus cooling the compressed Freon gas in it (R. Nicholas, 2002). This gas passes through the expansion coil and is converted into low pressure, low-temperature partial gas and partial liquid Freon fluid (R. Nicholas, 2002).
- ***Indoor unit***: The indoor unit produces the cooling effect inside the room or the office. The indoor unit houses the evaporator coil or the cooling coil, along with a blower and the filter (R. Nicholas, 2002). After passing through the expansion coil, the chilled Freon fluid enters the cooling coil (R. Nicholas, 2002). The blower sucks the hot, humid and filtered air from the room and it blows it over the cooling coil (R. Nicholas, 2002). As the air passes over cooling coil, its temperature reduces drastically and loses the excess moisture (R. Nicholas, 2002). The cool and dry air enters the room and maintains comfortable conditions typically around 25°C to 27°C. The temperature inside the space can be maintained by a simple thermostat control. The setting should be such that comfortable conditions

are maintained inside the room, and there is a chance for the compressor to trip at regular intervals (R. Nicholas, 2002). Multi-split air conditioners are also commonly used. In units for one outdoor unit, there are two indoor units, which can be placed in two different rooms or at two different locations inside a large room. Since there is a long distance between the indoor and the outdoor unit, there is always a loss of some cooling effect; hence - for the same tonnage - split air conditioners produce a somewhat lower cooling effect than window air conditioners (R. Nicholas, 2002). With modern insulation materials, this gap has been reducing. There are many instances where there is no alternative to the split air conditioner.

c) **Centralised System**

Central air conditioning consists of a central cooling unit that will connect to ventilation ductwork that distributes cold air to each room. Central air conditioning plants are usually used for applications large residential blocks, hotels, commercial buildings having multiple floors and hospitals, where cooling loads are significant and the initial capital cost can be justified. In centralised air conditioning systems, there is a plant room where a large compressor, condenser, thermostatic expansion valve and the evaporator are kept typically situated (BSRIA, 2010). They perform all the functions similar to a standard refrigeration system, however, all these parts have higher capacities (BSRIA, 2010). The compressor is of the open reciprocating type with multiple cylinders and is water cooled (R. Nicholas, 2002). The compressor and the condenser are of shell and tube type (R. Nicholas, 2002). While in small air conditioning systems, a capillary is used as the expansion valve, in the central air conditioning systems a thermostatic expansion valve is used (R. Nicholas, 2002). One of the main benefits of this system is that it is completely silent and highly effective in air conditioning the whole house. Two types of central air conditioning plants or systems used in Saudi houses:

- ***Direct expansion or DX central air conditioning plant***: In this system, the compressor and the condenser are housed in a plant room, while the expansion valve and the evaporator or the cooling coil and the air-handling unit are housed in the separate room (R. Nicholas, 2002). The cooling coil is fixed in the air-handling unit, which also has large blower housed in it (R. Nicholas, 2002). The blower sucks the hot return air from the room via ducts and blows it over the cooling coil (R. Nicholas, 2002). The cooled air is then supplied through various ducts and into the spaces, which is to be cooled (R. Nicholas, 2002). This type of system is beneficial for small to medium buildings.

- ***Chilled water central air conditioning plant***: This type of system is more common in large buildings comprising a number of floors. A plant room again will typically house the compressor, condenser, throttling valve and the evaporator. The evaporator is a shell and tube. On the tube side, the Freon fluid passes at extremely low temperature, while on the shell side the brine solution is passed (R. Nicholas, 2002). After passing through the evaporator, the brine solution is chilled and is pumped to the various air-handling units installed on different floors of the building (R. Nicholas, 2002). The air-handling units comprise the cooling coil through which the chilled brine flows (R. Nicholas, 2002). The blower sucks hot return air from the room through ducts and blows it over the cooling coil (R. Nicholas, 2002). The cool air is then supplied to the space to be cooled through the ducts (R. Nicholas, 2002). The brine solution, which has absorbed the room heat, comes back to the evaporator, is chilled and is again pumped back to the air-handling unit (R. Nicholas, 2002).

There have been a few attempts to reduce the energy usage of such AC systems with a range of experiments and investigations carried out over the last few years that aimed to optimise the performance of AC systems in the hot and humid area. These investigations concluded that although the conventional cooling equipment is adequate to meet the sensible and latent loads and maintain acceptable humidity levels at the hottest times of the day, the scope to reduce primary energy consumption is limited. Without a radical re-think of the problem, HVAC systems will continue to be the major contributor to energy consumption in hot and humid regions (Dubey, Howarth, & Krarti, 2016).

2.3 Thermal Comfort in The Hot and Humid climate of K.S.A

Thermal comfort is defined as "That condition of mind which expresses satisfaction with the thermal environment" (Fanger, 1970). Thermal comfort can vary significantly from region to region. (Nicol & Humphreys, 2002). According to Givoni, there are six major climatic zones. As shown in the psychometrics chart in Figure 2.8, the hot and humid zone is limited between dry bulb temperature of 33°C to 40°C and absolute humidity range between 23% to 65% (Givoni, 1994). By determining the thermal comfort temperature range of a specific environment or climate zone, cooling or heating energy consumption can be efficiently controlled (Givoni, 1994). In addition, the study of what is now termed 'adaptive' thermal comfort can determine the thermal comfort standard that responds to the relevant local climatic condition (Nicol & Humphreys, 2002). Applying such 'adaptive' comfort standards will reduce energy consumption and by address the 'over-cooling' that is common where one international standard (ASHRAE) is applied to all climatic zones (Olesen, 1982).

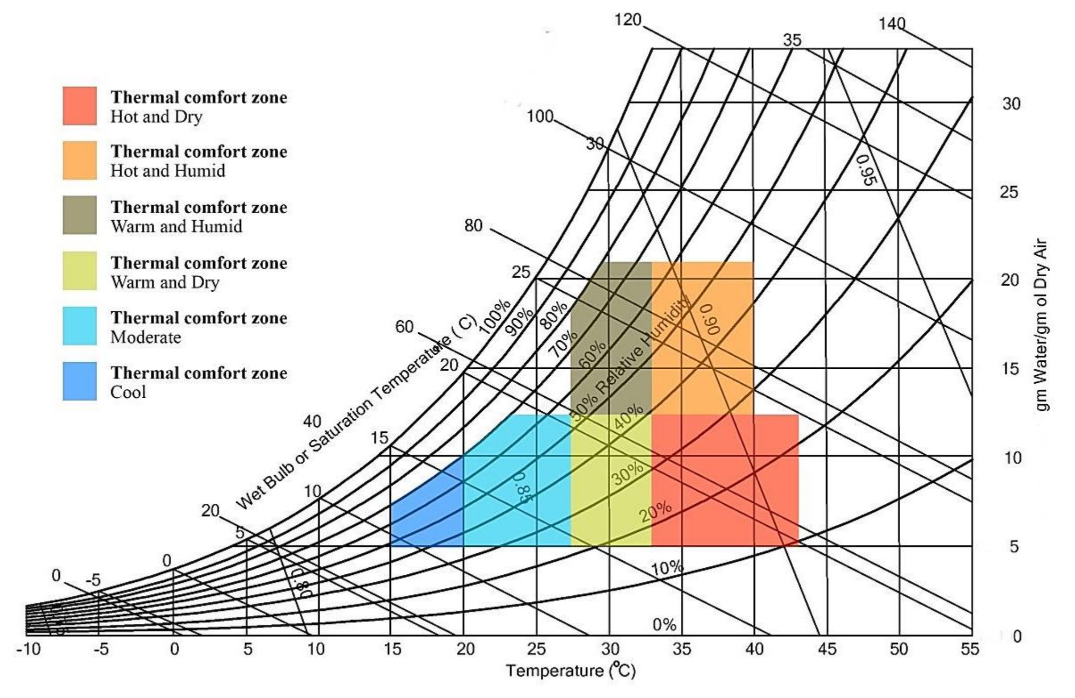


Figure 2.8: Psychometric chart shows thermal comfort zones of various climatic conditions (Givoni, 1994).

2.3.1 Factors determining Thermal Comfort

The major factors that influence the determination of thermal comfort range include environmental factors and personal factors (Givoni, 1994). These factors were extensively discussed as follows:

a) Environmental Factors

The most important environmental factor is solar radiation. The solar radiation direction is varying with time, date and latitude (Olesen, 1982). Among the diverse climatic variables in the environment, solar radiation is considered as the main climatic variable usually taken into account in climatic responsive building design (Givoni, 1994). Another environmental variable that affects thermal comfort is the air temperature. Air temperature is considered as the most effective environmental factors that affect the amount of heat released from a human body to achieve thermal comfort (Olesen, 1982). The healthy internal body temperature is approximately 37°C, whilst the temperature of skin surface ranges from 35°C to 37°C according to the ambient temperature (Nicol & Humphreys, 2002). The human body releases heat generated by its metabolic processes, which is determined in the main by the level of physical activity and food intake (Nicol & Humphreys, 2002). The air temperature should therefore fall within a specific range to optimise the release of heat to the surrounding environment that prevents any overheating discomfort (Fanger, 1970).

Relative humidity (the mixing ratio of the air at a given temperature) also has a crucial influence on thermal comfort levels (Olesen, 1982). When the relative humidity is high, discomfort can occur (Olesen, 1982). The acceptable relative humidity level is normally considered to be in the range 30% to 65% (CIBSE, 2005). In order to avoid discomfort as a result of high relative humidity, higher levels of air movement are required. (CIBSE, 2005).Air velocity, driven in the main by wind pressures or the stack effect (hot air rising) causes air movement from the warmer surface to a cooler (CIBSE, 2005). Table 2.2 shows the normal human reactions to changes in air speed.

Another environmental factor that influences human thermal comfort is precipitation. Precipitation can cool the atmosphere by reducing the amount of solar radiation from the sun due to the cloud cover that blocks the solar radiation during rainfall (Olesen, 1982). Simultaneously, it increases the amount of water vapour in the atmosphere as it normally increases relative humidity.

Air Speed	Human Reaction
< 0.1 m/s	Stuffy
To 0.2 m/s	Unnoticed
To 0.5 m/s	Pleasant
To 1.0 m/s	Awareness
To 1.5 m/s	Draughty
> 1.5 m/s	Annoying

Table 2.2: Human reactions to different air velocity (Nicol & Humphreys, 2002).

b) Personal Factors

There are four main personal factors that could affect human thermal comfort. These are the metabolic rate, clothing level and acclimatisation (Fanger, 1970). Metabolic processes are divided into two types: muscular metabolism and basal metabolism (Fanger, 1970). Muscular metabolism processes usually happen when a person is performing physical work and activities while Basal metabolism is a constant and automatic process (Fanger, 1970). A person's activity determines the amount of energy released (Fanger, 1970). The heat output ranges from a minimum of 70 W to 700 W, depending on the activity level. Table 2.3 shows the amount of energy released for different activities (Fanger, 1970).

Activity	Energy released (Watts)
Sleeping	Minimum 70
Seating, moderate movement, e.g. typing	130 – 160
Standing, light work at machine or bench	160 - 190
Seating, heavy arm, and leg movement	190 - 230
Standing, moderate work, some walking	220 - 290
Walking, moderate lifting or pushing	290 - 410
Intermittent heavy lifting, digging	440 - 580
Hardest sustained work	580 - 700
Maximum heavy work for 30 min duration	Maximum 1100

Table 2.3 Amount of energy released by different activities (Fanger, 1970).

Another personal factor that could influence occupant's thermal comfort is clothing levels. The effect of clothing is measured in the unit 'clo-value' (De Dear, 2004). Table 2.4 has listed the clo-value of various garments, however, to date, no specific standard data available for Arabic clothing. In Arabian Gulf region including Saudi Arabia, there are some cultural norms that require male and female to wear a typical outdoor dress that may have a relatively high clo-values, nevertheless, such type of clothes are not necessarily to be worn inside the house. An experimental study conducted by Al-ajmi et. al (2008) to measure the clo-values of a number of Arabian Gulf garments as worn by males and females in the region during both summer and winter seasons. Measurements of total thermal insulation values (clo) were obtained using a male and a female shape thermal manikin in accordance with the definition of insulation as given in ISO 9920, ISO 7730 and ASHRAE standard 55. The findings showed that the measured thermal insulation values of males typical outdoor dress ranged from 1.05 clo to 1.70 clo, while the measured thermal clothing insulation values of females typical outdoor dress ranged from 1.19 clo to 2.11 clo. However, the findings of this study also showed that, in such warm region, occupants (indoor) usually demonstrate a low to moderate clo-values. The measured average clo-values of both male and female typical indoor clothes were in the range between 0.55 to 0.62 (Al-ajmi et. al, 2008). These figures are fairly equivalent to De Dear measured clo-values of typical indoor summer clothes indicated in Table 2.4.

Clothing	clo - Value
Naked	0.0
Brief	0.06
T-shirt	0.09
Bra and Panties	0.05
Long underwear upper/lower	0.35
Shirt light and short sleeve	0.14
Shirt, heavy and long sleeve	0.29
Skirt	0.22 – 0.70
Trousers	0.26 – 0.32
Working Clothes	0.8
Typical indoor summer clothes	0.44 – 0.60
Typical indoor winter clothes	1.0
Heavy business suit	1.5

Table 2.4: Clo-value of various garments (De Dear, 2004).

Health status is another personal factor, which can affect the thermal comfort of a person. Usually the body feels colder when the body temperature internally increases above the air temperature; however, this commonly happens when there is an underlying health issue

Another important factor that could influence human thermal comfort is the person's acclimatization (Nicol & Humphreys, 2002). The human body is homoeothermic. It has thermal adjustment mechanisms that enable most people to adapt to the surrounding thermal environment (Nicol & Humphreys, 2002). This adjustment mechanism can adapt to both conditions, either in the cold or in the warm environment (Nicol & Humphreys, 2002). The adjustment mechanism in cold environment is called vasoconstriction, where the blood vessels contract, which decreases the blood flow volume to the skin (Nicol & Humphreys, 2002) reducing skin temperature restricting heat dissipation rates. On the other hand, the adjustment mechanism in a warm environment is called vasodilatation. In this case, the blood vessels expand increasing the blood flow volume and skin temperature with a concurrent increase in heat dissipation rates (Nicol & Humphreys, 2002).

2.3.2 Adaptive Thermal Comfort

Investigating thermal comfort through field studies dates back as early as the 1930s. Bedford conducted a field study based on the adaptive method. Some environmental and climatic data were measured in his field study, which includes air temperature, relative humidity, radiation and air movement. Simultaneously measurements were recorded of occupant response (Olesen, 1982).

Nicol and Humphreys carried out another study on adaptive comfort in 1973. This study has covered several locations with various climates. The results demonstrated that although indoor temperature increased from one climatic condition to another, the mean vote comfort temperature showed no significant change (Nicol & Humphreys, 1973). These results demonstrated that humans have the ability to adapt over time to a relatively wide range of thermal environments in which they find themselves. Humphreys covered a wider diversity of climates with a similar study in 1976. The results again demonstrated this adaptive phenomenon and reinforced the results predicted by Nicol and Humphreys (Nicol & Humphreys, 2002).

Brager and de Dear carried out a field study in 1998, based on naturally ventilated buildings located in a warm climate. This study utilised the Predicted Mean Vote (PMV) model (Fanger 1970) and the occupant's comfort votes were recorded. Their study aimed to examine the validity of the (PMV) model in predicting the thermal comfort in a warm climate (Dear et al., 1998). This PMV model was formed from Fanger's heat balance equation. Their results had shown that the actual comfort votes from the occupants were higher than the comfort temperature that was predicted by PMV model. Thus, Brager and de Dear, have concluded in their study that occupants were tolerant to a higher air temperature than what was predicted by the PMV model (Dear et al., 1998).

During the summer of 1997 and 1998, a similar survey using the PMV model was carried out by a group of researchers. (Ealiwa, Taki, Howarth, & Seden, 2001). The field study was conducted in the hot-dry climate of North-Africa. The maximum temperature during summer was 47°C, while the minimum night temperature was 30°C. The results of the 'Adaptive Model' showed that 80% of the occupants were 'thermally satisfied' at an air temperature range between 30°C to 35°C, that was much higher than the standard PMV model had predicted. Again, this demonstrated that the inhabitants of hot countries were tolerant to higher air temperatures than what was predicted by the PMV model.

This phenomenon had been experienced by Humphreys during his visit to Pakistan in 2001 where the outside ambient temperature was approximately 40°C. He however felt great relief and thermally comfortable when he entered a building that he believed had an internal air temperature of 25°C. When he checked the actual air temperature he found it to be 32°C – an indoor temperature that would rarely be considered as 'comfortable' in the UK. (Nicol & Humphreys, 2002).

In 1975, Humphrey examined 36 thermal comfort field studies from various global climatic conditions. It has been observed that in naturally ventilated buildings; there is a significant relationship between average monthly outdoor temperature and comfortable indoor temperatures. Occupants seem to be thermally neutral over a larger range of indoor mean temperatures. Humphreys found two equations to predict thermal comfort; one for air-conditioned buildings and another for naturally and mixed mode-ventilated buildings. In naturally ventilated building the correlation between the outdoor monthly mean temperature and the neutral temperature is linear and strong (r = 0.97). In his paper presented at Windsor 2010, he showed that comfort temperature ($\boldsymbol{Tn}$) in a naturally ventilated building could be predicted from outdoor monthly mean temperature ($\boldsymbol{To}$) by using the following equation:

$\boldsymbol{Tn} = \mathbf{11.9} + \mathbf{0.534}\, \boldsymbol{To}$ (Equation 2.1)

In air-conditioned buildings, the correlation was curvilinear and less strong (r = 0.72), and the comfort temperature ($\boldsymbol{Tn}$) can be predicted from the outdoor monthly mean temperature ($\boldsymbol{To}$) using the following equation;

$\boldsymbol{Tn} = \mathbf{23.9} + \mathbf{0.295}\, \boldsymbol{To} - \mathbf{22}$ $(-[\, \boldsymbol{To} - \mathbf{22})/(\mathbf{24}\sqrt{\mathbf{2}}]\mathbf{2})$ (Equation 2.2)

In parallel, very important research has been carried out in order to develop an international adaptive comfort standard. Analysis of the data included in the ASHRAE RP-884 database involving data of comfort surveys around the world de Dear and Brager (2002) has shown that "occupants of naturally ventilated buildings prefer a wider range of conditions that more closely reflect outdoor climate patterns while PMV predictions fit very well with the preference of occupants in HVAC buildings. A revised version of ASHRAE Std 55, known as Adaptive Comfort Standard (ACS), has been produced to be applied to naturally ventilated buildings since the original version is found to be irrelevant for naturally ventilated buildings.

The same conclusions have been reported from various old and recent comfort field studies (Webb 1959, Nicol 1973, Humphreys 1975 Busch 1992, Nicol and Roaf 1994, Matthews and Nicol 1995, Taki et al. 1999, Nicol et al. 1999, Bouden and Ghrab 2001). As a result of the field studies, it was found that the optimum comfort temperature in naturally ventilated buildings is a function of the outdoor temperature, and may be predicted by linear equations of the following form, (Humphreys 1978, Auliciems and de Dear 1986, Nicol and Raja 1995):

$$\boldsymbol{T_{comf} = 0.31\, T_{out} + 17.8} \qquad \text{(Equation 2.3)}$$

While Humpreys (1978), Humphreys and Nicol (2000) and Nicol (2002) have proposed a similar expression for free-running buildings (which includes most naturally ventilated buildings outside the heating season):

$$\boldsymbol{T_{comf} = 0.534\, T_{out} + 11.9} \qquad \text{(Equation 2.4)}$$

Based on these results a new adaptive thermal comfort for naturally ventilated buildings has been integrated into ASHRAE - 55 Standard. McCartney and Nicol (2002) have suggested that a running mean of the outdoor temperature is a better predictor of indoor comfort temperature than the monthly means used by Humphreys (1978) and later by de Dear and Brager (2002), and at the same time allows for deviations of the weather from long-term average conditions which may occur from time to time, especially with climate change. As a close analysis by Humphreys and Nicol (2000) suggests that there is a remarkable agreement between their work and the 1998 ASHRAE database (Humphreys 1978, de Dear 1998). It is also found that the relationship between the two databases for air-conditioned buildings is more complex, showing a 2°C difference in indoor comfort temperatures between the results of Humphreys in 1978 and those of de Dear in 1998.

The above thermal comfort temperature equation demonstrates that the comfort temperature is related to the outdoor temperature, it proves that the comfort temperature is subject to change according to climate and season. As Nicol notes,"whichever equation is used, indoor comfort is related to the temperature outdoors".

The comparison between the static and the adaptive approaches studies is that the predicted thermal comfort from PMV model differs from the thermal comfort obtained by field study of the actual votes. Humphreys noted that the issue with the static approach is that it could be misleading when utilised to predict the mean comfort votes of groups of people in everyday conditions in buildings, specifically in hot climatic conditions. Fanger proposed that the variation in results arises from inaccurate data input (Fanger, 1970). Studies have demonstrated that due to the effect of human, environmental personnel and other factors, occupants in a different region of the world experience comfort at a different temperature.

Therefore, using PMV to predict comfort temperature could be more accurate in the air-conditioned building than in naturally ventilated buildings. The measurements of metabolic rate and clothing insulation are hard to evaluate precisely and these may have influenced the PMV result. Furthermore, some environmental variables such as the air speed are difficult to measure, as it can vary over short timeframes.

2.3.3 Thermal Comfort level

The purpose of this section is to determine the thermal comfort zone for the hot and humid climate of KSA. There is little data on this subject that is specific to Saudi Arabia that can prescribe the thermal comfort range and neutral temperature for air-conditioned and naturally ventilated buildings. ASHRAE Standard 55 (2013) suggest the thermal comfort range to be from 23°C to 26°C in summer season and from 20°C to 23°C in winter. In 2013, ASHRAE Standard 55 suggested a comfort range between 25°C to 28°C, however, when the relative humidity is 55%, the suggested comfort range is between 24°C to 27°C (Table 2.5) (ASHRAE, 2013).

Season	Optimum temperature	Acceptable temperature	Assumptions for other PMV inputs
Winter	22°C	20 - 23°C	Relative humidity: 50 % Mean relative velocity: <0.15 m/s Mean radiant temperature: equal to air temperature Metabolic rate: 1.2 met Clothing insulation: 0.9 clo
Summer	24.5°C	23 - 26°C	Relative humidity: 50 % Mean relative velocity: <0.15 m/s Mean radiant temperature: equal to air temperature Metabolic rate: 1.2 met Clothing insulation: 0.5 clo

Table 2.5: Thermal comfort condition in summer and winter seasons (ASHRAE, 2013).

However, Table 2.6 lists the findings of research that was conducted from 1953 to 2016 investigating the indoor thermal comfort range for air-conditioned, mixed and naturally ventilated buildings in hot and humid climate. Thermal comfort appeared to range from 22.7 ºC to 31.0 ºC and the average upper limit of calculated to be 29.2 ºC.

These findings again show a variation in thermal comfort temperatures between fully air-conditioned and naturally ventilated buildings. It was found that the occupants who live in the naturally ventilated building have more tolerance to high dry bulb temperature compared to occupants in the air-conditioned building. This is the rationale behind the lower thermal comfort temperature range in the fully air-conditioned building. Moreover, the comfort range in the naturally ventilated building is wider than in air-conditioned buildings.

Year	Authors	Type of study	Country	Cooling approach	*Tcomf*-comfort temperature (ºC)
1953	Ellis	Field study	Singapore	Naturally	24.4 ºC to 29.4 ºC
1986	Sharma and Ali	Field study	India	Naturally	26.0 ºC to 31.0 ºC
1992	Busch	Field study	Thailand	AC	23.0 ºC to 28.0 ºC
1997	Zain Ahmed et al.	Field study	Malaysia	Mixed	24.5 ºC to 28.0 ºC
1999	Nicol et al	Field study	Pakistan	Naturally	21.0 ºC to 31.0 ºC
2000	Karyono	Field study	Indonesia	Mixed	23.3 ºC to 29.5oC
2000	Khedari et al	Field study	Thailand	Naturally	27.0 ºC to 31.0 ºC.
2001	Sapian et al.	Field study	Malaysia	Naturally	26.0 ºC to 29.5 ºC
2001	Ismail & Barber	Field survey	Malaysia	AC	20.8 ºC to 28.6 ºC
2005	Sh Ahmad	Simulation	Malaysia	Naturally	23.6 ºC to 28.6 ºC
2008	Al-Homoud et.al.	Field study	Saudi Arabia	AC	23.0 ºC to 26.5 ºC
2009	Hassan Radhi	Simulation	Bahrain	AC	22.0 ºC to 27.0 ºC
2015	Ghabra and Ford	Field study	Saudi Arabia	Naturally	24.5 ºC to 28.4 ºC
2016	M Khalfan	Field study	Qatar	Mixed	20.0 ºC to 27.0 ºC

Table 2.6: Comfort range of indoor condition in mechanically, naturally and mixed ventilated buildings under hot and humid climate.

Comparing comfort conditions based on Fanger's PMV model, ASHRAE (2013) Standard 55 with the field studies results have shown that the average upper thermal comfort temperature limit is 29.2ºC which is 2.9ºC higher than Fanger's neutral temperature for Jeddah and approximately 2.2ºC higher than the ASHRAE (2013) Standard 55. To determine the most accurate estimation of indoor comfort temperature, the average of the measured and calculated comfort temperature for mechanically, naturally and mixed ventilated buildings was considered. As a result, the predicted thermal comfort range of occupants living in naturally or mixed ventilated building in hot and humid climate should fall between 23ºC to 28ºC with the neutral temperature predicted to be 25.5ºC and a relative humidity range of 45% to 70%. While the thermal comfort range for occupants living in air-conditioned buildings is predicted to be between 23ºC to 27ºC with neutral temperature at 25ºC and a relative humidity range of

30% to 60%. As a result of this estimation, the following psychometric chart was made to illustrate the thermal comfort zones for air-conditioned, mixed and naturally ventilated buildings in hot and humid climate (Figure 2.9).

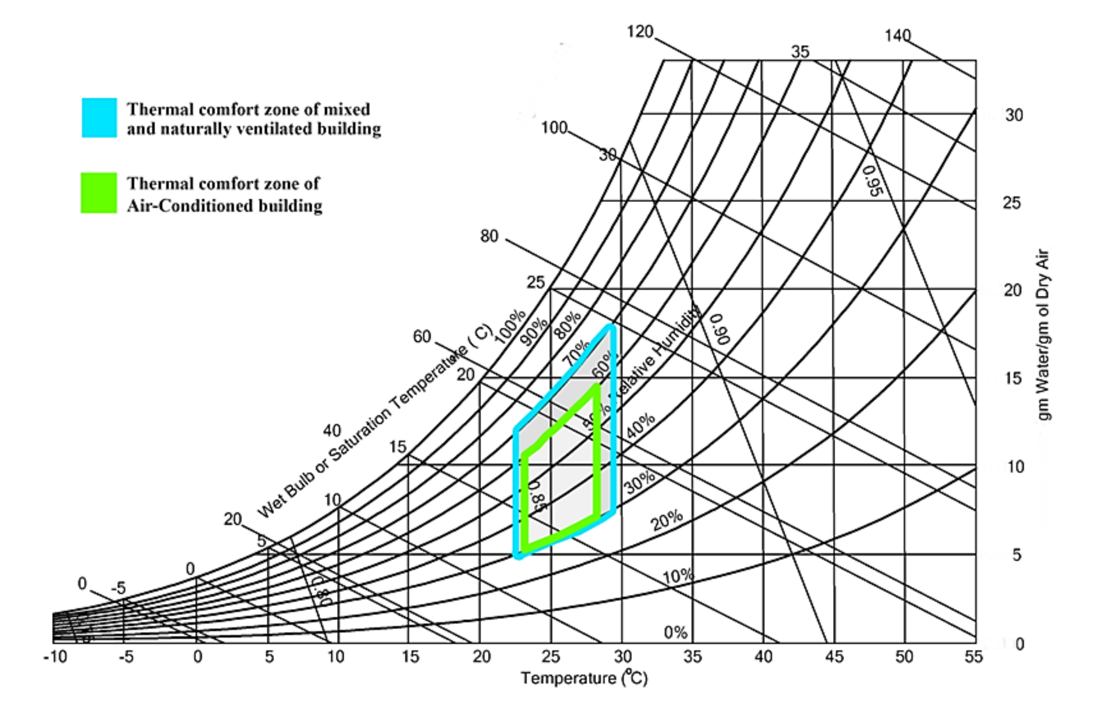


Figure 2.9: Psychometric chart shows that thermal comfort zone of air-conditioned, mixed and naturally ventilated building in hot and humid climate.

2.4 Passive Cooling Potentials in Hot and Humid Climate

'Passive', or 'natural', ventilation is the ventilation of a building with outside air without the use of a fan or other powered mechanical system. Passive cooling systems are typically associated with the design of new buildings but there are also cases where existing buildings have been adapted using the same principles. Jeffrey Cook (1989) defines the term 'passive' as, "any design technique, which transfers the indoor heat to natural heat sinks". Cook (1989) and Abram (1986), have categorised the passive cooling techniques into five main categories; heat avoidance, ventilative cooling, evaporative cooling, radiative cooling and earth coupling. Passive cooling can also be described as design approaches concentrated on controlling the heat gain to improve the indoor thermal comfort by preventing heat gain or removing the indoor heat by natural cooling (Givoni, 1983). The term 'passive cooling' is comparatively new, however, the application of passive cooling has been used worldwide since ancient times (Givoni, 1983).

Researchers such as Givoni (1983), Balaras (1996) and Cook (1989) are in agreement that passive cooling strategies in hot humid climates must address three parameters; heat gain prevention, heat gain modulation and heat dissipation. This can be done by removing the heat by enhancing passive cooling strategies such as ventilative, evaporative, earth sinks and radiative cooling.

In hot humid climates, achieving reasonable comfort standards for the occupants is a big challenge (Givoni, 1994). The real task in hot humid climates is not only reducing the indoor air temperature but also removing - or at least minimising - relative humidity (Roaf, 2012). Evaporative cooling is relatively ineffective when RH is high.

Hot and humid climates are considered as a unique challenge in building design. ASHRAE perceives that all buildings in warm humid climates should be designed for the purpose of passive cooling and in this case, the building should be 'open' as possible, in order to maximize the possible cross ventilation. If this is so, the building would be somewhat inappropriate configuration for traditional air conditioning. In an air-conditioned building, a different design approach should be adopted, so the building should be 'closed' and well insulated. In such a climatic zone, the designer should take an early decision whether active or passive cooling system would be adopted. These approaches can be described as climate inclusive or climate exclusive. Passive buildings, due to the limitations in achieving an interior climate that falls in the middle of the "comfort zone", will require occupants to accept a wider range of temperature and relative humidity values. Passively cooled buildings might also require lifestyle changes. In countries where hot arid or hot humid climate is both extreme and the norm, lifestyles have evolved, along with indigenous and vernacular architectural types that allow life to slow its pace during the heat of the day. Activities may sometimes move from the interior to a cooler exterior or transitional space. These sorts of programmatic changes might need to be worked into the planning of the building (ASHRAE, 2012). The following sections discuss some previous studies involved in attempting passive cooling strategies in hot humid climates.

2.4.1 Ground-Based Cooling Strategies

Earth cooling systems usually take advantage of the consistent temperature of the soil to work as a sink/dump to extract heat and cool the building. This passive cooling strategy would be more effective when earth temperatures are significantly cooler than air temperature, however, Kenneth Labs in a study (in Cook 1989, p.197) reported that this strategy requires that the ground temperature to be within the comfort zone range (i.e., 20°C to 25°C) (Labs, 1990). Kreider and Rabl (1994) have agreed with Labs argument that, such passive techniques would be more efficient in climates where the temperature underground is within the comfort zone. In case of Jeddah (KSA), the annual average ground temperature varies according to several factors such as ambient air temperature, humidity level and soil type, condition and depth. The average soil temperature at 2 m was measured between 28.3°C and 31.1°C, which is upper the recommended comfort limit.

Soil temperatures in hot and humid climatic regions of Saudi Arabia behave differently to those in Europe. In Europe, the soil temperature fluctuates at relatively shallow depths and is directly influenced by air temperatures. The soil temperature stabilises at 4 metres. The temperature of the un-shaded soil at this depth is approximately equivalent to the mean annual ambient dry bulb temperature (Givoni.1994) however, in shaded soil by forest trees or structure, the temperature at 4 m depth underground follows closely to the minimum ambient air temperature. In one study Givoni proposed an approach of having a raised wooden shack on stilts at approximately 0.6 m above the measured soil. During summer months, the ambient air temperature in Florida ranges from 24°C to 38°C. During this month, the cooled soil temperature at 1 m depth ranges between 24°C and 25°C, which is similar to the minimum ambient air temperature rather than the average (Givoni, 1994).

The great thermal capacity of the earth has made it a very useful heat sink for building cooling or heating purposes. The rationale behind this is due to the soil temperature remaining fairly constant throughout the year at increasing depths. The constant soil temperature is usually approximately equal to the mean annual air temperature. In winter, the soil temperature increases with increasing depth up to a certain depth and hence the use of earth as a heat source. Meanwhile, in summer, the soil temperature decreases with increasing depth, which provides the use of earth as a heat sink (Givoni, 1994). Soil temperature for depths of 6 m to 8 m is relatively unaffected by air temperatures.

In hot and humid climatic regions, the constant temperature of earth can be a major source of passive cooling via a ground pipe. In order to maximise the cooling effect, pipes must be buried underground as deeply as possible in order to take advantage of the constant temperature of deep-earth. In such climatic regions, the earth's temperature at a depth of approximately 4 m is almost constant throughout the year at about 27°C.

In the 1980's, earth tubes started to get the attention of architects and engineers as a possible option to enhance or reduce conventional air conditioning loads. The concept of routing air through underground tubes or chambers to achieve cooling effect appears to be a relatively simple technique. Ground tubes have to have large diameters through which the air is drawn by a mechanical fan. As the air travels through the pipes, it gives up some of its heat to the surrounding soil, especially where soil conductivities are high. This presumes of course that the earth is several degrees cooler than the incoming air (Labs, 1990).

This dissipation can be achieved either by direct contact of a significant section of the building envelope with the ground or by injecting air that has been previously circulated underground into the building by means of earth-to-air heat exchangers (Kreider, J. F., & Rabl, 1994).

A building exchanges heat with the environment by conduction, convection and radiation. For an ordinary building, the main mechanism is convection, since most of the building envelope is in contact with ambient air. Then comes radiation and finally conduction, since the area of the building envelope in contact with the ground is the smallest. The principle of ground cooling by direct contact is to increase conductive heat exchange. The building temperature drops because the ground is at a lower temperature than the air during the cooling period (Cook, 1989).

The direct earth-to-building contact ground cooling has many advantages in its performance. It is a low maintenance passive cooling strategy with minimal heat gains and solar exposure. Underground houses were built in southern Tunisia and eastern Spain to protect occupants from their hot and arid climates and large houses were excavated in northern China to cope with severe winter climate (Cook, 1989).

In some places on the globe such as desert and semi-desert countries, large excavations are not suitable due to the geological conditions. Another technique was introduced in Iran (1978), which is the indirect-to-building ground contact cooling. In this country, the air is channelled through tunnels buried underground into the building with the aid of wind towers (Kreider, J. F., & Rabl, 1994). Krarti and Kreider (1996) also stated that this low energy cooling or heating technique became increasingly popular in Europe and America after the oil crisis in 1973.

Despite the advantages of the direct-to-building ground contact cooling, it also created environmental problems such as indoor condensation and poor indoor air quality (Labs, 1990) and (Cook, 1989). As Saudi Arabia has a low average air velocity throughout the year, having direct earth contact to the building would minimise the number of openings, which result in a reduction of natural ventilation into the building and hence an even lower air velocity.

(Carmody & Sterling, 1985) has explained that earth-contact buildings have advantages related not only to their energy performance but also to visual impact, preservation of surface open spaces, environmental benefits and noise-vibration control and protection. Tzaferis, (1992) analysed various numerical models to study the flow and thermal characteristics of the heat transfer fluid, which circulated through an earth-to-air heat exchanger, (without considering the thermal capacity of the earth,) and compared the results obtained from many models. Kavanaugh & Rafferty (1997) reviewed a few alternatives for the ground-loop heat exchanger design. The high cost of long ground loops is one of the primary factors that may lead to the consideration of a hybrid system. Other factors include limited land area, the cost of the land or the high cost of high-efficiency heat pumps. Kavanaugh revises and extends the design procedures recommended by ASHRAE (1995). The revisions to the practice of a hybrid ground-source heat pump (GSHP) system design involve balancing the heat flow to the ground on an annual basis, in order to limit heat build-up in the borehole field. (Phetteplace, Gary and Sullivan, 1998) described a study that has been undertaken to collect the performance data from an operating hybrid GSHP system at a 24,000 ft2 (2230 m^2) military base administration building in Fort Polk, La. (Yavuzturk, Cenk and Spitler, Jeffrey D and Rees, 1999) used a system simulation approach to compare the advantages and disadvantages of various control strategies for the operation of a hybrid GSHP in a small office building.

2.4.2 Night Cooling Strategy

Night cooling is considered as one of the low-energy passive cooling techniques which work to reduce the building cooling load and enhance the thermal comfort of occupants by using outdoor air obtained through increasing night-time ventilation rates. Night cooling is an effective cooling strategy to reduce the indoor air temperatures by using the cooler ambient air as a source for natural cooling.

Several researchers have studied the performance of night ventilation strategies. Givoni (1994) has conducted an experimental study of night ventilation in California where night ventilation was more effective in comparison with full-day ventilation, especially where a building has relatively high thermal mass. A study by Pfafferott (2003) has concluded that the efficiency of night ventilation may be influenced by significant factors such as ventilation rate, the thermal storage capacity of the building fabric, the difference between the exterior and interior temperatures as well as solar and incidental heat gains (Pfafferott, 2003). Both studies concluded that night ventilation could reduce indoor air temperatures between 1.5°C to 2°C.

In Beijing and Shanghai, Da Graça, Chen and Glicksman (2002)¸ have undertaken simulations for a six-storey complex apartment building to assess the actual performance of the night and daytime ventilation. Day and night ventilation techniques cannot work efficiently where air temperatures and humidity remain high throughout the period of darkness (GC Da Graça, Q Chen, LR Glicksman, 2002), however, studies conducted by Wang, Liu and Wang to examine the effect of different ventilation techniques and façade designs on indoor thermal comfort for passively ventilated apartments in Singapore, concluded that night ventilation combined with wall insulation, would be more efficient than the daytime ventilation on its own. Such night ventilation techniques clearly produce greater heat flushing where diurnal temperature fluctuations are large (Wang Y, Liu Y, Wang D, 2014).

In the tropical region of northern Australia, Aynsley (1999) low night time wind speeds were not sufficient to drive cross ventilation, however, Sreshthaputra (2003) explored some promising findings on night ventilation cooling in the hot-humid tropics based on computational fluid dynamics (CFD) simulations. A case study that looked at Temples in Bangkok, Thailand showed that night ventilation that produces and 20 air changes per hour, reduced the maximum air temperature in the afternoon by 2°C in comparison with daytime ventilation alone.

In general, nocturnal cooling strategies can be more efficient in areas where the daytime temperatures are between 30°C to 36°C, and the night temperatures are 20°C or below. In this condition, daytime ventilation is not desirable, because heat can be stored in the thermal mass of the building and the indoor temperatures will remain elevated at night (Givoni, 1994).

2.4.3 Radiant Cooling Strategy

As defined in Martin (Cook 1989, p.139), radiative cooling, is the procedure whereby heat absorbed by the building mass during the day be re-radiated to a clear sky at night. Radiative cooling is an indirect heat-loss process that involves exposing interior spaces to the heat sink of a massive body of water or masonry, then exposing the mass to the planetary heat sink of a clear night sky. The mass absorbs heat from the interior and then releases that heat in the same process that maintains Planet Earth's thermal equilibrium to the 'Skydome'. The only caveat in the process is that it is most effective where the diurnal (day-night) temperature swing is in excess of 6°C and where the night sky is relatively clear (Cook, 1989)

Radiant cooling relies on this mechanism to dissipate heat from a building or an occupant's body. One of the more common radiant cooling systems uses the roof of a building as a radiator to dissipate heat to the night sky. This process cools the roof, which in turn serves as a heat sink for the occupied space underneath. The effectiveness of such a system depends chiefly on the details of the roof and the local climate. It will work well in hot humid climates only when the skies are predominantly clear. In such conditions, ambient night air passing near the roof could be cooled by about 2°C to 3°C, which could then be channelled into the building to provide additional cooling (Givoni, 1998).

To enhance the performance of such a system further, a desiccant bed can be incorporated into the roof structure to dehumidify the passing air. More work is still required to optimise the cooling potential of this technique in hot humid climates. Experience may be drawn from other climates, particularly hot and arid ones, in which nocturnal radiant cooling is more widely used thanks to their predominantly clear skies (Givoni, 1998).

For decades, the strategy of passive radiative cooling has been adopted across the world. There are two main types of radiant cooling systems. The first type is systems that deliver cooling through the structure of the building (slabs). This technique works efficiently in arid climates, however, in hot-humid regions, the high humidity could reduce the rate of radiative heat transfer at night (Raman, Anoma, Zhu, Rephaeli, & Fan, 2014)

Masonry massing is the key to such historic examples of radiative design as the pueblos and Spanish missions of the Southwest, but since the invention of Harold Hay's patented "Skytherm" system attention has been focused on using roof-sited water as the radiative mass. In a typical roof-pond (or thermo-pond), bags or bins of water on the roof are covered with moveable insulation during the day to absorb heat from the interior spaces below. At night, the insulation is removed and the heat stored in the water is released to the cool skydome (Givoni, 1994). Other systems designed along the same lines use floating insulation, which can be immersed in the roof pond at night, or stationary insulation over which the water is piped at night. In any configuration, radiative cooling is popular in both the research and design communities because it can also be used for heating in winter; the exposed mass absorbing solar radiation by day and when subsequently insulated from the night sky transmits this heat to the interior spaces by night (Givoni, 1998).

The strategy's efficacy as a cooling technique can be improved by spraying water on the rooftop water containers to add evaporative cooling to the radiative effect. Where humidity is high at night the effect will be significantly reduced.

One of the main issues that has to be addressed is how best to control indoor relative humidity. This will involve the dehumidification of the supply air or reducing infiltration/ventilation rates. Where internal relative humidity is above 70 % for long periods the likelihood of mould growth increases. The challenge is to find a low energy dehumidification technique (Givoni, 1998). This issue will be investigated to determine the possibility of using such techniques in the hot humid climatic regions such as the city of Jeddah.

Various studies carried out by researchers on radiative cooling are summarized in this section. The simplest passive radiative cooling technique is to paint the roof white. White paint does not significantly affect radiation rates at night since both white and black paints have almost the same emissivity in the long wave range. The advantage of a white painted roof is that by absorbing less solar radiation during the daytime (Albedo effect), the temperature of the roof remains lower.

Muselli (2010) presented a low-cost radiative coating material (1/m^2) that limited heat gains during the day. He studied its reflective UV-VIS-IR behaviour and compared it with that of other classical roofed materials available in industrial and developed countries. His simulation results showed that the low-cost white opaque reflective roofs would reduce cooling energy consumption by between 26 to 49%, compared with uncoated materials for a surface temperature of T_O = 60°C. As radiant cooling uses the roof as the "cold collector", it is applicable only to low-rise buildings, especially to single-storeyed buildings with flat roofs, or for cooling the top floor of a multi-storeyed building (Muselli, 2010). From the climate aspect, as it depends on longwave radiation during the nights, it would be most effective in regions, that have clear sky conditions during the night hours. A detailed discussion of radiant cooling systems is presented in Givoni (1998).

The first radiant cooling (and heating) system and the only one commercially available is the "Skytherm" developed by Harold Hay in 1978. In this system, the (horizontal) roof is made of structural steel deck plates. A Report of Marlatt et al. discusses the performance of a prototype, and several buildings heated and cooled by the "Skytherm" system, including the Atascadero building. The section of the Marlatt Report dealing with the performance of the buildings, which have applied the "Skytherm" system, is summarized in Givoni (1994). Cook (1989)

Bagioras and Mihalakakou (2007) claimed that passive cooling resources are the natural heat sinks of planet earth. The three heat sinks of nature are the sky, the atmosphere and the earth. Heat dissipation techniques are based on the transfer of excess heat to lower temperature natural sinks. Heat dissipation from a building to the sky occurs by long-wave radiation, a process called radiative cooling. In fact, the only means by which the earth loses heat is radiative cooling. The sky equivalent temperature is usually lower than the temperature of most bodies on earth; therefore, any ordinary surface that interacts with the sky has a net long-wave radiant loss.

Bassindowa et al. (2007) and Farmahini Farahani et al (2009) investigated the experimental and theoretical applications of long-wave nocturnal radiative cooling and its relative efficacy in different climate conditions.

Imarori et al. (2005) claimed that radiant cooling should be considered as a passive cooling option and has significant potential for energy and peak power saving. When radiant cooling is used with displacement ventilation, i.e., when ventilation air is introduced at a low level, it flows by natural means to replace exhaust air. Such a system has been suggested to offer quiet comfort and energy efficiency superior to that of conventional air-conditioning systems.

Vangtook and Chirarattananon (2005) showed that a cooling tower could be employed to provide cooling water for radiant cooling and for pre-cooling of the ventilation air to achieve thermal comfort. If a more exacting condition is required, then precooling the ventilation air with cool water generated from active cooling can help achieve thermal comfort, superior to that of conventional air-conditioning, while substantial energy savings can still be achieved.

Mouhib et al. (2009) explained how a glass substrate coated with a stainless steel-tin double layer was used to achieve the inverse greenhouse effect. Practical tests on radiative cooling were performed during clear nights using a black-body radiator covered by the coated plate. With the glass facing the sky, the black-body temperature was observed to be 6°C below that of ambient air and the cooling effect was estimated to be 27.9 W/m^2.

2.5 Passive versus Active Cooling System

Passive cooling includes the application of natural processes and passive technologies without the use of a conventional cooling system while active cooling systems typically require a power source to drive fans, pumps or compressors/evaporators. The efficiency of such cooling systems needs to be closely evaluated.

Air conditioning systems (AC) are the most common technical solution for maintaining thermal comfort, however, their growing utilisation is leading to a significant increase in electricity consumption. Although buildings that are naturally ventilated generally use less energy than those with mechanical based ventilation or air conditioning systems, they may not be able to achieve comfort conditions in hot humid climates. Costs for passive ventilation systems can be balanced against the capital and operating savings achieved by minimising the size of heating, ventilating and air-conditioning (HVAC) systems required. It has been claimed that passive systems can often save both energy and money in comparison with active cooling systems (Hill, 2005) however such techniques have in the main been limited to climatic zones with modest summer cooling loads.

During the summer months introducing the required ventilation air needed for respiration, odour and contaminant dilution will invariably warm the building and this effect can be cumulative where the building has a high thermal mass. Where passive cooling and passive design is not sufficient to meet users needs, supplementary mechanical ventilation/cooling can be provided. It is therefore possible to integrate active cooling systems with passive cooling techniques in hybrid combination to allow a predominantly passive system to deliver the required level of thermal comfort when external temperatures are close to their circadian extremes (Givoni, 1994).

Passive cooling techniques are also closely linked to thermal comfort of occupants. Some of the techniques used for passive cooling do not actually reduce the cooling load of the building itself, but rather extend the tolerance limits of the occupant's thermal comfort in a given space. It is also possible to increase the effectiveness of passive cooling with mechanically assisted heat transfer techniques that enhance the natural cooling processes. Such applications are called hybrid' cooling systems. Their energy consumption is maintained at very low levels and the efficiency of the systems and their applicability can be greatly improved.

Since passive cooling alone cannot yield indoor thermal comfort, especially in hot and humid climatic regions the task is to see if a hybrid system combining two natural heat sinks (sky and ground) can provide sufficient cooling capacity. Such a hybrid system may integrate two or more cooling technologies in a manner that overcomes the limitations of any single system and when combined with 'fabric first' design measures may demonstrate the potential to displace air conditioning.

2.6 Low Energy Cooling Approaches and HCS Potential

The term "hybrid cooling" is commonly used for the combination of natural and mechanical systems. Hybrid normally describes systems that can provide a comfortable internal environment using an interplay of natural ventilation and mechanical systems, depending on the seasonal demands. The main difference between conventional ventilation systems and hybrid systems is the fact that the latter has, "an intelligent control system that can automatically switch between natural and mechanical modes in order to minimise energy consumption" (Cook, 1989).

This emerging trend is primarily to promote natural passive cooling strategies and the next priority is to improve the active cooling techniques either by retrofitting or by alternate systems/techniques. There is however relatively few examples where such strategies have been attempted in hot and humid climate regions particularly in Saudi Arabia. This limited research base has been grouped under the following four categories:

a) Active cooling system management: optimising the energy efficiency of all mechanical and/or electrical cooling systems (HVAC) systems.
b) Passive cooling strategies include the application of solar, wind, evaporative, night, radiant, ventilative, geothermal and biomass cooling strategies.
c) Passive design and measures encompass all design and retrofitting strategies related to thermo-physical performance, adopted for energy management in a building without the aid of any mechanical means.
d) Low energy hybrid "mixed-mode" cooling systems: includes the combination of both natural passive and low energy active cooling applications.

a) Active Cooling System Management

The electric energy consumption in buildings due to HVAC systems is remarkably high, especially in hot humid regions. It has been established that conventional AC systems consume circa 70% of the total electricity consumption of residential buildings in KSA. One proven way of achieving energy efficiency in HVAC systems is to design systems that use novel configurations of existing system components. Attempts have addressed the energy conservation in HVAC systems in KSA, as summarised in Table 2.7.

Bahel et al. (1985) found that for an average 100 m^2 residence (located in Dhahran - KSA) equipped with a 17.6 kW air conditioner, consumed about 22200 kWh of electricity for space cooling over 2600 operating hours (this was within 13% of the measured value). Their study extended for similar residences in different climatic zones of KSA to determine the effect of degradation in the seasonal coefficient of performance (COP) of an air-conditioner caused by cyclic operations. It found that cyclic losses can significantly reduce with design changes that prevent refrigerant migration during the off-cycle period. Liquid desiccant solutions have the property of holding water vapour; therefore, they can be used to overcome the latent part of the AC cooling load.

Kinsara et al. (1996) studied a system using the CaCl2 solution as the liquid desiccant. Iqbal and Al-Homoud (2007) have investigated different types of HVAC systems for an office building and different feasible ECMs were evaluated using Visual DOE 4.0 program. A Variable Air Volume (VAV) system instead of the current Constant Air Volume (CAV) system resulted in an annual electric energy saving of up to 17%. Najid (2010) also reported a similar study.

Addressing the issue of energy efficient ventilation, Budaiwi and Al-Homoud (2001) showed that more than a 50% reduction in ventilation energy requirements could be obtained through a well-designed ventilation strategy. Another area of focus was the operational strategy of the AC system itself.

Budaiwi (2003) investigated the impact of HVAC operation strategies on energy consumption and thermal comfort in an office building in Dhahran, KSA by using Visual DOE energy simulation program. This study was extended to assess the impact of operational zoning and HVAC system intermittent operation strategies on the energy performance of mosques and commercial buildings. Up to a 23% reduction in annual cooling energy was achieved by employing suitable HVAC operation strategy and system over-sizing and 30% reduction was achieved by appropriate operational zoning.

Alshaalan (2012) studied the possibility of enhancing the Energy Efficiency Ratio (EER) for room air conditioners and increasing the number of condenser rows, was proven to be the best option for achieving higher EER.

In a more recent development, Almutairi et al. (2015) have performed Life Cycle Assessment (LCA) of residential AC systems to evaluate the environmental impacts and identified the use phase as the highest contributor.

The following table summarises the key published research studies that have attempt to optimise the efficiency of existing HVAC technologies and the impact of retrofitting on the energy performance of Saudi buildings (Table 2.7).

Year	Authors	Study focus
1985	Bahel et al.	Seasonal performances of residential-sized, central air-conditioners
1988	Bahel and Srinivasan	To compute the cooling load and seasonal energy consumption for residences
1996	Kinsara et al.	Liquid desiccant system compared with conventional AC system
2001	Budaiwi and Al-Homoud	Impact of ventilation strategies on contaminant concentration behaviour and corresponding ventilation cooling energy requirements
2003	Said et al.	Outdoor design conditions, degree-days, bin data and weather data sets generated from weather histories
2003	Budaiwi	Impact of HVAC operation strategies on energy consumption and thermal comfort in office building
2007	Iqbal and Al-Homoud	Impact of ECMs, including different types of HVAC systems, on energy consumption of office buildings
2010	Najid	Impact of HVAC system operation and selection on energy efficiency in office buildings
2011	Fasiuddin and Budaiwi	Impact of operational zoning and HVAC system intermittent operation strategies on the energy performance of commercial buildings
2012	Al-shaalan	Enhancing EER for room air conditioners
2013	Budaiwi and Abdou	Impact of operational zoning and HVAC system intermittent operation strategies on the energy performance of mosques
2015	Almutairi et al.	LCA of residential AC system

Table 2.7: Summary of recent published studies and researches on the optimization of the mechanical HVAC systems application in Saudi buildings.

b) Passive Cooling Strategies

There are relatively few experimental studies that have evaluated the potential of passive cooling in Saudi Arabia's hot and humid climate. Most of the experiments involved in assessing the thermal performance of evaporative cooling strategies, which would be more appropriate for hot and dry climates, however, an empirical study was conducted by Mohsen et al, (1987) in the aerodynamics laboratory at King Abdul-Aziz University in KSA to investigate the relationship between the opening size and ventilation rates in residential buildings. Various sizes of light well openings to the exterior space were evaluated. The result showed that increasing the opening size is found to have a linear relationship with an increase in air velocity. It concluded that constant opening of light wells is crucial for efficient natural ventilation in buildings.

Bajwa et al (1993) have examined the effectiveness of passive evaporative cooling strategy through experiments on a two-story full-scale house in the eastern hot and humid region of Saudi Arabia. The evaporative cooling system consists of a wind tower internally covered by 5 cm thick evaporative pads supplied by re-circulated water through a pump to keep pads wet. The cooled air is circulated directly or indirectly through the ducts to the room. This experiment was carried out during July to September with the AC system turned off. The results showed that the system has performed well despite the high background relative humidity. Overall results have concluded that the passive evaporative cooling technique significantly reduced the operation time of the air conditioning system during the hot summer.

Bajwa (1993) has also conducted an experiment to assess the cooling potential of night ventilation to reduce the cooling energy consumption and improve indoor thermal comfort in residential buildings located in the eastern region of Saudi Arabia. The tested house had external insulation and heavy internal thermal mass. The Predictive mean vote (PMV) was recorded every 3 minutes and compared with the ambient temperature to assess the performance of the passive night cooling strategy. Based on climate analysis the testing period of the experiment was in October. During the testing period, windows are left open during the night to benefit from the outdoor cooler air. The results of the experiment showed that the indoor temperature is approximately 10°C lower than the outdoor ambient temperature during daytime with an acceptable indoor thermal comfort level being met for over 65% of the test period.

Al-Hemiddi and Al-Saud (2001) have conducted another experiment related to passive natural ventilation to investigate the influence of a ventilated interior courtyard on the thermal performance of a family house in the hot climate in Saudi Arabia. The square shape floor plan with an internal courtyard was surrounded by un-insulated walls and roof. The experiment was carried out from August to September with a fully opened window during the night to allow cross ventilation. The results revealed that the average temperature of the spaces surrounding the courtyard was lower than the mean ambient temperature as a result of shading and increased cross-ventilation.

Three further experiments were designed and investigated by Bassindowa et al (2007) to evaluate the feasibility of using radiative cooling strategy in Jeddah, Saudi Arabia, The first experiment was made on recording the temperature history of two black painted plates, one of them in a horizontal position and the other inclined 45° while the second experiment involved a plate that was thermally insulated and covered with 100μm thick plastic sheet. The third experiment was designed to examine the radiative cooling efficiency of cool two identical fabricated shelters. These simple experiments concluded that radiative cooling effect can be efficiently utilised for dropping the sink temperature even in hot and humid climatic condition such as Jeddah, Saudi Arabia.

The following table summarises the key published research studies on the potential impact of passive cooling applications on the thermal energy performance of Saudi houses (Table 2.8).

Year	Authors	Study focus
1987	Mohsen et al	Aerodynamics and Ventilation in Buildings: Experimental investigation
1992	Bajwa	Effectiveness of Nocturnal Ventilative Passive Cooling Strategy in the Maritime Desert Climate of the Arabian Gulf Region
1993	Bajwa et al	The Potential of the Evaporative Cooling Techniques in the Gulf Region of the Kingdom of Saudi Arabia
2001	Al-Hemiddi and Al-Saud	The Effect of a Ventilated Interior Courtyard on the Thermal Performance of a House in a Hot–Arid Region,"
2007	Bassindowa et al	An Experimental Investigation On night radiative cooling

Table 2.8: Summary of recent published studies and researches on passive cooling application in Saudi buildings.

c) Passive Design and Measures

Most of Saudi's present residential buildings have been built in the last few decades during the rapid economic development. Nevertheless, these buildings were designed and constructed with little or no consideration of the local climate or energy conservation. Major energy savings can of course be achieved by minimising the thermal transmission of the building fabric (Abdelrahman,1993). Selecting thermo-physically appropriate wall materials for building construction in KSA can minimise heat gain and reduce cooling energy consumption (Al-Hadrami and Ahmad, 2004).

Al-Naimi (1989) studied the cooling energy saving potential of residential buildings by retrofitting the building envelope. The study involved examining the thermal and energy performance of local masonry materials such as concrete blocks, clay bricks, sand-lime bricks and prefabricated walls.

Budaiwi (2011) has studied the influence of envelope design parameters on the energy performance of mosques in hot and humid climate.

Al-mofeez (2007) studied the potential of energy saving by retrofitting a one-story house in Dhahran; the study showed 40% saving in AC energy consumption due to building envelope retrofitting.

Al-Hazmy (2006) has studied the heat transfer analysis of local hollow brick. Thermal insulation is one of the most significant energy conservation measures in buildings (Al-Kasmoul, 2006), and its utilization in Saudi Arabia has increased significantly in recent years (Ahmad, 2002). The thermal and energy performance of various types of thermal insulation materials were studied.

Al-Homoud (2004) presented an overview of the main principles of the most commonly used thermal insulation materials in the building; he also demonstrated the role of appropriate material selection as a function of climatic conditions and building type. Under the same topic, another review was reported by Abdelrahman and Ahmad (1991) who emphasised the application and procedure to select the types and thickness of appropriate insulating materials. The study emphasised that insulating the walls and the roof (15mm thick insulation) can reduce the annual energy consumption and peak cooling load by more than 27% and 23% respectively (Said & Al-Hammad, 1993).

Ahmad (2002) examined the optimisation of insulation thickness, payback period and cost analysis for various wall structures, while Al-kasmoul (2006), Al-Ajlan (2006), Budaiwi et al. (2011) and Abdou and Budaiwi (2005) have examined the characterisation of commonly utilised insulation materials in KSA. The thermo-economic analyses of insulation materials, insulated envelope and finding the ideal thickness of insulation, for typical climatic conditions of KSA were reported by Al-Sanea (2012). A study by Al-ghamdi and Al-feridah (2011) has shown that providing insulation on the flooring has an influence on the electrical energy consumption of the building.

Tinker and Al-buijan (1978) addressed the issue of overheating caused by the direct solar gain and Aldawoud (2013) investigated the thermal performance of electro-chromic glazing in buildings and has demonstrated its efficiency in reducing solar heat gains in comparison with the conventional fixed exterior shading devices.

Aldossary et al. (2014) have investigated the domestic energy consumption patterns in the city of Jeddah as a result of implementing thermal retrofitting solutions include shading devices, domestic renewable energy sources, and efficient glazing. The IES-VE simulation results suggested an energy consumption reduction in a range of 21% to 37%.

The following table summarises the key published researches and studies on the potential impact of various passive design measures on the thermos-physical and energy performance of Saudi buildings (Table 2.9).

Year	Authors	Study focus
1987	Tinker and Al-buijan	Overheating caused by the solar gain through the fenestration of buildings.
1989	Al-Naimi	The potential for energy conservation in residential buildings in Dammam Region, Saudi Arabia.
1990	Eben Saleh	Thermal performance of insulation materials
1991	Abdelrahman and Ahmad	Cost-effective use of thermal insulation in hot climates.
1993	Abdelrahman	Energy consumption of residential building with different bricks and prefabricated walls.
1993	Said and Al-Hammad	Energy conservation measures for residential building
2001	Al-Sanea and Zedan	Effect of insulation location (outside or inside the wall)
2002	Ahmad	Cost analysis and thickness optimization of thermal insulation materials used in residential buildings in KSA
2002	Al-Sanea and Zedan	Optimum insulation thickness
2002	Budaiwi et al.	Thermal characterization of insulation materials
2003	Al-Sanea	Thermal performance of roof structure subjected to periodic changes in ambient temperature
2004	Al-Homoud	The Effectiveness of Thermal Insulation in Different Types of Buildings in Hot Climates.
2005	Al-Homoud	Review of insulation materials
2005	Al-Sanea et al.	Effect of electricity tariff on optimum insulation thickness
2005	Abdou and Budaiwi	Thermal characterization of insulation materials
2006	Al-kasmoul	Characterization of commonly used insulation materials in KSA.
2006	Al-Ajlan	Measurements of thermal properties of insulation materials by using transient plane source technique.
2006	Al-Hazmy	Heat transfer analysis of hollow brick available in local market
2007	Al-Mofeez	Energy saving potential of retrofitting a residential building
2008	Baig and Antar	Conjugate heat transfer analysis of hollow brick available in local market
2009	Al-Hadrami and Ahmad	Thermal performance of residential building with different types of locally available bricks
2010	Antar and Baig; Antar	Conjugate heat transfer analysis of hollow brick
2011	Budaiwi	The effect of envelope design parameters on the energy performance of mosques
2011	Al-Sanea and Zedan	Dynamic thermal characteristics of insulated building walls
2011	Al-Ghamdi and Al- feridah	Effect of floor insulation on energy consumption of building
2012	Al-Sanea et al.	Effect of thermal mass on thermal performance of walls; effect of masonry material and surface solar absorptivity on critical thermal mass thickness
2013	Alahmed	Optimization of DSF configuration
2013	Aldawoud	Performance of electrochromic glazing
2014	Aldossary et al	Domestic energy consumption patterns in a hot and humid climate: A multiple-case study analysis.

Table 2.9: Summary of recent published studies and researchers of the impact of passive design and thermal retrofitting on energy performance of Saudi buildings.

d) Low Energy Hybrid Cooling System

The implementation of the mixed-mode hybrid cooling technique in hot and humid climate is very challenging and has not been adequately studied. Few researches have addressed the potential hybridisation of the current mechanical cooling systems, especially in Saudi Arabia, whereas integrating renewable low energy sources such as solar energy had the biggest share. PV technology received serious attention as a renewable clean energy source for buildings (Al-Saleh, 2009). Saudi Arabia has a considerable level of solar radiation, and PV systems are a prospective candidate for deployment (SEEC, 2015). Building-integrated Photovoltaics (BIPV), which refers to the integration of photovoltaic cells into building envelope exterior surfaces, is increasing PV application. A recent assessment of techno-economic has highlighted some key advantages of BIPV technology for residential buildings in the GCC countries. These advantages include savings in capital cost, growth in the exported oil and natural gas and lowering in the CO_2 emissions from conventional power plants. Recently, there is an effort to promote sustainable houses in GCC countries and Middle East is known as The Solar Decathlon Middle East (SDME) which was created through an agreement signed between Dubai Water and Electricity Authority (DEWA) and the Department of Energy of the United States of America (SDME, 2016).

Almasoud and Gandayh have demonstrated that if the costs of health and environmental issues were considered, the cost of fossil fuel energy would be significantly higher than the cost of solar energy. Some researchers have been studying the deployment of PV technology in Saudi's buildings. These include hybrid (PVþdiesel) power systems proposed for residential and commercial buildings (Shaahid, 2015) and the study on the integration of PV into the hospital building envelope (Osman J, 2012). Another promising potential area in KSA is solar air conditioning systems. Solar thermal and PV are the basic modes of solar cooling, however, this system in KSA is uneconomical without government subsidy (El-Sharawi et al, 2013).

Researchers have also studied liquid desiccant cooling and hybrid absorption-desiccant systems; Gandhidasan (1994), Al-Farayedhi et al. (2002) and Shaahid and Elhadidy (2003) however the conclusions demonstrated limited potential where ambient RH is high. The thermal and energy performance of hybrid water cooled PV system that applied in the east coast of Saudi Arabia was assessed by Bahaidarah et.al (2013). The results proved that water cooling the PV module reduced the temperature by 20% leading to an efficiency enhancement of 9% electricity output. Energy savings as a result of applying a hybrid IEC (indirect evaporative cooling)/DX-based AC system in various simulated climatic conditions was investigated by Youssef et.al (2014). The results showed that fresh air pre-cooling using IEC has energy savings range from 10% to 70% when compared to using just DX-based AC system. Al-Mogbel et.al (2013) investigated the feasibility of implementing solar-driven adsorption chillers to domestic air-conditioning in Saudi Arabia.

El Khashab and Al Ghamedi (2015) discussed the potential of hybrid wind/solar energy system in the west coast area of Saudi Arabia. An extensive study carried out by Ramli, et .al (2016) through investigating the energy production and cost from both wind turbine and photovoltaic (PV) in the hybrid system. The results indicated that the PV array has a higher electricity production than the wind turbine generator.

In similar climatic condition, scientists and researchers had many studies on the different methods to develop a hybrid desiccant cooling system by using renewable energy in hot and humid climates. Niu et al (2002) investigated an air-conditioning system combining chilled-ceiling with desiccant cooling to find energy saving potential in hot and humid weathers. They concluded that chilled-ceiling combined with desiccant cooling could save up to 44% of primary energy, in comparison with constant volume all-air system. Lafuenti et al (2002) proposed new configuration for solar cooling system by using the solid desiccant wheel as a dehumidifier and single stage LiBr-water absorption cycle as a chiller for cooling unit. Stabat et al (2003) simulated indirect evaporative system and desiccant cooling system for one office building in Trappes (close to Paris) to find limits of feasibility and energy consumption of the desiccant cooling system. They found that indirect evaporative cooling can be used in temperate climates that their climate is not too humid.

Tsay et al (2006) investigated the applicability of combining desiccant cooling system with a heat pump for an experimental building located in Ciba city, Japan where was hot and humid. They found that the relatively low regeneration temperature provided by exhaust heat condenser of a heat pump can improve the energy efficiency.

Fong et al (2011) carried out the simulation and empirical studies of solar hybrid desiccant cooling system used for commercial premised with high latent cooling load in subtropical Hong Kong. It was found that the solar hybrid desiccant cooling system had more superior cooling and energy performance than the conventional centralized air-conditioning (AC) system in the mentioned location. Also, Fong et al.(2011) developed a simulation model (TRNSYS) of an integrated radiant cooling by absorption refrigeration and desiccant dehumidification for high- tech offices in subtropical climate.

The following table summarizes the major published studies and researchers on low energy hybrid cooling application in Saudi buildings and other hot and humid climate riegon until the date (Table 2.10).

Year	Authors	Study focus
1975	Sayigh and Abdul-Salam	Preliminary design of solar house
1981	Sayigh	Performance comparison of various solar AC techniques
1994	Gandhidasan	Open-cycle liquid desiccant system
1997	Ahmed et al.	Hybrid open-cycle vapour absorption and liquid desiccant system
2002	Al-Farayedhi et al.	Hybrid liquid desiccant and vapour-compression system
2002	Lafuenti, et al.	New Solutions for the Use of Solar Cooling in Hot and Humid Weather Conditions.
2002	Niu, J, et.al,	Energy savings potential of chilled-ceiling combined with desiccant cooling in hot and humid climates.
2003	Shaahid and Elhadidy	Hybrid PVþdiesel power system for the residential building.
2003	Stabat, et.al	Limits of feasibility & energy consumption of desiccant evaporative cooling in temperate climates
2006	Tsay, et al.,	Study on the applicability of combining a desiccant cooling system with a heat pump in a hot and humid climate.
2011	Fong, K., et al.	Investigation on solar hybrid desiccant cooling system for commercial premises with high latent cooling load in subtropical Hong Kong
2011	Fong,K, et.al.	Solar hybrid cooling system for high-tech offices in subtropical climate Radiant cooling by absorption refrigeration and desiccant dehumidification
2011	Maerten and Tan	Improved conceptual design
2012	Osman	Integration of PV into the envelope of a hospital building
2013	El-Shaarawi et al.	PV powered vapour compression system
2013	Al-Mogbel et.al	The Potential of Solar Adsorption Air-Conditioning in Saudi Arabia: A Simulation Study.
2013	Bahaidarah et.al	The thermal and energy performance of hybrid water-cooled PV system.
2014	Shaahid et al.	Hybrid PVþdiesel power system for residential buildings.
2014	Youssef et.al	Energy Saving Potential of Indirect Evaporative Cooling as Fresh Air Pre-cooling in Different Climatic Conditions in Saudi Arabia
2015	El Khashab, and Al Ghamedi	The potential of hybrid wind/solar energy system in the west coast area of Saudi Arabia
2016	Ramli, et .al	The energy production and cost from a hybrid wind turbine and photovoltaic (PV)

Table 2.10: Summary of recent published researches and studies on low energy hybrid cooling application in Saudi's buildings.

2.7 Critical Discussion and Knowledge Gap

There is a wide scope for further research in almost all the areas mentioned. Actually, many technologies which have been adopted worldwide are yet to be introduced in KSA. For instance, solar energy utilization needs enhanced research to realize their outstanding merits for the existing and future buildings in the Kingdom. Computer-aided simulation and optimization techniques need to be applied to perform technical and thermo-economic analyses on various solar cooling options such as absorption/adsorption, liquid/solid desiccant and hybrid systems. While studying the viability of PV technology in buildings, the economic assessment should incorporate the monetary share of human health and other environmental benefits (with respect to fossil fuel utilization), in order to justify the cost. Apart from solar, wind, geothermal and biomass options have also been proposed for buildings which open many research ventures. Possible research could investigate the potential integration of passive and active cooling approach ‘hybrid’. Such a hybrid system may integrate two or more cooling technologies in a manner that overcomes the limitations of any single system and when combined with ‘fabric first’ design measures may demonstrate the potential to displace air conditioning.

There is scope for research on identifying energy-efficient envelope materials and structures for Saudi Arabian buildings. One of the weaknesses identified is the poor efficiency of external walls, with U-value range from 2.2 to 2.8 W/m^{2}K. In a hot environment as in KSA, this causes excess heat leak into the house, thereby increasing the AC load. It has been established that using efficient external walls could achieve energy savings up to 60%. However novel envelope materials and structures proposed for identical climates should be studied. Thermo-economic analysis on insulation thickness of building envelope with different structural materials has scope for extension. The concept of ‘Cool or Green Roof’ shall be explored for Saudi environment. Impact of climate change on the design of energy-efficient building envelope is another potential research area. The studies on envelope and glazed windows by Tinker and Al-buijan (1987) and Aldawoud (2013) need to be pursued for developing adequate glazing strategies for Saudi buildings.

Many methods have been proposed by various researchers for the energy conservation and management in HVAC systems. These include but are not limited to, heat recovery and utilization, absorption refrigeration systems, multi-air system, thermal cool storage, ventilation control, system optimization and the use of modelling and simulation tools. Even though many works were reported, there is a wide scope for further research to explore the viability of most of the aforementioned options in KSA. Many reviews are available to guide new researchers in this area.

This study has identified many weaknesses in the architectural design of Saudi buildings, that could result in excessive energy consumption. These included inappropriately large space for the occupants, the building shape that is badly conducive for solar heat gain and lack of proper shading strategy. Hence additional researches should incorporate the architectural design aspects, and other passive design considerations such as natural ventilation, skylights, building orientation, night ventilation, shading strategy, etc. Useful references include the

Based on the comprehensive review and critical discussion of the literature, and in order to define the knowledge gap which the current study attempts to fill, the general findings of literature review can be summarised and classified as follows:

There is in the main a limited number of research studies that address the issue of cooling efficiency in hot and humid climatic regions and particularly within the Saudi context (See Tables 2.7 - 2.10). In addition, few authors have addressed the issue of building performance in residential building such as (Sayigh and Abdul-Salam, 1975) (Bahel et al, 1985) (Bahel and Srinivasan, 1988) (Said and Al-Hammad, 1993) (Budaiwi and Abdou, 2013) (Almutairi et al, 2015) (Shahid and Elhadidy, 2003) (Shaahid et al, 2014) (Matrawy et al, 2015) (Abdelrahman, 1993) (Ahmad, 2004) (Al-Mofeez, 2007).

Most of the current studies on passive or low energy cooling strategies were often focussed on either optimising the energy performance of current active AC systems (Filippin et al, 1998) (Ashley and Reynolds, 1993) (Garg, 1991) (Hassid, 1985) (Millet, 1988) (Gandemer 1992) (Bahel et al, 1985) (Bahel and Srinivasan, 1988) (Kinsara et al, 1996) (Budaiwi and Al-Homoud, 2001) which resulted in modest energy saving potentials. Those that focussed on architectural design measures that involved thermo-physical improvements to the building fabric and envelope (Givoni, 1998) (Roaf, 2004) (Bansal, 1992) (Malama, 1996) (Rousseau, 1996) (Peuportier, 1995) (Eben Saleh, 1990) (Abdelrahman and Ahmad, 1991) (Al-Sanea and Zedan, 2001) (Budaiwi et al, 2002) also demonstrated a relatively limited reduction in cooling energy (10% - 30%). Passive interventions on their own were insufficient to meet thermal comfort requirements during the summer months. It can be concluded that most of the studies were simply trying to inhibit heat gain to mitigate AC cooling demand.

The experimental researches and studies that have addressed the potential application of passive cooling strategies such as ventilatiive, evaporative, radiative and geothermal strategies (Mohsen et al, 1987) (Bajwa, 1992) (Bajwa et al, 1993) (Al-Hemiddi and Al-Saud, 2001) conclude that, despite its tempering and ventilation effect, the application of such passive strategies in current buildings are insufficient to maintain the desired thermal comfort especially in buildings with relatively low thermal mass.

Most of the conducted research studies that addressed the potential application of hybrid cooling system either addressed the integration mixed mode mechanical cooling or the integration of passive techniques such as solar or radiant with active mechanical cooling scenarios, while retaining the base AC system (Kinsara et al, 1996) (Said et al, 2003) (Al-shaalan, 2012) (Budaiwi and Abdou, 2013) (Ahmed et al., 1997) (Al-Farayedhi et al, 2002) (Shaahid and Elhadidy, 2003).

Therefore, the primary aim of this current research involves assessing the potential for hybridising two low carbon semi-passive cooling systems as an alternative to conventional AC systems. This research aims to bridge the gap between building designers and building physicists, by developing prototypes that can combine natural passive strategy with low energy active cooling technology in so-called hybrid or mixed-mode systems, and combined with 'fabric first' design measures to optimise cooling potentials. Figure (2.10) summarises the results of the literature review.

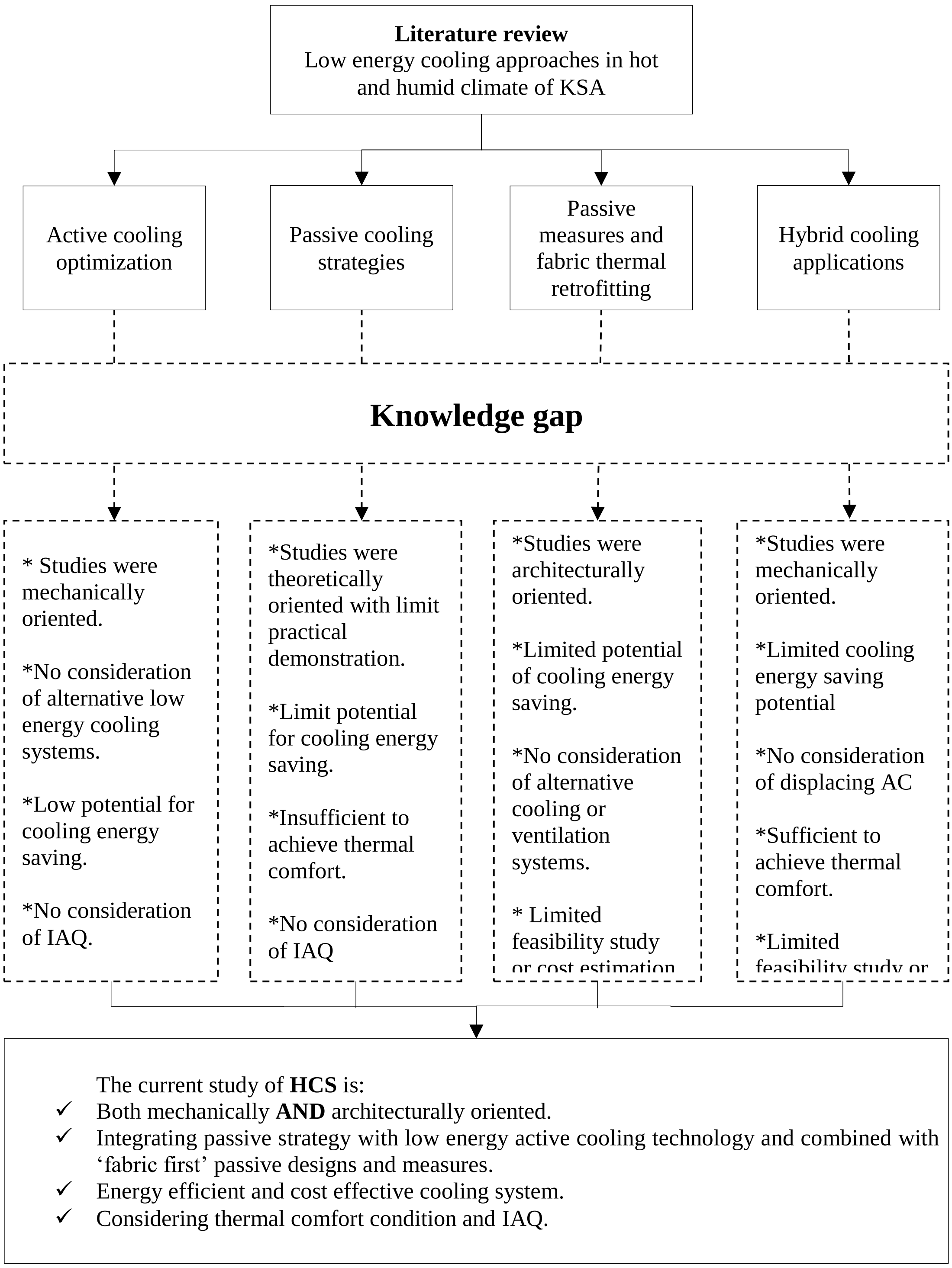


Figure 2.10: Literature review findings and a critical gap of knowledge exposure

2.8 Conclusion

Active cooling systems such as air conditioners are becoming ubiquitous in residential buildings in KSA. Although AC systems are responsible for the majority of domestic electricity consumption, this type of cooling system contributes to greenhouse gas emissions, that are having increasingly negative impacts on the environment.

Studies by Filippin et al, (1998), Ashley and Reynolds, (1993) Garg, (1991), Hassid, (1985) have shown the limitations of a range of current approaches to the problem with almost all studies demonstrating a limited potential in reducing energy use. The literature review has confirmed that a more radical approach is required to assess low energy cooling strategies if conventional air conditioning is to be superseded.

Most of the research has demonstrated that applying passive cooling strategies has some potential to save a proportion of the required energy to cool while reducing emission levels (Givoni, 1998) (Roaf, 2004) (Bansal, 1992), (Malama, 1996), (Rousseau, 1996). Nevertheless, such passive cooling strategies in hot humid regions are difficult to accomplish in peak summer due to the high temperatures and relative humidity.

Some authors argue that these passive solutions can be further developed and or optimised by incorporating passive design measures to enhance the thermo-physical performance of building fabric which can have a significant impact on building cooling energy consumption and indoor condition (Al-kasmoul, 2005) (Al-Ajlan, 2006) it is likely that a possible solution could be found by combining passive and active low energy cooling systems.

A mixed mode or hybridised cooling systems could integrate a range of passive strategies with low energy technology to optimise cooling performance (Kinsara et al, 1996) (Said et al, 2003) (Al-shaalan, 2012) (Budaiwi and Abdou, 2013). This research aims to examine the potential application of such novel HCS combined with 'fabric first' design measures as an alternative cooling strategy towards reducing cooling energy consumption, CO_2 emissions and maintaining the desired thermal comfort and indoor air quality across all seasons.

3 CHAPTER | Research Methodology

3.1 Introduction

Generally, the methodology is a framework which is accompanied by a specific set of the paradigmatic presumptions that are used to conduct a research programme. Research methods are the diverse procedures and techniques that are used to conduct the research, while the term methodology is typically used to refer to the series of procedures that aim to systematically solve a research problem (Kothari, 2004). The term methodology can be defined as the science of considering how to perform the research, "scientifically", however in this context, the term methodology is used to indicate, all the approaches employed across the various research stages (Nicholas, 2010).

A distinction can also be drawn between method and technique. The term 'research technique' usually indicates the conductance and tools that are employed to perform the research process which includes data collection, managing records and expressing opinions. In contrast, research method indicates the conductance and tools used in experiments construction and research techniques (Nicholas, 2010). Consequently, the term 'methods' is more general and is the aspect that refers to the generation of techniques (Kothari, 2004).

The methodology used described in this chapter attempts to illustrate the research paradigm, approach, methods and strategies, including a justification explaining the advantages and disadvantages of each approach and method taking into consideration their practical applicability to the research questions (Collins et.al, 2004).

This chapter presents a detailed description of the method design in order to ensure that its aims and objectives are addressed. The first section of this chapter outlines the main concepts of the research paradigm. The second section highlights the employed research approaches to achieve the specific aims and objectives and to answer the research questions. The third section presents the research method and strategy for each research stage and describes their appropriateness. The fourth section describes the conceptual framework and flow chart (Figure 3.1).

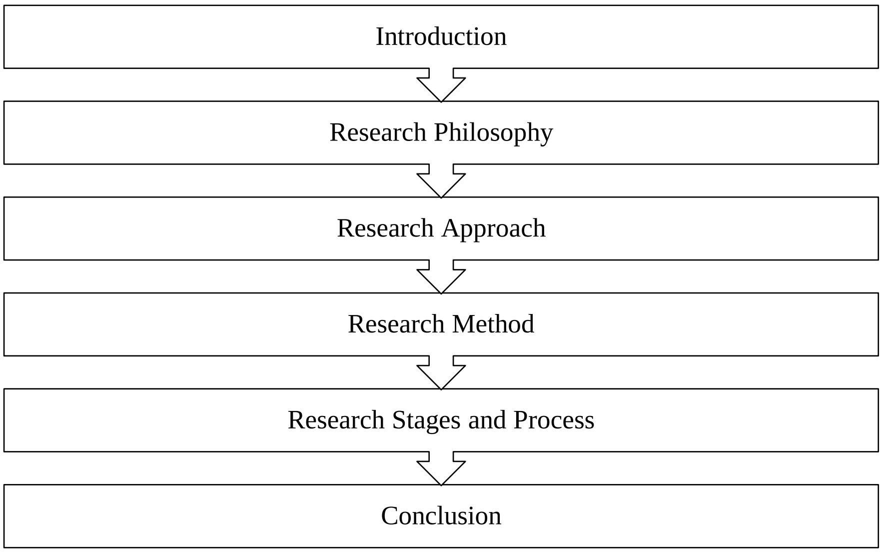


Figure 3.1: Flowchart of research methodology.

3.2 Research Philosophy

Research has been defined as an activity that involves, "finding out, in a systematic way, things you did not know" (Nicholas, 2010). A methodology can be defined as the "philosophical framework within which the research is conducted or the ground upon which the research is based" (Collins et.al, 2004). Any research aims to contribute to the body of knowledge within its area through study, experimentation, comparison and observation (Cross, 1999). Research can be defined as utilising a systematic method and objective in order to search for knowledge or to determine an applicable solution to a specific problem. According to Jonker and Pennik, a research paradigm comprises of a framework of presumption and beliefs about the way in which the world is perceived which, in turn, informs and leads the researcher's behaviour. The research philosophy remains implicit rather than explicit, however, these fundamentals can profoundly influence the actual practice of research (Jonker & Pennink, 2010). Any research philosophy must work with the sources, nature and knowledge development (Kothari, 2004).

As presented in Figure 3.2, the identification of the research paradigm is located at the outer layer of the 'research onion', accordingly it is the first topic that requires to be established in the research methodology. In general, there are several branches of research philosophy which may be relevant to science and knowledge. These branches include pragmatism, positivism, realism and interpretivism, however, the selection of a particular philosophy for a research programme is influenced by additional factors such as the practical implications of the research (Saunders et.al 2009).

The current research adopts a positivist research philosophy; the rationalisation of this selection is that positivism involves building knowledge obtained through observation (sensible), based on measurement. With this philosophy, the researcher's role is restricted to collecting data through this 'objective' approach and the findings are normally quantifiable (Nicholas, 2010). This research addresses perceptible phenomenon, such as the increase in cooling energy consumption, which can be monitored and numerically measured. Positivist studies commonly employ a deductive approach linked with a phenomenological philosophy (Kothari, 2004).

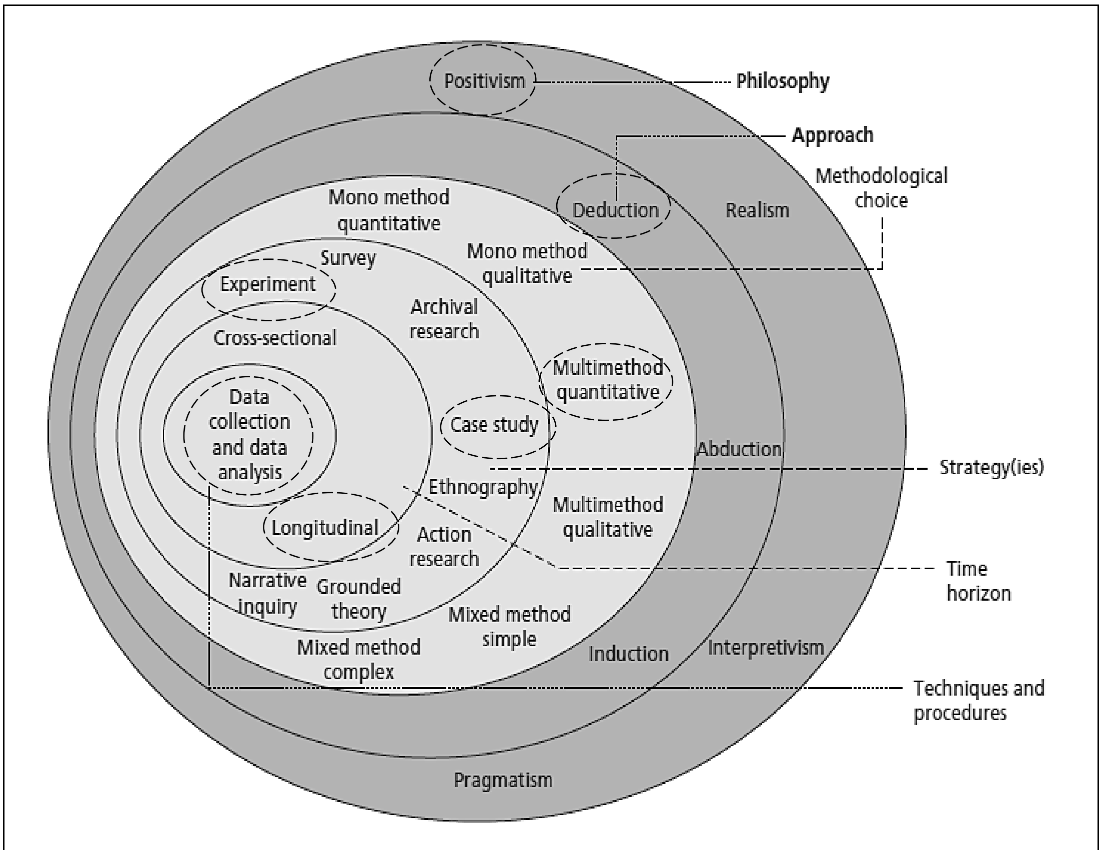


Figure 3.2: Research philosophy structure and conceptual framework (Saunders et.al, 2009).

3.3 Research Approach

The research approach is the way that the research is conducted. The research approach is divided into three types including, deductive, inductive and 'abductive' approach (Nicholas, 2010). The research hypothesis is the major distinctive point between deductive and inductive approaches. A deductive approach examines the validity or presumptions (hypotheses/theories) embedded in any hypotheses, while an inductive approach leads to the emergence of new theories. An 'abductive' approach (lateral thinking), starts by disregarding the usual 'top down or bottom up' design logic. It is, in essence, a search for completely new paradigms. The initial affirmation in any deductive approach is usually on causality with the research conducted in order to assess the impacts specific assumption (such as applying novel cooling strategies in Saudi dwellings). An inductive approach will usually concentrate on looking at previous research phenomena from a different view point (Kothari, 2004) (Figure 3.3).

A deductive approach is commonly coupled with quantitative research such as data collection and analysis based on quantitative numerical data such as energy consumption and indoor air temperatures. The Inductive approach is usually coupled with qualitative research (Jonker & Pennink, 2010). Although the literature review, in itself, is considered as an inductive research exercise, in general, the current research adopts a deductive approach which corresponds with the research hypotheses, aim and objectives, and answers research questions (Figure 3.3).

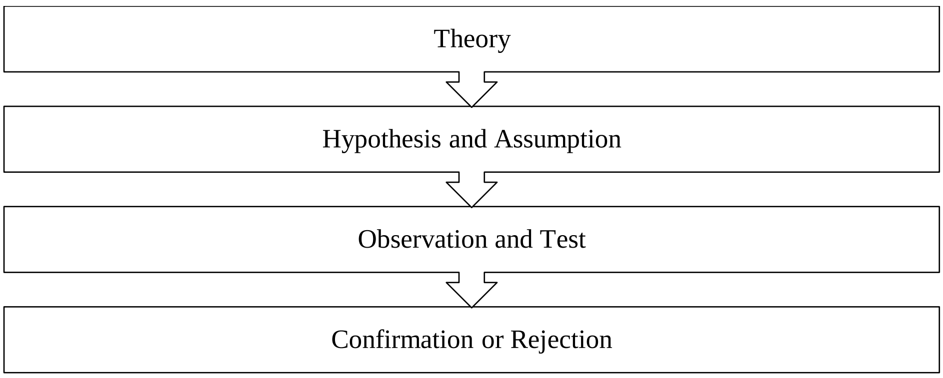


Figure 3.3: Deductive research approach path.

3.4 Research Method

Basically, the current research adopts a quantitative method in data collection. such method involves various research strategies including observation, case studies, survey and new experiments (prototypes). While the selected methodological strategy to conduct this research is a"multi-method quantitative analysis" by using case study as a methodological choice to obtain the primary research data combined with field experiment to develop and test a new cooling paradigm that can be analysed, assessed and compared with the primary findings of the base case analysis. A detailed rationalisation and description of the selected methods are outlined in this section. In order to meet the research aims objectives and answer the research questions, the research programme was divided into three main stages. Each stage uses a specific methodological choice or strategy.

The initial stage was to collect primary data in order to investigate the most significant factors driving high levels of residential cooling energy consumption in Saudi Arabian dwellings. It was important to observe and analyse the actual thermo-physical and energy performance of the existing main house typology. A case study was selected to obtain the required baseline data,"within a specific context and in a specific period and geographical location" (Lukka, 2003). The essence of case studies is to explore and investigate contemporary real-life phenomenon through contextual analysis (Creswel, 2008)

The rationale behind adopting such a strategy is that the case study is the optimum strategy to observe and critically analyse the current research problem, answer research questions and obtain the required database.

Based on the case study results it was necessary to adopt an experimental strategy in order to design and develop a viable alternative cooling system applicable to the selected base case design. (Cross, 1999). An experiment is a procedure that is performed to support, rebut, or validate a hypothesis. Experiments provide a useful insight into cause-and-effect by demonstrating what result occurs when a specific factor is manipulated (Creswel, 2008). An experimental research method in engineering and architectural disciplines usually concerned with the development of conceptual projects challenging conventional and consolidated practices. The main objective of this method is to explore original thought trajectories and develop innovative design tools and methodologies (Cross, 1999).

The experimental method in this research is divided into three phases. The first phase involves field experiments to obtain the primary measurement and database such as (ambient air, ground and radiant sky temperatures). Based on these field measurements, the second phase involves the design of low energy cooling systems integrated with ‘fabric first’ passive architectural design techniques to reduce the total cooling load by excluding solar conductive and convective gains. The third phase involves employing numerical modelling and simulation software DesignBuilder as tools to conduct parametric analysis and model the various systems that can be compared with the base case study analysis to quantify energy savings and running costs.

3.4.1 Research Data Analysis and Assessment Tools

3.4.1.1 Computational Modelling and Simulation

Usually, simulation models are used to represent a real-world system in a virtual environment and to assess the system’s performance under different operating conditions. Simulation software can predict the thermal behaviour of buildings prior to their construction and simulate the costs of energy in existent buildings in their current conditions, establishing the best thermal retrofitting measures to adopt in the buildings under analysis. The calculation of energy consumptions spent in dwellings still to build or to retrofit allow a more accurate determination of design charges and help to decide with highest accuracy the possible devices to be used in a room (limited zone) or dwelling. Energy simulation software tools can also allow considering all the regulations in force and simultaneously provide a sense of comfort to its inhabitants through a correct design of heating and cooling systems. Such software have also available tools to improve constructive solutions through simulating the incorporation of passive solar systems in buildings, such as horizontally and vertically shading systems and a more accurate study of the HVAC system loads to use.

Since the current study aims to determine the effect of passive measures and hybrid cooling application on building energy and thermal performance, and due to the complexity and difficulty of physically modeling and monitoring such hybrid system, it was crucial to employ a professional simulation software to computationally (virtually) model and test such innovative hybrid technology as if it existed in reality. Therefore, the current study relies heavily on the use of modelling and simulation as a basic tool to measure the actual thermo-physical and energy performance of the case study building and assess the influence of the passive measures and hybrid cooling applications on building thermal and energy performance.

Currently, there are a number of energy simulation software tools with different levels of complexity and response to different variables. Among these software, the complete simulation software tools are the EnergyPlus, the ESP-r (Energy Simulation Software tool), the IDA ICE (Indoor Climate Energy), IES-VE (Integrated Environmental Solutions - Virtual Environment) and TRNSYS. Being the most complete software tools, these are also the most complex and therefore require greater expertise.

The following section presents a comparative review of these five energy modelling and simulation software in order to appraise their features and capabilities and to justify the current selection of DesignBuilder combined with EnergyPlus simulation engine as an optimum data analysis and assessment tool to accommodate such hybrid system design and passive applications.

- ***EnergyPlus***

EnergyPlus is one of the most known energy simulation software tools. Its development began in 1996, sponsored by the Department of Energy (DOE) from United States of America (USA). The EnergyPlus has the features and capabilities of BLAST and DOE-2, however, is an entirely new software tool that combines the heat balance of BLAST with a generic HVAC system.

The EnergyPlus aims to develop and organize software tools in modules that can easily work together or separately. It is important to outline that EnergyPlus does not exist a visual interface that allows users to see and model the building. In this case, third-party software tools like DesignBuilder need to be used.

EnergyPlus is a thermal simulation software tool that allows the analysis of energy throughout the building and the thermal load and it is used by engineers, architects and researchers to model the energy use in buildings. The operating conditions are determined through database support. Shading, insulation, HVAC systems, areas of computational fluid dynamics (CFD), electricity, renewable energy embedded systems, lighting, natural ventilation, combined heat and power generation, facades photovoltaic systems for control of indoor air quality can also be included in the models pre-determined. The EnergyPlus is extremely useful and is a powerful tool to simulate many innovative technologies (DOE, 2014).

- ***ESP-r***

The software tool ESP-r (Energy Simulation Software tool) is intended to support the construction project with regard to energy and environmental performance in a realistic and accurate way. The software tool is a mathematical software for a project manager that coordinates the data, simulation, CAD applications, different tools for evaluating performance, display and report generators. The ESP-r uses several complex equations to deal with all aspects at the same time (geometry, construction, operation, distribution, heat dissipation). These equations are integrated into successive time steps in response to the influences of the occupants and climate control systems (IBPSA, 2016).

The geometry of the building can be set in CAD software tools or other similar tools to allow the specification of the geometry of buildings. The models created in this software can be exported to EnergyPlus. The time simulation of the building with ESP-r simulation tool can vary in a range from one minute to one hour. The outputs of the simulations can be viewed by the interactions between the domains of assessment or exported to other graphics software. The software tool simulates models for heating, cooling, lighting, ventilation, other flows of energy and water use. However, the program requires a great knowledge and expertise from its users and requires a long learning process.

- ***IDA ICE***

The thermal simulation software tool IDA (Indoor Climate Energy) is based on a general system simulation platform with a modular system. The multi-domain physical systems are described in the IDA using symbolic equations starting with a simulation language Neutral Model Format (NMF - Neutral Model Format). The user defines the tolerances which control the accuracy of the solution, thus allowing the isolation of numerical modelling approaches (IBPSA, 2016).

- ***IES VE***

The simulation software tool IES (Integrated Environmental Solutions - Virtual Environment) provides the design professionals with a variety of variables in simulation analysis of buildings. The model works on the geometric representation that represents the building. The software tool allows interaction with other energy simulation software tools. The simulation software tool incorporates a tool for dynamic thermal simulation of heat transfer processes of buildings, which is the ApacheSim (IBPSA, 2016).

The simulation software tool was tested using the IES ASHRAE 140 and is qualified as a dynamic model in CIBSE system of classification. The software tool provides an environment for the detailing of the building systems, allowing their optimization taking into account criteria such as comfort and energy. The dynamic tool ApacheSim can be dynamically linked to the Macro FLO dynamic tool for natural ventilation and HVAC Apache dynamic tool to perform analysis of air leaks and for analysis of natural lighting and shading. The results should be automatically exported (IBPSA, 2016).

- ***TRNSYS***

TRNSYS is a transient system simulation software tool with a modular structure that has been specially designed to develop complex systems related to energy, outlining the problem in a number of smaller components. The components (Types) may range from simple heat pump to a multi-zone of a building complex.

The components are configured through the graphical user interface known as TRNSYS Simulation Studio. In the simulation software tool energy TRNSYS the construction of the building can be achieved by the introduction of data on dedicated visual interface, known for TRNBuild. The software tool sets the time intervals which may vary from 15 minutes to an hour but may be able to perform simulations in the time interval of 0.1 seconds.

The library software tool in addition to a multi-zone allows the use of many commonly used components, including solar panels, photovoltaic systems, HVAC systems, cogeneration systems, hydrogen, among others. It also allows the creation of routines to manipulate weather data and other data by changing the simulation results. The modular nature of this software tool facilitates the addition of mathematical models to the software tool. The components can be shared among multiple users without having to recompile the software tool due to the use of DLL technology. In addition, this energy simulation software tool allows the user to incorporate other components developed in software tools such as Matlab, Excel, VBA. Each of the assessed energy simulation software has certain characteristics and specific applications (IBPSA, 2016).

In order to better understand specific features of each software, Table 3.1 presents a summary of the key features of each of the software tools mentioned above, in particular: solution of simulation; duration of calculation; geometric description; renewable energy systems; electrical systems and equipment; HVAC systems.

From the investigated energy simulation software tools, DesignBuilder combined with EnergyPlus is the most complete integrated tool for modelling and simulating building cooling, heating, ventilating and lighting systems. Apart from energy use, the software can be used for load calculations and to model passive applications, natural ventilation, thermal comfort, water use, green roofs, photovoltaic systems and has the capability to calculate the energy and CO_2 savings for the purposes of building energy efficiency.

Beside its capability to model and examine a complex systems and techniques such as the hybrid system (GPCS and HRCS), the major distinction of EnergyPlus among the other simulation software is that, such simulation software is combined with graphical user interfaces (DsignBuilder) where virtual buildings can be modelled with flexible geometry input and extensive material libraries and load profiles.

However, there are some limitations of the use of DesignBuilder and EnergyPlus include the inability to accommodate complete interactions between different passive or active mechanical systems. For instance, in simple HVAC it is not possible to use radiant heating together with cooling in any particular zone. These limitations are due to EnergyPlus generally requiring all HVAC data to be either automated or manually defined. An overview of the selected modelling and simulation software including its key features and potentials were extensively discussed in chapter 6.

Features	Energy Plus	ESP-r	IDA ICE	IES	TRNSYS
Simulation solution					
Simulation of loads, systems and solutions	✓	✓	✓	✓	✓
Iterative solution of nonlinear systems	✓	✓	✓	✓	✓
Duration of calculation					
Variable time intervals for HVAC interaction	✓	✓			✓
Selection of building systems and user	✓	✓	✓	✓	✓
Dynamic variables based on transient solutions	✓	✓	✓		
Complete geometric description					
Walls, roofs and floors	✓	✓	✓	✓	✓
Windows, skylights, doors and external coatings	✓	✓	✓	✓	✓
Polygons with many faces	✓				
Imports of building from CAD programs	✓	✓	✓		✓
Export geometry of buildings for CAD software	✓	✓	✓		
Import/export of simulation models	✓	✓			
Calculation of thermal balance	✓	✓			✓
Absorption/release of building moisture	✓		✓	✓	
Internal thermal mass	✓	✓	✓	✓	✓
Human thermal comfort	✓	✓	✓	✓	✓
Solar Analysis	✓	✓		✓	✓
Analysis of Isolation	✓	✓	✓		
Advanced fenestration		✓	✓	✓	
Calculations of the building in general	✓	✓	✓	✓	✓
Surface temperatures of zones	✓	✓	✓	✓	✓
Airflow through the windows	✓	✓	✓	✓	✓
Driving surfaces	✓			✓	✓
Heat transfer from the soil	✓	✓			✓
Thermo-physical variable	✓			✓	
Daylighting and lighting controls	✓	✓		✓	✓
Calculation of coefficients of wind pressure	✓	✓	✓	✓	✓
Natural Ventilation	✓	✓	✓	✓	✓
Natural and mechanical ventilation	✓		✓		✓
Control open of windows for natural ventilation	✓	✓	✓		✓
Infiltration in multiple zones	✓	✓	✓		
Renewable Energy systems					
Solar Energy	✓	✓		✓	✓
Ground pipe ventilation system	✓				
Photovoltaic panels	✓	✓	✓	✓	✓
Hydrogen Systems		✓			
Wind Energy		✓			✓
Electrical Systems and Equipment					
Energy Production through R.E.	✓				✓
Management of electric power loads	✓	✓			✓
Electricity generators	✓	✓			✓
Network connection		✓			✓
HVAC Systems					
HVAC idealized	✓	✓	✓	✓	✓
A possible configuration of HVAC systems	✓	✓	✓	✓	✓
Repetitions cycle air	✓	✓	✓	✓	✓
Distribution systems	✓	✓	✓	✓	✓
Modelling and monitoring CO_2	✓		✓	✓	✓
Each distribution of air per area	✓	✓	✓	✓	✓
Forced air unit per zone	✓	✓	✓	✓	✓
Equipment Unit	✓	✓		✓	✓

Table 3.1: Comparison of various simulation software features and capabilities.

3.5 Research Stages and Process

This section describes the process and stages which are sequentially presented in order to create a coherent approach. The hypothesis was addressed in three main stages including the corresponding method to respond to each objective. The first stage involved generating baseline thermo-physical and energy performance of a typical residential block in Jeddah - Saudi Arabia. The second stage involved developing an alternative viable low-carbon hybrid cooling system that could handle such a hot and humid climate. The third stage involved utilising energy modelling and simulation software DesignBuilder to numerically model and simulate the developed HCS in tandem with the 'fabric first' passive design measures (PDMs). The simulation results can determine whether the measures are likely to be cost-effective taking into account the predicted energy savings in use against the additional capital spend required over a standard AC (baseline) installation. The following section outlines the three stages and the research aims to be achieved by each stage.

1) **Stage 1 |** ***Examine the thermo-physical and energy performance of a typical existing block in K.S.A***: *Case Study*: Since the current study is concerned with the issue of high residential cooling energy consumption in Saudi dwellings, it is essential to identify the factors that have led to such a high energy usage. Therefore, this stages preliminary aim is to addresses the current thermo-physical and energy performance of an existing house block in Jeddah.

- **Data collection**: Data collected included, layout and construction techniques for a flat complex, climatic database, and monthly electricity bills for each flat, in order to identify typical average energy consumption levels per annum.
- **Data analysis tool**: Modelling and simulation software was the selected tool to obtain the primary result of the simulated case. The selected case study was also modelled (form, fabric, occupant density, domestic appliances, HVAC system and the climatic condition profile) to check the veracity of the simulation tool against the actual energy use profiles. This exercise can increase the confidence level by measuring the margin of error between the simulation and the actual usage.

At the same stage, the simulation results were classified into three phases: (Figure 3.4):

- **Phase 1**: based on the simulation results it was necessary to analyse the thermo-physical performance of building fabric and construction materials used in building envelope (walls, roof floor and window glazing). This analysis includes the heat gain and thermal capacity of these elements. The analysis aims to understand the design shortcomings that have led to such high energy consumption in Saudi houses.

- **Phase 2**: based on simulation result it was necessary to analyse the energy performance of the case study building including monthly and annual energy usage and the residential cooling load for each flat which could be compared with the simulation predictions.
- **Phase 3**: Based on the simulation results it was important to investigate indoor air quality using CO_2 and humidity as a proxy. The indoor temperature in various zones was measured longitudinally in order to define the adaptive thermal comfort level that is considered to be one of the key target criteria.

The main purpose of this stage is to address the following research objectives:

- ***Objective 1***: To assess the current energy use and mechanical cooling approaches in existing dwelling typologies.
- ***Objective 2:*** To identify the reasons for the high cooling energy demand in current dwellings.
- ***Objective 3***: To determine the actual thermo-physical performance of a housing block's envelope and fabric in current house typologies in Saudi Arabia.

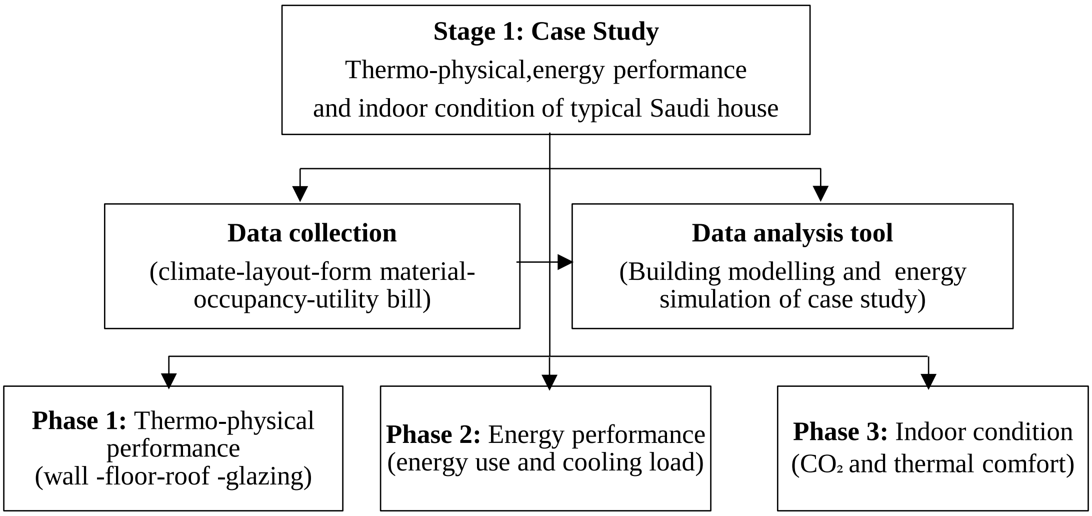


Figure 3.4: Diagram illustrates the first stage phases and process.

2) **Stage 2 | *Developing a viable Hybrid Cooling System (HCS)***. This stage involved developing low carbon cooling strategies as an alternative to the conventional AC system. This stage consists of two main phases:
    - **Phase 1**: Based on simulation results, it was clearly important to deal with the weaknesses of the thermo-physical performance of building fabric identified in the first stage and identify a range of potential thermal solutions that could be applied to increase the thermal efficiency of the building fabric. It was therefore necessary to reformulate the thermo-physical properties through applying passive design measures (PDMs) such as (window shading and glazing, wall and floor insulation and thermal mass) into the baseline to enhance the thermal performance.
    - **Phase 2**: According to the primary simulation findings, it was important to consider a range of low energy cooling systems that could address peak summer temperatures, however, developing such hybrid systems necessitated a parametric analysis combined with testing prototypes in field trials.

This stage addresses the following research objectives:

- ***Objective 1**:* To investigate the potential implementation of a range of viable passive design measures aimed at reducing heat gain and cooling load.
- ***Objective 2**:* To develop viable HCS combined and model their performance when combined with passive low energy measures as measured against the current employment of AC systems.

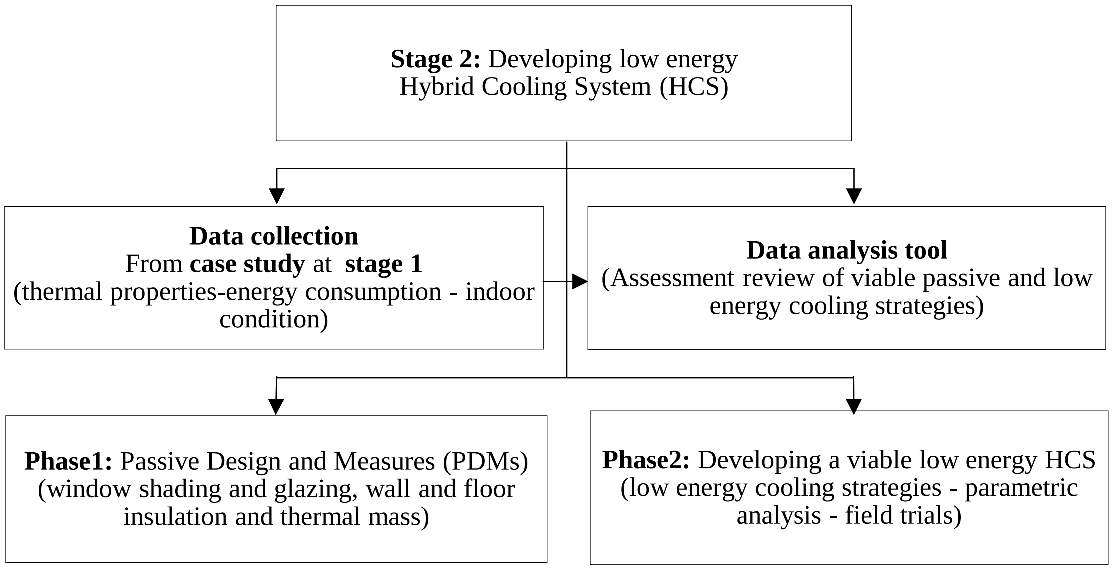


Figure 3.5: Diagram illustrates the second stage phases and process.

3) **Stage 3 | *Efficiency validation of HCS application*:** This stage involved assessing and validating the energy and cooling efficiency of the proposed HCS. Numerical modelling and energy simulation was conducted to examine the energy savings and likely indoor conditions as a result of applying the HCS and PDMs. This stage was conducted in two phases:

- **Phase 1**: Based on the application of HCS combined with PDMs, it was necessary to examine the impact of the implemented systems and validate its effectiveness. The integrated system was computationally modelled and simulated in order to monitor the cooling energy performance and assess the indoor condition. The simulation process aims to obtain annual, monthly, daily, and hourly variations of energy consumption rates and internal temperatures.
- **Phase 2**: The predicted energy savings were then reviewed against the additional capital costs of the applied measures to calculate pay-back periods over a standard AC installation.

The main purpose of this stage is to address the following research objectives:

- ***Objective 1**:* To validate and assess the influence of the proposed HCS application in reducing cooling energy consumption, CO_2 emissions while ensuring indoor comfort is maintained throughout the year.

- ***Objective 2***: To estimate the capital and life cycle running cost of the applied PDMs and HCS and calculate the payback timeframe.

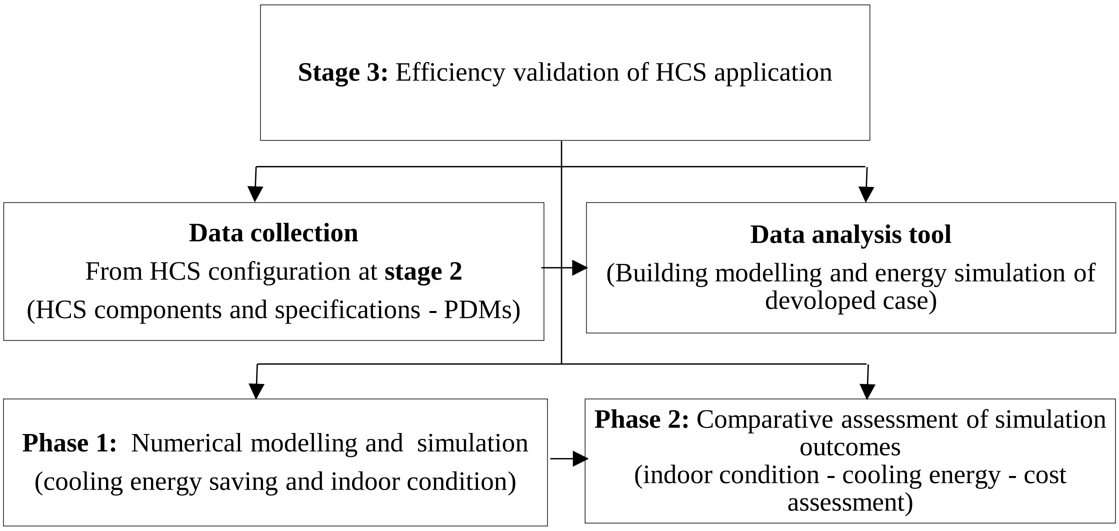


Figure 3.6: Diagram illustrates the third stage phases and process.

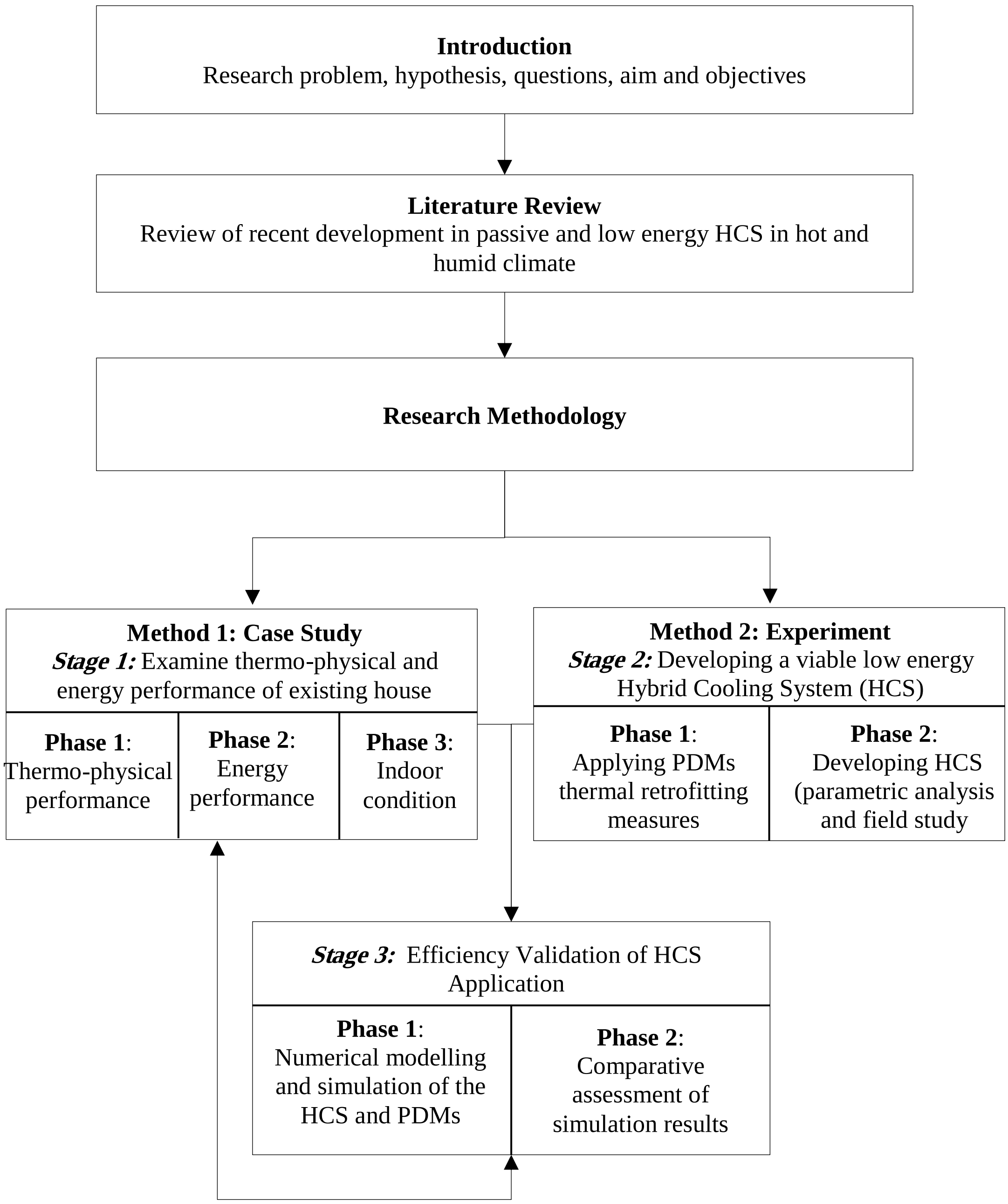


Figure 3.7: Diagram shows research logical process and flowchart.

3.6 Conclusion

Methodology is a framework associated with a specific set of paradigmatic presumptions that are used to conduct a research programme. This chapter presented the research paradigms, the general methodological and strategies including a justification of approach selection. The first section of this chapter specified the main concepts of the research paradigm or philosophy. The second section presents the chosen research rationalization and illustrates the research approach to achieve the desired aim, objectives and answer the research questions. The third section presents the adopted research method and strategy in each research stage and describes their appropriateness. The fourth section performs the research stages, process and flowchart.

In addition, a detailed description of the methods for this study was performed in order to ensure that the research aim and objectives are addressed. This research adopts a quantitative method in data collection and analysis supported by field trials of prototypes.

Three main stages were illustrated in this chapter including the corresponding method that was employed to respond to each objective at each stage. The first stage involved the selection of a housing typology as a case study to investigate the thermo-physical and energy performance of the most common house type in Saudi Arabia. The second stage focused on developing a viable HCS combined with PDMs. The third stage involved proposing the methods to cool the revised design and employing numerical modelling and simulation to obtain initial results that can be used to conduct a comparative assessment against the baseline case and then to optimise the systems and strategies by more detailed parametric analysis.

4 **CHAPTER |** Residential Energy Scenario and Thermal Performance in KSA: Case Study

4.1 Introduction

As the population grows more rapidly than ever, the world is confronted with major challenges presented by globalisation, meeting housing needs, global warming and resource scarcity. The US Energy Information Administration (EIA) has estimated that by 2030, the global energy consumption will rise by over 70% (EIA, 2015). As buildings consume the most energy it is crucial to find an alternative, low energy solution to reduce energy consumption. Failing to do so may well result in future energy and electricity shortages especially in the developing countries such as Saudi Arabia (WEC, 2015).

This chapter addresses this phenomenon by identifying the thermal and energy performance of a current housing block in KSA. As the most challenging conditions are found in the hot and humid regions of Western KSA, Jeddah was considered as an appropriate regional test bed. The study discusses the energy consumption patterns in Jeddah and associated CO_2 emission rates, based on computer simulations and actual case study field data.

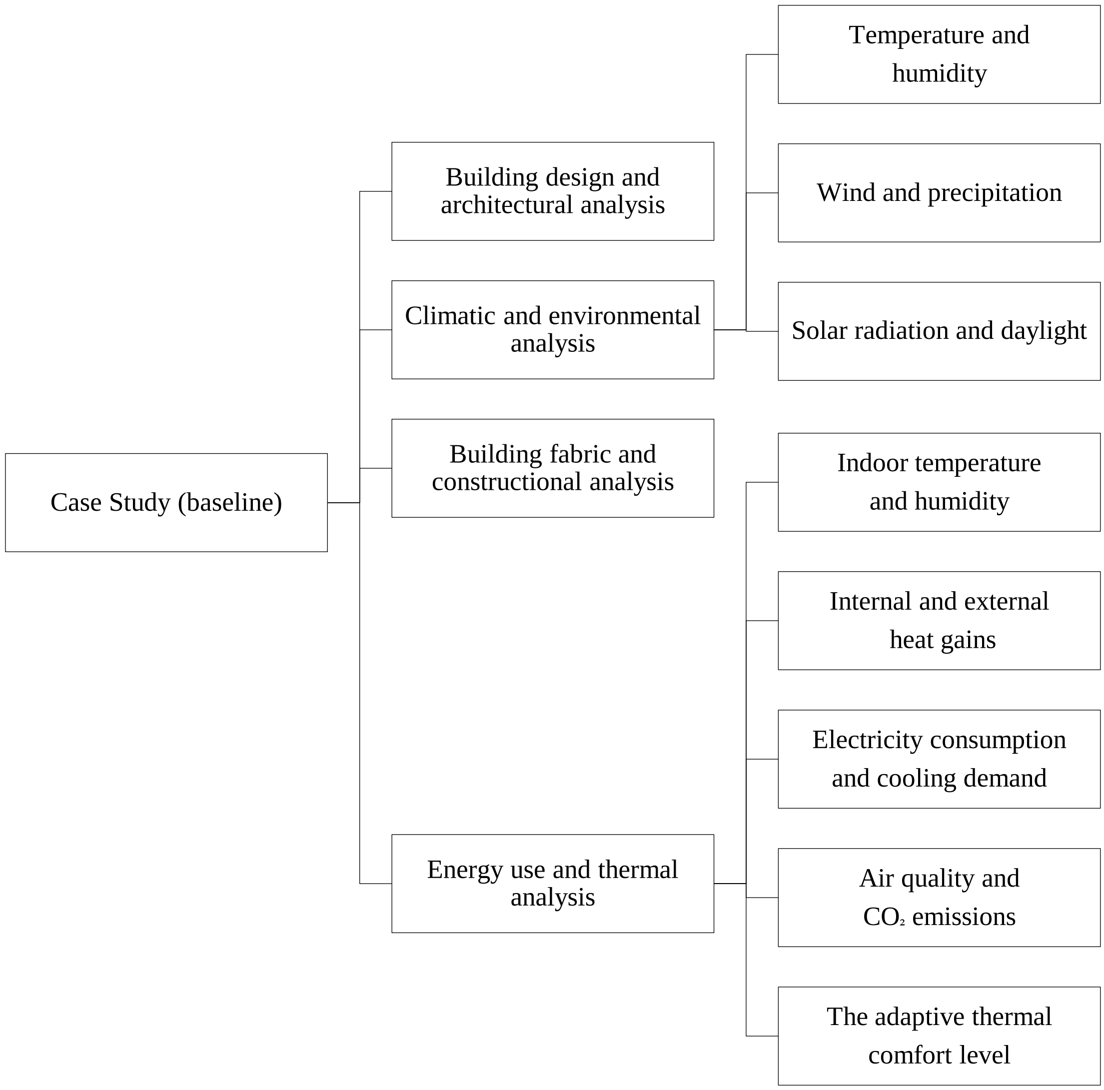


Figure 4.1: Chapter structure and outline.

4.2 Energy and Thermal Performance of Typical House in Jeddah

According to Central Department of Statistics and Information (CDSI), the total land area of Saudi Arabia is about 2,149,690 sq. km and the total occupied dwellings are circa 1,526,678. In addition, it is estimated that population growth in Saudi Arabia will rise in the coming years as will the cost of living (CDSI, 2015). The building industry therefore plays a key role in energy demand by contributing to environmental issues ranging from the excessive use of energy to environmental pollution (CSO, 2017).

Prime energy sources in Saudi Arabia are dependent on oil and natural gas. Oil forms 63% of total energy sources while gas forms 37% (Figure 4.2). The total installed electricity generation capacity is fired by oil and natural gas. The share of oil in the electricity generation is 34% while 66% of the total oil production is used for exploring, transferring and exporting purposes (EIA, 2015) (Figure 4.3).

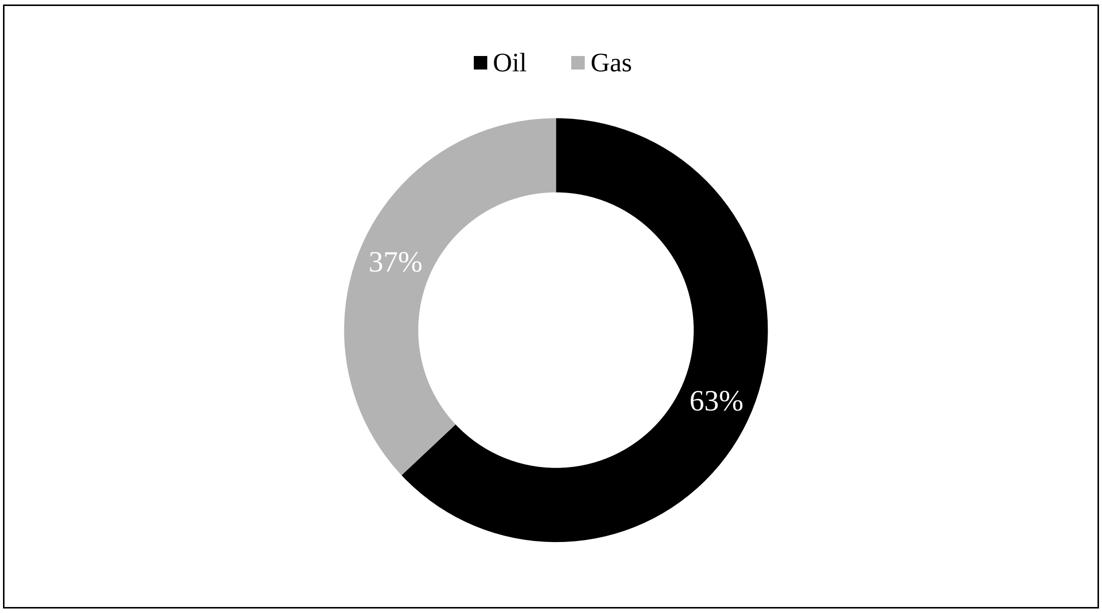


Figure 4.2: General segmentation of energy sources in KSA (CDSI, 2015).

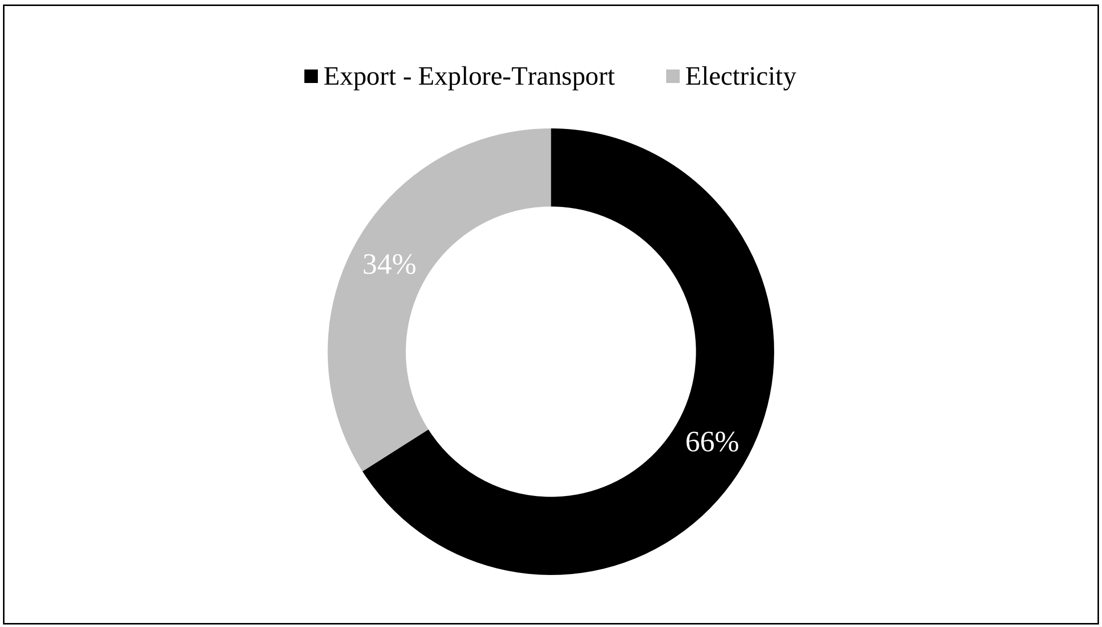


Figure 4.3: Oil consumption breakdown in KSA (EIA, 2015).

According to the Saudi Electricity Company (SEC), building sector consumes circa 77% of the total electricity consumption, with industry sector accounting for only 16% (Figure 4.4). Within the buildings sector, energy consumption in residential buildings is 52% of the total. This compares with commercial, governmental, industrial and agricultural sectors which consume 12%, 7%, 18%, and 5% respectively (Figure 4.5).

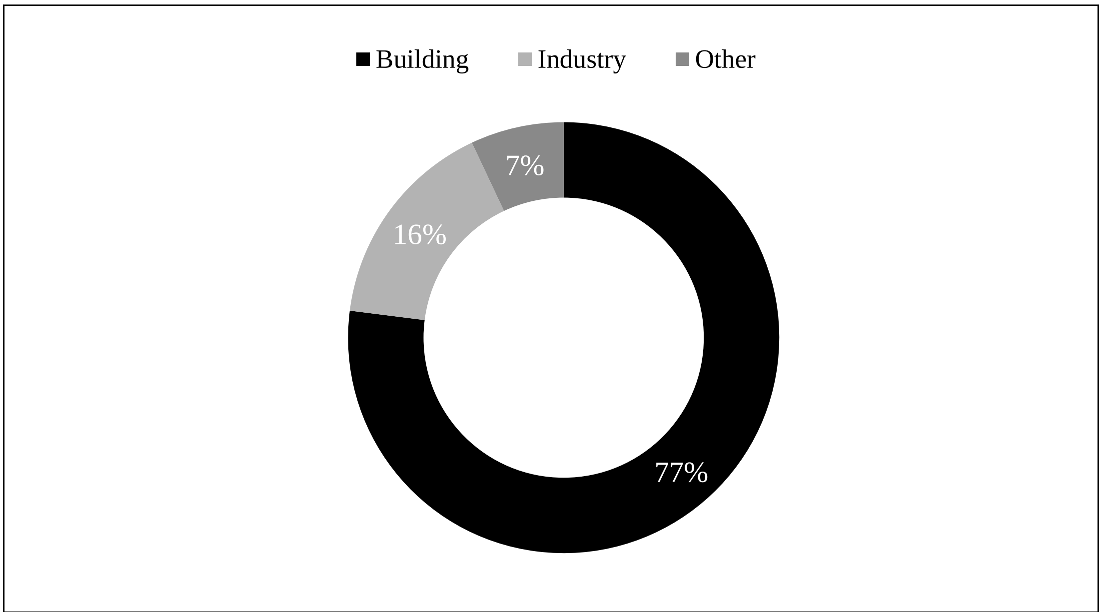


Figure 4.4: Electricity consumption by sector breakdown (SEC, 2015).

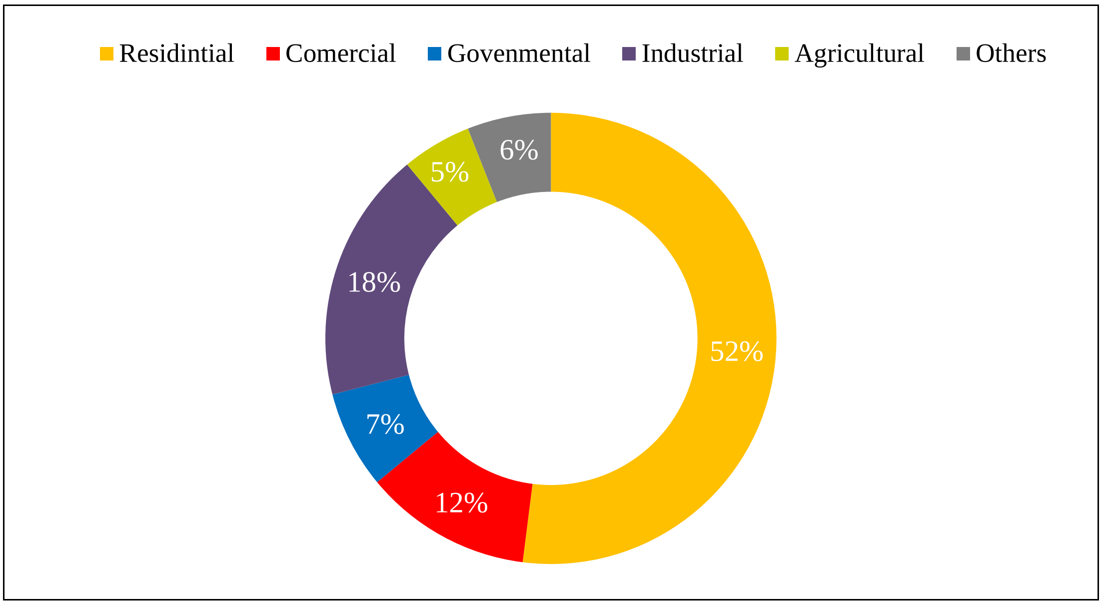


Figure 4.5: Buildings sector electricity consumption breakdown (SEC, 2015)

Within the residential sector, electricity used for cooling and air conditioning purposes dominate electrical consumption (69%). This is considered to be the key factor in the dramatic rise in peak loading across the Kingdom **(**Figure 4.6) (SEC, 2015). According to Saudi Energy Efficiency Centre (SEEC), the harsh climatic conditions and poor building envelope are responsible for more than 74% of the total load due to the high usage of mechanical air conditioning systems to maintain the desired thermal comfort level (SEEC, 2015).

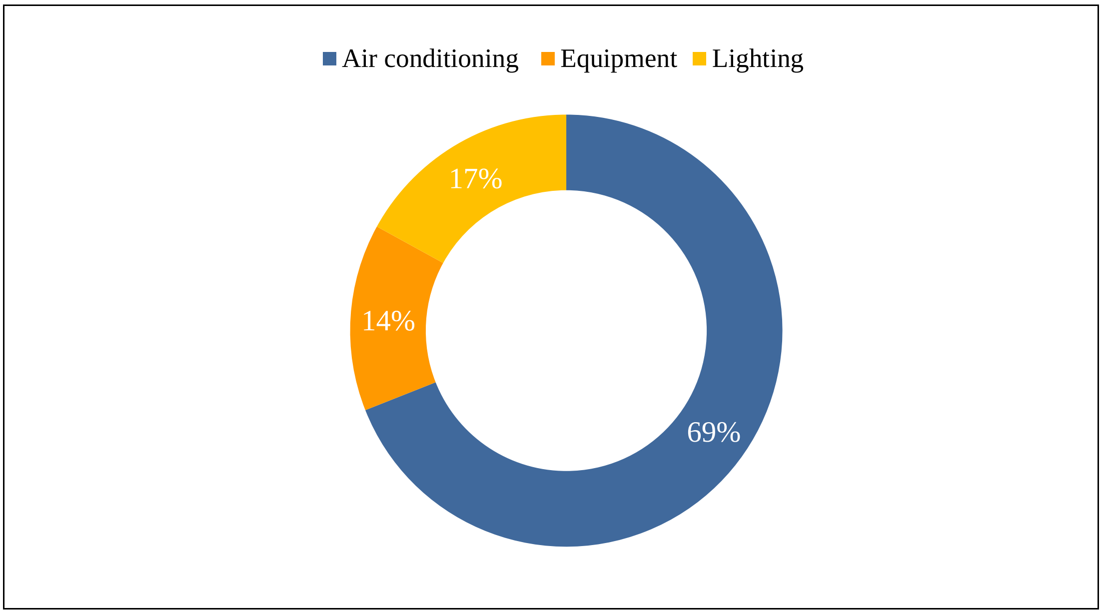


Figure 4.6: Residential electricity consumption breakdown in KSA (SEC, 2015).

According to the Central Department of Statistics and Information (CDSI), a survey conducted in 2015 reported that almost 61% of the population of Jeddah is housed in flats while 25% living in villas, 9% in traditional vernacular dwellings and 5% living in other housing types including palaces (Figure 4.7). The number of flats in Jeddah is approximately 367,000 and the city requires approximately 953,000 new housing units before the end of 2029. Therefore, among all residential typologies in KSA and particularly in the city of Jeddah, the residential block was chosen to be the case study.

Dwellings in Saudi Arabia have been historically designed and constructed with little regard to energy efficiency and how they respond to extreme climatic conditions. About 70% of buildings in Saudi Arabia have no thermal insulation applied to walls, floors or roofs. The relatively low cost of electricity and the absence of building standards requiring such measures, has led to a reliance on mechanical AC systems (Taleb, 2014). The deployment of sustainable energy technologies in Saudi Arabia, such as wind and solar photovoltaic (PV), is at a low level given the solar and wind resource, due to ‘cheap’ oil and the absence of regulations and building codes (Dubey et.al, 2016).

In order to investigate the thermo-physical and energy performance of current houses, the following section represents a case study of typical residential building prototype to examine the physical, thermal and energy performance of the most common housing block typology in KSA.

These analytical studies involve physical and energy audit of each zone of the building. The adopted energy modelling and simulation software DesignBuilder was utilised to formulate the baseline models presenting the thermal and energy behaviour of the selected case. A detailed energy audit was undertaken to collect the thermal, physical and operational properties.

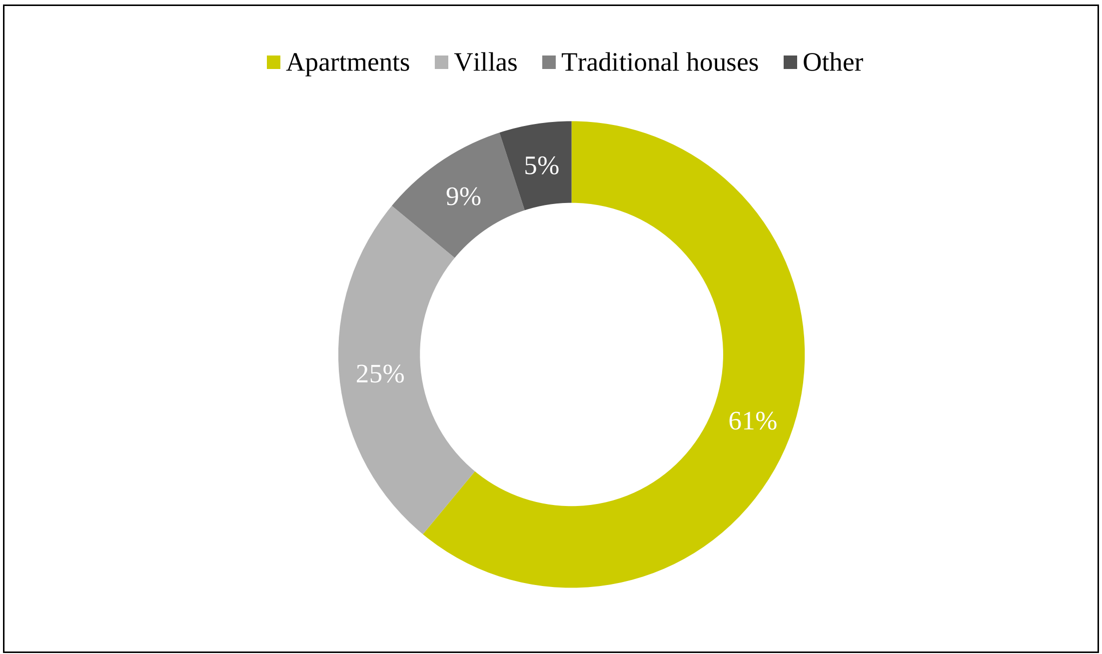


Figure 4.7: Residential building typologies in Jeddah (CDSI, 2015)

Figure 4.8: The variation in residential buildings types in Jeddah- KSA (CDSI, 2015)

4.2.1 Building Design and Architectural Analysis

This section aims to analyse the initial data of the building envelope, form and design. The typical residential flat complex in the city of Jeddah is a six-storey residential block comprising of twenty flat units with a floor area of 1532 m² and a footprint of 650 m². Each of the twenty (three-bedrooms) flats are occupied by an average of 5 residents per flat and is assigned a car parking space on the ground floor (Table 4.1). The flats are elongated and symmetrical around a staircase with a mid-axis perpendicular to the street (Figure 4.9).

Type	Description
Number of floors	6 floors
Number of units	20 flats (16 flats in floor 1 -4 and 4 flats at floor 5 and 6)
Unit area	Flats: 76.6 m² × 20= 1532 m²
Orientation	Front Elevation facing North
Plan shape	Rectangular
Occupants	Average 5 - 6 per flat- total occupants 100

Table 4.1: Building specification and characterization.

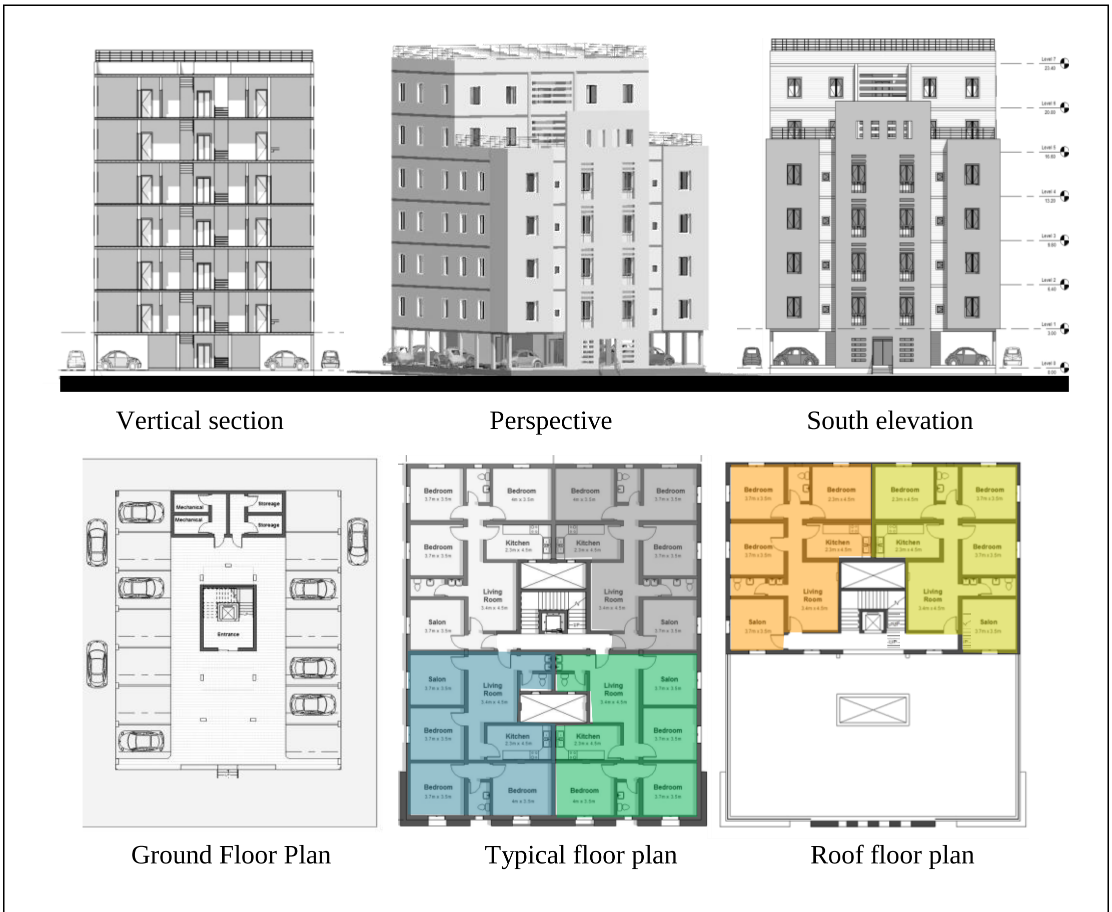


Figure 4.9: Architectural drawing and floor plans.

4.2.2 Climatic and Environmental Analysis

4.2.2.1 Temperature and Humidity

Climatic conditions play a significant role in people's daily lives as Jeddah, being on the Eastern edge of the Red Sea, has high humidity and extreme temperatures during the summer (up to 45°C) with high humidity over 70%, however unlike other urban areas in Saudi, Jeddah has a relatively moderate temperature in the winter season (November to February) with an average daily low of 17°C. Historically, the lowest temperature recorded in Jeddah was 10.0°C in March 1983 while the highest temperature was 49.0°C recorded in June 1961 (GAMEP, 2016).

The mean annual high temperature (T_{mh}) in summer is regularly 34.8°C while the mean annual low temperature(T_{ml}) is around 27.3°C (Figure 4.10). The average annual wet-bulb temperature (T_{wb}) recorded in Jeddah is quite comparable to the average annual low temperature; however, the dry-bulb temperature (T_{db}) is relatively higher than the mean annual high temperature (Figure 4.11) (GAMEP, 2016).

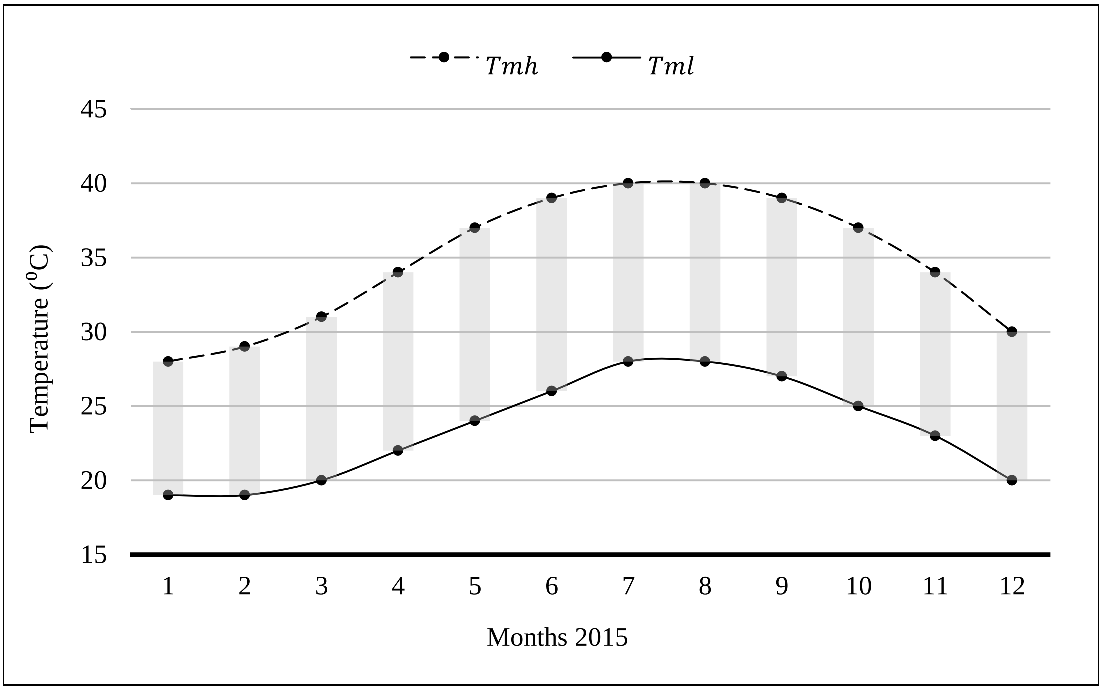


Figure 4.10: Average monthly, mean high and low temperature in Jeddah (GAMEP, 2016).

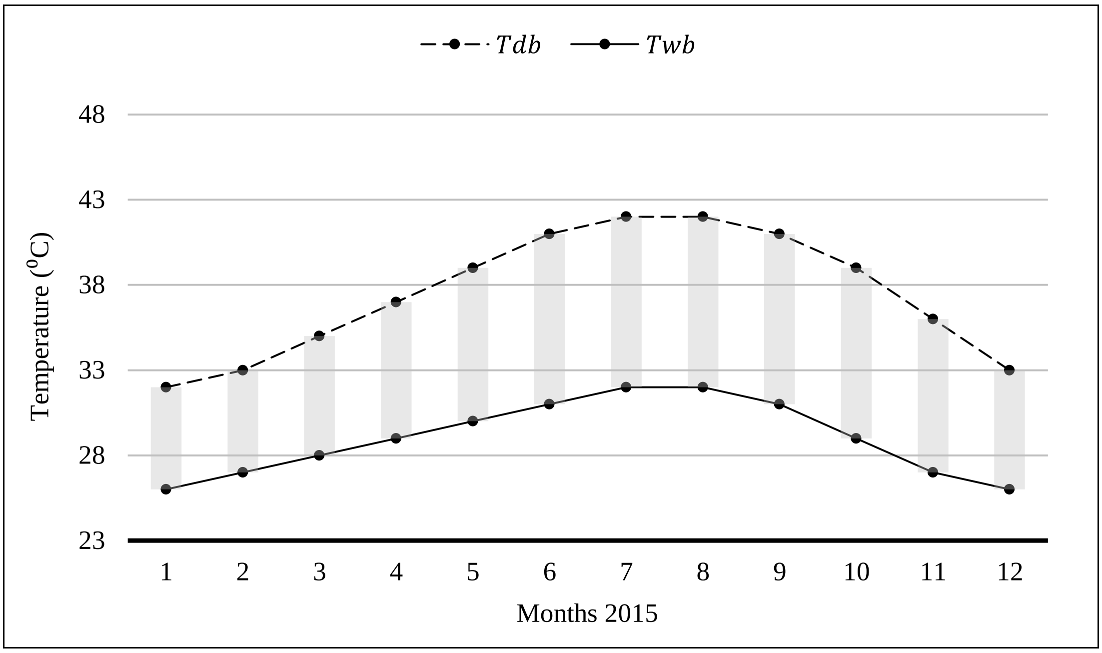


Figure 4.11: Average monthly high and low dry and wet bulb temperature in Jeddah (GAMEP, 2016).

Humidity reaches its highest levels in summer due to the temperature of the red sea and it is lower in winter due to the effect of the cooler air with high pressure. The recorded mean annual low relative humidity (RH_{ml}) percentage is almost 57% which is considered as a comfortable level, whilst the mean annual high relative humidity percentage (RH_{mh}) is around 70% over the course of the year (Figure 4.12) (GAMEP, 2016) .

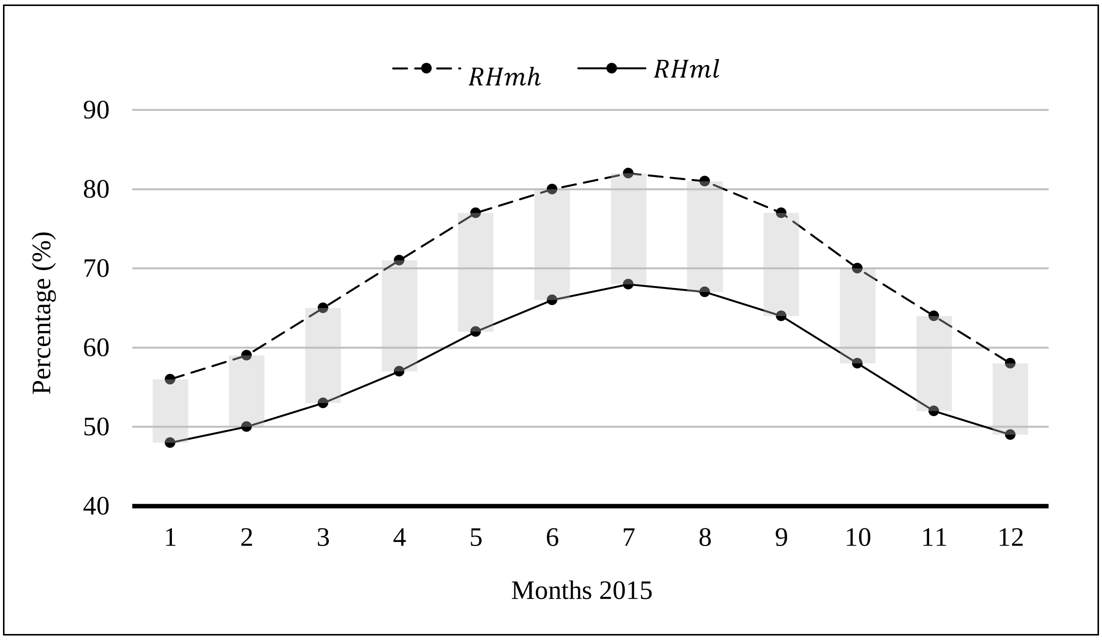


Figure 4.12: Average monthly high and low relative humidity percentage (GAMEP, 2016).

4.2.2.2 Wind and Precipitation

Jeddah is a coastal city on the shore of the Red Sea with the prevailing winds from the North West. Throughout the year, these winds are regular light-to-moderate, however, in winter Southern winds are more regular (Figure 4.13). When wind speed increase from this direction they can whip up severe sandstorms and are also associated with heavy rain and thunderstorms. Typical wind speeds vary from 0 km/h to 32.7 km/h, which is consider calm to fresh breeze. Peak wind speeds rarely exceed 36 km/h, while the highest average wind speed is 19 km/h (March), with a low of 12 km/h (October). Wind speeds and direction are summarised in Figure 4.13 (GAMEP, 2016).

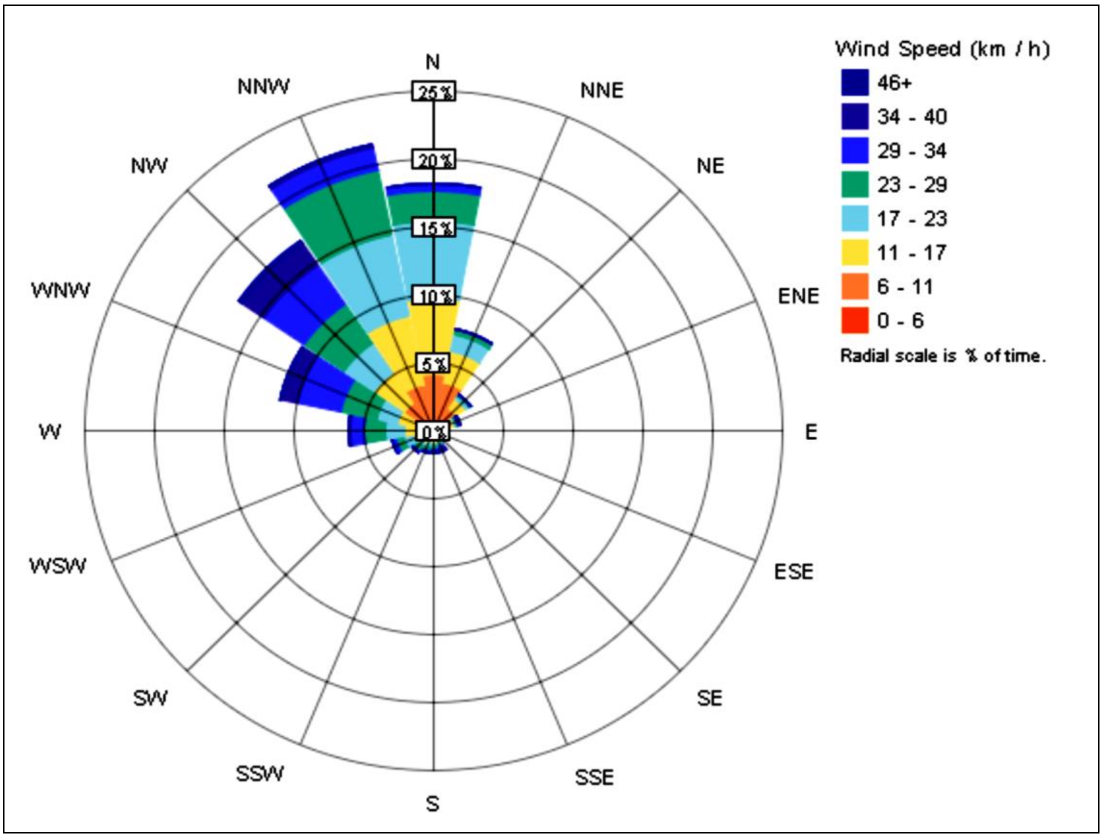


Figure 4.13: Wind speed and direction over the year in Jeddah (GAMEP, 2016).

Precipitation in Jeddah is rare (November and December) with the average annual chance of rainfall at around 2.8%. Precipitation is most likely around December when it is recorded during 7% of all days. The heaviest rainfall recorded is 14%. From May to October in the warm season, there is a 2.2% average chance of precipitation (Figure 4.14). When precipitation happens, 74% of days with precipitation have thunderstorms, 9% drizzle, 8% moderate rain and 7% heavy snow. During the winter season, from December to February, there is a 6% average chance of precipitation. (JRCC, 2015). The most common type of rainfall is that associated with thunderstorms that usually occur during the winter and spring seasons (Figure 4.14) (GAMEP, 2016).

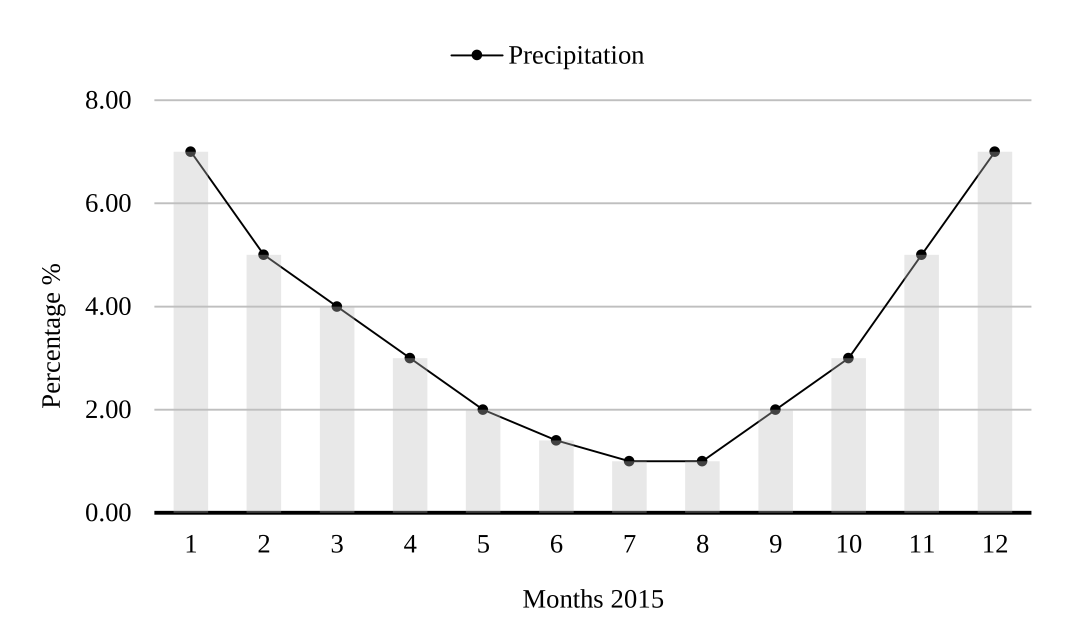


Figure 4.14: Average monthly precipitation percentage in Jeddah (GAMEP, 2016).

4.2.2.3 Solar Radiation and Daylight

Solar radiation falling on Jeddah dominates the climate patterns of the city. The amount and intensity of this solar radiation vary with the length of days over the course of the year (Almasoud & Gandayh, 2015). Jeddah is a hot and humid city and therefore it has a relatively high solar radiation over the year.

According to the Energy Research Institute of King Abdul-Aziz City of Science and Technology KACST, the daily average solar radiation in Jeddah is between 5.8 to 8.6 kWh/m^2/day. The daytime length varies from month to month; in Jeddah the shortest day recorded was on 22nd of December with 10:46 hours of daylight, while the longest day was in June 20th with 13:29 hours of daylight. The earliest sunrise was on 4th of June at 5:37 am, with the latest sunset at 7:10 pm on 7th of July. On January 16^{th,} the latest sunrise recorded was at 7:09 am whilst the earliest sunset was at 5:37 pm on November 28th (Figure 4.15) (GAMEP, 2016).

To focus on measuring the solar radiation and daylight of the selected case study, Figure 4.16 illustrates the measurement of annual sun path, sunrise and sunset times. The sun path diagram for the chosen location was calculated by 'Ecotect'software showing the solar altitude. The sun angle or solar azimuth is represented as the angles on the diagram perimeter, in a clockwise direction from North. The sun paths create the Vertical Shadow Angle (VSA) and the Horizontal Shadow Angle (HSA) upon a building with the curved lines representing daylight hours (Figure 4.16).

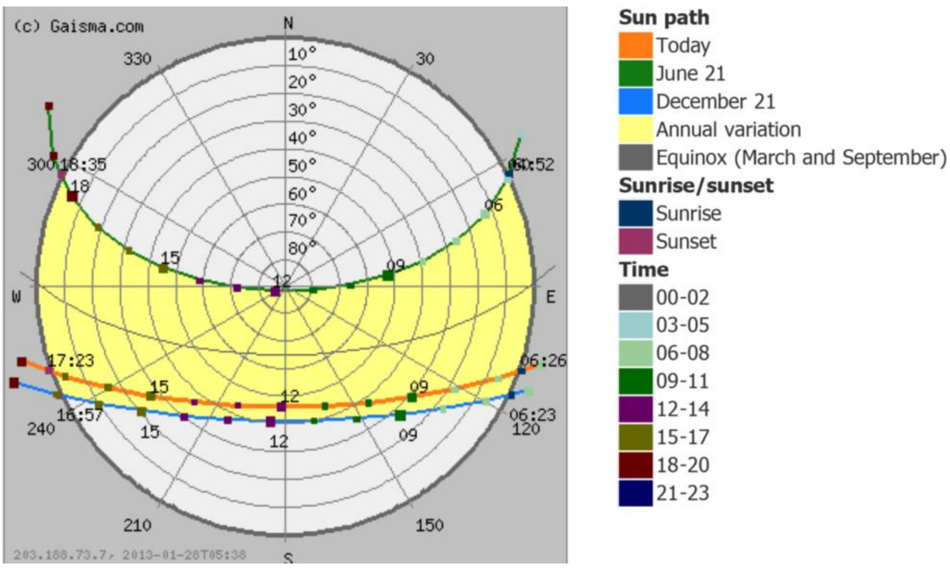


Figure 4.15: Annual variation sunrise and sunset times in Jeddah (GAMEP, 2016).

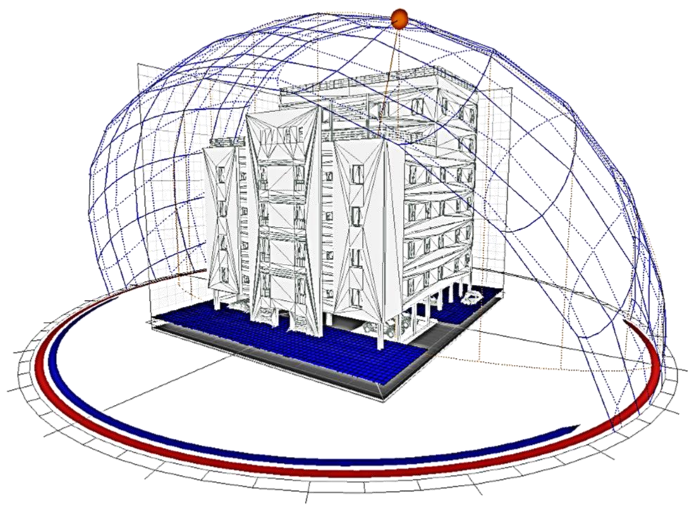


Figure 4.16: Annual sun path, sunrise and sunset times in Jeddah (Ecotect, 2015).

Based on the solar path model and the analysis of daylight length in various months, Figure 4.17 shows the actual solar daylight flux entering the selected building. The daylight flux of the selected case was analysed by 'Ecotect' to identify whether the internal spaces are receiving sufficient daylight. The graph in Figure 4.17 demonstrates that all internal zones have received a sufficient amount of daylight (between 100-200 lux and lumen/m²) (Figure 4.17).

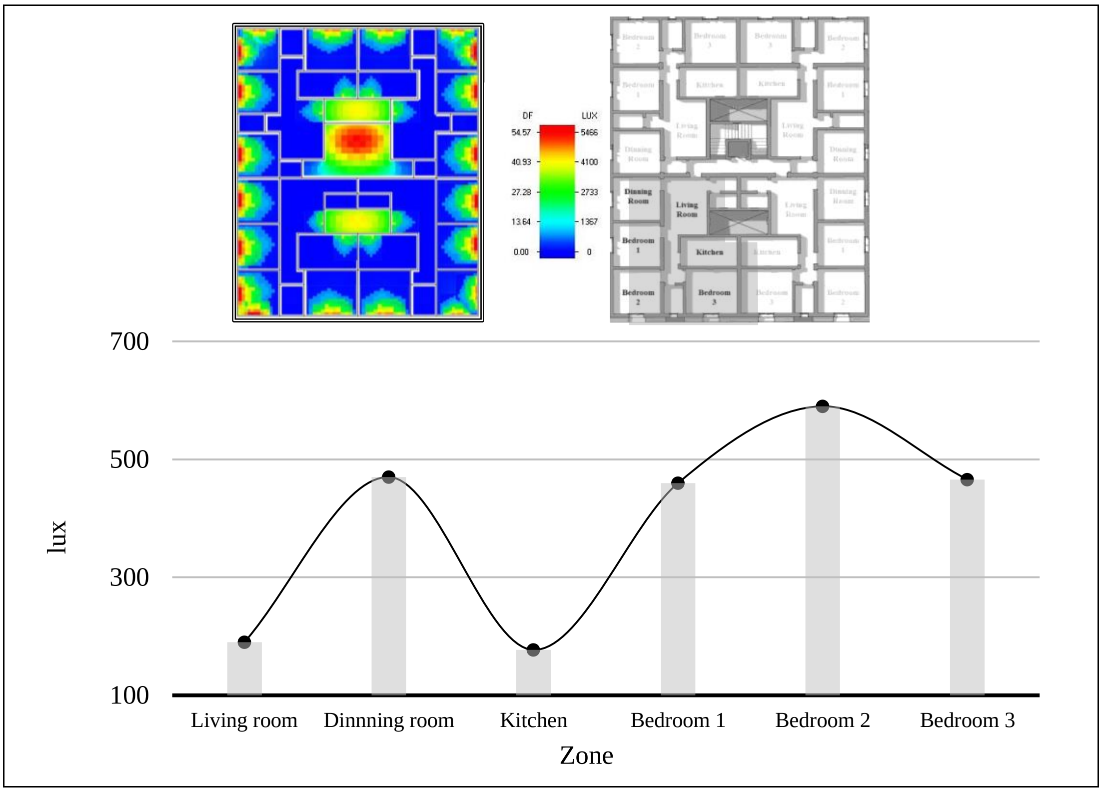


Figure 4.17: Variation of daylight flux in flat zones (Autodesk, 2015).

4.2.3 Building Fabric and Constructional Analysis

Building fabric is a critical component of any building; which plays a fundamental role in protecting the building occupants and modulating the indoor environment by controlling the energy flow between the exterior and interior. The efficient design of the building fabric can result in a significant reduction in heating and cooling loads (Givoni, 1983).

Historically, Saudi houses have been constructed using clay, brick and timber and depended on the availability, suitability and adaptability of these materials to the existing climate and topography (Budaiwi & Abdou, 2000). As a result of the population increase and the changing in the desired standard of living, traditional building materials have become limited and cannot satisfy demand. Concrete, brick, gypsum and plastics have now in the main The most common system of house construction is the reinforced concrete frame, which is employed in different types of buildings over the country due to its durability, flexibility, and rapidity in construction. The reinforced concrete structure is a simple system consists of reinforced concrete columns and beams and filled by concrete blocks or bricks in between to shape the external and internal walls (Table 4.2). Ordinarily, the roof and floors are constructed from reinforced concrete slabs filled with concrete blocks. As shown in Table 4.2, the baseline typical walls construction have three layers including 25 mm exterior cement plaster, 200 mm hollow concrete brick or block, coated by 25 mm interior cement plaster that produces a U-value of 2.92 W/m²K. While roofs and floors are constructed from reinforced concrete slabs filled with concrete blocks and produce a U-value of 2.77 W/m²K. Windows are typically constructed from metal frames (150 mm x 120 mm) combined with 4 mm single glazing units produce a U-value of circa 5.3 W/m²K.

Most of the building materials are manufactured in Saudi Arabia utilising imported raw materials. These construction materials include steel, concrete cement, marble, gypsum and plaster. While there is a lack of insulating material availability as the market has yet to develop and mature. however different types of insulation materials are now being introduced to the construction market in order to meet the demands for a more thermally efficient building envelope.

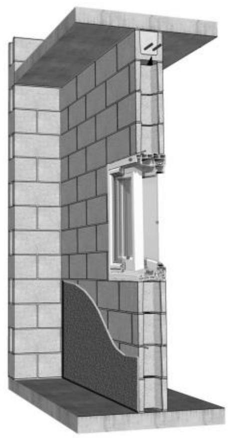
	Material	Thickness (m)	Density (Kg/m³)	K -value (W/m K)	R-value (m²K/W)	Model
Wall	Plaster (dense)	0.025	1800	0.870	0.028	
	Concrete blocks	0.225	1602	0.79	0.289	
	Plaster (dense)	0.025	1800	0.870	0.028	
	U-Value= 2.92 W/m²K					
Floor and Roof	Ceramic tiles	0.015	2000	1.00	0.015	
	Mortar	0.08	1800	0.87	0.092	
	Concrete blocks	0.225	1600	1.00	0.22	
	Plaster (dense)	0.025	1800	0.87	0.028	
	U-Value= 2.77 W/m²K					
Window	Metal frame	0.007	1618	0.97	0.068	
	Single panel	0.002	1400	0.78	0.27	
	Metal frame	0.009	1740	1.14	0.074	
	U-Value= 5.35 W/m²K					

Table 4.2: Typical thermo-physical specifications of building fabric and structure.

4.2.4 Energy Use and Thermal Analysis

The thermo-physical and energy performance of the case study building has been assessed and computationally analysed using DesignBuilder in conjunction with EnergyPlus simulation engine. The initial simulation results implicate indoor temperature, humidity, external and internal heat gain and cooling load. The energy performance was analysed on a daily, weekly, monthly and yearly basis, while the detailed description of the adopted energy simulation software including validation test was presented in chapter 6 in this research.

4.2.4.1 Indoor Temperature and Humidity

The indoor condition of the simulated case study building was computationally monitored based on the climatic data profile of the simulation software. The graph in Figure 4.18 illustrates the indoor conditions including the mean monthly, ambient (T_{amb}), indoor (T_{ind}), radiant (T_{rad}), operative (T_{optv}) temperatures and relative humidity level (RH_m). These figures demonstrate the temperature amplitude in summer months from the mid April until mid October. During the winter months the operative temperatures, which is the average of indoor and radiant temperatures, were below the mean monthly ambient temperature while the average monthly relative humidity level was in range between 40% and 65% (Figure 4.18).

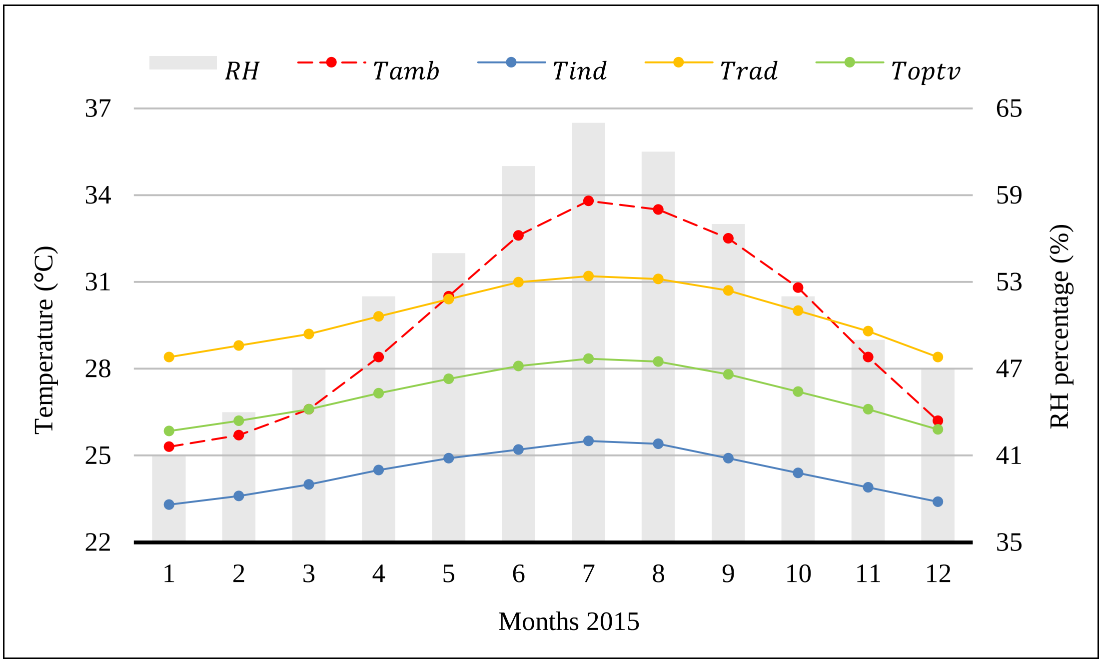


Figure 4.18: Average monthly indoor, radiant, operative temperatures and relative humidity.

4.2.4.2 Internal and External Heat Gains

Building heat gains were categorised into two sources; internal heat gains which include occupants, computers, copiers, machinery and lighting, while the external heat gain sources included solar gain, transmitted by radiation, convection or conduction through the building openings, envelope and fabric. The heat gain of the simulated building prototype depends on two main factors; the temperature difference between ambient air and the desired indoor comfort temperature moderated by the thermal capacity of the building fabric.

As illustrated in Figure 4.19, the external heat gains formed around 78% of the total calculated building gains. The highest percentage of heat was through walls (40%) while the percentage of heat passed through windows, roofs and floors were 12%, 9% and 10% respectively. The total infiltration through other surfaces and openings including planned ventilation was approximately 7% of the total building heat gain (Figure 4.19).

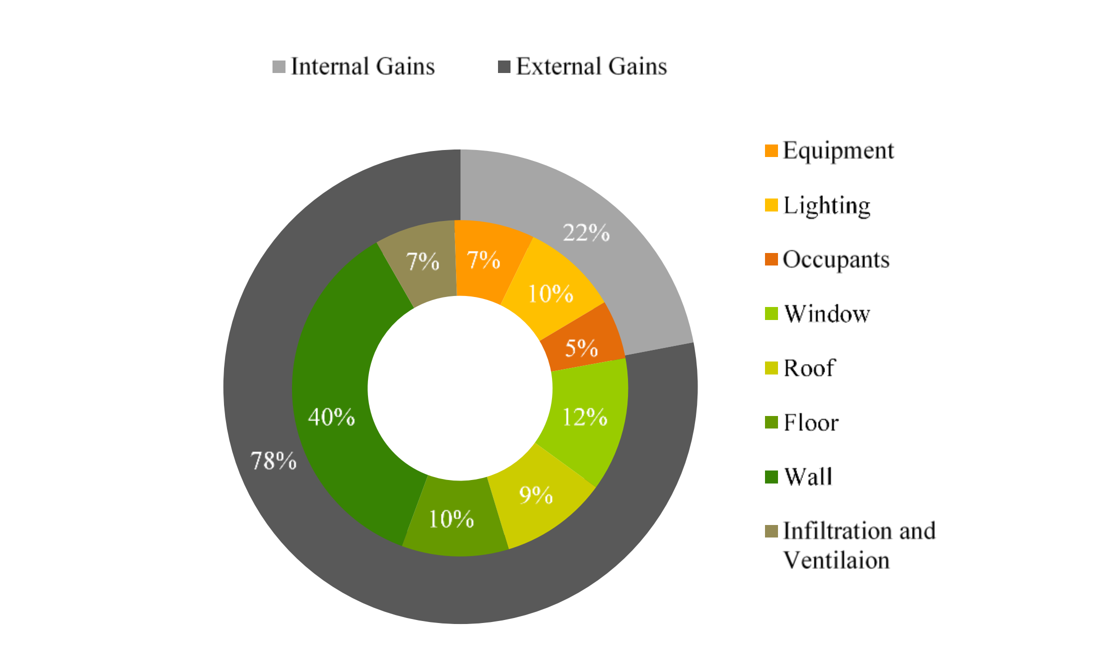


Figure 4.19: Building annual heat gains breakdown.

According to Figure 4.20, the average monthly "casual" heat gain through internal equipment that includes oven, fridge, computers and TV was approximately 2746 kW/month, while occupant's heat gain was 1978 kW/month. Internal lighting systems, (typically 50 W Halogen spotlights), emitted an average of 3887 kW/month. Such inefficient lighting systems formed around 40% of the internal heat gain and 10% of the total building casual heat gains.

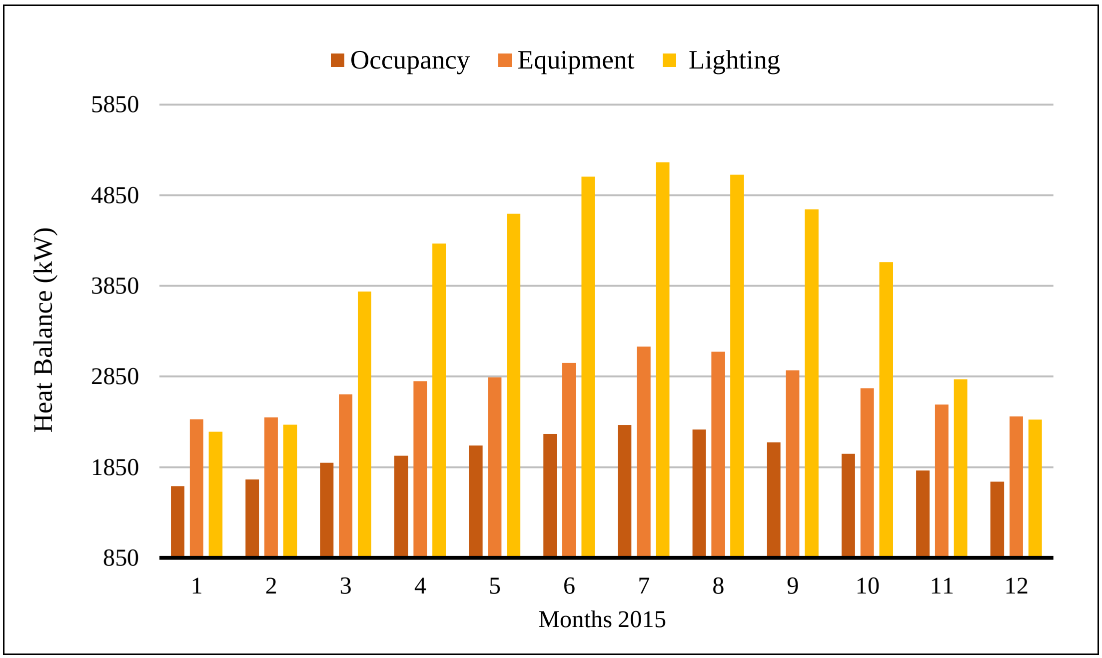


Figure 4.20: Building monthly internal heat gain per elements.

As illustrated in Figure 4.21 walls shaped around 40% of the total building heat gain with an average figure of 15555 kW/month. In summer months, from April to September, most of the heat gain was through external walls when the average external heat gain exceeded 29417 kW/month (Figure 4.21).

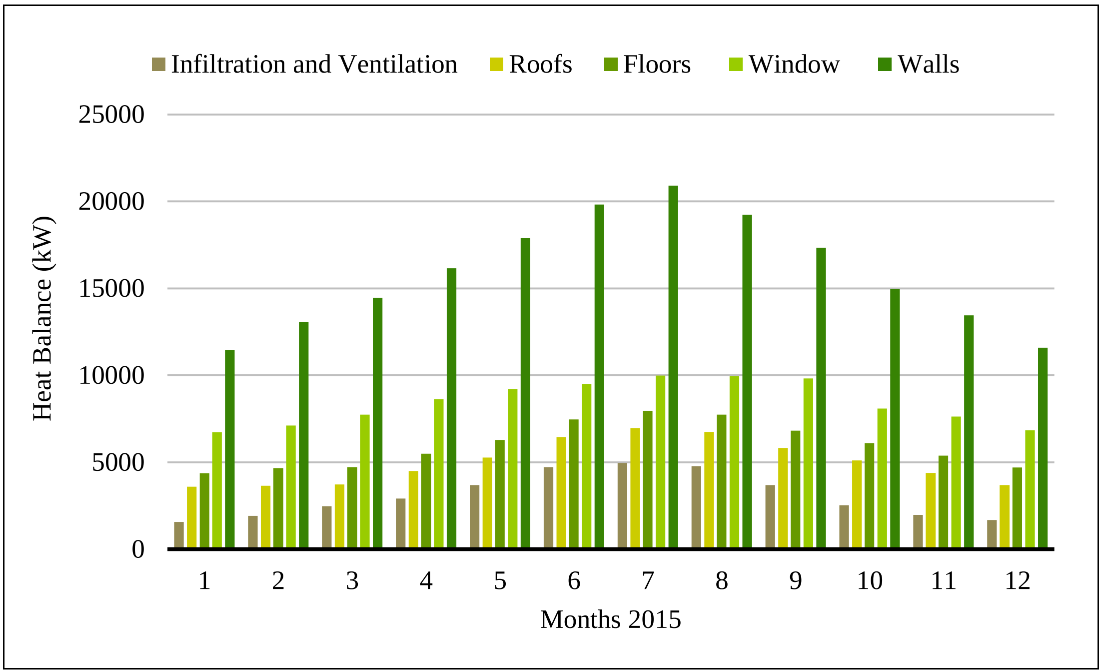


Figure 4.21: Building monthly external heat gain per elements.

4.2.4.3 Electricity Consumption and Cooling Load

The results of the computer simulation predicted an average annual consumption per flat of 3149 kWh/flat while the average monthly consumption was 2624 kWh/month/ flat. The total annual energy consumption for the block was 629862 kWh/year that equates to almost 411.13 kWh/m² and around 6298.62 kWh per capita. These results were compared to the actual electricity consumption as stated in the utility bills. This comparison showed that the simulation predictions were remarkably close to actual consumption that verifies the validity and reliability of simulation software (Figure 4.22).

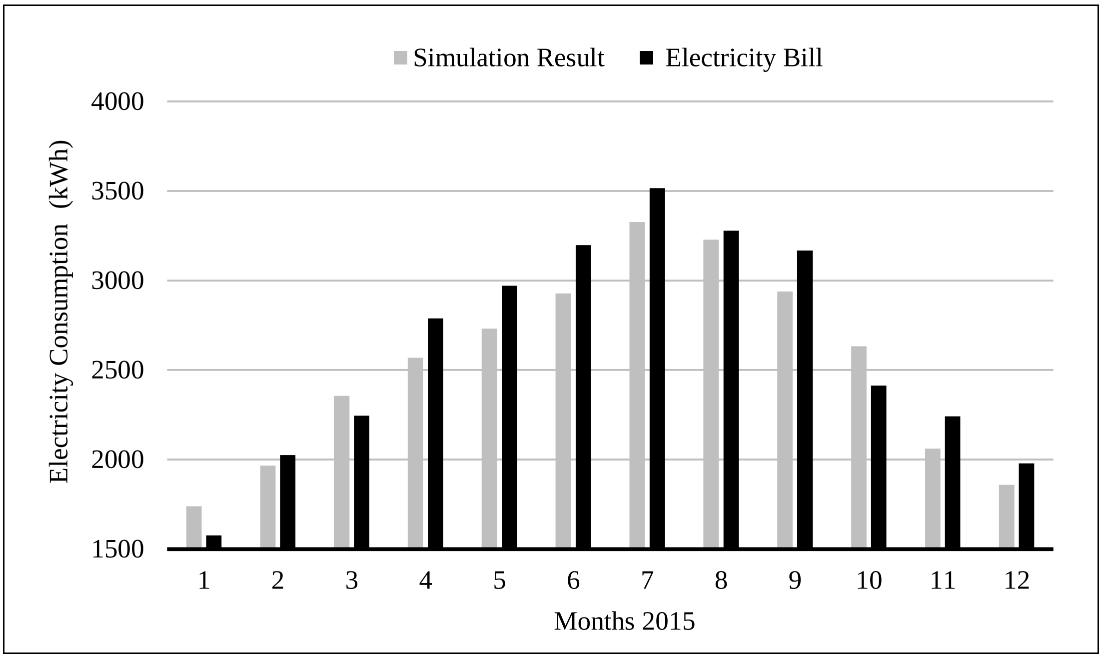


Figure 4.22: Domestic electricity usage rate per flat of the simulated building in comparison with the electricity bill.

These consumption figures are high especially in comparison with other countries with similar climatic conditions. By breaking down the energy use it was demonstrated that the key factor for high electricity consumption was the energy used for cooling.

As illustrated in Figure 4.23, domestic air conditioning systems formed around 74% of the total residential energy consumption. AC systems dominated the total cooling energy use (70%) while fans and other cooling applications shared around 4% of the total. Lighting systems were the second largest consumer at 18%, whilst the other domestic appliances for cooking and freezing consumed around 8% (Figure 4.23).

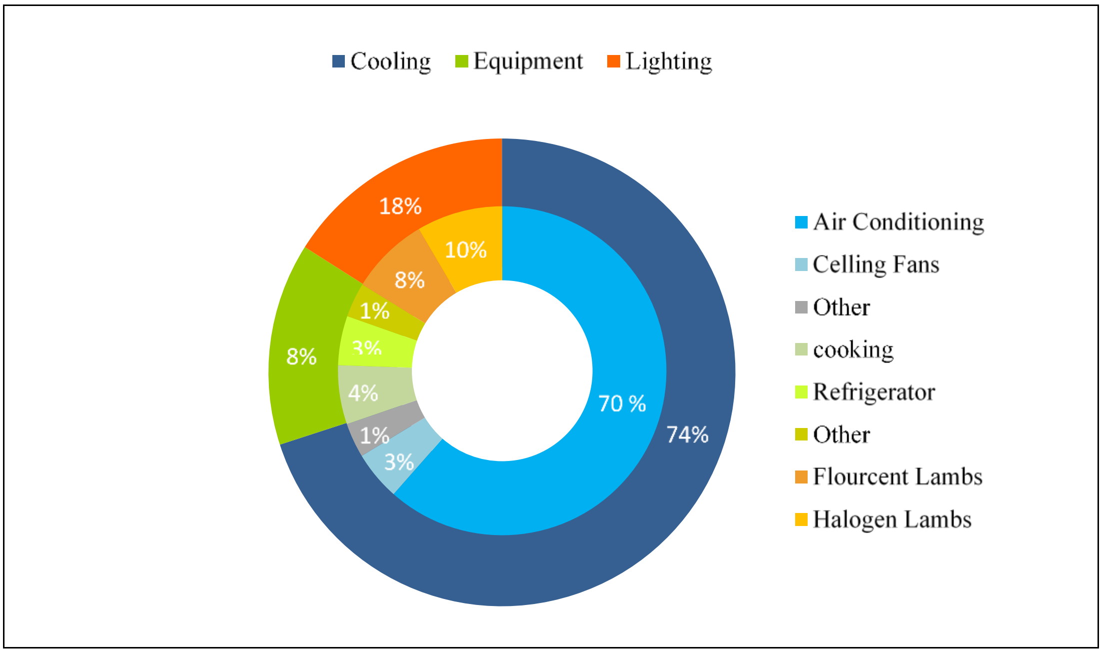


Figure 4.23: Division of residential electricity consumption.

Figure 4.24 details the average monthly cooling energy consumption and correlates cooling demand with the total electricity consumption. Electricity consumption rates increase according to the cooling demand, especially in summer months from April to October, with consumption peaking in July at approximately 70523 kWh (Figure 4.24).

The total annual cooling energy consumption was 466967 kWh, which formed 74% of the total electricity consumption and equates to an average of 23348 kWh/year/flat (305 kWh/m^2/year and 4670 kWh/year/capita).

Cooling energy varies significantly between flats, due to orientation and floor level, ranging from an average annual consumption of 22000 kWh/year on the first floor to 23000 kWh/year on the second and third floors, 24000 kWh/year on the fourth floor, 23000 kWh/year on the fifth floor and 26000 on the sixth (Figure 4.25).

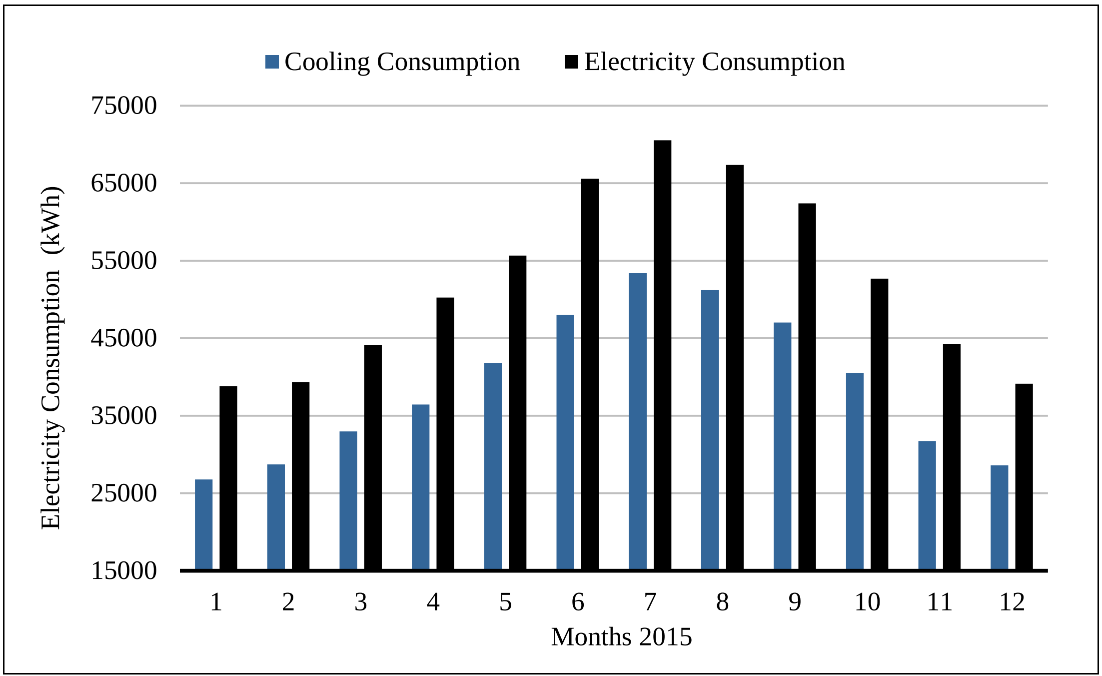


Figure 4.24: Comparison between monthly electricity and cooling consumption.

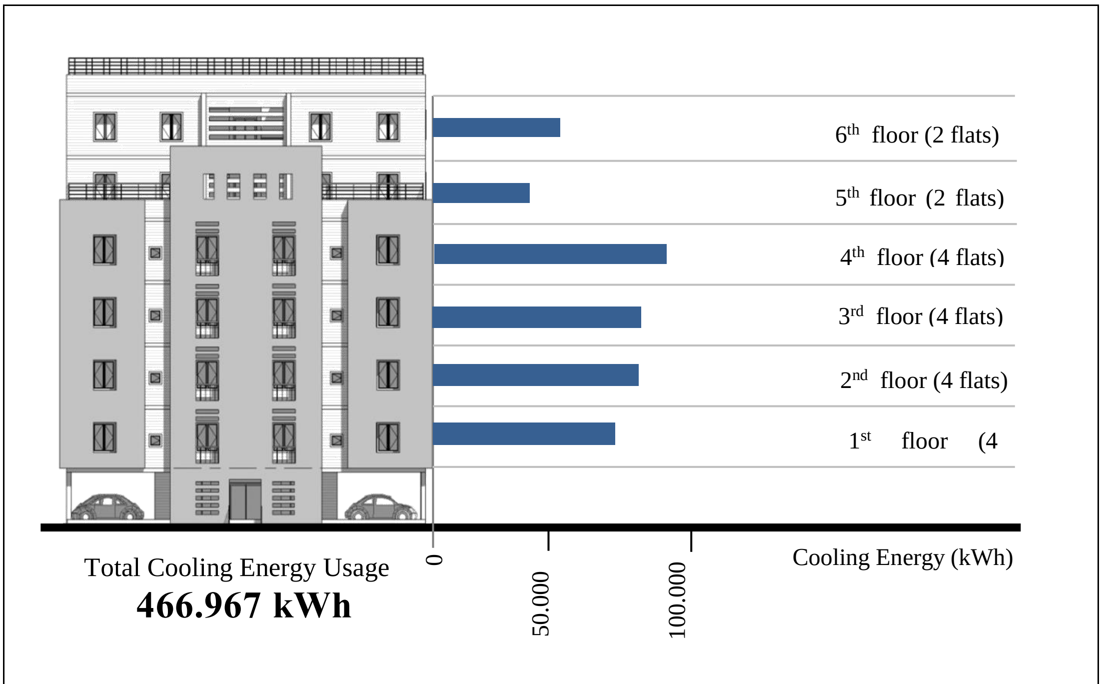


Figure 4.25: Division of residential cooling energy consumption per flat.

Sensible and latent cooling loads calculations were carried out to accomplish the objective of providing a database for investigating the optimum potentials for energy load reduction, operation control and system design.

Figure 4.26 represents the monthly sensible cooling load breakdown of the simulated case study building. The sensible cooling load, which refers to the dry bulb temperature, is a measurement of the amount of heat that must be removed from the interior in order to maintain the desired indoor temperature. The set-point temperature of the simulated case was configured to be 26°C and the simulation results of calculating the building cooling load were based on this temperature.

As can be seen, external walls dominated the cooling load accounting for 186662 kWh/year with an average monthly figure of 15555 kW while, floors, roofs and windows were responsible for almost 31% of the total cooling load. Building occupants, equipment, lighting fixtures and ventilation and infiltration formed around 29% of the total cooling load. These figures vary from month to month according to the climatic condition, average occupancy level and equipment usage (Figure 4.26).

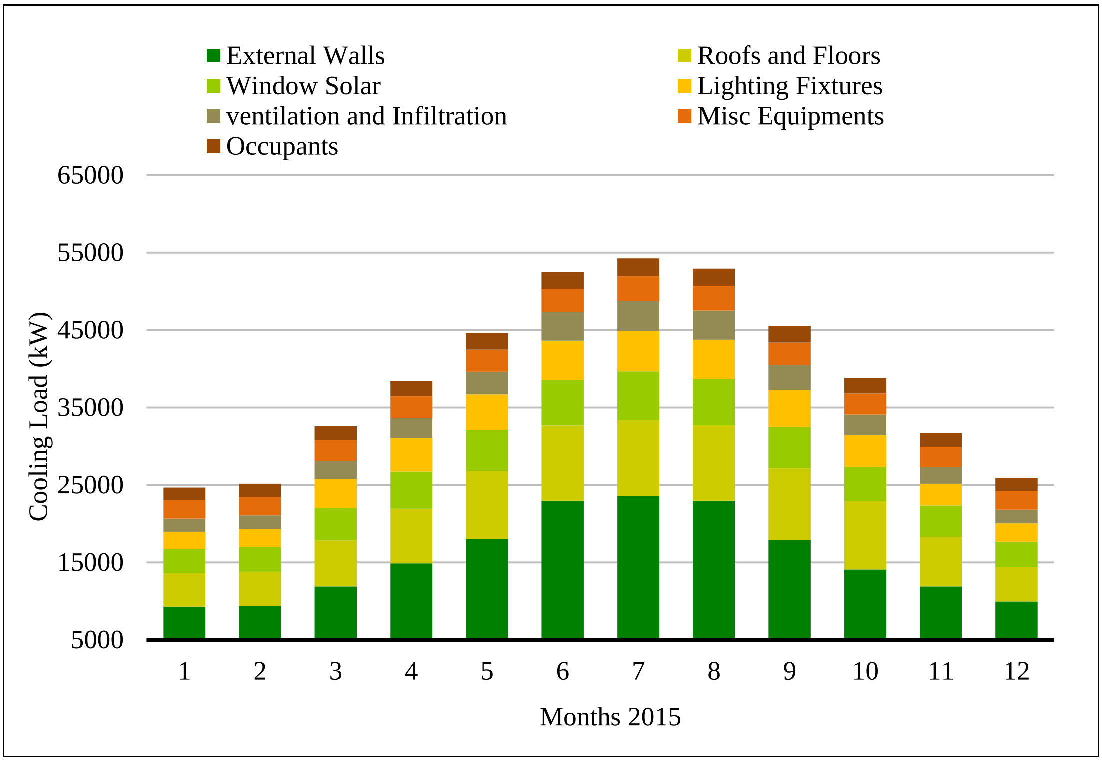


Figure 4.26: Average monthly cooling load by elements.

4.2.4.4 Air Quality and CO_2 Emissions

The monthly average CO_2 emissions of the simulated baseline model are illustrated in Figure 4.27. The total annual calculated CO_2 emissions were approximately 503889 kg/year with an average monthly emission of 41990 kg/month and 2099 kg/month. Per capita emissions were calculated to be 5038 kg which is over twice the developed world average CO_2 emission per capita at 2.5 tonnes (World Bank, 2013).

Based on the International Energy Agency (IEA) Electricity-specific emission factors for grid electricity, in Saudi Arabia, the factor of carbon emissions per kWh of electricity consumed is 0.82 kg CO_2/kWh. Accordingly, the total annual CO_2 emission was calculated to be 516486 kg/year, a figure that is relatively similar to the CO_2 footprint of the simulation output at 503889 kg/year.

Figure 4.27, shows the monthly average CO_2 emission of the simulated house varies from month to month according to cooling load and occupancy number. There is an obvious correlation between CO_2 emissions and AC use, during the summer months (Figure 4.27).

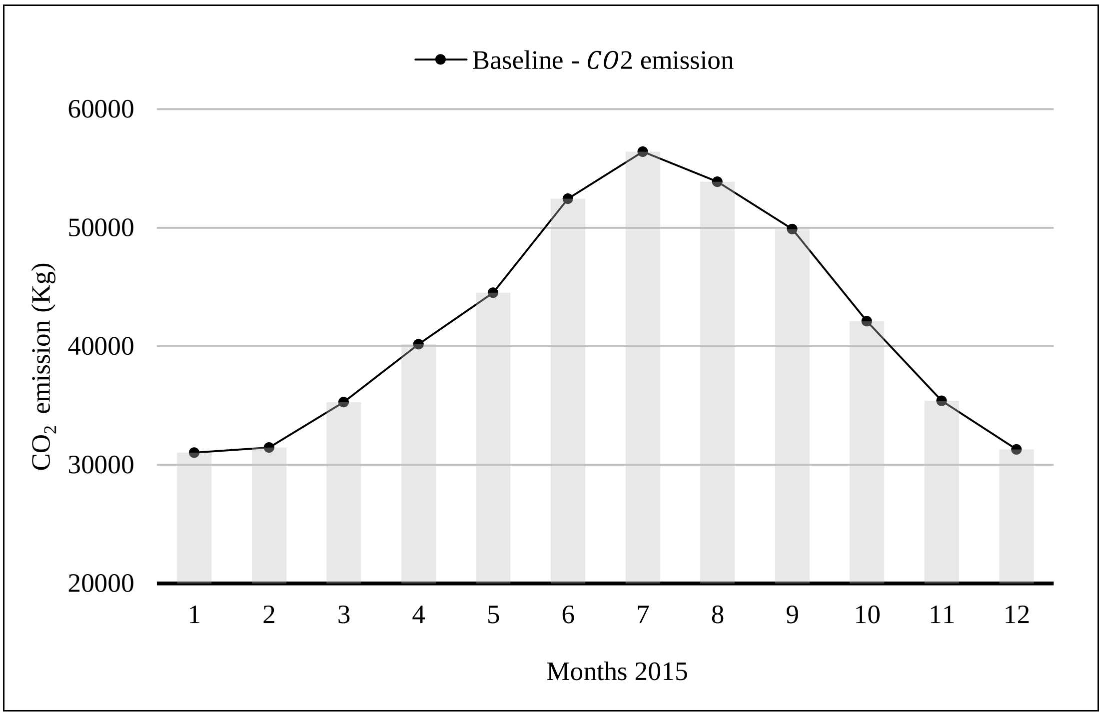


Figure 4.27: Average monthly CO_2 emission per Kg.

In addition to CO_2 emission calculation, the internal concentration of CO_2 was monitored. Figure 4.28 shows the indoor carbon dioxide concentration in various months. The main contributor to the carbon dioxide concentration inside the building zones was the rate of air exchange and circulation. Since AC is the adopted cooling approach in the simulated baseline model, the average monthly concentration of CO_2 in the internal air was approximately 807 ppm, which is classified according to ASHRAE 62 as a medium to low air quality.

Generally, the CO_2 concentration in indoor air increased by increasing AC system usage, especially in an enclosed space without natural ventilation. The highest average CO_2 concentration was recorded in peak summer (July and August) at 952 and 926 ppm respectively due to the continuous use of mechanical AC systems while in winter season the indoor CO_2 concentration dropped to an average of 725 ppm as a result of taking advantage of continuous circulation of relatively cool outdoor air. The AC system sustained the internal RH within the comfort zone with an average figure between 45% to 55% compared to an average outdoor RH that peaked at 85% (Figure 4.29).

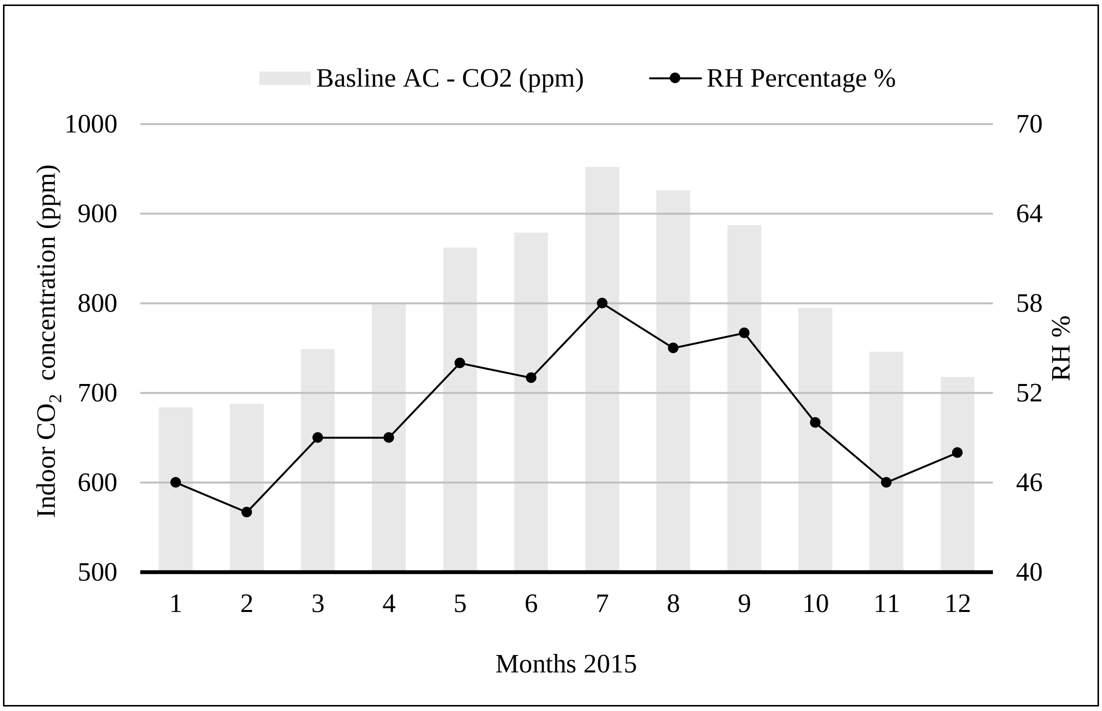


Figure 4.28: Average monthly indoor RH condition and CO_2 concentration level.

4.2.4.5 The Adaptive Thermal Comfort Level

The predicted thermal comfort adaptive level of the simulated building is based on the climate data profile of the simulation tool which is based on the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) Standard 55. According to ASHRAE, in summer when the relative humidity is 50% the optimum neutral indoor temperature for mechanically ventilated space is 24°C and the proposed comfort temperature is range between 23°C to 26°C, whereas, in winter when the relative humidity is 50%, the proposed optimum indoor temperature is 22°C and the proposed acceptable temperature ranges between 20°C to 23°C.

Therefore, the thermal comfort zone of the city of Jeddah can be determined in the psychometric chart based on the obtained climatic data (Figure 4.29). The result was in line with the investigation reported in chapter 2 to determine the thermal comfort zone for air-conditioned spaces.

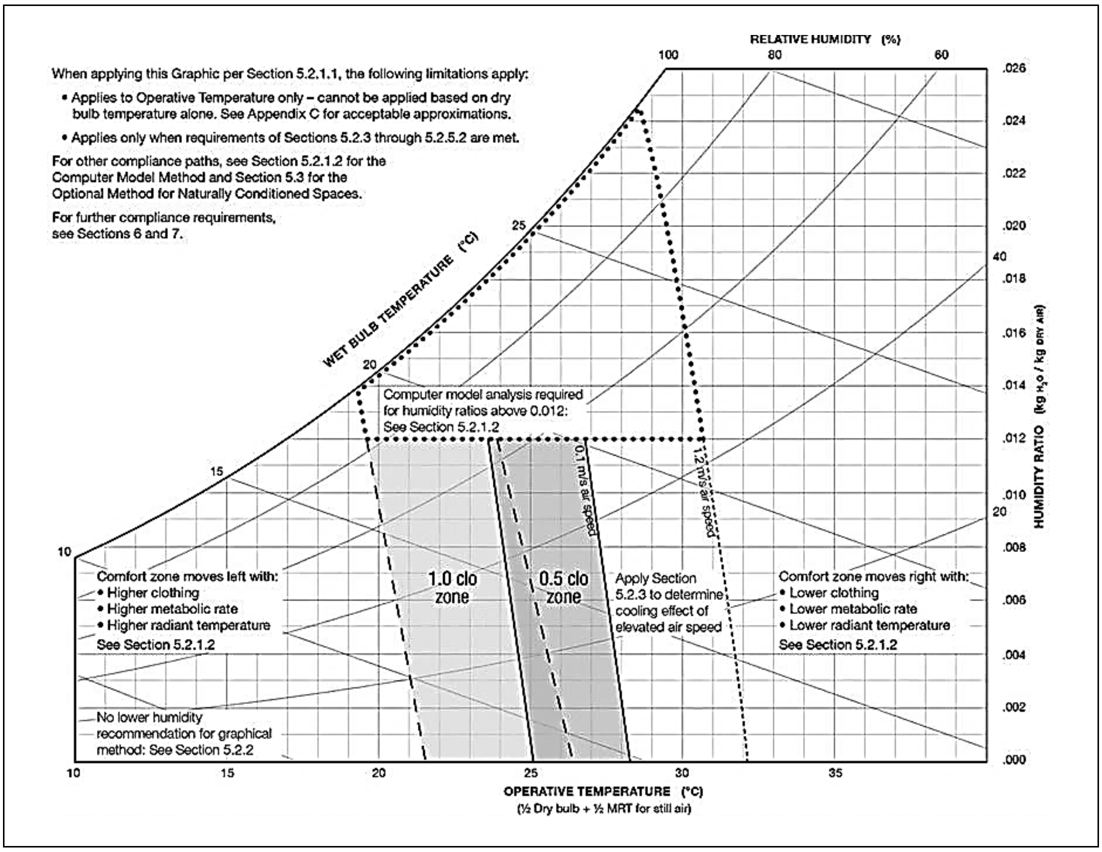


Figure 4.29: Indoor climate condition on a psychometric chart of ASHRAE 55 (ASHRAE, 2013).

4.3 Conclusion

Saudi Arabia's domestic energy consumption increase rapidly. In such hot climate region, air conditioning (AC) of dwellings is by far the major consumer representing 69% of domestic energy use and drives peak loading. Future projections predict a continuous increase in energy use as the majority of existing buildings are poorly designed for the prevailing climate, leading to excessive use of mechanical AC.

Therefore, this chapter aimed to diagnose and identify the issues related to the high energy consumption and CO_2 emission per capita in existing Saudi houses. An analytical study was carried out to identify and observe the actual thermo-physical and energy performance of current residential flats. In addition, this chapter conducted a detailed analysis of the total building sensible and latent heat gains, electricity consumption and carbon emissions determined by computational modelling and energy simulation.

The selected case study was numerically modelled and a series of computer simulations were run to predict daily, weekly, and monthly energy use and cooling load. The simulation results show that space cooling dominates the total energy use by 74%. Lighting systems were the second largest consumer by 18%, while other domestic appliances consumed around 8% of the total energy use.

The analysis of sensible and latent cooling loads showed that external walls dominated cooling loads by 40%. Floors and roofs formed around 19% of the total cooling load. Solar heat transfer through windows was responsible for almost 12% of the total cooling load. While lighting systems and other domestic appliances together formed around 29% of the total annual cooling load.

As a result, the total annual calculated CO_2 emissions were approximately 503889 kg/year with an average monthly emission of 41990 kg/month and 2099 kg/month and 5038 kg/ capita, which is over twice the developed world average CO_2 emission per capita at 2.5 tonnes. The primary findings have demonstrated high energy consumption and cooling loads due to the relatively poor thermal performance of the building fabric, low cost of electricity bills and the absence of sustainable standards in the construction industry which has led to an assortment of low-quality buildings that requires almost constant AC system to maintain the desired indoor thermal conditions.

5 CHAPTER | Developing Low Energy Hybrid Cooling System (HCS)

5.1 Introduction

As cooling energy accounts for such a high percentage of the total energy use, there is great scope for energy savings and reducing carbon emissions if cooling demand is minimised. This chapter proposes a series of measures and strategies to minimise heat gains and cooling loads through adopting a logical hierarchy and process, starting with the application of 'fabric first' passive design measures (PDMs). These PDMs will include a consideration of orientation and spatial organisation, shading and increasing the albedo effect, incorporating vegetation and the use of materials such as insulation and clay to reduce heat gain through the building fabric. In addition to this, it reviews and selects passive cooling strategies (PCS) that exploit natural heat sinks (deep ground and clear sky).

Mainly, this chapter involves developing low-energy Hybrid Cooling Systems (HCS) that perform in isolation or synergistic combination with PDM provide indoor thermal comfort without incurring a high electricity and cost penalty.

Jeddah is not adjacent to the coastline and therefore the focus was quickly turned to techniques that can radiate heat to a clear sky and use deep ground temperature stability to cool incoming air required for ventilation and high indoor air quality.

The HCS explores the combination of these techniques (Ground Pipe Cooling System (GPCS) and Hydronic Radiant Cooling System (HRCS)) which can then be combined with the impact of the 'fabric first' passive design and measures (PDMS). To test the viability of these systems prototypes were constructed and field trials are undertaken to demonstrate 'proof of concept'.

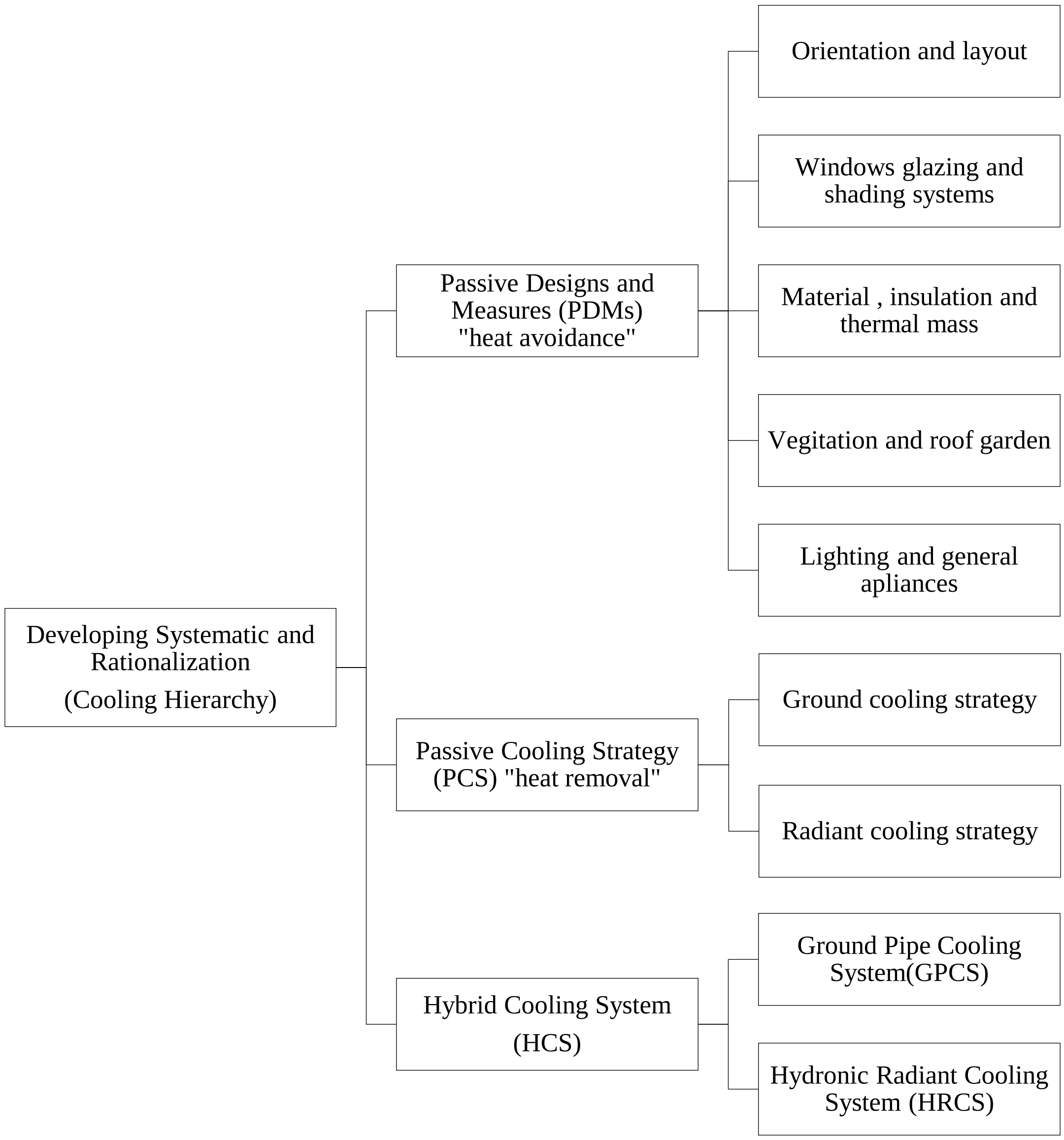


Figure 5.1: Chapter structure and outline.

5.2 Building Cooling Hierarchy

Building cooling system is an integral part of the overall building design. Despite the fact that AC is predominating the cooling approach in current modern dwellings in Saudi Arabia, such mechanical cooling systems are not supposed to be the first priority. As demonstrated in the current study, using AC is energy intensive with high associated levels of CO_2 emissions, therefore, a rationale logical hierarchy of cooling strategy and process was considered. Beginning with passive design measures (PDMs) for heat avoidance to passive ventilative cooling strategy (PCS) for heat removing and to a mixed mode cooling system and then fully mechanical AC systems (Figure 5.2). Therefore, the following section addresses the systematic cooling approach and extensively outlines the cooling hierarchy that was considered prior to designing and developing the experimental HCS in order to optimise cooling efficiency and ensure that energy use associated with cooling is minimised.

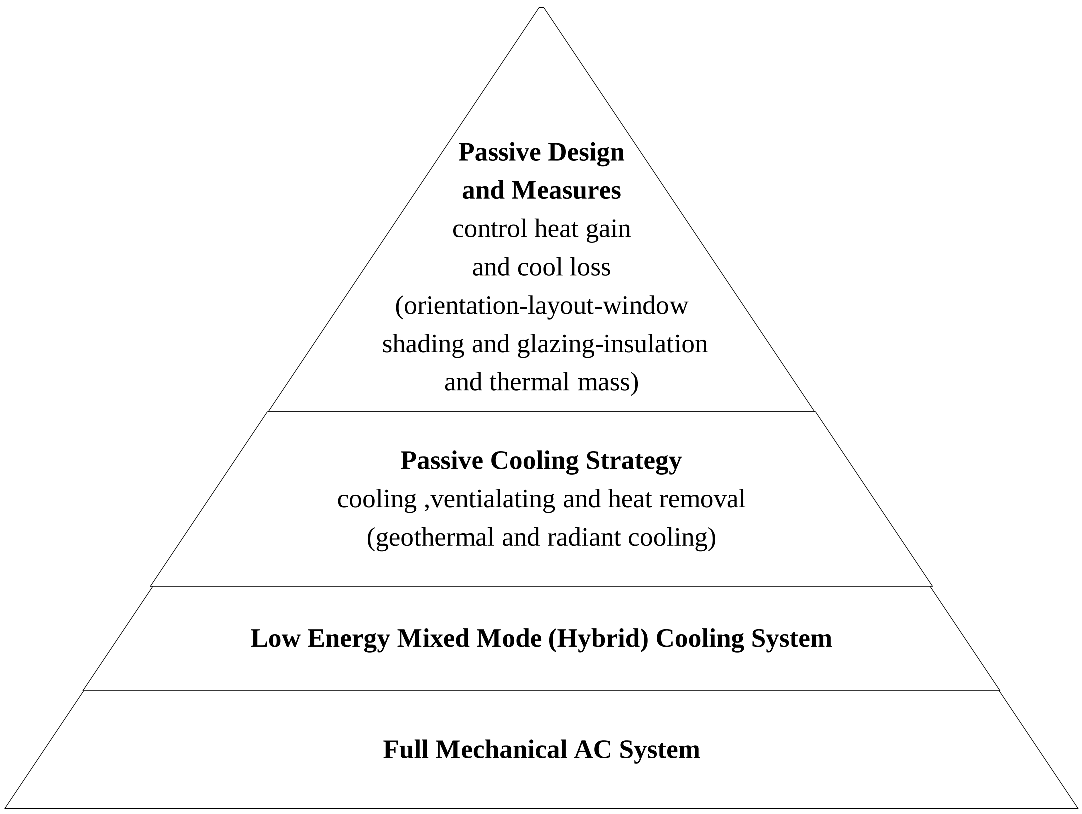


Figure 5.2: Building cooling hierarchy and process.

5.2.1 Passive Design and Measures (PDMs)

It is a significant challenge to achieve the desired thermal comfort condition for the occupants by using solely passive designs measures and strategies (Cook, 1989). The role of PDMs is to simply reduce cooling loads. There is a clear understanding that in peak summer additional more active measures will be required, however, the task is to quantify what can be achieved in a cost-effective manner with intention to reduce heat gain by 30% to 50% These key measures and thermal retrofitting strategies include building orientation, window solar shading and glazing systems, wall and roof insulation, possibly increasing thermal mass and the installation of energy-efficient lighting and equipment. The following section is a review of the most significant passive design measures that are the most likely candidates for incorporation in hot and humid climate zones.

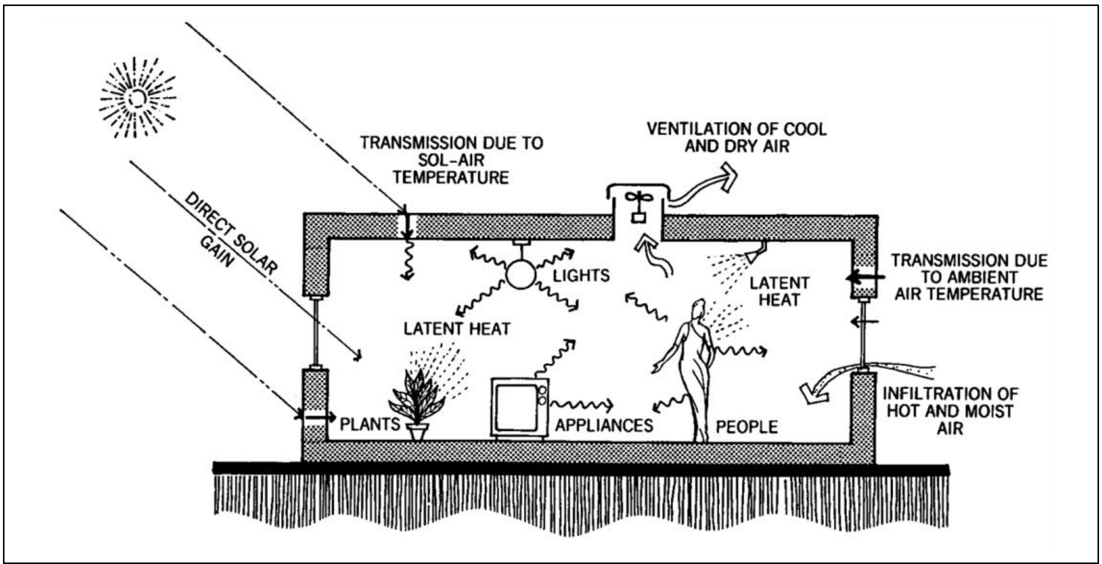


Figure 5.3: The external and internal heat gain sources (Givoni, 1994).

5.2.1.1 Orientation and Layout

The orientation and spatial organisation clearly influence the capability of building to ventilate and receive/avoid solar radiation (Givoni, 1998). While it is impractical to re-orient certain internal volumes after the building has been completed, additional measures can be incorporated in existing buildings. Applying either internal or external insulation to the building envelope can lead to a significant reduction in cooling demand as heat transfer is reduced through the fabric (Roaf, 2012). The optimum orientation requires a recognition of sun paths, at different times of the year. As illustrated in Figure 5.4, the sun path of the simulated baseline building model was varied from month to month. The sun path analysis conducted by the "Ecotect" climate analysis tool shows that, in summer, the sun path from East to West was slightly sloped to the north with approximately 13 hours daylight whilst in winter the sun path sloped to the south with 11 hours of daylight.

As a result of the shortest sides of the building that North and South facing received the minimum solar radiation and heat while the longest sides that East and West facing received the maximum daylight and solar heat gain. It is relatively easy to shade windows from the high mid-day sun and if the site density is high traditionally buildings are shaded from low sun angles by neighbouring properties.

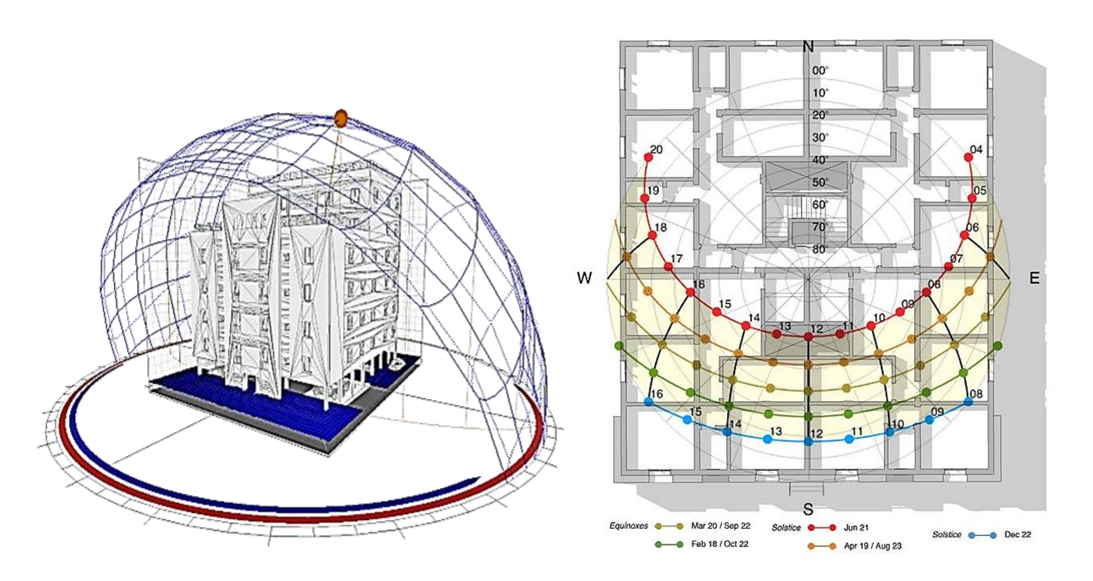


Figure 5.4: Building orientation and sun path analysis (Ecotect, 2015).

The layout and spatial organisation have a major influence on the building envelope's surface area to volume ratio and consequently the rate of heat exchange and potential for natural ventilation and day-lighting. The more compact the floor plan, the smaller the exposed surface area of the walls or the roof and consequently the heat exchange with the surrounding environment is reduced (Givoni, 1994). The block used as the baseline case study is almost a cube and therefore has an optimal surface area to volume ratio.

Figure 5.5 shows the layout of a typical floor plan. The living room (Majlis) where the family spends most of their time is compact and sheltered by ancillary spaces such as dining and bedrooms without the surfaces being exposed to direct solar radiation and ambient air. The inner atrium is a multi-height space open to the sky and has the potential to be utilised as a source of natural daylight and stack ventilation as well as a service void. These rooms at external walls require to be insulated and window shading and double glazing could be incorporated in order to minimise heat gain and cooling demand.

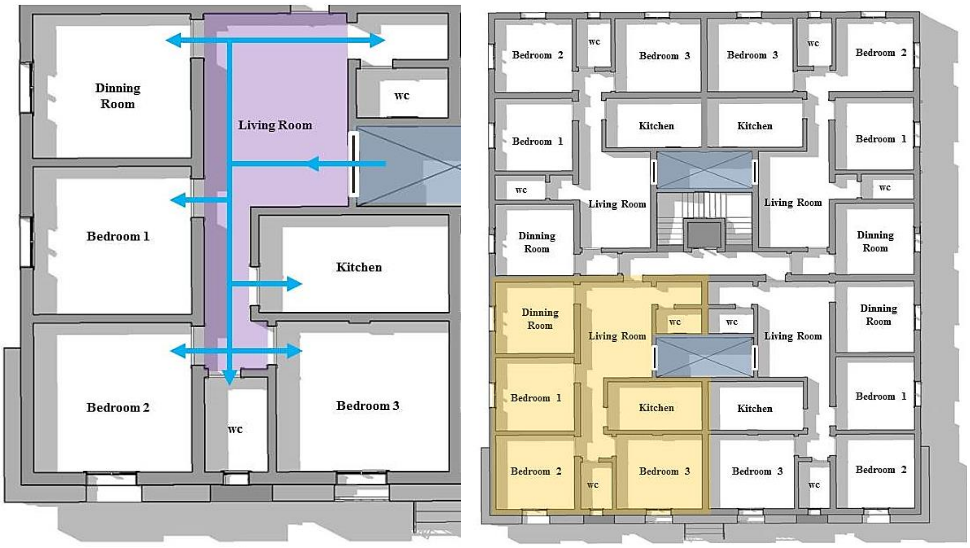


Figure 5.5: Spatial organization and building layout.

5.2.1.2 Window Glazing and Shading Systems

Windows can play a key role in determining energy performance through orientation, size, shading and glazing type (BSRIA, 2010). Since the window size in the baseline case study building is fixed (1.50 m x 1.20 m) with single clear glazing unit and without shading, this allows both radiative and convective gains.

Effective shading can be achieved by several means, including shading devices, vegetation and special glasses or nearby structures. In general, external shading is considered as the most effective, since it intercepts solar radiation and heat before it passes into the internal space through the building envelope.

There are two typical types of window shading; external shading and internal shading. For the external shading, there is an additional classification into fixed and moveable shading devices. Although both external and internal shades are effective in controlling solar gain, external shading is the more effective due to blocking the solar radiation before passing through window glazing.

The following section discusses these types of shading devices, showing their overall performance with reference to heat gain (Figure 5.6).

1) **External Shading**

   This is a more efficient tool widely as an integral part of building façades. External shading devices can be divided into two types, fixed shading and operable shading (Givoni, 1998).

   a) ***Fixed External Shading***: This type of shading is characterised by it being a part of the building fabric, with no need for maintenance or adjustment. There are three main types of fixed external shading (horizontal, vertical and overhang - see Fig. 5.6). The horizontal shading is usually recommended on southern facades where the sun path in the sky is high, while vertical shading is recommended in eastern and western facades, as the sun path in the sky is low at dawn and dusk. In some cases, an integrated shading system which consists of both vertical and horizontal devices may be required, particularly in a case where the building is oriented towards south-west or south-east. Overhang horizontal shading is recommended during the summer when the sun is high in the sky for most of the day (Givoni, 1998).

   b) ***Moveable External Shading:*** This type of shading devices has similar advantages of the internal shading devices, being more interactive with building occupants and amenable to their needs, furthermore the ability to block solar heat and radiation prior to passing through the window glazing. This kind of shading however requires regular maintenance to maintain its performance and appearance. These exterior shading devices include awnings, shutters, roller shutters and louvres (Givoni, 1998).

      - **Awnings**: Awnings are more effective due to their ability to block direct solar radiation. Awnings are commonly made of fabric or metal and attached above the window and extend down and out. The awning can decrease direct heat gain and reflect sunlight, however, they also partially block the view (Givoni, 1994).
      - **Shutters**: Shutters are movable coverings, which are usually made of wood or metal. Shutters could be either solid or slatted with fixed or adjustable slats. The advantage of a shutter beside reducing heat and solar gain is that it can provide both privacy and additional security (Givoni, 1994).
      - **Louvres**: The advantage of adjustable louvres is their ability to control the level of sunlight entering the building interior from any angle and can be adjusted either manually or automatically from both inside or outside

depending on the design. In addition, the slats can be horizontal or vertical (Givoni, 1994).

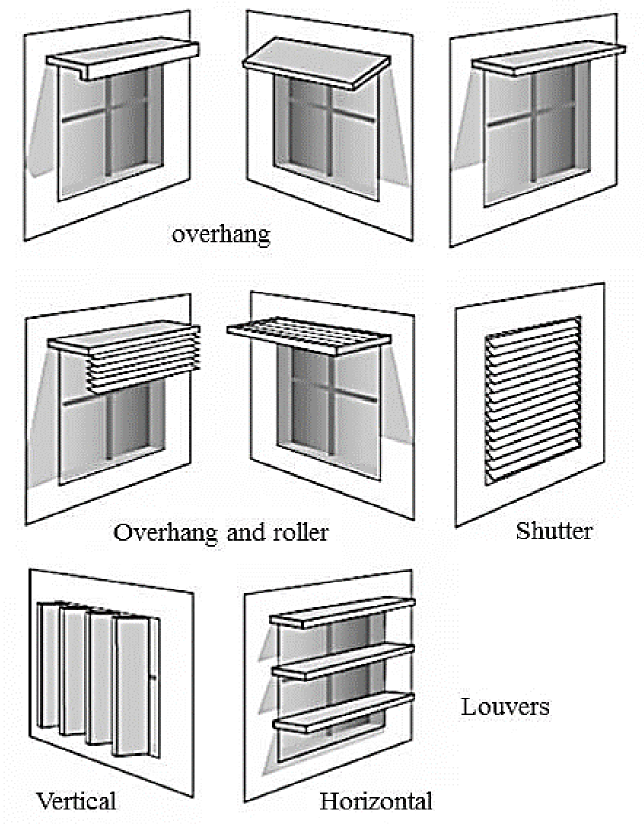


Figure 5.6: External shading device types.

A key issue, which must be considered in designing a shading system, is its possibility to conflict with day-lighting. Reducing the penetration of daylight due to unsuitable shading design can increase the demand for artificial lighting, which then offsets the energy savings from decreased heat gains. Such a conflict can be lessened by using movable shading devices such as louvres, which allow the occupants to control their domestic lighting and thermal environment. When this shading is accompanied by low U-value and high shading coefficient glass, the result is that unwanted solar and heat gain and consequently, cooling load will be considerably reduced (Givoni, 1998).

The efficiency of a shading device regarding its quantitative thermal performance is measured by its shading coefficient (Sc) as illustrated in Table 5.1.

	Shading Type	Shading Coefficient (SC)
Internal Shading	Venetian blinds (ref)	0.45
	Venetian blinds (light)	0.58
	Venetian blinds (dark)	0.75
	Roller blinds (light)	0.39
	Roller blinds (medium)	0.60
	Roller blinds (dark)	0.81
	Draperies (light)	0.40
	Draperies (medium)	0.65
	Draperies (dark)	0.80
External Shading	Exterior Venetian	0.10
	Horizontal .adjustable	0.10
	Vertical adjustable	0.10
	Vertical Fins	0.30
	Canvas awing (light)	0.20
	Canvas awing (Dark)	0.35
	Overhang	0.20
	Trees (dense)	0.20
	Trees (Medium)	0.40
	Trees (light)	0.60

Table 5.1: Shading coefficient (SC) for varies internal and external shading devices.

In terms of window glazing systems, one of the most significant properties of the glass is its opacity towards longwave radiation from the inside, leading to the greenhouse effect, which causes an excessive rise in the room temperature. Proper glazing choice can provide good daylighting and reduce electric lighting requirements. (Givoni, 1994). The quantitative thermal performance of the glazing depends upon its U-value in addition to its shading coefficient as is shown in Table 5.2. According to glass choice and a significant amount of solar gain can be reflected by the outer pane while still achieving reasonable G value allowing visible light (shorter wave) to pass into the building (Givoni, 1994). As the current glazing is single pane clear float, there is significant scope to increase the performance of the components and reduce heat gain.

Glazing Type	U – Value (W/m²K)	R-Value (m²K/W)	Shading Coefficient (SC)
Single clear	5.4	0.19	0.82
Single reflective (bronze)	4.0	0.22	0.20
Single tinted (bronze)	5.2	0.20	0.57
Single tinted (green)	5.0	0.21	0.56
Single low - E (bronze)	4.6	0.22	0.42
Single low - E (clear)	4.8	0.22	0.66
Single low - E (green)	4.4	0.23	0.41
Double clear	3.2	0.31	0.65
Double tinted (bronze)	3.1	0.32	0.48
Double tinted (green)	2.9	0.34	0.46
Double tinted (grey)	2.8	0.35	0.45
Double reflective	2.5	0.38	0.16
Double low - E (clear)	1.98	0.50	0.45
Double low - E (bronze)	1.89	0.52	0.35
Double low - E (green)	1.88	0.53	0.37
Double low - E (grey)	1.91	0.52	0.34
Triple pan clear	1.87	0.53	0.28
Triple tinted (bronze)	1.69	0.58	0.28
Triple tinted (green)	1.66	0.60	0.28
Triple tinted (grey)	1.74	0.56	0.28
Triple low - E (clear)	1.16	0.86	0.28

Table 5.2: Shading coefficient (SC) and U – value for varies glazing systems.

5.2.1.3 Material, Insulation and Thermal Mass

As was observed from the base case analysis the thermal performance of the building envelope was relatively poor with a U-value of circa 2.26 W/m^2. In hot humid climates, modern materials such as plasterboards, lightweight concrete blocks and insulation have to be imported from colder climates. There are several factors that need to be considered in selecting an appropriate building material. Factors include thermal conductivity (K-value) - and resistivity (R-value) that gives an indication of how quickly the materials transfer or resist heat flux. The higher the R-value the better the thermal performance and heat retention, however, the quantitative thermal performance of the building materials depends upon its U-value, which is the heat transfer coefficients or thermal transmittances (CIBSE, 2005). Table 5.3 presents different k, R and U values for a range of building materials.

In order to minimise the thermal influence of solar radiation, multiple layers of materials might be required to make up a building envelope. In summer the use of insulated thermal mass construction can delay heat transfer through the building fabric and help to keep the interior cool as the surface has a slow response. Insulation materials, such as glass fibre or polyurethane foam, can effectively reduce the conductive heat transfer through opaque surfaces that receive intensive solar radiation. High thermal mass materials such as concrete and dense blockwork have the capacity to absorb heat gains. If ventilation is increased at night, the heat absorbed can be 'flushed out', allowing the thermally massive wall or floor to store 'coolth' to keep the interior comfortable during the subsequent day (Givoni, 1994). Strategic use of thermal insulation can therefore be relatively cost-effective and optimise the energy efficiency of a building. Applying thermal insulation to the external walls, roof and floor will reduce the cooling load on the AC system and by saving annual energy costs may have a relatively quick pay-back timeframe.

	Common Building Materials in the density of (100 kg/m³)	Conductivity (K Value) (W/mK)	Resistance (R-Value) (M²K/W)	Transfer (U-Value) (W/m²k)
Walls	Brickwork (outer leaf)	0.045	2.22	0.45
	Brickwork (inner leaf)	0.033	3.03	0.33
	Lightweight aggregate concrete block	0.040	2.50	0.40
	Concrete hollow block	0.030	3.33	0.30
	Red clay hollow block	0.026	3.84	0.26
	Concrete (medium density)	0.062	1.61	0.62
	Reinforced concrete (2% steel)	0.104	0.71	1.04
	Mortar (protected)	0.050	2.00	0.50
	Mortar (exposed)	0.053	1.88	0.53
	Gypsum	0.030	3.33	0.30
	Sandstone	0.088	1.13	0.88
	Limestone (soft)	0.061	1.63	0.61
	Limestone (hard)	0.077	1.29	0.77
Surface Finishes	Plasterboard	0.030	3.33	0.30
	Fibreboard	0.025	4.00	0.25
	Tiles (ceramic)	0.056	1.78	0.56
	External sand-cement rendering	0.076	1.31	0.76
	Plaster (dense)	0.043	2.32	0.43
	Plaster (lightweight)	0.030	3.33	0.30
Floors & Roofs	Solid concrete slab	0.032	3.12	0.32
	Hollow core concrete slab	0.028	3.57	0.28
	Tiles (clay)	0.050	2.00	0.50
	Tiles (concrete)	0.071	1.41	0.71
	Wood wool slab	0.020	5.00	0.20
Insulation Materials (100 mm thickness)	Glass Fibre	0.032-0.044	3.10-2.25	0.32-0.44
	Rock Fibre	0.035-0.044	2.85-2.25	0.35-0.44
	Sheep's Wool	0.042	2.38	0.42
	Expanded Polystyrene (EPS)	0.036	2.77	0.36
	Extruded Polystyrene (XPS)	0.029-0.036	3.44-2.77	0.29-0.36
	Polyurethane Foam Board (PUR)	0. 22-0.29	4.45-3.44	0.22-0.29
	Polyisocyanurate Foam Board (PIR)	0.021-0.022	4.76-4.54	0.21-0.22
	Phenolic Foam Board	0.021	4.76	0.21

Table 5.3: K, R and U-values of various building materials (Givoni, 1998).

The colour of a building's surface can also play a significant role in reflecting or absorbing solar gain. Any coloured surface tends to absorb a part of the visible spectrum and reflects the rest; this process differentiates from colour to another due to different percentages of absorption and reflection. For maximum heat absorbance, dark colours are preferred, whereas, white paint is preferable to minimise absorbance in clear warm climatic conditions (Givoni, 1994).

There have been some recent developments in building exterior coatings with the emergence of heat reflective paints, which can reflect up to 80% of the solar radiation. A building's exterior coat can be measured by its ability to reflect or absorb solar radiation. Table 5.4 illustrates the previous points for different building materials according to their colours. There are also selective surfaces that can manipulate absorption and emissivity coefficients, ideal where a building or surface is required to lose heat to a clear night sky through black body infra-red radiation.

Colour	Absorptivity	Reflectivity
Whitewash, new	0.25	0.75
White, dirty	0.30	0.70
White paint	0.15	0.75
Light (grey, green, brown)	0.45	0.55
Dark (grey, green, brown)	0.75	0.25
Black paint	0.85	0.15
Aluminium foils, polished	0.05	0.95
Aluminium foils, oxidized	0.15	0.85
Aluminium paint	0.50	0.50
Cool wall or roof coating	0.20	0.80

Table 5.4: Absorptivity and reflectivity coefficient of various building coating and colours (Givoni, 1998).

5.2.1.4 Vegetation and Green Roof

Insulated and protected roofs can efficiently reduce the amount of solar heat absorbed by the roof membrane, thus leading to cooler indoor temperatures (Givoni, 1994). Research conducted by Nottingham Trent University has demonstrated that on a typical day with a temperature of 18.4°C, the temperature beneath a normal roof membrane was 32°C, whereas, the temperature beneath the membrane of a 'green' roof was approximately 17.1°C. A recent study conducted in Chicago, USA, estimated that such an approach could have a pay-back of approximately $100 million as the demand for air conditioning and ambient air pollution would be reduced (Roaf, 2012). Vegetation in the form of trees, climbers, pergolas or high shrubs can effectively provide shading for the building's exterior surfaces. Ground cover plants can also minimise the reflected and absorbed long-wave radiation emitted towards the building. The evapotranspiration process of green surfaces can cool the ambient air and nearby surfaces by what is known as the “adiabatic” effect. Wall climbing plants can also decrease wind speeds next to the wall surfaces and provide thermal insulation especially when the ambient air temperature is higher than that of the walls (Givoni, 1994).

Case studies in hot humid climates show that ‘green’ roofs can achieve a temperature 4°C to 11°C below that of an exposed roof surface, depending on the construction of the roof, planting details and surrounding conditions. A ‘green’ roof can provide cooling in several ways. The plants shade the roof and together with the substrate layer, act as insulation. The substrate layer and roof structure can combine and serve as an additional thermal mass that delays heat transfer from the exterior while absorbing heat from internal sources depending on the position of any insulation layer (Al-Ajlan, 2006).

Where the use of a green roof is not widely practicable in Saudi Arabia due to the harsh climate and lack of irrigation, a roof with a high ‘albedo’ can play a similar role in minimising the heat absorbed, while vegetation could be utilised to shade and adiabatically cool the zones at ground floor level.

5.2.1.5 Lighting and General Appliances

There is a significant relation between lighting systems and building internal heat gain and energy consumption. The current use of inefficient Halogen spotlights generates a significant amount of heat and cost. They are only 30% efficient and give 70% of their energy out as heat rather than light (SEEC, 2015). In contrast, LED (light emitting diodes) uses 10% of the energy needed to produce the same lumen output as a halogen or incandescent lamp. An LED can last up to 50000 hours and produce a high quality, natural-looking light that is indiscernible from that provided by halogens or other lamp types (SEEC, 2015). The following table shows the general comparison between traditional Halogen floodlights and LED lamps.

Characteristic	Traditional Halogen Floodlight	LED Floodlight
Colour	2700 K	2700 – 5000 K and RGB
Light Energy (%)	10%	80%
Heat Energy (%)	90%	20%
Life	1000 – 2000 hours	25000 – 50000 hours
Dimming	yes	yes
Energy use	Inefficient	Efficient
Lumen Efficiency	9 to 10 lumens /W	50 to 60 lumens /W

Table 5.5: Comparison between traditional Halogen floodlight and LED lamps.

Domestic appliances such as ovens, dishwashers, washing machines, clothes dryers, and water heaters also add to the internal casual gains. Designers can play a significant role in cutting internal heat gain by providing special areas for these appliances and activities, such as semi-external decks and patios. New energy-efficient appliances can now use 50% less energy and therefore produce less heat than older models. Another technique to limit the impact of appliances on internal heat gain level is to block heat sources, such as cooking appliances, laundry rooms and water heaters should be isolated from the main living spaces with heat gains and water vapour build ups quickly vented to external air. It is also possible to set running time schedules (by mobile phone) for these appliances in order to control electricity consumption and reduce peak demand by running appliances after mid-night (SEEC, 2015).

5.2.1.6 The Proposed Passive Designs Measures (PDMs)

The previous review and investigation of viable passive designs measures aim to determine the optimum cost-effective and energy efficiency passive 'fabric first' design measures to optimise the thermo-physical performance of building envelope and fabric with the intention of reducing a significant percentage (30 % - 50 %) of external and internal heat gains, cooling load and CO_2 footprints. Therefore, three retrofitted models of building fabric were computationally modelled and simulated using DesignBuilder software as a tool to assess various retrofit parameters such as walls, floors and roofs thermal insulation and windows shading and glazing. The design of such retrofitted models of building fabric are of course complying with local building regulations and codes which for instance require a maximum standard thickness of external wall of 250 mm and 350 mm for floors and roofs (slabs) with preference to utilize locally manufactured materials available in the Saudi construction materials market as an affordable and cost-effective choice (SBC, 2015).

Since the current baseline case study model is relatively huge and difficult to be simulated as one model, it was ideal to select a single flat zone as a template to measure the thermal influence of the three different retrofitted models compared to the baseline. The selected case study zone is a typical 76.6 m^2 (three- bedrooms) flat occupied by an average of 5 people (0.065 per m^2). The zone is mechanically conditioned with cooling set-point temperature at 28ºC and set-back at 23ºC according to the adaptive thermal comfort level of air conditioned building as defined by ASHRAE standard 55.

As previously outlined in section 4.2.3 of chapter 4, the baseline typical walls construction have three layers including 25 mm exterior cement plaster, 200 mm hollow concrete brick or block, coated by 25 mm interior cement plaster that produces a U-value of

2.92 W/m²K. While roofs and floors are constructed from reinforced concrete slabs filled with concrete blocks and produce a U-value of 2.77 W/m²K. Windows typically combine 4 mm single glazing units with a U-value of circa 5.3 W/m²K.

However, in the model (A), the specifications of walls were retrofitted to incorporate 20 mm of Expanded Polystyrene (EPS) to fill the hollow cores of concrete blocks with a 25 mm lightweight plaster and white paint which produce a U-value of 1.04 W/m²K. While the construction of floors and roofs were retrofitted to incorporate 20 mm of Polyisocyanurate Foam Board (PIR) above the 300 mm pre-cast concrete slabs and topped with 20 mm white ceramic tiles, that produced a resultant U-value of 1.25 W/m²K. To reduce solar heat gain and improve the thermal efficiency of windows, vertical fins (0.30 SC) were added combined with a standard 4 mm thick single reflective glazing units with a U-value of circa 4.0 W/m²K (Table 5.6).

In model (B), external walls were thermally improved by incorporate 25 mm of Polyurethane Foam Board (PUR) insulation on 200 mm hollow clay blocks (Ziegel) with a 25 mm lightweight polymer render and white mineral paint that produced a U-value of 0.91 W/m²K. Floors and roofs were constructed using 300 mm of reinforced concrete slabs thermally insulated by 30 mm of Polyisocyanurate Foam Board (PIR) and topped with 20 mm of ceramic tiles, that produced a U-value of 0.82 W/m²K. Windows were thermally optimised by incorporating an overhang shading devices (0.20 SC) and standard 4 mm thick clear double glazing units with a U-value of circa 3.2 W/m²K (Table 5.6).

While in model (C), walls specifications were retrofitted to incorporate 50 mm of Polyurethane Foam Board (PUR) insulation, on 200 mm hollow clay blocks (Ziegel) with a 25 mm lightweight polymer render and heat reflective white mineral paint (Keim) to increase the Albedo effect and produce a U-value of 0.41 W/m²K. Floors and roof were constructed using 200 mm of hollow core concrete slabs topped with 50 mm of Polystyrene Insulation Boards (XPS) insulation and 20 mm white ceramic tiles, with resultant U-value of circa 0.31 W/m²K. To avoid both direct and indirect solar radiation, adjustable horizontal louvres were added to the windows combined with standard 6 mm double-glazing units that produced a U-value of 2.5 W/m²K (Table 5.6).

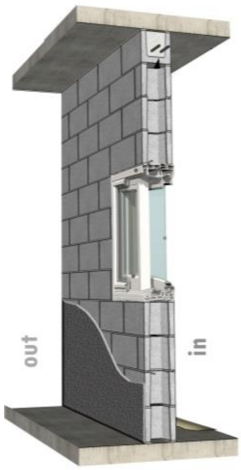
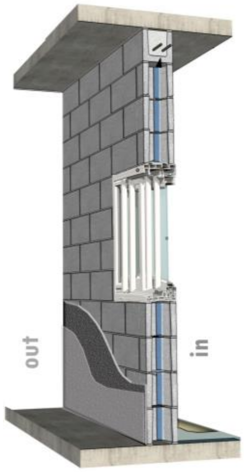
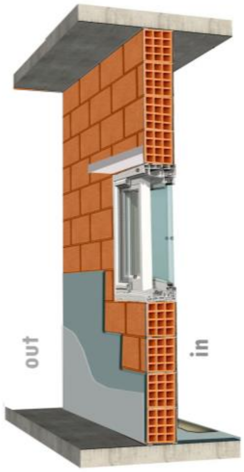
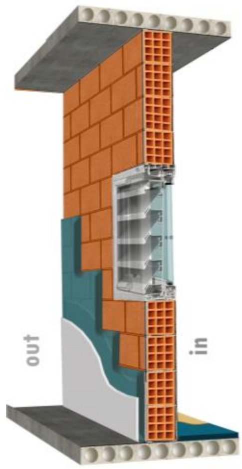
	Baseline	Model (A)	Model (B)	Model (C)
				
Wall	*200 mm concrete block *25 mm cement plaster	*200 mm concrete block. *20 mm Expanded Polystyrene (EPS). *25 mm plaster.	*200 mm clay blocks. *25 mm Polyurethane Foam Board (PUR). *25 mm polymer render and white paint	*200 mm clay blocks *50 mm Polyurethane Foam Board (PUR) *25 mm polymer render and reflective white paint (Keim)
	U-value 2.92 W/m^2K	*U-value 1.04 W/m^2K*	*U-value 0.91 W/m^2K*	*U-value 0.41 W/m^2K*
Floor and Roof	*250 mm concrete slabs filled with concrete blocks	*300 mm pre-cast concrete *20 mm Polyisocyanurate Foam Board (PIR) *20 mm white ceramic tiles.	*300 mm of concrete slabs *30mm Polyisocyanurate Foam Board (PIR) *20 mm of ceramic tiles.	*200 mm hollow core concrete slabs (TermoDeck®) *50 mm Polystyrene Insulation Boards (XPS) *20 mm ceramic tiles.
	U-value 2.77 W/m^2K	*U-value 1.25 W/m^2K*	*U-value 0.82 W/m^2K*	*U-value 0.31 W/m^2K*
Window	*4 mm single glazing units	*vertical fins *4 mm single reflective glazing unit.	*overhang shading *4 mm double glazing unit.	*adjustable horizontal louvres *6 mm double-glazing unit.
	U-value 5.3 W/m^2K	*U-value 4.0 W/m^2K*	*U-value 3.2 W/m^2K*	*U-value 2.5 W/m^2K*

Table 5.6: Design and configuration of the baseline and the three retrofitted models of building fabric

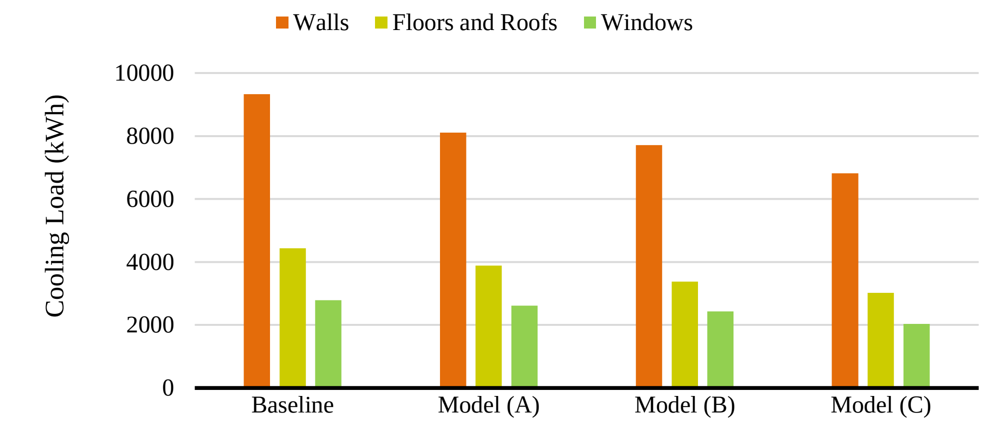
The design and configuration of the three retrofitted models were subject to numerical modelling and simulation using DesignBuilder in conjunction with EnergyPlus simulation engine as a tool to assess the thermal efficiency of such retrofit strategies.

The simulation result as tabulated in Figure 5.7 shows that there is a disparity in cooling load reduction percentage between the different retrofitted models due to incorporating different designs and measures in order to improve the thermal efficiency of baseline building fabric. Initially, three thermal enhancements strategies were conducted; the most effective strategy was in optimising the thermal efficiency of floors and roofs.

As can be seen in Figure 5.7, in models (A and B) incorporating more thermal insulation resulted in decreasing the baseline floor cooling load by almost 19%, however, besides adding thicker thermal insulation boards, the standard 300 reinforced concrete slab (as in model (A) and (B)) were retrofitted with 200 hypocaust concrete slab (as in model (C)). This efficient and cost-effective strategy led to a substantial reduction of baseline annual floors cooling load from 4439 kWh to 3018 kWh (32%) (Figure 5.7).

Similarly, as can be seen in Figure 5.7, in the model (A), adding more insulation to walls by incorporating 20 mm of Expanded Polystyrene (EPS) produced a reduction of circa 14% of the baseline walls cooling load. Furthermore, the thermal capacity of walls was improved in the model (B) through incorporating 25 mm of Polyurethane Foam Board (PUR) insulation on 200 mm hollow clay blocks (Ziegel) which reduced the baseline walls cooling load by 19%. However, the peak cooling load reduction (27%) of baseline walls cooling load was achieved in the model (C) due to incorporating 50 mm of Polyurethane Foam Board (PUR) insulation (only 8% additional saving in cooling load with almost double thermal insulation thickness compared to model B). Although adding more and thicker layers of thermal insulation might be efficient, however, such approach has a limited impact on walls thermal behaviour and thus cooling load (Figure 5.7). Moreover, such thermal insulation pattern (50 mm in the model (C)) is costly and highly limited. Furthermore, by incorporating thicker wall insulation, the wall thickness may exceed the standard limit (maximum 250 mm). Therefore, using 50 mm of Polyurethane Foam Board (PUR) insulation is more affordable and available (Figure 5.7).

Likewise, windows cooling load were considerably reduced from 2788 kWh to 2035 kWh (27%) due to retrofitting the baseline single glazed windows with Low-E 6 mm double glazed windows. In addition, the adjustable horizontal louvres that added to the windows in the model (C) were able to avoid direct, indirect and low angled solar heat gain and thus reduce cooling load (Figure 5.7).



	Baseline	Model (A)	Model (B)	Model (C)
Walls	9333	8109	7716	6814
Floors and Roofs	4439	3884	3377	3018
Windows	2788	2610	2433	2035

Figure 5.7: Cooling load reductions in accordance with different retrofitted models of building fabric.

Based on the aforementioned simulation results of the retrofitted models and the comparative assessment of the thermal behaviour of various fabric designs and measures compared to the baseline, the suggested key PDMs can be summarised as follows:

a) Windows Shading and Glazing Systems

In order to avoid direct, indirect and low-angled sun radiation, an adjustable horizontal louvred shading device (0.10 SC) was chosen to automatically control sunlight level and provide additional privacy and security. In addition, standard 6 mm thick double glazing window units with a U-value of circa 2.5 W/m^{2}K were incorporated to reduce heat gain.

b) Materials, Insulation, Colour and Thermal Mass

The wall specification was retrofitted to incorporate 50 mm of Polyurethane Foam Board (PUR) insulation, on 200 mm hollow clay blocks (Ziegel) with a 25 mm lightweight polymer render and heat reflective white mineral paint (Keim) to increase the Albedo effect. This reduced the U-value from 2.92 to 0.41 W/m^{2}K. Floors and roof construction used 200 mm hollow core pre-cast concrete slabs (TermoDeck®) topped with 80 mm of the concrete screed, 50 mm of Polystyrene Insulation Boards (XPS) insulation and 20 mm white ceramic tiles, that produced a resultant U-value of 0.31 W/m^{2}K, representing an improvement in thermal resistivity of 87%. (XPS) insulation was also added to the roof deck and the soffit of the ground floor ceiling.

c) Vegetation and Green Roof

A specification for a 'green' roof to protect the slab from solar gain was added to areas not required for access, as was vegetation to the immediate surround on the ground floor to inhibit the heat island effect from paving and roads. The intention is to use the condensate from the ground pipe supply ventilation to irrigate these elements. Such greenery can also improve air quality in the immediate surrounds by absorbing modest quantities of particulate matter and other products of combustion. This creates a 'microclimate' with the air temperatures predicted to be 4ºC to 9ºC lower than ambient. It is from this zone that the supply air for the ground pipe supply ventilation system will be drawn. In addition, there is scope to incorporate 30 m^2 of roof-mounted PV array, to provide the electricity required to drive the supply fans and pumps during daylight hours.

d) LED Lighting and General Appliances

In addition to fabric measures, LED lamps on automatic controls were introduced throughout the development to further lower casual heat gains. Energy-efficient appliances were also included in the simulation calculations.

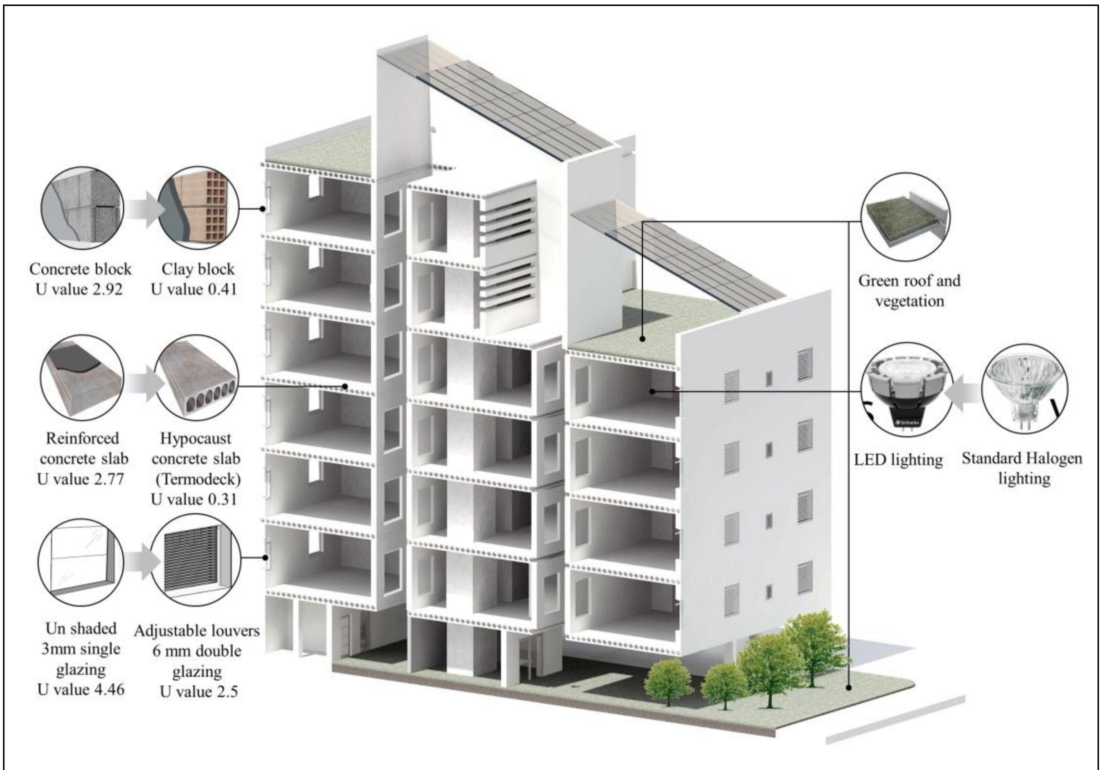


Figure 5.8: Key passive designs and measures (PDMs).

5.2.2 Passive Cooling Strategy (PCS)

Although, ‘fabric first’passive design measures were considered as heat avoidance techniques, some form of ventilation or cooling strategies will still be required in peak summer. There are some cases where existing buildings can incorporate new natural or hybrid passive cooling and ventilation techniques as they normally use less energy than air-conditioned buildings. This cooling approach involves a controller that minimises the total influence of the heat gain to deliver the interior at a temperature lower than the exterior ambient (Givoni, 1994).

To ensure effective performance, these passive strategies require two key factors: a heat sink whose temperature is lower than the interior, combined with an enhanced scenario for heat transfer towards the heat sink. Such conditions could possibly be achieved through the use of natural heat sinks which can be classified into four types;

1. sky: which transfers heat by long-wave radiation.
2. ambient air: transfers heat mainly through convection.
3. water: which transfers heat by conduction.
4. ground/soil: which transfers heat by conduction.

These cooling sources can be deployed in various strategies and cooling systems. The heat absorption into these heat sinks can be achieved through the natural procedures of heat transfer including, convection, radiation, evaporation and conduction or over mechanical enhancing by means of low energy fans or pumps (hybrid cooling). The most common passive cooling strategies have been classified as nocturnal ventilative cooling, radiant cooling, evaporative cooling, and ground pipe cooling, however, according to the comparative assessment of passive cooling applications conducted in chapter 2, the most viable PCSs that could be adapted to the extreme temperatures in KSA, ground pipe ventilative and nocturnal radiant cooling strategies have the greatest potential.

5.2.2.1 Ground Cooling Strategy

The vast thermal capacity of the earth has made it a very beneficial heat sink for building cooling or even heating purposes. This fact has been studied and proven by several researchers (Mihalakakou et al., 1995). It is known that the earth absorbs approximately 50% of the solar energy that our planet receives. As a result, the ground earth remains at a fairly constant temperature just a few meters below its surface all year round (Labs, 1990). The key principle of a ground pipe cooling strategy is exploiting this constant ground temperature as a heat sink for absorbing high air temperatures during peak summer (Pfafferott, 2003). Traditionally, this ventilative cooling technique is widely applied in hot climate countries over the globe as a passive natural cooling strategy. The rationale behind this phenomena is the daily and seasonal temperature amplitude, which is greatly reduced in the ground with increasing depths up to 4 m depth where the soil temperature remains constant over the year. Usually, the constant soil temperature is approximately equal to the mean annual ambient air temperature (Kavanaugh & Rafferty, 1997; Labs, 1990; Pfafferott, 2003).

However, being in hot and humid climate region such in KSA (Jeddah) with daytime summer temperature exceed 45ºC which affects the ground soil temperature (average 32ºC at 2 m depth) and thus the cooling efficiency of ground earth to act as reliable 'heat pump' and provide the desired indoor thermal comfort condition (average 25ºC).

Therefore, this research investigated the potential of utilising the ground for supply ventilation rather than a ground source heat pump (GSHP), however, in some cases the ground pipe supply ventilation is assisted with a heat pump which can increase the cooling capacity and hence optimise thermal performance.

The ground pipe cooling system works with a long-buried pipe with one end for the ambient air intake and the other end for providing cooled air to the desired space. In the 1980's, ground pipe approved a great deal of attention from architects and civil engineers, as an option or aid to conventional air conditioning. While the concept of routing air through underground pipe or chambers to achieve a cooling effect appears like a good proposal. Possibly a few hundred systems were constructed, but information on the practical application of the concept is imperfect.

Usually, the ground pipe is buried underground at the ultimate depth that could give most efficient results. This technology uses the ground as a heat sink for cooling purposes in warm countries where the channelled ambient air, via the buried pipe, transfers excess heat to the ground by convection. There should be adequate air flow into the buried pipe intake to produce cool air at the other pipe end for occupants thermal comfort. If there is insufficient air flow, a fan blower is needed at the buried pipe air intake to stimulate the air flow. The pipes that make up an earth loop are usually made of clay, concrete or polyethylene and can be buried under the ground horizontally or vertically, depending on the characteristics of the site.

The ground passive air cooling, also sometimes referred to as earth or labyrinth cooling (two different passive cooling systems), involves using pipes/'earth tubes' (Vertical or horizontal) buried in the ground or labyrinthine concrete passageways beneath a building to passively cool fresh air, which is then supplied to a building's interior (and potentially moved through the building using a passive stack system).

A thermal labyrinth decouples thermal mass from the occupied space, usually by creating a high thermal mass concrete undercroft with a large surface area (Grazzini, 2009). Decoupling the thermal mass means it can be cooled to a lower temperature than if it was in the occupied space. This stored 'coolth' can be used to condition the space in hot periods. The labyrinth layout needs to balance optimum thermal storage with the air resistance of the system. Creating air turbulence, by increasing the roughness and incorporating bends, improves heat transfer. However, incorporating too many bends may increase the air resistance beyond the point where the system can be part of a passive or naturally ventilated scheme. Thermal labyrinths are suited to new, mechanically-ventilated buildings with cooling demand that are located in climates with a large temperature difference between day and night. As labyrinths are often constructed directly beneath a building, only the sides and floor of the labyrinth are in contact with the earth and the top of the labyrinth is directly coupled with the building. This means that the labyrinth needs to be well insulated from the building to prevent heat transfer. The earth contact of the labyrinth gives the benefit of steady ground temperatures, however, the undisturbed ground temperature cannot be used in calculations, as it will be affected by the presence of the building and the operation of the labyrinth. This means that optimisation of the design requires a complete thermal simulation of the system (Grazzini, 2009).

When the ambient air temperature can itself meet the cooling requirements of the building, the labyrinth can be bypassed so that its cooling potential is retained for use during peak conditions. During the unoccupied period when the ambient air temperature is low, night cooling is used to 'charge' the labyrinth (Grazzini, 2009).

One of the first applications of a 'therm labyrinth' was the 1977 Royal Academy of Music complex in London existing theatres and music studios by Bill Holdsworth (Holdsworth 2005). Also in Germany, there are several projects with so-called 'Thermo labyrinth' systems built, par example Stadttheater Heilbron, and Terminal 1 Hamburg Airport. Recently in Australia, there is built Federation Square in Melbourne where the outside air is led in a labyrinth under the square and blown into the atrium of the main building (Bellew 2004, AIRAH 2003). By doing this a significant cooling effect is being realized. Other projects a business school designed by Cesar Pelli Architects for the University of Illinois, the Grand Rapids Art Museum in Michigan and the Earth Centre in Doncaster by FeildenClegg Bradley Architects. The Davis Alpine House at Kew Gardens is the most recent evolution of the idea. Wilkinson Eye Architects designed the building in collaboration with Atelier Ten (Bellow 2006)

As a conclusion from various projects and published literature, the performance of ground pipe cooling is affected by four main parameters include:

1. pipe length;
2. pipe radius or diameter;
3. depth of the pipe inserted into the ground;
4. air flow rate inside the pipe.

Many researchers found that the resulting temperature at the buried pipe outlet decreases with increasing pipe length, decreasing pipe diameter, decreasing the mass flow rate of flowing air in the pipe and increasing depths up to 4 m (Santamouris et al., 1995) and (Ghosal and Tiwari, 2006). These parameters were extensively discussed (section 5.2.3.1) to determine the optimum and 'best fit' design of the ground pipe system.

Ground pipe supply ventilation systems have relatively high initial costs with the ground loop representing the highest component of this cost. The rationale behind this relatively high initial cost is the fact that there is limited market competition in this field. Over the past decade, development in drilling technology has enhanced the affordability of many systems. Maintenance costs are relatively low because there are fewer mechanical components than conventional cooling systems, and most components are underground and therefore protected from the weather.

By employing such natural low energy cooling and ventilation strategy, substantial conventional equipment such as a chiller, large ducts, mechanical and control room, added structural roof support, are eliminated thereby, reducing building cooling energy consumption. Ground cooling system has the lowest life-cycle cost of all currently existing cooling systems and the most environmentally clean system on the market, Geothermal systems are also considered as cost-effective cooling system which positively influences the environment by providing a constant source of 'coolth' twenty-four hours a day using minimal fossil fuels (Pfafferott, 2003) .

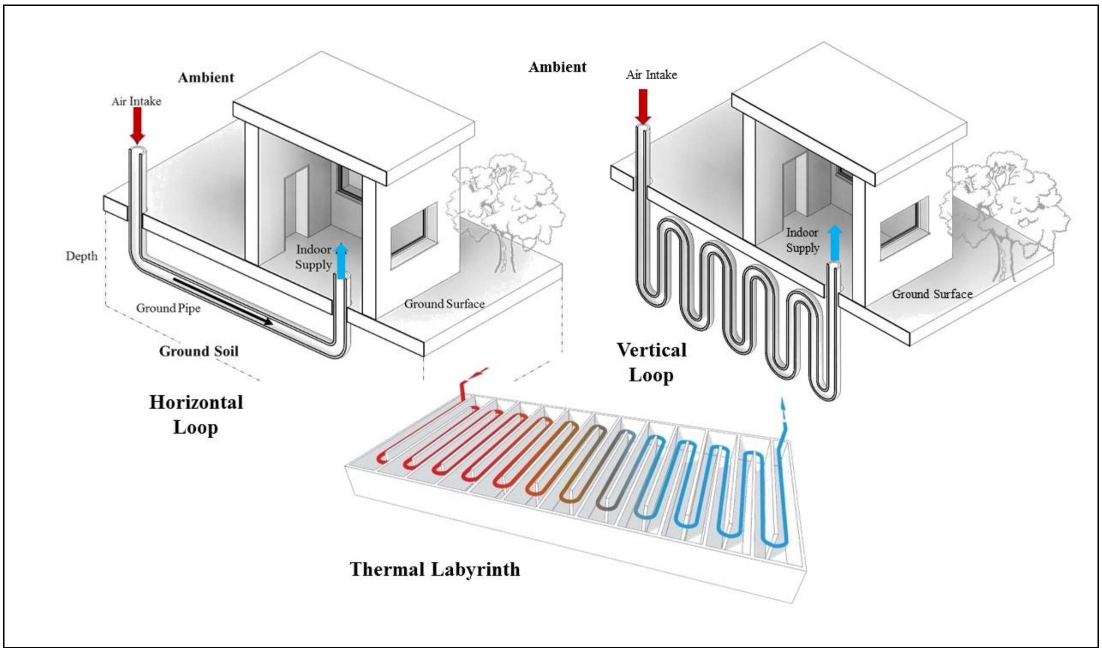


Figure 5.9: Ground-based supply ventilation techniques.

5.2.2.2 Radiant Cooling Strategy

This passive cooling technique utilises the emission of infrared thermal radiation to a clear dark night sky. This strategy can lead to roof surface temperatures falling substantially below the ambient air temperature (Givoni, 1994). Passive cooling by long-wave radiation to the night sky has been determined as a potentially productive means to reduce indoor spaces cooling energy and can be integrated with indoor active or hybrid cooling system, however, to date such cooling strategy and technique has not been commercially available.

Over the past decade, the number of radiant cooling systems designed, installed and commissioned around the world has increased. Radiant cooling systems are gaining exposure and popularity for a variety of reasons including energy efficiency, superior comfort, architectural flexibility and control and they are claimed to be cost-effective (Raman et al., 2014). Such a cooling strategy, which is popular in Europe, is rarely found in Saudi buildings due to the lack of familiarity with radiant cooling technology and concerns with moisture control problems. Radiant cooling systems are usually hydronic, circulating water in pipes in thermal contact with the 'black body radiator'. Typically the circulating water only needs to be 2-4°C below the desired indoor air temperature (Cook,1989). The radiative cooling strategy is based on heat loss by longwave radiation emission from one body towards another lower temperature body, which acts as a heat sink. This is the mechanism that allows the earth to disperse the heat received from the sun, to maintain its thermal balance (Labs,1990). There are two approaches to applying radiative cooling in buildings: passive radiative cooling or hybrid radiative cooling. In passive radiative cooling, the building envelope gets cooler and radiates heat directly towards the sky, while in hybrid radiative cooling, the radiator usually is not part of the building envelope, but a metal plate attached to the building. The mechanism of such a radiator is the opposite of solar collector plate. In this case, water is circulated at night to disperse heat rather than collecting solar gain during the day (Givoni,1998).

The simplest passive technique is to paint the roof white**.** White paint does not significantly influence the radiation rate at night, due to both white and black paints having approximately the same emissivity in the long wave range. The white painted roof is absorbing less solar radiation during the day, hence, the temperature of the roof remains lower, and can be easily cooled by radiation at night (Givoni,1994). Another technique is a movable insulation system that can be installed on a building's roof. This system consists of a movable insulating material over the roof of the building, which allows the exposure of roof fabric directly to the night sky with an insulating layer during the day protecting the thermal mass in order to lower the heat gain from solar radiation. A flat plate air cooler is another technique that can be used for cooling water in a loop, similar to the solar collector linked to a storage tank; this flat-plate air solar collector without glazing consists of a horizontal rectangular duct and topped with high emissivity radiator. Such hydronic radiant cooling systems typically use chilled water running in pipes in thermal contact with the surface (Givoni, 1994)**.** In the hydronic radiant strategy, heat is removed by the water and absorbed by the passively cooled ceiling, floor or walls. Having these cooled surfaces close to the desired indoor air temperature will offer a significant source of cooling and reduce cooling energy consumption (Cook, 1989). Radiant cooling can also be integrated with other energy-efficient strategies such as nighttime heat flushing, indirect evaporative cooling, or ground source heat pumps (Givoni, 1994).

Essentially, there are two typical types of building radiant cooling systems. The first type is chilled slabs that involve delivering cooling through the building structure, usually slabs which are chilled via embedded water pipes. The second type of building radiant cooling systems is ceiling panels that involve delivering cooling through specialised panels. Generally, concrete slabs systems are cheaper and offer more thermal mass than panel systems, while a panel system is more flexible (Figure 5.10). Ceiling panels can be retrofitted and attached to any ceiling and can be more easily integrated with ceiling ventilation supply. Chilled slabs cost less per unit of surface area than ceiling panels (Mihalakakou et.al, 1998). Table 5.7 outlines a general comparison between chilled slabs and ceiling panel radiant cooling systems.

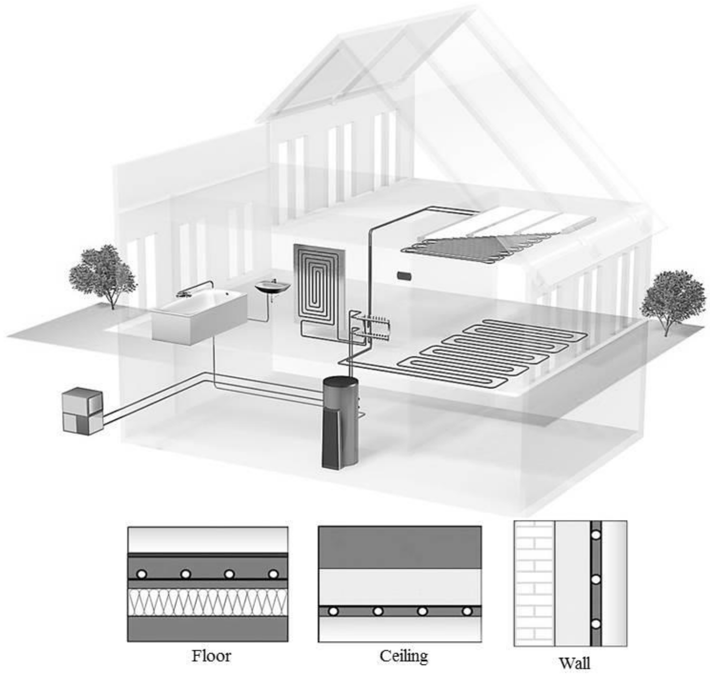


Figure 5.10: Types of radiant cooling techniques in building (REHAU, 2013).

System	Slab-Integrated Systems	Panel Systems
Method	Pipes are embedded on floors, walls or ceilings	Mats of small, closely spaced tubes are embedded in plastic, gypsum or plaster on walls and ceilings
Thermal mass	High	Low
Thermal inertia	High	Low
Typical surface area	Up to 100% of ceiling/floor area	50-70% of ceiling area
Cooling surface temperature	18-24 °C	13-15 °C
Cooling capacity	75.71 W/m²	94.60 W/m²
Best application	Buildings with high-performance envelopes-moderate climates-use with natural ventilation and/or low-energy cooling sources	Buildings with variation in skin loads-buildings with highly space variable internal loads-mixed-mode buildings with zoned or seasonal operation
Additional Opportunities	Use to remove solar loads from structural elements, or to create a "constant-temperature" slab or pre-cooled building-lower cost per unit surface area	Good for retrofit applications including supplementary space conditioning-some designs integrate acoustical solutions.

Table 5.7: Comparison between chilled slabs and ceiling panel radiant cooling systems applications.

Based on research conducted by the Lawrence Berkeley National Laboratory (LBNA), radiant cooling systems consume less energy than conventional cooling systems. Cooling energy savings by radiant cooling strategy are in the range of 40% compared to conventional systems depending on the climatic condition. These savings are basically attributed to less energy needed to move heat transfer medium (water) in comparison with conventional HVAC where air is used. Additionally, most of the energy savings are attributed to less energy being required to pump water compared with distributing air with fans (Mihalakakou et.al, 1998).

Radiant cooling can efficiently transfer some cooling to off-peak night-time hours by coupling the system with the building mass, however, condensation caused by high humidity may form on some surfaces that fall below the dew point. The surface temperature should not be equal or below the dew point temperature in the indoor space. Some standards have suggested that the indoor relative humidity limit is 60-70%. With an air temperature of 26°C dew point is reached between 17°C and 20°C, however, evidence suggests that condensation may not occur when reducing the surface temperature to below the dew point temperature for a short period of time. Using a dehumidifier can minimise the humidity level and maximise the cooling capacity (Mihalakakou et.al, 1998). In order to achieve thermal comfort, ASHRAE Standard 55-2010 recommends that floor slab temperatures be above 18.9°C for occupied spaces while recommending walls and ceilings temperature to be above 16.7°C as a minimum cooling temperature (Table 5.8).

Occupied zone surface	Recommended surface temperature	
	Maximum heating	Minimum cooling
Floor	28.9°C	18.9°C
Wall	40°C	16.7°C
Ceiling	26.7°C	16.7°C

Table 5.8: The recommended radiant surface temperature providing thermal comfort (ASHRAE, 2010).

Economically, radiant cooling has lower initial and lifecycle costs compared with conventional cooling systems. The relatively lower initial costs are attributed to the integration of design elements and building structure, while lower life-cycle costs result from reduced maintenance (Mihalakakou et.al, 1998).

5.2.3 Hybrid Cooling System (HCS)

In hot humid climatic condition, it is challenging to maintain the desired thermal comfort condition by employing a completely passive cooling method (Givoni, 1994). Hybrid cooling systems which involve integrating passive cooling strategies with low energy active mechanical cooling technology may optimise cooling efficiency (Cook, 1989). Some key passive cooling approaches include cross ventilation, passive stack ventilation, passive night-time cooling and earth cooling may not be able to maintain the desired year-round indoor thermal comfort, especially in summer peak demand, whereas, maintaining the indoor thermal comfort by only active cooling is an energy profligate process (Alaidroos & Krarti, 2016). A solution may therefore be found in integrating passive cooling with low energy active cooling technology in combination with 'fabric first' measures.

Referring to the analytical studies of viable passive cooling strategies in hot – humid climates outlined in chapter 5, the findings have theoretically and experimentally demonstrated that geothermal and radiant cooling strategies have the ability to adapt to such climatic conditions. The design of HCS intends to integrate two cooling systems: Ground Pipe Cooling System (GPCS) as a ventilative cooling strategy with the radiative cooling effect of a Hydronic Radiant Cooling System (HRCS).

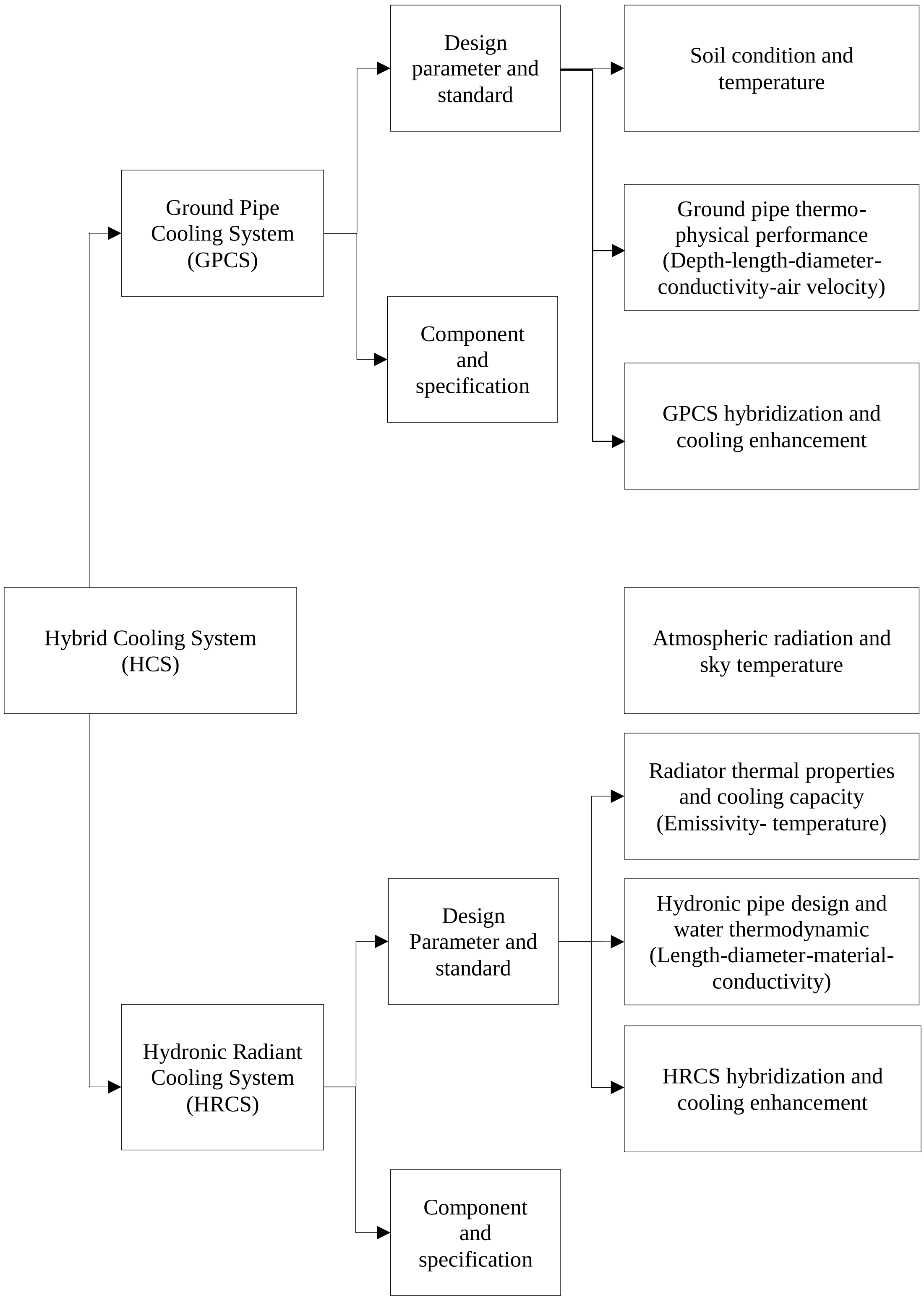


Figure 5.11: HCS design structure and study outline.

5.2.3.1 Ground Pipe Cooling System (GPCS)

The proposed GPCS consists of a series of long open loop pipes buried underground with the ductwork diverted through hypocaust concrete floor slabs. The hot exterior air is drawn through these large diameter pipes where it releases some of its heat to the surrounding soil, this relatively cool air is then distributed to the building interior. In addition, some potential issues such as condensation forming within the pipework were considered in the system design. Various factors and parameters that determine the efficient design of GPCS cooling performance were considered include the ambient temperature, relative humidity, soil temperature, heat exchange surface area, pipe thermo-physical behaviour, air flow rate and buildability.

To test the hypothesis required both simulation and field measurements. For instance, Mihalakakou et al. (1995) have developed numerical model inside a TRNSYS software environment to estimate the soil temperature at various depths underground. Additionally, in 1995, Mihalakakou et al. have designed a parametrical model in TRNSYS environment simulation software. The result of the study confirmed that the developed model could precisely predict the thermal performance of the ground pipe which was then validated against experimental data. The parametric study addressed parameters such as pipe length, depth, radius, and airflow within the pipe (Mihalakakouet al., 1995).

Lee and Strand (2006) examined the thermal performance of a ground pipe by the use of EnergyPlus computer modelling software. The results were again validated against experimental data. Crawley et al. (2005) have classified the capabilities and features of a set of computer modelling and simulation software and found that EnergyPlus has the capabilities and features needed. EnergyPlus Ground pipe model was validated against the data obtained from experiments conducted by many researchers. It was found that 'EnergyPlus' data have similar temperature trends with field data (Lee and Strand, 2008). Therefore, numerical modelling and simulation software DesignBuilder associated with EnergyPlus were combined in this study as an appropriate additive 'tool set' to conduct a parametrical analysis of GPCS experimental model with the aim of examining ground soil temperatures and the thermal performance of GPCS. The results obtained from the parametric study were validated against field trials and measurements of the ground pipe physical experimental model to determine the optimal pipe diameter and air flow rates.

1) GPCS Design Parameters and Standards

In order to achieve the optimum design of GPCS, various design parameters were considered. There are five main design parameters that affect the cooling capacity of GPCS. The most crucial parameter is the temperature amplitude between ambient air and ground soil. Another significant parameter is related to the design of the ground pipe itself, which includes pipe diameter, length, depth, bend diameter and airflow rate inside the pipe. These parameters were modelled and tested in the following sections in order to optimise cooling performance.

a) Soil Condition and Temperature

Soil temperature is an important factor that affects the feasibility of GPCS configurations and thus its cooling performance. Due to the lack of studies relating to Jeddah soil conditions and temperature, it was necessary to perform field trials and measurements to obtain this data profile at various depths up to 4 m in order to determine the optimum depth to bury the ground pipe. The seasonal soil temperature amplitude differs from place to place and month to month as a function of incident solar radiation, rainfall, local vegetation cover, water table level, soil type and thermal properties (Kavanaugh & Rafferty, 1997). In view of that, as the city of Jeddah is built on the Red Sea coastal plain, soil condition and water level are varied in each part of the city.

Geologically, Morris (1975) has divided Jeddah into two parts; the western part which is mostly a depositional plain with soil materials such as silt, clay and coral with a relatively high water table between 2 to 5 m in depth, whereas the eastern part of the city is covered by poorly sorted sand, silt and gravels derived from the crystalline rocks by mechanical weathering and redistributed as sheets of sediments during the periods of flooding with an estimated water level in this area is in the range of 4 to 10 m in depth. On a map of the 6 km long central part of Jeddah and the top 6 m of sub-soil, Laurent et al. (1973) explored three soil units; one fill unit, one soil-rock unit and one rock unit (Figure 5.12). Al-Oahtani (1979) collected data for an average depth of 20m from the area studied by Laurent et al. (1973) and additional locations in the south and north. Based on previous observations research conducted by Abu Hajar (1991) which covered a wider area in north and south. showed four soil units; one fill unit and two rock units which are listed in Table 5.9 including the environment of their deposition. According to the ground soil distribution in Jeddah and based on the field experiment and the observations of the above investigators, the selected base case study which is located in western part of Jeddah city and based on the observed soil material in this location, it was found that, the soil condition is classified as moist sandy soil while the groundwater level in this area is approximately in range between 2 to 6 m depth.

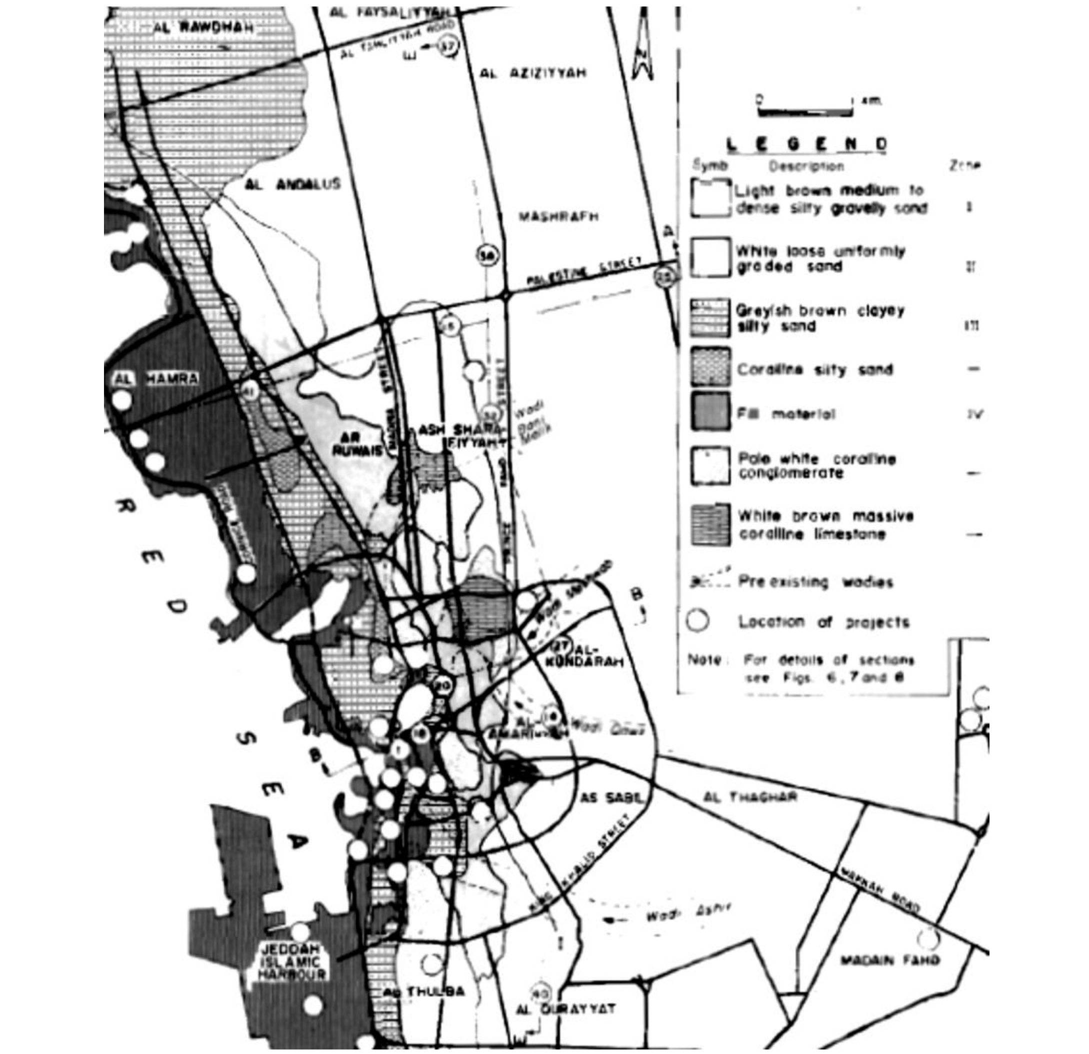


Figure 5.12: Soil distribution map of Jeddah (Abu Hajar, 1991).

Material type	Unit No.	Description	Environment of deposition	Observed thickness
Soil	1	Light brown medium to dense silty gravely sand	Continental	10 m (Jeddah – East)
	2	White loose uniformly graded sand	Marine	8 m (Jeddah – Centre)
	3	Greyish brown loose to dense clayey silty sand	Continental	14 m (Jeddah – South)
	4	White loose to dense coralline silty sand	Marine	17 m (Jeddah – Centre)
	5	Fill material (Gravelly sand with some silt	Man-made	40 m (Jeddah – West)
Rock	1	White coralline conglomerate	Marine	11 m (Jeddah – North)
	2	Light brown massive coralline limestone	Marine	50 m (Jeddah – West)

Table 5.9: Soil and rock units in the city of Jeddah (Abu Hajar,1991).

Each of the observed ground soil and rock types has a certain coefficient of heat capacity and thermal conductivity. Heat capacity which is also known as specific heat indicates the ability of a material to store heat. For instance, the heat capacity of the dry soil is about 0.035 W/m^2K of temperature change, which is almost one-fifth of the heat capacity of water. The thermal conductivity of ground soil is another crucial factor that affects the performance of GPCS. The thermal conductivity of ground soil indicates the rate at which heat will be transferred between the ground pipe and the surrounding soil. Consequently, the thermal conductivity of the soil and rock determine the required pipe length, loop and material, which in turn influences, fluid pumping energy requirements, cooling performance and pipe installation cost (Givoni, 1994).

Table 5.10, shows the thermal conductivity and diffusivity of different soil and rock types. As shown in the table, the thermal conductivity of soil is considerably increased when the soil is saturated with water. This effect is higher for sandy soils than for clay or silt, due to the coarse soils are more porous and hence, hold more water when becoming wet. Therefore, groundwater level is another significant factor in boosting the thermal behaviour of soil, and thereby, the cooling capacity of GPCS. As the groundwater level in selected location is relatively high, installing a vertical long serpentine pipe is more beneficial in order to maximize the heat exchange between the circulating air in the pipeline and the ground soil.

Soil and rock	Thermal conductivity (w/m-k)	Thermal diffusivity (m^2 day^1)
Sandy soil (dry)	0.43 - 0.69	0.023
Sandy soil (moist)	0.87 – 1.04	0.044
Sandy soil (soaked)	1.9 - 2.42	0.065
Silty sand	1.4 - 1.72	0.056
Clayey sand	0.74 - 1.18	0.042
Clay soil (dry)	0.35 - 0.52	0.036
Clay soil (moist)	0.69 – 0.87	0.038
Clay soil (wet)	1.04 - 1.56	0.045
Gravel	0.9 – 1.25	0.047
Gravel (sandy)	2.51	0.079
limestone	1.3	0.044
Sandstone	1.63 – 2.08	0.059

Table 5.10: Typical values of thermal conductivity and diffusivity for Soil and rock.

The high thermal capacity of the ground soil allows the temperature below a certain depth to remain constant throughout the year. Soil temperatures behave differently from area to another. Commonly, the deeper the soil, the smoother the ground temperature curve. Soil temperature stabilises around 4 m depth. Un-shaded soil temperature at this depth is almost equal to the mean annual ambient dry bulb temperature, however, the temperature at a 4 m depth of soil shaded by structure or trees follows nearly the minimum ambient air temperature (Givoni, 1994). This theory has been confirmed by Givoni when he proposed an approach of shading soil by wooden shack 0.6 m above the measured soil. The result was that during summer months when the ambient air temperature in Florida ranges from 24ºC to 38ºC, the shaded soil temperature at 1 m depth ranged between 24ºC to 25ºC, which is similar to the minimum ambient air temperature rather than the average (Givoni, 1994).

Since there is a lack of studies and experiments addressing the ground temperature of Jeddah; three approaches were adopted to obtain the actual ground temperature at varies depths to determine the optimum depth to bury the ground pipe. The first approach is through theoretical and mathematical calculations derived from Kasuda and Archenbach (1965). In addition, field trials were carried out to measure the average monthly ground soil temperature at variable depths. These results were subject to comparison with the data obtained from EnergyPlus simulation software which is derived from a weather data profile.

The US Department of Energy (DOE) provides annual weather files for thousands of global locations. The DOE calculation presumed a thermal diffusivity for worldwide locations of 2.71 x 10-8 m^2/s, which gives an inaccurate reading of ground temperature calculation due to the variation of this value from area to another according to the climatic conditions, therefore a mathematical model was used to validate the estimation of soil temperatures shown in equation 5.1 which was derived by Kasuda and Archenbach (1965).

$$\boldsymbol{Tg\ =\ Tm-\ As^{-z\sqrt{\pi/365\alpha}}cos\{2\pi/365[t-\underset{\circ}{t}-z/2\frac{\sqrt{365}}{\pi\alpha}}\quad \text{(Equation 5.1)}$$

Based on the above equation, $\boldsymbol{Tm}$ refers to the mean annual ground temperature at (z = 0 m) while $\boldsymbol{As}$ is the annual temperature amplitude at the surface (z=0 m) in °C, z the ground depth in m, $\boldsymbol{t}$ is the year-day, $\boldsymbol{\underset{\circ}{t}}$ is the phase constant (day of the year when the lowest ambient air temperature occurs), and $\boldsymbol{\alpha}$ is the thermal diffusivity of the soil (m^2/day). The presumptions that were employed in the deduction of this model are firstly, the sinusoidal temperature fluctuation at the soil surface, $z = 0$. Secondly, soil temperature is constant at an infinite depth and is equal to the annual mean ambient air temperature. Thirdly, throughout the year, the soil thermal diffusivity is constant, however, $\boldsymbol{Tm}$, $\boldsymbol{As}$, and $\boldsymbol{\underset{\circ}{t}}$ of the Jeddah climate was set as follows by the numerical ground temperature model:

Monthly maximum mean ambient temperature 34.7°C.

Monthly minimum mean ambient temperature 23.8°C.

January 11th marks the lowest ambient surface temperature at 11°C.

$\boldsymbol{Tm}$ is (39.7+ 18)/2 = 28.8°C.

$\boldsymbol{As}$ is (28.8/2) = 14.4°C.

$\boldsymbol{\underset{\circ}{t}}$ is (31 + 11) = 42 days.

$\boldsymbol{\alpha}$ is as measured (0.0912 m^2/day)

Inserting these values into equation 5.1 gives the theoretical ground temperature model, however, inserting these values into equation 5.2, gives the theoretical ground temperature at various depths and days of the year:

$$\boldsymbol{Tg\ =\ 28.8-\ 14.4e^{\ -0.31z}\ cos\{\frac{2\pi}{365[t-40-17.9z]}\}}\quad \text{(Equation 5.2)}$$

In order to validate the calculated average ground soil temperature at various depths, field investigations were conducted to measure the actual ground soil temperature at three depths (0.5 m, 1 m, 2 m). The field trials measurements were carried out on the site of the selected case study building in Jeddah. The soil condition at the site is moist sandy soil with some gravel exposed to solar radiation (Figure 5.13). The conducted field experiment aimed to measure the ground soil temperature in Jeddah at various depths up to 4 m deep which is the maximum depth that soil temperature is found to be constant across the globe. However, it was challenging to dig 4 m deep as it requires hiring heavy plant, especially in such soil condition. Therefore, since the field measurement aims to validate the theoretical and simulated soil temperature, the field experiment was limited to 0.5 m, 1 m and 2 m depth. A trench was dug out using a backhoe. The pipe was assembled and buried in the trench at 0.5 m, 1 m and 2 m deep. The field investigation utilised three 0.12 m diameter PVC pipes assembled and installed in the dug holes (Figure 5.13). The field work measurements were carried out from June to August 2015 (summer season) which includes measurements of outdoor ambient temperature (T_{amb}), ground soil temperature (T_{soil}) at 0.5 m, 1 m and 2 m deep below ground. TGU-4500 "Tinytag" data logger with built-in sensors was placed inside the buried pipes to measure the ground temperature (Table 5.11). Figure 5.14 illustrates the measured hourly soil temperature at various depths in the period between 15th to 19th of July 2015.

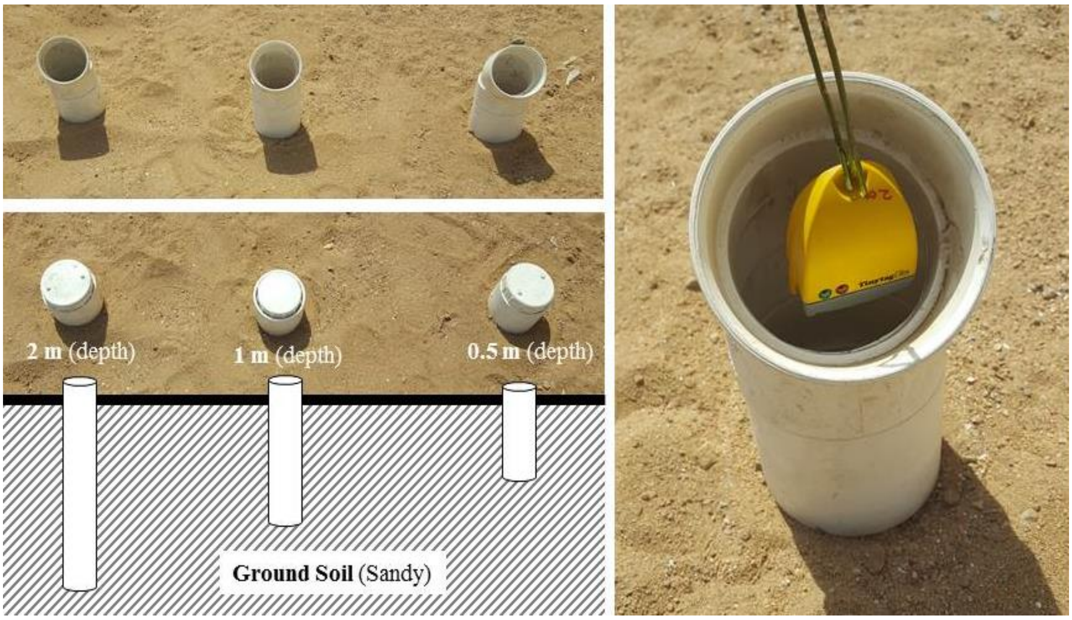


Figure 5.13: Field measurement of soil temperature at three various depths (0.5 m, 1 m, and 2 m).

Standards	Specifications	Model
Temperature measurement range	-25 to +85°C	
(RH) Measurement range	0 to 95%	
Accuracy (temperature)	+0.35oC from 0o to 50oC	
Accuracy (RH)	+2.5% from 10% to 90%	
Voltage accuracy	The sum of +0.2% and +10μV	
Overload protection	> +30V	
Input range	+70mV	
Reading rate	Up to 10 readings per Second	
Input connectors	Miniature thermocouple	
Output connector	CAB-0007-USB	
Battery life	1-year typical use	
Memory	64K bytes	
Weight	46 g	
Dimensions	58 x 33 x 23 mm	

Table 5.11: Specifications of TGU-4500 Tinytag data logger (Gemini Data Loggers, 2015).

As illustrated in Figure 5.14, the key reading of ground soil temperature measurement shows that soil temperature (T_{soil}) at 0.5 m, 1 m and 2 m depth were in line with hourly ambient temperature variations. These fluctuations between soil temperature at various depths and ambient temperature were wider at the day time in the period between 06:00 am until 07:00 pm and more closer in the afternoon while at night, the soil temperature at various depth were more convergent and slightly lower than ambient.

Likewise, the fluctuation rate between soil temperature at 0.5 m,1 m and 2 m depths were wider in the daytime and relatively narrower at night. For instance at 13:00 hrs the temperature gap between soil at 1m depth and ambient was approximately 6°C. This gap gradually narrowed until it reached 2°C at midnight. At 12:00 pm the difference between soil temperatures at 0.5, 1 m and 2 m was 2°C and 5°C respectively, while at 12:00 midnight, the difference was less than 2°C. Over the entire period, the soil temperature at 2 m depth was more constant over the day with temperature fluctuations between 29.2 to 36.1°C which is approximately 4°C to 7°C lower than the average ambient temperature.

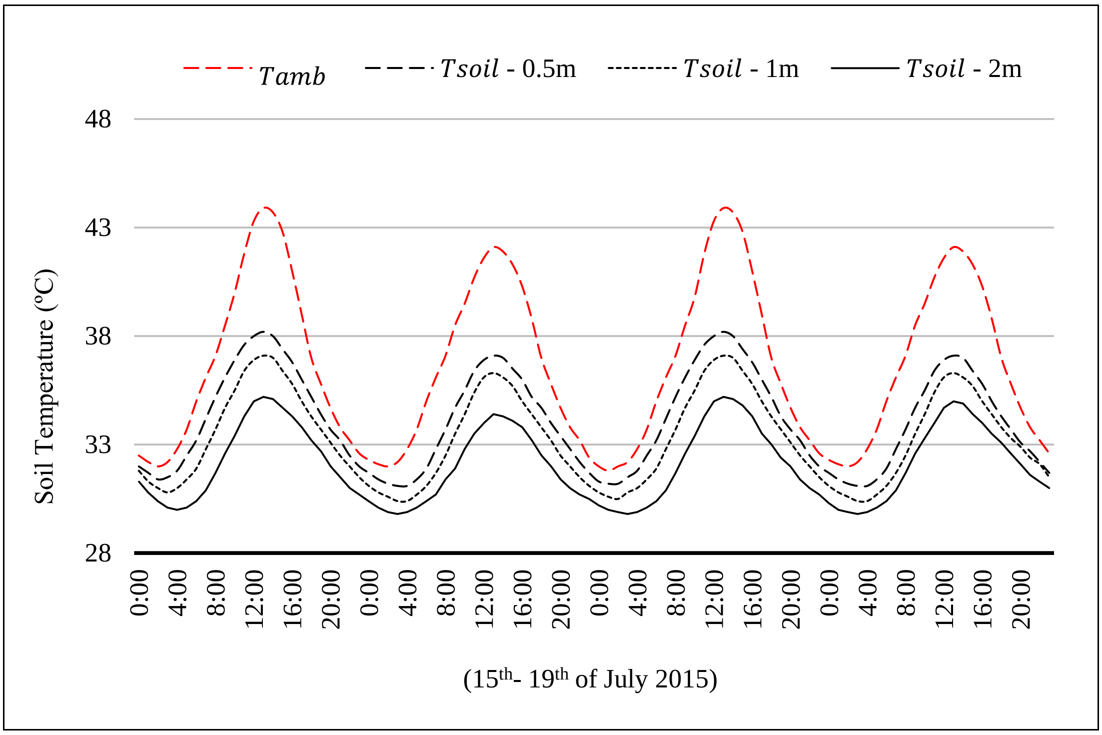


Figure 5.14: Hourly measured soil temperature at various depths on 15th and 19th of July 2015.

For validation purposes, and in order to consider all the soil temperature data obtained from the three approaches, the result of mathematically calculated average ground soil temperature at various depths was compared with measured and computationally modelled EnergyPlus produces a set of results as shown in Figure 5.15 which can produce the most efficient thermal performance with regard to pipe depth, diameter an length.

As illustrated in Figure 5.15, the modified ground soil temperature of Jeddah at 4 m depth was lower and more constant than the soil temperatures at other depths. The minimum average soil temperature was recorded in February at 24.5°C while the maximum was in July at 27.75°C. The total average annual ground soil temperature was 27°C relatively close to the mean annual dry bulb temperature at 27.1°C which emphasize the theoretical approach of ground soil temperature estimation and in line with Givoni findings when he found that un-shaded soil temperature at 4 m depth is almost equal to the mean annual ambient dry bulb temperature (Givoni, 1994).

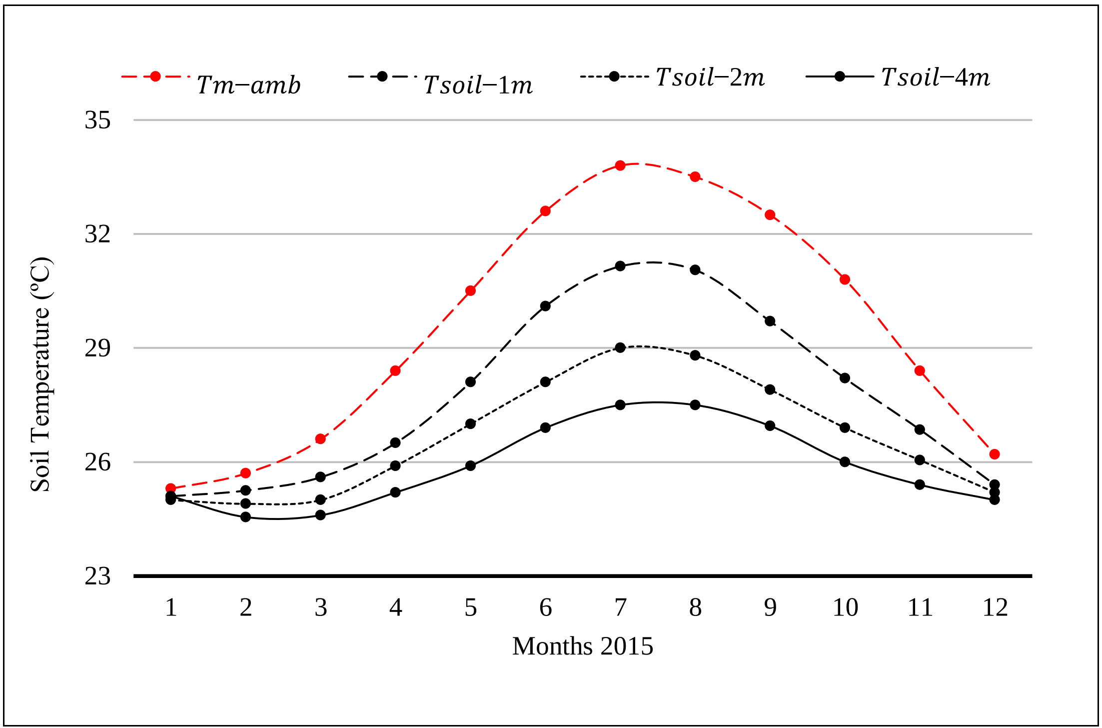


Figure 5.15 :Average monthly-modified soil temperatures at various depths of Jeddah.

There is a range of confounding factors that can be considered when estimating the ground soil temperature such as shading and ground coverage with greenery or hard standing. In 1994, Mihalakakou et al. carried out a study on ground pipe cooling potential of multiple earth-to-air heat exchanger under short grass-covered soil and bare soil and found that short grass-covered soil has a significantly higher cooling capacity than bare soil, nevertheless, the pipe below both soil conditions provided cooler outlet air temperature than ambient (Mihalakakou et al., 1994).

An observation carried out by (Jacovides et al., 1996) on soil temperatures of two different soil surfaces included both bare soil and short grass-covered soil in Greece. The result has shown that there was only 1°C difference in soil temperature between the bare soil and short grass-covered soil during winter, while, in summer, there was a difference of 7°C (Jacovides, 1996). According to this result, it has demonstrated that during the summer the mean soil surface temperature of the bare soil is higher than the mean air temperature. This should be as a result of high solar radiation on the un-shaded soil in hot summer.

A similar study was carried out by Givoni in 2007. In this study, Givoni compared the temperatures of soil shaded by a raised building with the temperature of soil covered by tall grass. The result has shown that the soil temperature under the raised building is approximately equal to the daily minimum dry bulb temperature, whilst the soil temperature below the tall grass is almost equal to the daily average dry bulb temperature (Givoni, 2007). Givoni's finding can be implemented in current case study building by shading the soil surface and ground level to decrease the air temperature in pipe inlet thus, enhancing the cooling capacity of ground soil and GPCS.

b) **Ground Pipe Design and Thermo-Physical Performance**

The proposed GPCS consists of a long-buried pipe with two pipe ends above the ground, one end as an inlet for ambient air intake while the other end is an outlet to provide cooled air to the indoor space. The Coefficient of Performance (COP) of such GPCS is substantially influenced by various parameters including pipe length, diameter, depth air flow rate and pipe conductivity. In terms of pipe material, there are different materials that could be chosen such as steel duct, clay tiles, PVC and the modern HDPE with anti-microbial coatings. Although, the thermal conductivity of the pipe material influences the rate of conduction it may not have a direct impact on the overall performance of the ground pipe. Despite the fact that, concrete and clay conduct more heat than plastic, the concrete pipe is thicker and has a thermal resistance similar to 0.00635 m of HDPE. Aluminium conducts heat faster, but it is harder to lay and install underground than PVC pipes (EGEC,2008). Overall, HDPE (High-Density Polyethylene) seems to be an ideal choice of material, due to it being flexible, durable and hygienic (Table 5.12).

Parametric studies were performed to determine the influence of these variables, by developing an experimental numerical model using energy modelling DesignBuilder and simulation EnergyPlus software (Figure 5.16). A computational simulation of the experimental model was set up on five different parameters in order to determine the optimum values of each parameter for 'best fit' design of the system (Table 5.13). The standard values of each parameter were set at 30 m for pipe length, 2 m for pipe depth, 0.10 m for pipe diameter, and 5 m/s for air velocity, thus, at every simulation process only one variable was changed while the other variables were maintained at standard values (Table 5.13). The simulated model consist of of high density polyethelyne (HDPE) pipe loop buried in ground soil with two ends one is externaly placed as an air intake and the another is linked to a simple model of the retrofitted case study building (45 m³) surrounded by thermally insulated clay block wall and covered by insulated TermoDeck® slabs. The simulation process were run over the summer period (peak cooling season) from 15th of April to 15th October in order to clearly tests the influnce of ambient and ground soil temperatures amplitude on pipe oulet air temperature. Also, the simulation model was set up based on the measured soil temperature and annual weather profiles defined in EnergyPlus considering the ambient temperature in the added area where the the ground pipe air inlet is assigned (Figure 5.16)

Material	Symbol	Thermal Conductivity (W/(m. K)
Polyvinyl chloride	PVC	0.14 - 0.19
Polyethylene (Little density)	LDPE	0.35
Polyethylene (High density)	HDPE	0.43 – 0.52
Polypropylene	PR-R	0.24
Polybutylenes	PB	0.23
Aluminum -Plastic	PAP	0.45

Table 5.12: Thermal conductivity coefficient of various pipe materials.

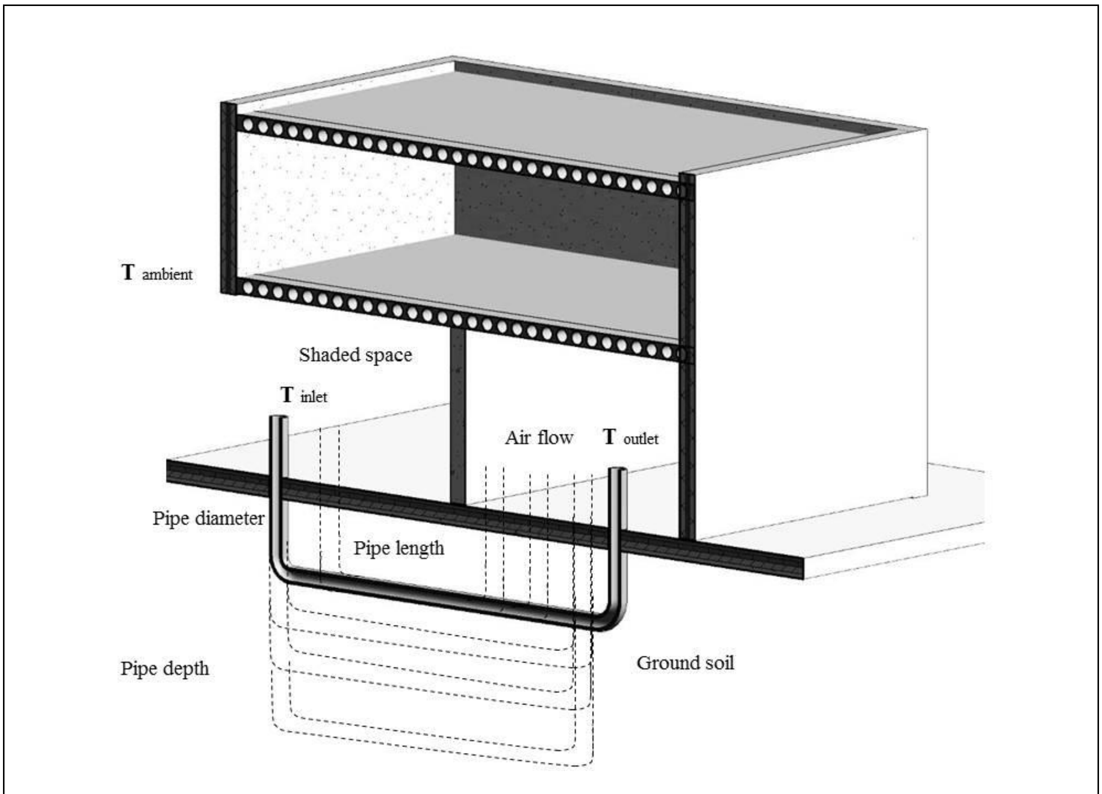


Figure 5.16: Experimental model of GPCS parametrical analysis.

Parameter	Standard value	Values
Length	30 m	10 m, 30 m, 50 m,80 m, 100 m
Depth	2 m	0.5 m, 1 m.2 m.4 m.8 m.
diameter	0.10 m	0.025 m. 0.05 m, 0.10 m 0.20 m, 0.40 m
Air velocity	5 m/s	2 m/s, 5 m/s, 8 m/s, 12 m/s, 15 m/s

Table 5.13: key parameters and variables of the GPCS parametrical study.

The first parametric study is to determine the effect of different pipe lengths used. The study is to investigate the minimum requirement for the buried pipe length to be to achieve earth pipe cooling. The primary findings of the simulation process to determine the impact of the pipe length on outlet air temperature showed that longer buried pipe produces a lower outlet air temperature. The rationale behind this is that longer pipe allows the air to circulate for more time underground and subsequently transfer more heat into the surrounding soil, however, the reduction in outlet air temperature as a result of increasing pipe length was varied. For instance, by increasing the pipe length from 10 m to 50 m, the average pipe outlet air temperature decreased by 2.2°C. However, increasing the pipe length above 80 m had no significant thermal effect on outlet air temperature. (Figure 5.17).

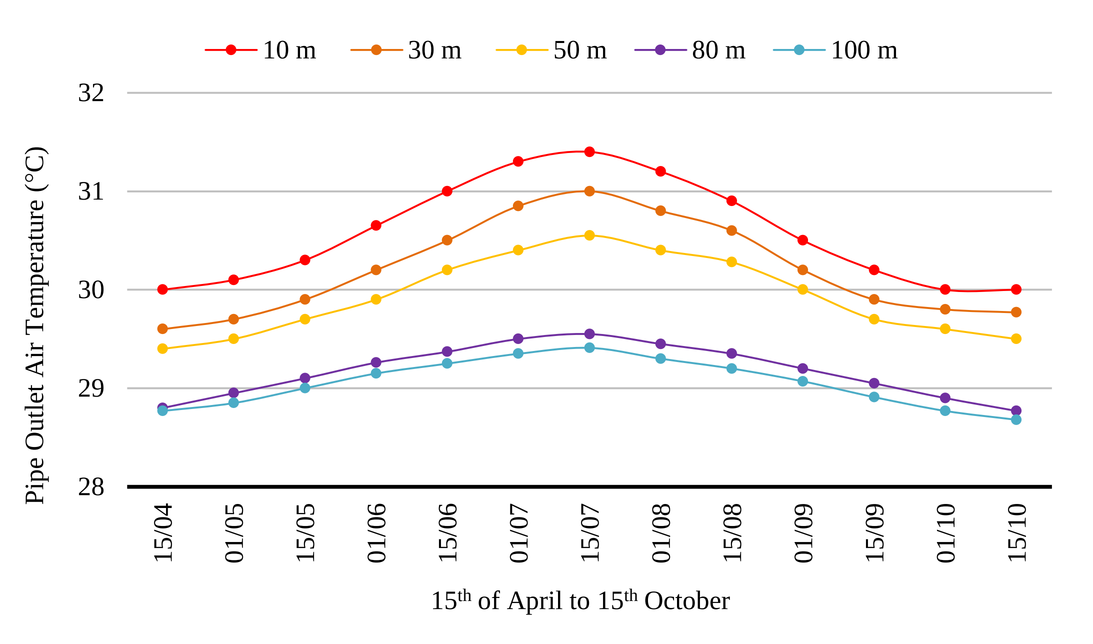


Figure 5.17: Effete of pipe length on outlet air temperature

Another parameter to consider in determining the thermal performance of the ground pipe is the depth. Figure 5.18 illustrates the impact of manipulating pipe depth on outlet air temperature. The results have proven that pipe depth is the most effective parameter that affects outlet air temperature. As shown in the graph, the pipe outlet air temperature decreased as the depth increased. For instance, changing the pipe depth from 0.5 m to 4 m significantly decreased the outlet air temperature by 4°C which is the lowest temperature range, however, when the pipe was buried beyond 4 m deep, there was no remarkable reduction in pipe outlet temperature which remained constant at an average temperature of 28.4°C (Figure 5.18).

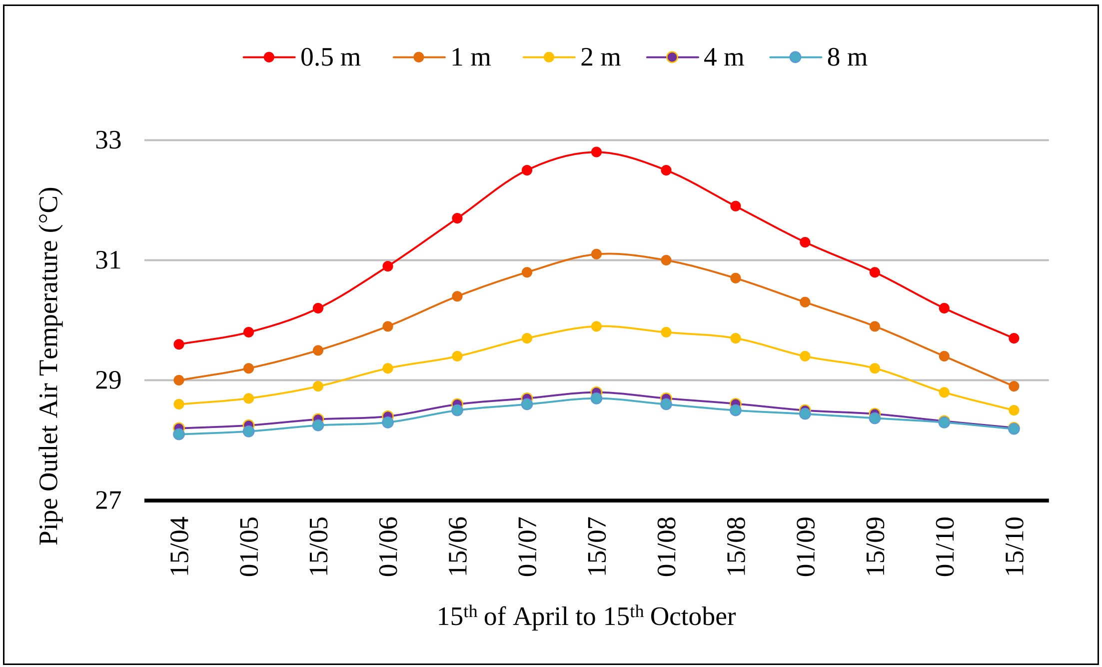


Figure 5.18: Effect of pipe depth on outlet air temperature.

Another parameter that has an influence on cooling performance is the diameter. As illustrated in Figure 5.19, increasing the pipe diameter resulted in higher outlet air temperature. The rationale behind this is that the wider diameter minimises the convective heat transfer coefficient (fewer air molecules in contact with the surface of the pipe) and consequently, the outlet temperature is higher. A smaller pipe diameter, the pipe centre point gets closer to the surrounding underground soil, allowing faster heat transfer to the soil. Therefore a smaller pipe diameter should be considered depending on the volume of air to be transferred. As illustrated in Figure 5.19, increasing the pipe diameter from 0.025 m to 0.2 m, led to a gradual increase in outlet air temperature of 1.3°C. The effect of diameter on outlet air temperature is not as influential in comparison with the other parameters.

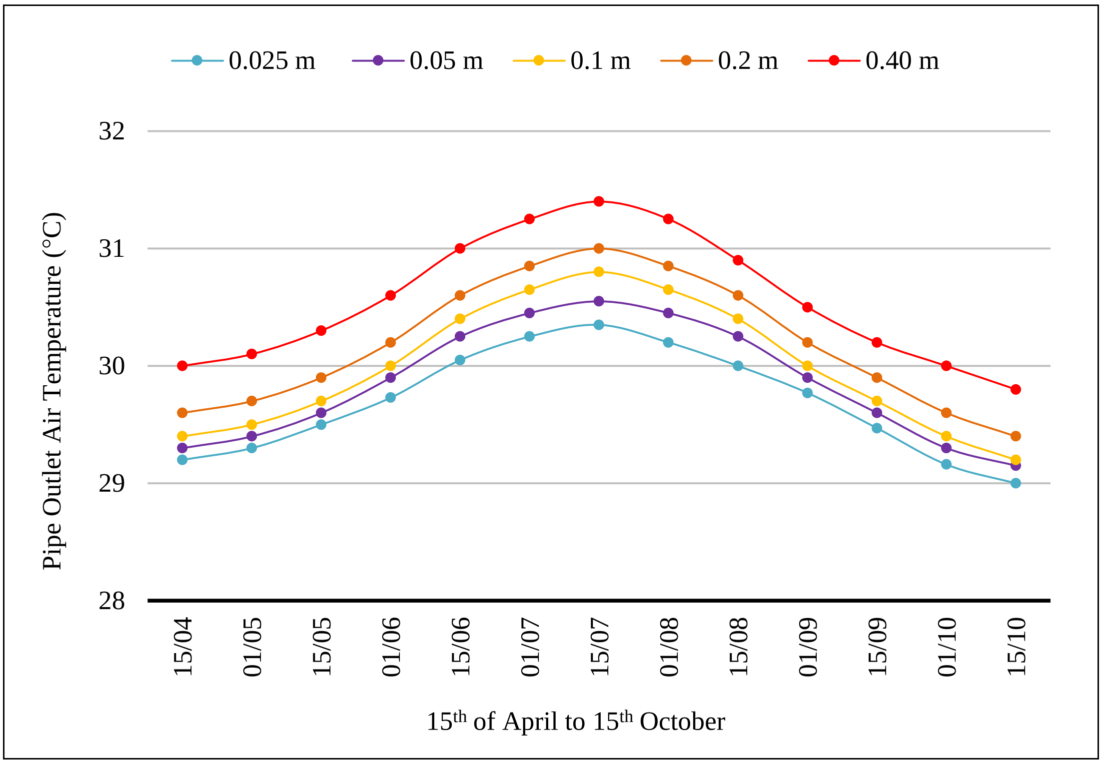


Figure 5.19: Effect of pipe diameter on outlet air temperature.

Similar to the other parameters, air velocity rate affects the ground pipe cooling performance. The findings in Figure 5.20 shows that increasing air velocity resulted in increasing pipe outlet air temperature. This led to reducing the temperature difference between pipe inlet and outlet, which consequently reduced the coefficient of performance (COP). The rationale behind this is due to the increased mass flow rate. As represented in Figure 5.20, when air velocity increased from 2 m/s to 15 m/s, the outlet air temperature increased by 1.7°C which means that ground pipe with lower air velocity rate performed better due to the air inside the pipe remaining in contact with ground soil for longer time allowing greater heat exchange.

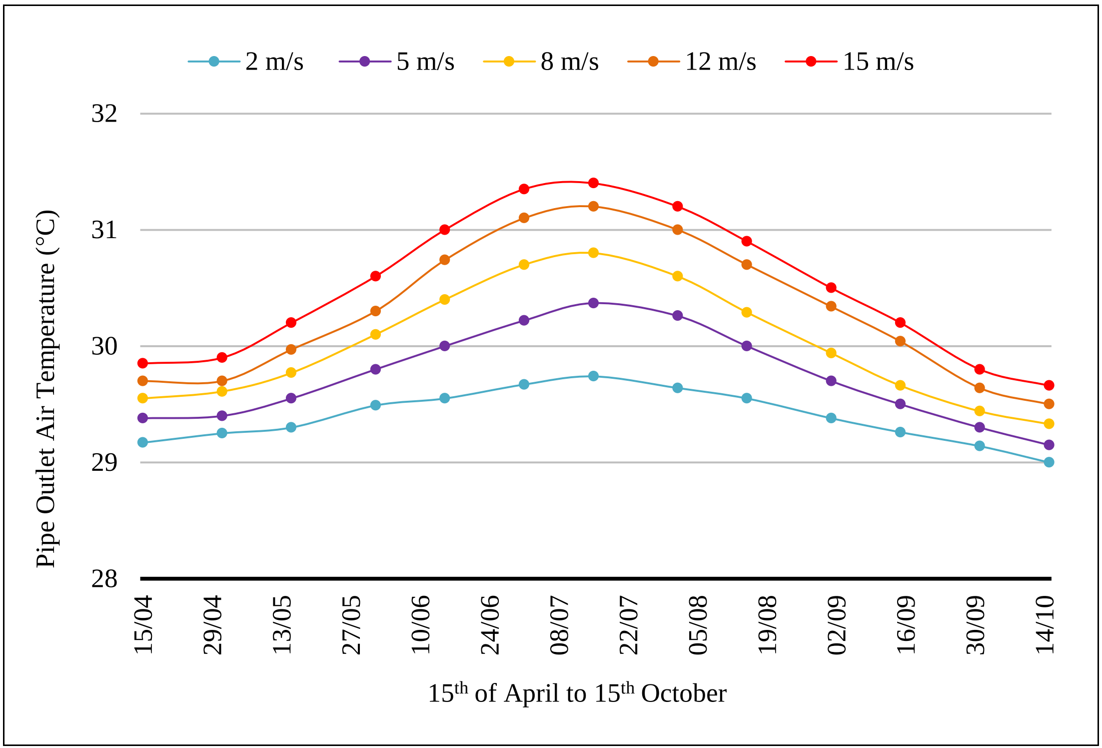


Figure 5.20: Effect of air velocity rate inside the pipe on outlet air temperature.

In general, based on the parametric analysis results, it was found that the resulting temperature at the buried pipe outlet decreases with increasing pipe length, decreasing pipe diameter, decreasing the mass flow rate of flowing air in the pipe and increasing depths up to 4 m. These findings are in line with the conclusion of Givoni (1994), Santamouris et al. (1995) and Ghosal and Tiwari (2006). However, as a result of the ground pipe sensitivity analysis, the lower pipe outlet air temperature during the simulation period was around 27.6°C. Based on the standard indoor thermal comfort condition, blowing such high air temperature directly to internal space is insufficient to meet the desired thermal comfort condition for occupants (23°C - 28°C). This necessitates employing low energy active cooling systems such as chilled water coil system as a backup to meet peak cooling demand.

Despite the above sensitivity analysis and parametric study, the other described GPCS performance factors such as soil condition, shading, water table level and pipe materials may have an equal influence on the GPCS performance (Goswami and Biseli, 1993). The number of bends in the pipework is also important as air turbulence increases at these junctions leading to an increase in energy transfer. A serpentine loop may thus be the most appropriate configuration.

c) GPCS Hybridization and Cooling Enhancement

The parametric study results have demonstrated the potential application of GPCS and its efficiency as a low energy passive cooling strategy requiring only a fan to move relatively large volumes of air. In addition, there is a potential of optimising the GPCS by the integration with other low energy cooling technologies such as heat exchanger and chiller.

Khedari et al. (2001) conducted a study of ground pipe cooling in Thailand, which has a hot and humid climate similar to Jeddah. The ground pipe cooling system consists of 40 m long PVC ducts with a 30 cm diameter, buried at 2 m depth. Results showed a drop of 4.3°C in air temperature between the pipe inlet and outlet.

Khedari et al. (2001) improved their investigations by coupling the ground pipe system with an AC system. In this experiment, the earth was used to absorb the heat released from the AC system condensing unit. The improved condensing unit was buried underground at 1m depth. The results showed that the condensing unit used less energy in comparison with the conventional AC system. The coefficient of performance (COP) of buried condenser air conditioner was 8.1 during night time and 7.1 during the daytime, while; the COP for a conventional air conditioner is less than 3.1 during night time and 2.8 during the daytime. In 2009, Li et al. investigated the soil temperature around various boreholes for many years. The results have shown that if the ground pipe system emits heat into the ground over the year, after 13 years of running the system the ground soil temperature could possibly increase up to 35°C. However, a solution has been proposed in order to reduce heat injected into the ground through the ground pipe by using a multi-function ground source heat pump system (MFGSHP), as a hybrid ground pipe system coupled with a heat pump for water heating. Further investigations of hybrid designs of ground pipe cooling systems conducted by Chel and Tiwari (2010) in New Delhi, India, showed that a Photovoltaic (PV) system can be integrated with a ground pipe cooling system and will benefit the PV output by keeping the panels cooler providing greater air flow to operate the fan and increase air flow rates in the ground pipe cooling system.

Maerefat and Haghighi (2010) under the climatic conditions in Iran proposed a hybrid design of the ground pipe cooling system. The proposed hybrid design coupled the ground pipe system with a Solar Chimney (SC) to produce a driving force enhancing the stack effect. This upward airflow extracts the air from outside to the ground pipe and then into the indoor spaces. The ambient temperature in Iran during summer is 34°C and 19°C under shaded ground soil temperature. By using three solar chimneys and one ground pipe, with an air change rate of 3 to 7 ACH, the indoor temperature remained within a range between 28.2°C and 31.9°C.

Based on the studies and investigation that addressed the GPCS design and cooling performance alongside the conducted field trials and parametrical analysis, the suggested GPCS is integrated with low energy active mechanical cooling systems in order to enhance the cooling efficiency of the GPCS. A DC chiller could be used at peak demand times to ensure internal comfort conditions are achieved. A fan is also proposed to be incorporated to control the air delivery rate. To determine the appropriate fan type and capacity, a range of criteria was considered including air flow rate, pressure and velocity. The required fresh air flow rate was calculated according to ASHRAE Standard 62.1-2007 which determines the minimum ventilation rate based on either the occupied space area or on the space occupancy number (Table 5.14).

TABLE 6-1 MINIMUM VENTILATION RATES IN BREATHING ZONE
(This table is not valid in isolation; it must be used in conjunction with the accompanying notes.)

Occupancy Category	People Outdoor Air Rate R_p		Area Outdoor Air Rate R_a		Notes	Default Values: Occupant Density (see Note 4)	Default Values: Combined Outdoor Air Rate (see Note 5)		Air Class
	cfm/person	L/s·person	cfm/ft²	L/s·m²		#/1000 ft² or #/100 m²	cfm/person	L/s·person	
Correctional Facilities									
Cell	5	2.5	0.12	0.6		25	10	4.9	2
Dayroom	5	2.5	0.06	0.3		30	7	3.5	1
Guard stations	5	2.5	0.06	0.3		15	9	4.5	1
Booking/waiting	7.5	3.8	0.06	0.3		50	9	4.4	2
Educational Facilities									
Daycare (through age 4)	10	5	0.18	0.9		25	17	8.6	2
Daycare sickroom	10	5	0.18	0.9		25	17	8.6	3
Classrooms (ages 5–8)	10	5	0.12	0.6		25	15	7.4	1
Classrooms (age 9 plus)	10	5	0.12	0.6		35	13	6.7	1
Lecture classroom	7.5	3.8	0.06	0.3		65	8	4.3	1
Lecture hall (fixed seats)	7.5	3.8	0.06	0.3		150	8	4.0	1
Art classroom	10	5	0.18	0.9		20	19	9.5	2
Science laboratories	10	5	0.18	0.9		25	17	8.6	2
University/college laboratories	10	5	0.18	0.9		25	17	8.6	2
Wood/metal shop	10	5	0.18	0.9		20	19	9.5	2
Computer lab	10	5	0.12	0.6		25	15	7.4	1
Media center	10	5	0.12	0.6	A	25	15	7.4	1
Music/theater/dance	10	5	0.06	0.3		35	12	5.9	1
Multi-use assembly	7.5	3.8	0.06	0.3		100	8	4.1	1
Food and Beverage Service									
Restaurant dining rooms	7.5	3.8	0.18	0.9		70	10	5.1	2
Cafeteria/fast-food dining	7.5	3.8	0.18	0.9		100	9	4.7	2
Bars, cocktail lounges	7.5	3.8	0.18	0.9		100	9	4.7	2
General									
Break rooms	5	2.5	0.06	0.3		25	10	5.1	1
Coffee stations	5	2.5	0.06	0.3		20	11	5.5	1
Conference/meeting	5	2.5	0.06	0.3		50	6	3.1	1
Corridors	–	–	0.06	0.3		–			1
Storage rooms	–	–	0.12	0.6	B	–			1
Hotels, Motels, Resorts, Dormitories									
Bedroom/living room	5	2.5	0.06	0.3		10	11	5.5	1
Barracks sleeping areas	5	2.5	0.06	0.3		20	8	4.0	1
Laundry rooms, central	5	2.5	0.12	0.6		10	17	8.5	2
Laundry rooms within dwelling units	5	2.5	0.12	0.6		10	17	8.5	1
Lobbies/prefunction	7.5	3.8	0.06	0.3		30	10	4.8	1
Multipurpose assembly	5	2.5	0.06	0.3		120	6	2.8	1

Table 5.14: Standard of minimum ventilation rate in various breathing zones (ASHRAE, 2007)

Based on the total occupied space of the case study building approximately 1532 m², (according to ASHRAE standard) the minimum required quantity of fresh air which equates to approximately 1532 x 0.3 = 459 l/s·m², Based on the occupancy load, the required fresh air per person in residential space is 5.5 l/s, As the average occupancy of the building is 100 people (5 x 20 flats) thereby, the required quantity of air is 100 × 5.5 (l/s per person) = 550 l/s person. According to CIBSE Guide B2 (2001) - the recommended fresh air supply rates for residential occupants is in a range between 6 to 8 l/s per person, based on the occupancy number the suggested fresh air quantity is therefore 600 to 800 l/person for the total occupants. Based on above standards and calculations, the average minimum required air per person is 7 l/s, 35 l/s for each flat with 5 occupants and 700 l/s for the whole building with 100 occupants.

Other criteria of fan blower selection are air pressure, which affects the airflow rate through the pipe (CIBSE Guide B, 2005). For instance, a significant air pressure loss could occur within a pipe as long as 40 m to 60 m, which reduces the air flow through the pipe. Therefore, it was crucial to identify the pressure loss of any specific pipe design before the selection of the fan power. The CIBSE Guide B was considered to determine the pressure loss per pipe length (Pa/m) (Table 5.15). This study used many values of two inputs include air velocity (m/s) and pipe diameter (m). The obtained pressure loss data were multiplied by plastic duct modified factors in (Table 5.16).

Pressure loss from chart (Pa/m)	*Correction factor for ducts of all diameters*			
	Plastered ducts	Spiral wound ducts	Aluminium ducts	Plastic ducts
0.1	1.03	0.97	0.96	0.90
0.2	1.05	0.96	0.95	0.90
0.5	1.07	0.95	0.93	0.88
1.0	1.08	0.94	0.91	0.85
2.0	1.08	0.93	0.90	0.84
5.0	1.09	0.92	0.88	0.80
10.0	1.09	0.91	0.86	0.77
20.0	1.10	0.90	0.85	0.75
50.0	1.10	0.88	0.83	0.71
100.0	1.11	0.86	0.79	0.68

Table 5.15: Pressure loss in various ducts types (CIBSE Guide B, 2005).

Air Velocity (m/s)	*Pipe diameter*			
	0.076 m	0.102 m	0.127 m	0.152 m
1	0.28	0.19	0.15	0.13
2	0.94	0.68	0.51	0.41
3	2.02	1.45	1.11	0.85
4	3.36	2.35	1.76	1.45
5	4.88	3.61	2.77	2.14
10	16.50	12.32	9.24	7.04

Table 5.16: Pressure loss, (ΔP x plastic duct modified factor from Table 5.16) per unit length (Pa/m).

As shown in Table 5.16, the pressure loss per unit length decreases when pipe diameter increases while increases when the air velocity increases. The 0.102 m diameter pipe and a 50 m long pipe were considered to determine the required fan power to provide sufficient airflow. Therefore, according to the values in Table 5.16, the pressure loss, ΔP of 0.102 m diameter and 50 m long pipe, with 5 m/s air velocity is 180.50 Pa.

As a result of the previous study of airflow and pressure, the determination of the appropriate fan specification has become more apparent. As the proposed GPCS employing PVC pipe to deliver the air, inline axial blower fan seems to be the most appropriate choice. Various fan blower manufacturing companies were considered to select the optimum fan that can properly fit the pipe design and efficiently deliver a sufficient airflow with optimum pressure and flow rate. The market leading supplier of commercial ventilation solutions 'Vent-Axia®' provides a complete range of low cost and energy efficient mixed flow in-line fans which is two and half times the pressure of traditional axial fans and dimensionally ideal for many pipe standards. In addition, the in-line fan can perform efficiently in both vertical and horizontal positions and can be adjusted providing variable speed control with an On/Off/sensor to meet its optimum performance. Table 5.17 lists the specifications of the various market available 'Vent-Axia®' inline duct fan models.

Model	Fan (Diameter)	Speed (RPM)	Volt	Watts	CFM	Pressure
ACM100	0.10 m	2096	115	26	101	0.5
ACM120	0.20 m	2289	115	65	293	1.2
ACM250	0.25 m	2467	115	169	478	1.3
ACM300	0.30 m	2467	115	241	754	2.5
ACM350	0.35 m	2500	115	335	1050	2.9
ACM400	0.40 m	1400	115	464	1829	1.1
ACM500	0.50 m	1400	115	756	2630	1.2

Table 5.17: Typical range specifications of various inline duct fan models.

In addition to controlling the air pressure and flow rate, the temperature of the delivered air needs to be constant at creation temperature to ensure delivering adequate cool air to internal spaces. In order to control the temperature of the delivered air the proposed GPCS will incorporate a thermal storage 'air plenum' which contains the chilled water coil system. Such a thermal storage plenum requires a sufficient capacity to store the cooled air to meet the varying cooling needs of a facility. The thermal storage needs to be insulated to maintain the 'coolth' and provide short-term attenuation. This thermal storage 'air plenum' can be sized according to the level of consumption, the compressor size and the modulation strategy.

A commonly used formula to determine the sufficient air tank size is:

t = V (p1 - p2) / C pa (Equation 5.3)

Where

V = volume of the receiver tank (m^3)

t = time for the receiver to go from upper to lower pressure limits (min)

C = free air needed (l/s)

Pa= atmosphere pressure (101325 Pa)

p1 = maximum tank pressure (Pa)

p2 = minimum tank pressure (Pa)

Based on the above equation and according to the previously calculated air flow rate of the current study, for an air compressor system with mean air consumption of 700 l/s, maximum tank pressure 110 psi, minimum tank pressure 100 psi and the time for the tank to go from upper to lower pressure is approximately 5 sec . As a result, the volume of the tank can be calculated by modifying (Equation 5.3) to:

V = t C pa / (p1 - p2) (Equation 5.4)

= (5 sec) (1/60 min/sec) (700 l/s) (101352 Pa) / ((758423 Pa) - (689476 Pa))

= 5.2 m^3

From the above calculation of air tank size, it was found that based on the airflow capacity each l/s equals .004 m^3 of air tank volume. While based on the compressor power, each kW equal 0.018 m^3 of air tank volume. Accordingly, the recommended air tank volume for the proposed GPCS is approximately 2.4 m^3 with a capacity of 3182.26 litres (700 gallons). With this capacity, the tank is able to store and maintain the desired cooled air received from underground. Table 5.18 and 5.19 lists the variation of recommended air tank receiver volume based on airflow capacity and compressor power.

Airflow capacity		Recommended Air tank receiver volume		
(cfm)	(m^3/h)	(ft^3)	(gal)	(m^3)
100	170	13	100	0.4
200	340	27	200	0.8
300	510	40	300	1.1
400	680	54	400	1.5
500	850	67	500	1.9
750	1275	101	750	2.9
1000	1700	134	1000	3.8
1500	2550	201	1500	5.7
2000	3400	268	2000	7.6
3000	5100	402	3000	11.4
4000	6800	536	4000	15.2
5000	8500	670	5000	19.0
10000	17000	1340	10000	38.0

Table 5.18: Recommended air tank receiver volume based on airflow capacity.

Compressor power		*Recommended Air tank receiver volume*		
(hp)	(kW)	ft^3	(gal)	(m^3)
5	3.7	3	20	0.1
7.5	5.6	4	30	0.1
10	7.5	5	40	0.2
15	11.2	8	60	0.2
20	14.9	11	80	0.3
25	18.7	13	100	0.4
30	22.4	16	120	0.5
40	29.8	21	160	0.6
50	37.3	27	200	0.8
60	44.8	32	240	0.9
75	56.0	40	300	1.1
100	74.6	54	400	1.5
125	93.3	67	500	1.9
200	149.2	107	800	3.0
350	261.1	188	1400	5.3
450	335.7	241	1800	6.8
500	373.0	268	2000	7.6

Table 5.19: Recommended air tank receiver volume based on compressor power.

Since the intention is to implement the proposed GPCS in a hot and humid climate, the amplitude of ground temperature in such condition especially in summer is considerably high, hence, the ground pipe outlet air temperature can be over the desired thermal comfort temperature especially in case of peak demand in summer. This necessitates an additional cooling strategy to meet the cooling demand. Therefore, the GPCS is integrated with a low energy cold water coil system installed in the proposed air tank to enhance the cooling performance. Such a cooling technique involves cooling the air by reducing sensible, latent heat and moisture content. For an efficient thermal performance, the chilled water inside the coil needs to be maintained in the range of 4°C to 10°C, however, if the indoor surface is cooled by another passive cooling strategy such as ceiling or floor chilling a higher temperature might be sufficient (14°C to 17°C) which may also prevent the formation of water condensation on the cool surface of the chilled water cooling coil (ASHRAE, 2010).

The coil is usually constructed from copper tubes, which are mechanically expanded into aluminium plate fins with self-spacing collars to ensure efficient heat transfer. The chilled water flows through the tubes from the connection header manifolds into individual circuits formed with copper return bends. The heat in the air is transferred when attached the water and cool by convection (air to water heat exchanger). Condensation of moisture from the air occurs thereafter which can be easily drained out. Such a chilled water coil system is already available on the market and is a relatively simple and cost-effective design especially when compared with a central HVAC system (CIBSE, 2015).

As the GPCS is implemented in a hot and humid climate condensation will regularly occur in the ground pipe especially in summer when the absolute humidity is high. If the moisture was to pond this would make an appropriate environment for the growth of mould and bacteria, however, any condensed moisture can either be collected for irrigation or allowed to drain from the pipe to earth through weep holes.

The psychometric chart was able to determine the amount of condensate forming on any given day. Two values were needed to estimate the amount of water in air; dry bulb temperature and relative humidity. Based on the average annual dry bulb temperature in Jeddah of 37.5°C with an average annual relative humidity of 65.8% the air contains about 0.028 grams of water in every gram of air. The psychometric chart illustrates that the air which had initially contained 0.028 kg of water per kg of air at the starting point of entering the pipe, is now completely saturated at about 0.025 kg of water. That means for every kg of air that entered the pipe, 0.003 (0.028 - 0.023) kg of water remain inside the pipe.

Since the average minimum amount of air entering the ground pipe is approximately 1483 cfm (42 m^3) and as the Volumetric Flow Rate (VFR) and specific volume in the psychometric chart is measured by (m^3/kg of dry air) by dividing the air volume by the specific volume (42 m^3/0.92) this result in 45.76 m^3 of dry air per minute. By multiplying the air volume by the moisture ratio (45.76 x 0.003) the result is 0.14 kg of water would condense out every minute, equal to 11.4 litres/hr. This produces on average about 272 litres/day (around 60 gallons) of distilled water every day.

This source of clean water could be stored underground as an emergency supply, or more likely will be used to irrigate the greenery that is proposed to surround the ground floor and provide shading to further reduce ground temperatures above the pipe.

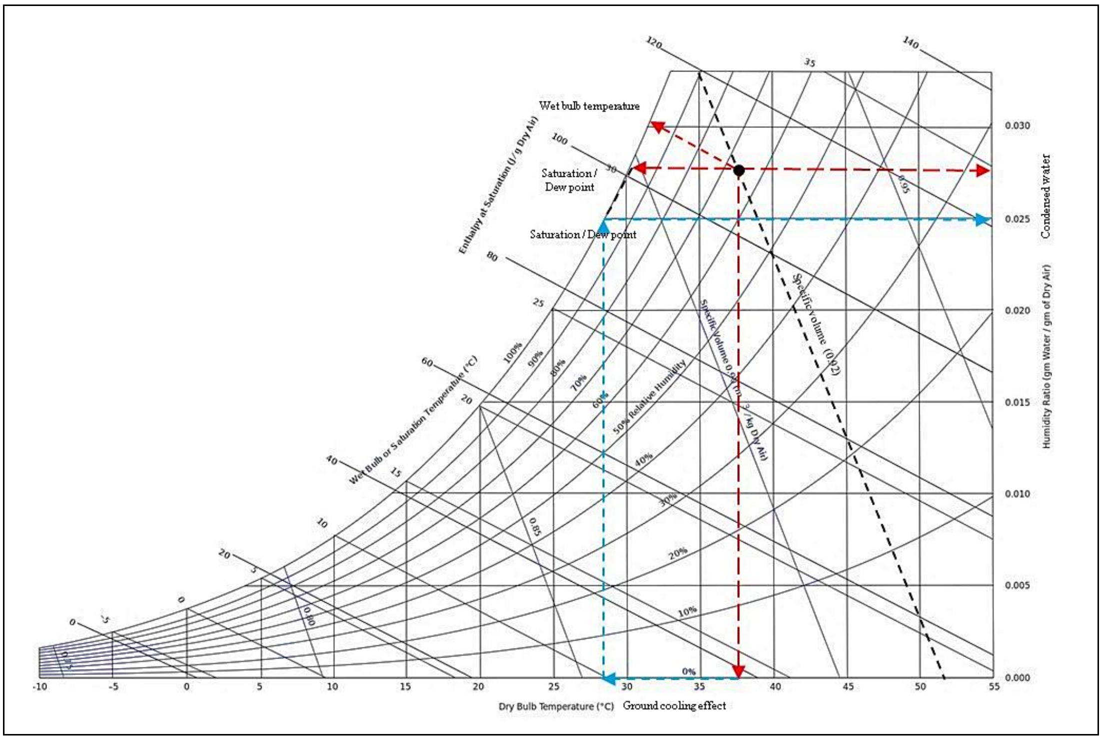


Figure 5.21: Psychometric chart presents physical and thermal properties of moist air.

A ground pipe is usually buried underground a depth that will provide optimum results. A sufficient air flow through the buried pipe was considered by employing inline fan to regulate the air flow. The design of GPCS is based on the theoretical review, field trials and measurements, mathematical calculations and parametrical studies. The proposed design of GPCS including its main components and specifications was outlined in Table 5.20.

the GPCS consists of four one-way open loop high-density pipe (HDPE) arranged in a serpentine form to maximise the contact surface area of the pipe allowing more heat exchange with ground soil, particularly at the bends. The ground pipe can be buried in deep trenches in a serpentine loop configuration, with the gaps between vertical risers backfilled before the top bends are attached. Each of the four ground pipe systems is 350 mm in diameter, 32 m long and buried at a maximum depth of 4 m. Another piping system was trialled to measure the impact of reducing the pipe diameter and included forty PVC pipes with various lengths at 200 mm diameter. Two pipes are connected to each of the twenty units with each of them performing as a central air supply and air exhaust (Figure 5.22). In addition, four pipes with 15 m long and 50 mm diameter were designed to perform as water sprinklers.

Another four PVC pipes with 12 m long, 50 mm diameter and 35° slope were designed to drain the condensed water inside the ground pipe into the domestic water tank to be sprinkled on the surface to cool the ground soil (Table 5.20).

The proposed low energy cooling applications as represented in Table 5.21 include four air intake inline fans with a 350 mm diameter and 1050 cfm (495 l/s) air flow rate for each fan which is considerably above the total average required air flow rate of 700 l/s. The intake fans were placed at the pipe inlet to blow the outdoor air through the ground pipe to the air tank. In addition, forty PVC inline mixed mode fans with 200 mm diameter and 293 cfm (138 /s) air flow rate were placed in pipes outlet attached to each unit to blow the air to internal spaces. In order to enhance the cooling efficiency of the GPCS and maintain the indoor temperature, the ground air is stored in two galvanized-steel air tanks (thermal storage air plenum) integrated with chilled water coil system (25 m long and 0.015 m diameter of the serpentine loop of copper coils) and insulated by foil-face insulation. The volume of each of the air tanks is 1.2 m^3 with a capacity of (350 gallons). In addition to this, a water pump with a maximum head of 9.5 m and 350 l/p/m flow is proposed to pump the condensed water from the water tank to the sprinkler heads. A complete description of the GPCS mechanism was extensively discussed in section (5.2.3.3).

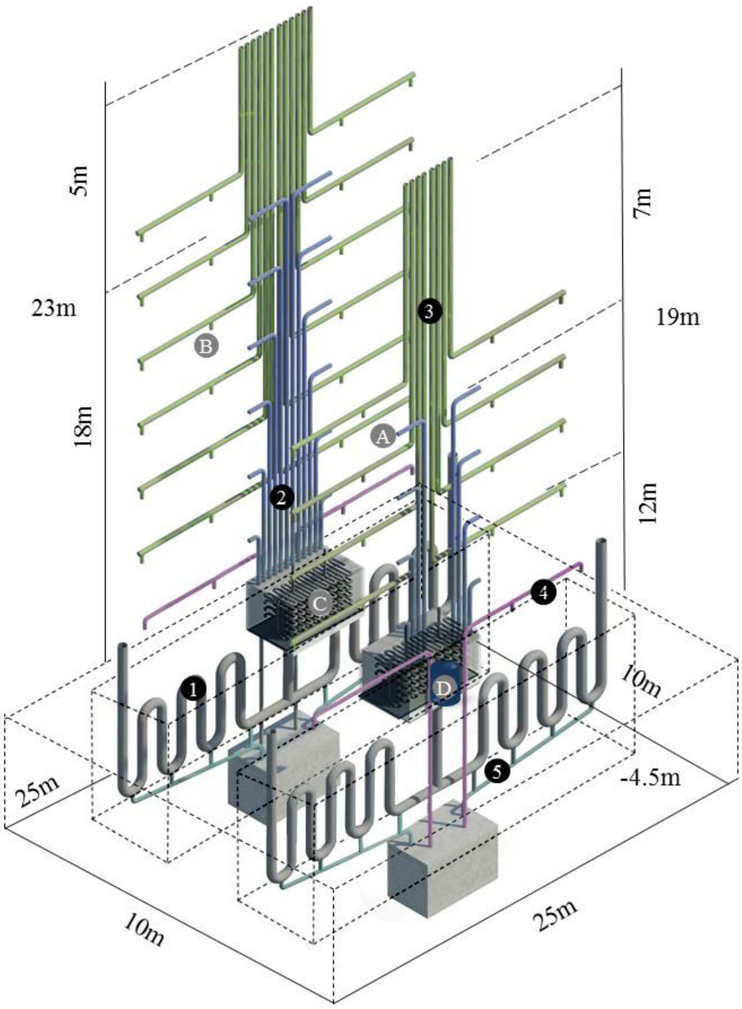
	Component and Specification	Model
1.Ground pipe	Material: High density Polyethylene (HDPE) Number: 4 Depth: (0 - 4 m) Length: 32m (for each) Diameter: 0.35 m	
2. Air supply	Material: PVC Number: 20 Height: (0 - 23 m) Length: (4 - 20 m) Diameter: 0.20 m	
3. Air exhaust	Material: PVC Number: 20 Height: (0 - 25 m) Length: (4 - 80 m) Diameter: 0.20 m	
4. Sprinkler	Material: PVC Number: 4 Height: (4.5 – 2.5 m) Length: 15 m (for each) Diameter: 0.05 m	
5. Moisture drain	Material: PVC Number: 4 Height: 1.4 m Length: 12 m (for each) Diameter: 0.05 m	

Table 5.20: Components and specifications of the proposed GPCS.

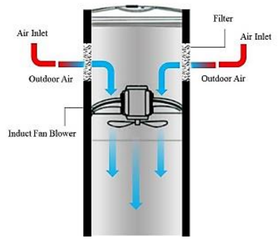
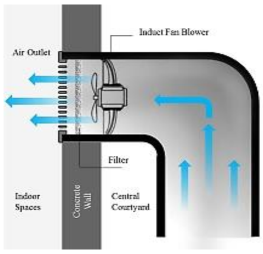
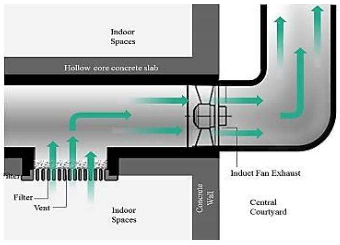
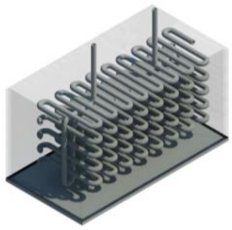
	Component and Specification	Model
(A)Inline air intake fan	Number: 4 Material: PVC Diameter: 0.35 m Voltage: 115V /Wattage: 335 Air flow: 1050 cfm (495 L/s) Motor RPM: 2500/ HP: 2.90	 
(B)Inline supply fan	Number: 20 Material: PVC Diameter: 0.20 m Voltage: 115V /Wattage: 65 Air flow: 293cfm (138 L/s) Motor RPM: 2289/HP: 1.2	 
(C) Inline exhaust fan	Number: 20 Material: PVC Diameter: 0.20 m Voltage: 115V /Wattage: 65 Air flow: 293cfm (138 L/s) Motor RPM: 2289/ HP: 1.2	 
(D) Air tank (Thermal Storage)	Number: 2 Material: galvanized-steel Volume: 1.2 m^3 - 1590 Liter. Cabinet with foil-faced insulation and 0.015 m Copper coil loops linked with the refrigerant gas compressor.	 
(E) Water pump	Number: 1 Max head: 9.5 m Material: Stainless Steel Volts: 230 V / Watts: 500 W Flow: 350 lpm Outlet Diameter: 0.20 m	

Table 5.21: Configuration and specifications of the low energy active cooling applications of GPCS.

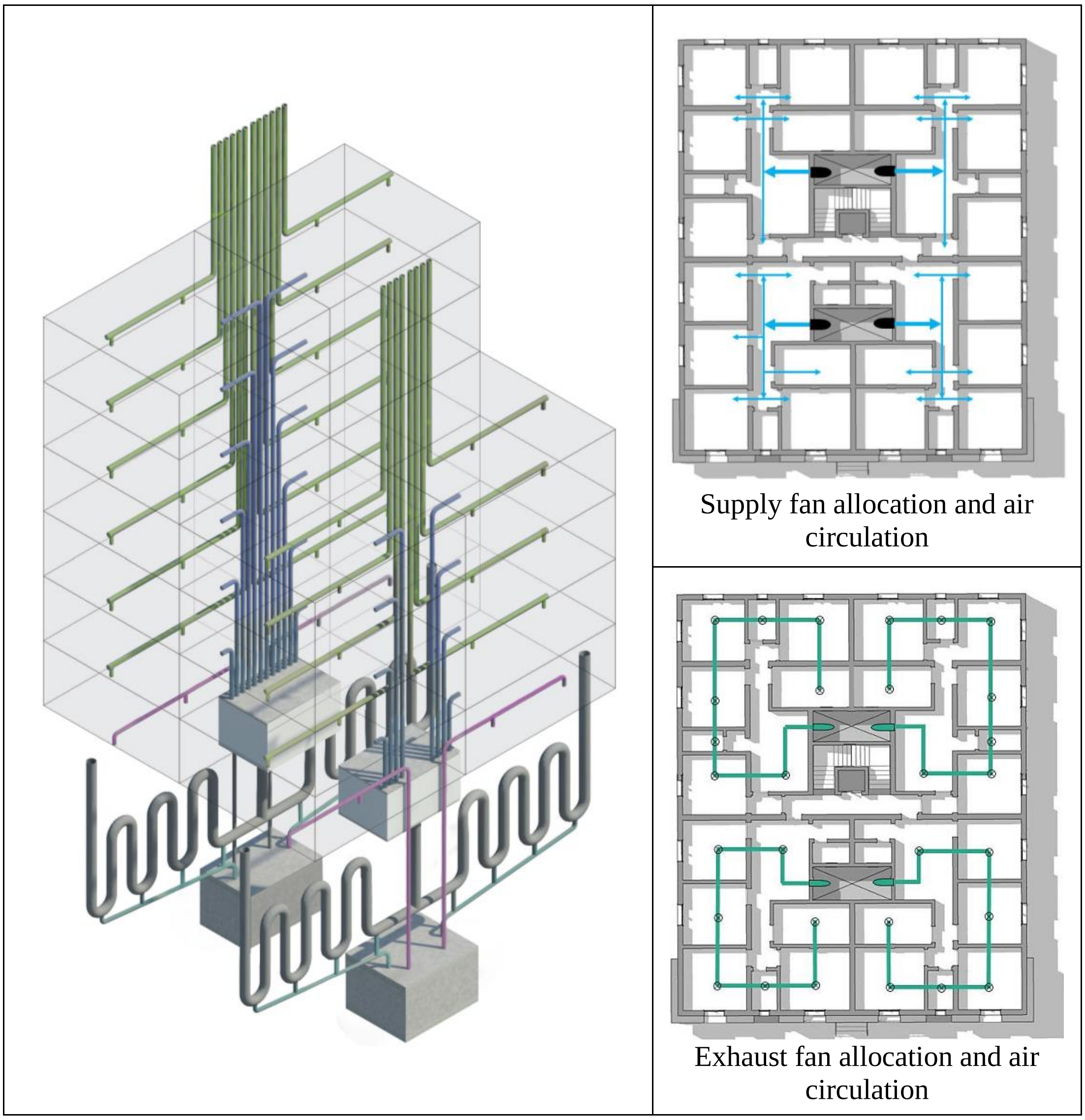


Figure 5.22: Ground Pipe Cooling System (GPCS).

GPCS is an efficient (ventilative) cooling strategy which delivers relatively cool underground air into building indoor spaces, while radiative cooling technique can effectively chill a large thermal mass (TermoDeck® hypocaust floor slabs) to sustain the indoor condition and optimise the cooling capacity.

5.2.3.2 Hydronic Radiant Cooling System (HRCS)

The fundamental of the radiant cooling system is that occupants are cooled by radiant heat transfer from their bodies to adjacent chilled surfaces such as walls, ceilings, or floors. Space cooling systems using water as a medium of ‘coolth’ is usually moved from chillers to concrete slabs chilled beam or ceiling panels. Chilled water circulates through embedded pipes to adjust the slab temperature and regulate an amount of the sensible load, thereby reducing the AC cooling load. This cooling technique is highly efficient since the system takes the advantage of the high thermal capacity of water, which is 3,500 times higher than the thermal capacity of air since water temperature changes slower than air temperature. In addition, a hydronic system can transfer the required amount of cooling with less than 5% of the energy need to deliver cool air to fans. HRCS is more efficient as the delivery temperatures of water is closer to indoor temperature (Vangtook & Chirarattananon, 2007).

The cooling source of HRCS can be passively generated from the clear night sky through atmospheric longwave radiation. Night radiative cooling phenomena is a concept known to produce a surface at a temperature lower than the ambient air as a result of infrared night radiation to a clear sky (Givoni, 1994). This cooling strategy can be suggested to be used as an efficient source of 'coolth' for the proposed HRCS especially if it is integrated into floor screeds.

1) HRCS Design Parameters and Standards

Cooling energy in HRCS is delivered through pipes embedded in concrete floor slabs circulating chilled water at approximately 14 - 20°C (Givoni, 1994). These systems can be used to optimise night cooling ventilation or to produce additional cooling source during peak times in summer. Chilled floors which consist of long rectangular sections containing a tube through which chilled water is circulated at around 17°C utilising convective air movement to cool indoor spaces, while chilled ceilings transfer cooling by radiation utilising a chilled water pipe arranged in a serpentine coil and fixed to a metallic panel (Givoni, 1994).

However, based on the comparative assessment of both chilled floors and ceilings systems that conducted in section 5.2.2.2, it was found that chilled floors approach has a higher thermal capacity as the hydronic system (chilled water pipes) is embedded in the thermal mass (TermoDeck® floors) of the building structure. In addition to its cooling efficiency, radiant cooling through floors requires higher water temperature (17°C) and less cooling demand to chill the water compared to (14°C) in chilled ceiling or beams. Moreover, such system has a lower initial and running cost.

The ideal thermal performance and cooling efficiency of such HRCS applications can be determined according to several factors and parameters including night sky clarity and temperature, surface radiation and emissivity (radiator), building fabric thermal properties, hydronic pipe thermo-physical properties and water thermodynamic (Mihalakakou, Ferrante,

& Lewis, 1998). Towards achieving an optimum design and performance of HRCS, the following parametric study and field experiments were conducted.

d) Atmospheric Radiation and Sky Temperature

The surface of the earth absorbs solar radiation from the Sun. This thermal energy is then redistributed by the atmosphere and ocean and radiated back into space at longer infrared wavelengths. Therefore, the surface upward longwave infrared radiation is a significant component of the surface radiation budget and an essential parameter of climate and hydrological models. The difference between the upward and downward longwave radiation gives the net longwave radiation at the surface (Vangtook & Chirarattananon, 2007). Many researches have been carried out on estimating the downward longwave radiation, however, measuring the atmospheric radiation is a complicated process due to radiometers measuring the energy exchange between the receiving surface and its direct surroundings. To achieve an accurate reading a radiometer must exchange radiation with a clear sky (Vangtook & Chirarattananon, 2007).

Radiative cooling usually happens when sky temperature T_{sky} is lower than roof temperature T_{roof} . In equation 5.6, Eicker and Dalibard (2011) have developed clear sky correlations to relate the effective sky temperature during clear conditions to the measurement of ambient temperature and humidity. Clouds, significantly influence the effective sky temperature, therefore some researchers have attempted to include cloudiness as part of correlations to calculate the effective sky temperature, for instance, the following correlation for T_{sky} that proposed by Aubinet (1994) includes a measure of sky cover, K_0 and uses the water vapor partial pressure P_d as a humidity measure.

$$T_{sky}=94+21.6\ 1n(P_d)-13K_0+0.341T_{amb} \quad \text{(Equation 5.7)}$$

By applying these equations, the effective sky temperature during clear sky conditions with low humidity could be 30°C cooler than the ambient air temperature, however, during humid and cloudy conditions, the sky temperature may be close to the ambient temperature. It is this difference between sky and ambient temperatures present a great potential for radiative cooling. Field trials were conducted to measure the sky temperature of Jeddah during typical summer day (25th of July 2016) by using a BENETECH GM320 Infrared temperature tester (Figure 5.23). Hourly readings of sky temperatures were recorded and the results form clear sky conditions compared with the calculated sky temperature from (Equation 5.6). The result shows that there is a slight disparity between the measured and calculated average hourly sky temperature especially in the afternoon and midnight period (Figure 5.24).

Figure 5.23: Sky temperatures measurements by BENETECH GM320 Infrared temperature tester under various sky conditions.

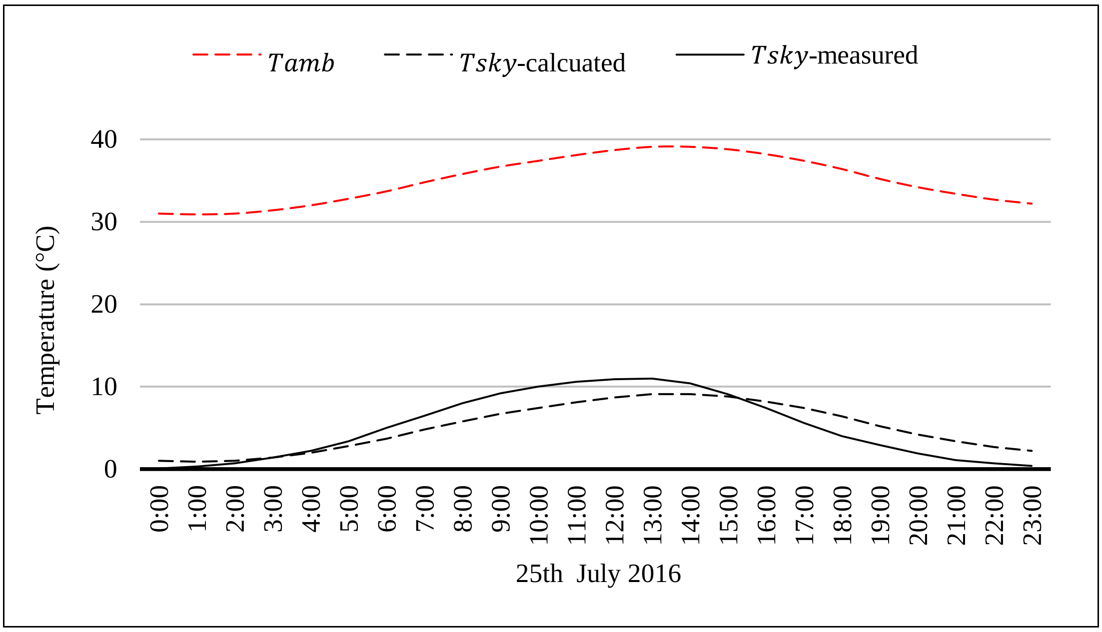


Figure 5.24: Comparison between the averages hourly calculated and measured sky temperatures.

e) Radiator Thermal Properties and Cooling Capacity

Theoretically, the levels to which radiation is emitted by the atmosphere and reflected back to the ground rely on various factors including the variations in temperatures and humidity levels and altitude of different cloud layers. To mathematically determine the effectiveness of night sky longwave radiative cooling, the following Stefan-Boltzmann equation can be applied, to calculate the net exchange of radiative heat ($Q_{radiative\ net}$) between the surface and the sky, where in Equation 5.5, σ is the Stefan-Boltzmann constant 5.67×10^{-8}

W/m^{2}K^4, ε is the surface spectral and directional average blackbody emissivity of the roof, A_{roof} is the roof area in m², and T_{roof} is the exterior surface temperature of the roof in °C.

$$Q_{radiative\ net}=\sigma\varepsilon A_{roof}\left(\left(T_{roof}+273.15\right)^4-\left(T_{sky}+273.15\right)^4\right) \quad \text{(Equation 5.5)}$$

One of the fundamentals of radiation is that all surfaces emit the standard amount of radiation based on its thermal properties (Petty, 2006). Thermodynamics can be used to assess the maximum thermal energy from the building surfaces. However, the ultimate reference for radiation is the concept of the 'black body' that can generate this energy (radiation) at any temperature and at any wavelength. A blackbody is an ultimate body that absorbs all incident radiation impinging on it, for all wavelengths and angles of incidence of the radiation, emitting the maximum radiant energy at every wavelength. The mechanism to describe system performance depends on the blackbody emission under the same conditions, using the coefficient called emissivity "Albedo". The emittance refers to a heat ratio emitted from materials compared to a blackbody on a scale from zero to one. A perfect reflector would have a value of 0; a blackbody would have an emissivity of 1 (Vangtook & Chirarattananon, 2007).

Several experiments were carried out to determine the night radiative cooling effect. Sayigh, (1976) made an experiment to investigate the night radiative cooling in Riyadh -Saudi Arabia. In his experiment, several metallic surfaces were designed as flat plate collectors where some of these collectors were covered with thin plastic covers. The ambient and surface temperatures were recorded. The result was that the surface temperatures of the metallic materials were lower than the ambient air temperature. Therefore, this surface was proposed to cool water during the night, to be used during the day for the cooling purpose (Sayigh, 1976).

Another experiment conducted by Michel and Biggs (1979) to investigate the effectiveness of radiative cooling and the thermal performance of two huts. One of the roofs of the hut was made of steel plate painted in white whereas the other was made of aluminium coated by 'Tedlar' PVF films sheet. It was reported that the white painted roof hut was cooled more than the 'Tedlar' aluminium roof, with approximately 22 W/m^2 of radiant loss (Michel and Biggs, 1979).

An experiment carried out by Al-Nimr et .al, (1998) in Irbid-Jordan to study the impact of night radiative cooling in cooling water. The system consisted of steel plate painted black as a radiator panel associated with water tank and a pump. A theoretical model was developed to calculate the radiation energy. It was found that the result of both experimental and theoretical model agreed. The system had the ability to emit around 3 MJ/m^2 per day to the sky.

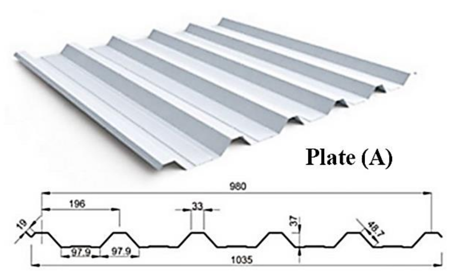
In another experiment, Ben Cheikh et al. (2004) designed a roof topped with aluminium plate painted with white titanium to increase the emissivity "Albedo" and followed by an air gap, with a rock and waterbed attached to a concrete ceiling. Results demonstrated the cooling impact of the application of such a roof on indoor condition and it was observed that peak indoor temperature peaked at around sunset.

A design proposal for radiator a roof design was experimented by Dimoudi and Androutsopoulos in 2006. In their experiment water pipes were embedded in a concrete roof. A radiator made up of steel plates was attached to the upper part of the roof while a radiator was also attached to the steel pipes. The aim was too cool the room below the roof. The results showed that the circulated water beneath the radiator was cooled at a temperature similar to the plate temperatures (Dimoudi and Androutsopoulos, 2006).

These experiments and studies have demonstrated the efficiency of radiative cooling techniques to passively cool buildings. Various radiator surface designs and materials were utilised, however, the blackbody radiator seems to be the more effective due to its high absorptivity level of solar radiation during the day and emissivity to emit heat to the night sky.

The climatic condition has a crucial influence on the efficiency of radiative cooling. It was therefore crucial to investigate the night cooling effect in Jeddah to explore the potential at a specific location. The field trial was performed on a typical summer day (25^{th} of July 2016). In this experiment, two corrugated metal plates (0.6 m x 1.0 m) were designed as blackbody radiators. Plate (A) was kept in the original white paint while plate (B) was painted black. Both plates were faced north and completely exposed to clear sky over the 24 hours (Table 5.22). The temperature of each plate was measured hourly through the day. The measurement tools that were used to measure the surface temperature is BENETECH GM320 Infrared Thermometer (Table 5.23).

Description	Specification
Product name	Galvanized colour coated metal
Surface treatment	Galvanized and coated
Thickness	0.14-1mm
Width	600-1250mm
Material	Colour Steel Plate/galvanized



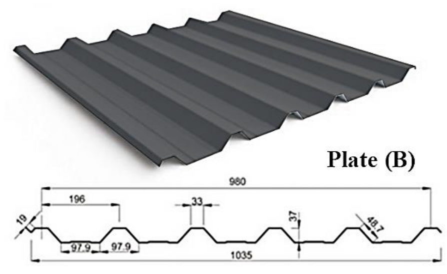


Table 5.22: Specification of the experimented galvanized corrugated metal sheet.

Description	Specification	Model
Model	GM320	
Weight	123 g / 4.34 oz.	
Dimensions	(14 x 7 x 3.5) cm / (5.51 x 2.76 x 1.38)	
Colour	Yellow, Black	
Material	Plastic	
Battery	2 x AAA batteries (Not included)	
Measuring Range	-50-380℃ (-58-626°F)	
Resolution	0.1℃ or 0.1°F	
Operating Temperature:	0 ~ 40C (32 ~ 104F)	

Table 5.23: Features and specifications of BENETECH GM320 Infrared temperature tester thermometer.

The highest measured temperatures for both plates (A) and (B) were at 52.8°C and 68.6°C respectively (Figure 5.25). The average hourly temperature recorded of each plate is illustrated in. During the day, there was a large temperature amplitude between the two plates along with the ambient temperature. The maximum average measured the temperature of the plate (A) was at 51.4°C while the maximum average temperature of the plate (B) was at 62.4°C. On the other hand, at night, the measured temperatures of both plates were lower than the ambient temperature. The lowest temperature recorded by either plate was just before sunrise (6:15am) at 29.6°C for plate (B) which is approximately 4.1°C lower than the ambient temperature, whereas, the minimum measured temperature of plate (A) was at 30.5°C which is almost 3.2°C lower than the ambient temperature. An average of 3.2°C of temperature drop was recorded for the plate (B) in comparison with 1.7°C for Plate (A) (Figure 5.26). It can be concluded from this experiment that the thermal properties and emissivity coefficient of surface material plays a crucial role in determining the radiating efficiency. Table 5.24 presents the absorptivity and emissivity coefficient of various common surface materials.

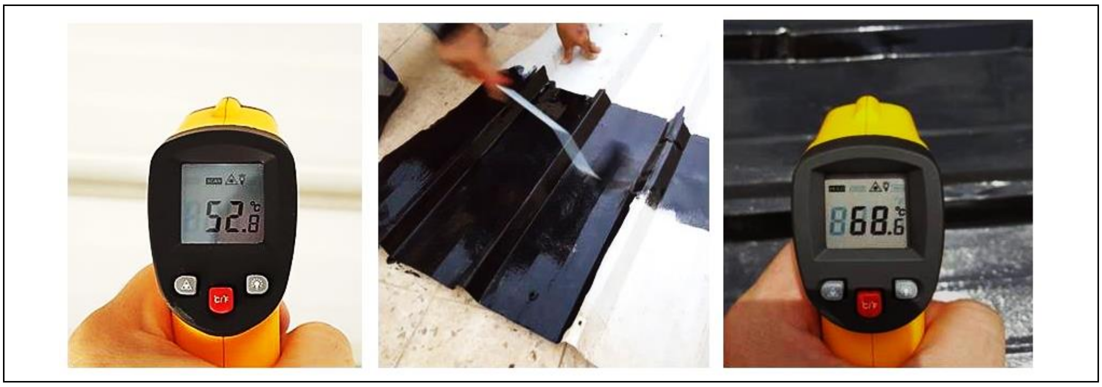


Figure 5.25: Maximum daily measured temperatures of plates (A) and (B).

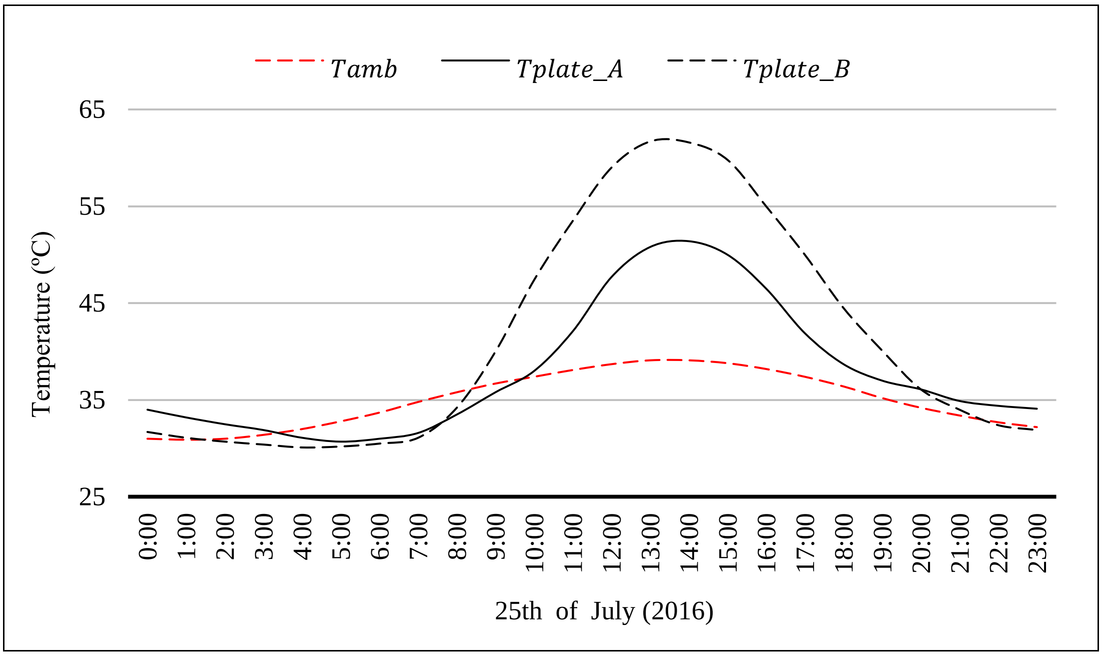


Figure 5.26: Variation of average hourly measured temperature between plates (A) and (B).

Material	Absorptivity	Emissivity
Aluminium	0.1..0.15	0.05
Copper	0.2..0.5	0.05
Glass (Pyrex)	----	0.9
Glass (quartz)	----	0.93
Glass (window)	0.1	0.9
Ice	0.3..0.5	0.92
Iron (cast-)	0.3	0.2..0.7
Nickel	0.2	0.05
Paper	0.3	0.95
Platinum	----	0.09
Polyurethane	----	0.9
PVC	----	0.9
Sand & soil	0.4..0.7	0.5..0.8
Silicon	0.3	0.3
Silver	----	0.02
Steel (carbon-)	0.2	0.2..0.6
Steel (stainless-)	0.4	0.2..0.3
Teflon (PTFE)	0.12	0.85
Titanium	0.4..0.7	0.2..0.5
Aluminium anodised	0.20	0.60
Aluminium (vessels)	0.15	0.20
Aluminised kapton	0.40	0.80
Aluminium, bright	0.20	0.05
Asbestos cement,	0.60	0.95
Asbestos cement, aged	0.75	0.95
Asphalt pavement	0.90	0.95
Brick, light puff	0.60	0.90
Brick, red rough	0.70	0.90
Cement, white Portland	0.40	0.90
Concrete, uncoloured	0.65	0.90
Marble, white	0.45	0.95
Paint, Aluminium	0.50	0.55
Paint, white	0.30	0.90
Paint, brown, red, green	0.70	0.90
Paint, black	0.90	0.90
Paper, white	0.30	0.90
Slate, dark	0.90	0.90
Steel, galvanized new	0.55	0.25
Steel, galvanized weathered	0.70	0.25
Tiles, red clay	0.70	0.90
Tiles, uncoloured concrete	0.65	0.90

Table 5.24: Emissivity and absorptivity values of various surfaces and materials.

Additionally, a further experimental study was performed. Plate (B) model was thermally retrofitted with 50 mm of rigid insulation board and fixed in a timber frame incorporating a black body radiator roof panel (Figure 5.27). The dimensions of the constructed roof model are (1.80 m x 1.0 m) and 0.35 m height. The radiator was fitted with 4.5 m long and 0.0125 m diameter PEX-pipes lying on the bottom surface of the radiator and linked with a 25 liters water tank to store cold water during the night (Figure5.27).

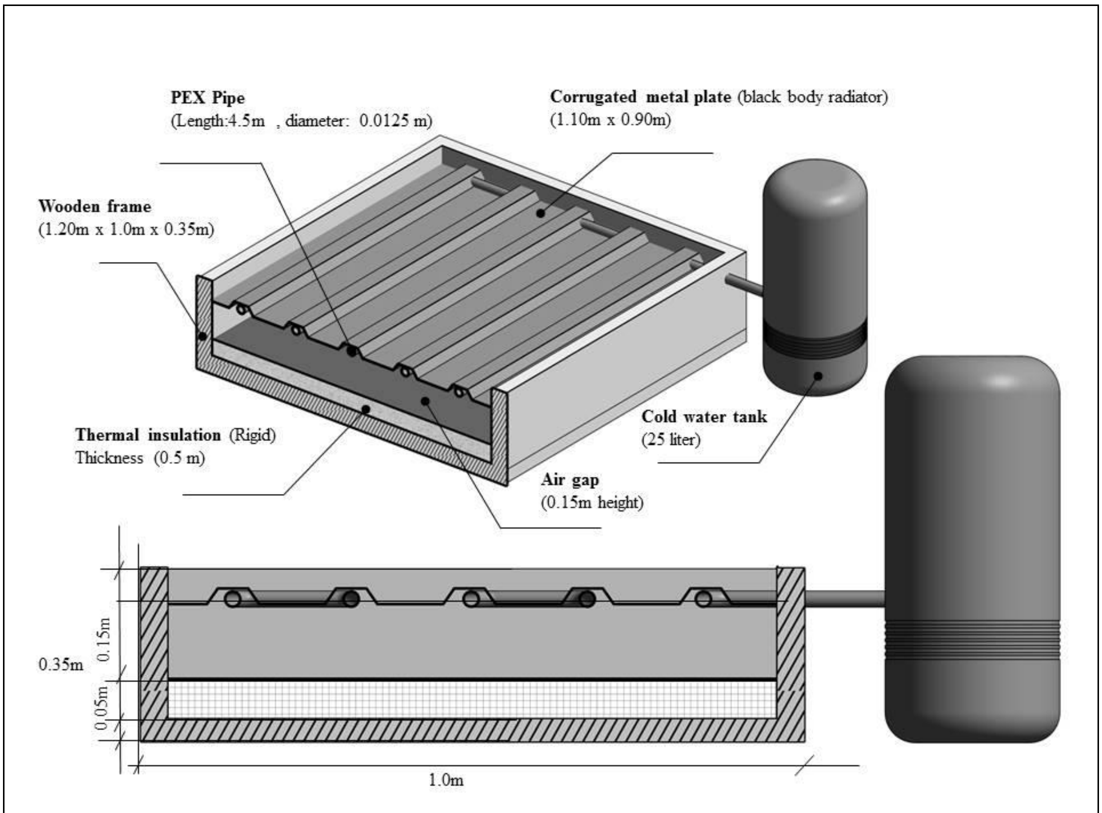


Figure 5.27: Experimental model design of blackbody radiator.

The metal radiator surface was exposed to solar radiation during the day while the water was circulated between the water tank and the fitted pipe loops in the bottom of radiator surface. Two measurement's tools were used in this experiment. A Digital Thermometer 2 K-Type Metal Thermocouple (Table 5.25) was used to measure the blackbody surface temperature, TGU-4500 Tinytag data logger was used to measure air temperature and GM320 Infrared Temperature Tester Thermometer to measure the water temperature (Figure 5.28).

Description	Specification	Model
Model	DM-68022	
Weight	300g (including batteries)	
Dimensions	149 x 71 x 41mm	
Colour	Yellow, Black	
Material	Plastic	
Battery	2 x AAA batteries	
Measuring Range	-50 ~ 1300C (-58 ~ 2372F)	
Resolution	0.1C or 0.1F	
Accuracy	0.4C 1%	
Operating Temperature	0 ~ 40C (32 ~ 104F)	
Operating Humidity	0 ~ 70% (R.H.)	

Table 5.25: Features and specifications of digital thermometer 2 K-Type Metal Thermocouple.

During the summer days of 29th - 30th of July 2016, the maximum average temperature of radiator surface was 58.1°C which is around 16°C higher than the ambient temperature while the maximum average air temperature in the 0.15 m gap located between the radiator and insulation layer was at 44.1°C which is 4°C higher than the ambient temperature due to heat retention caused by thermal insulation and the convective heat of radiator surface (Figure 5.29). However, during the night time, the radiator temperature dropped below the ambient temperature. The minimum recorded temperature of radiator surface was just prior to the sunrise (5:45 am) at approximately 23.4 °C which is almost 10.3°C lower than the ambient temperature. At the same time, the air gap temperature has recorded the minimum average hourly temperature at 24.2°C. The water outlet temperature fluctuated in a more limited range due to its thermal capacity and resistance, the minimum average temperature recorded was 24.8°C, which is almost 8.9°C lower than the ambient temperature (Figure 5.29).

This relatively crude prototype confirmed that hydronic night radiant cooling, operating in clear sky summer conditions, will have the capacity to supply a significant level of 'coolth' by radiant heat flushing. Additional efficiency gains would be possible by increasing the effectiveness of the thermal interfaces with flow rates being modulated to maximise heat flushing when sky temperatures are falling towards their diurnal minimum. Radiometer readings during the summer months dropped to 2.8°C demonstrating that there is a potential to increase heat loss if the thermal interfaces between the water pipes and panel emitter can be improved. The outcomes from these experiments clearly demonstrate the potential application of night radiative cooling in the studied location. Despite the fact that

Jeddah is a hot and humid city, passive radiative cooling can still be efficiently employed in current buildings for cooling and energy conservation purposes when the night is cloud free.

Figure 5.28: Field measurements of the blackbody radiator experiment on 29th – 30th of July 2016.

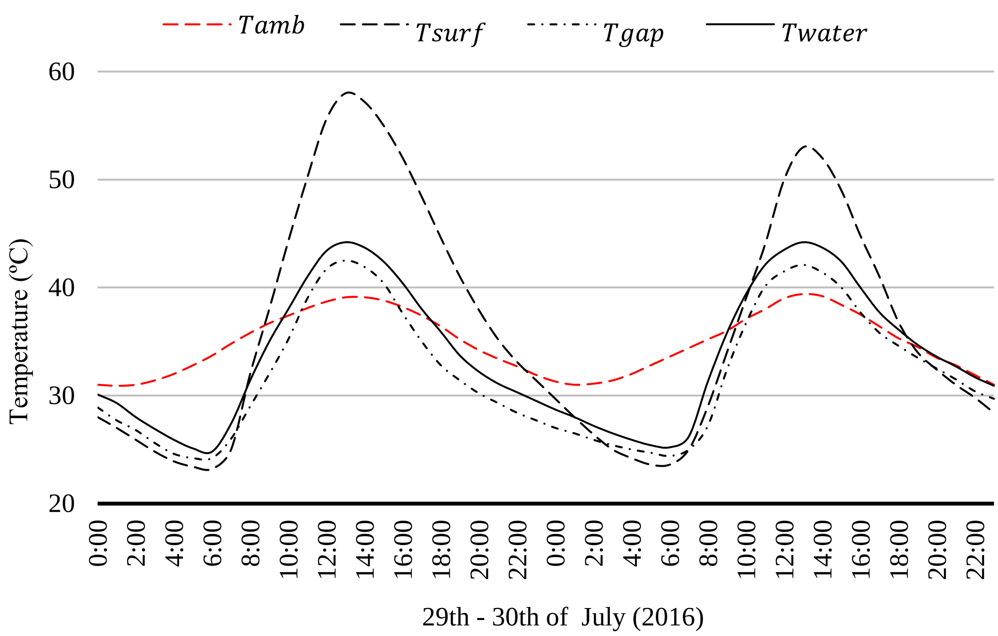


Figure 5.29: Variation of average hourly radiator surface and water temperature on 29th - 30th of July 2016.

f) Hydronic Pipe Design and Water Thermodynamic

Based on the comparative study among varies residential applications of HRCS and the assessment of the thermo-physical performance of building fabric in the current case study, the proposed HRCS is (ESS) Embedded Surface System, however, in order to determine the optimal HRCS that can be applied to the current case study building, it is necessary to employ the radiant system designs that can fit the current houses typology envelope and standard fabric. Many publications have addressed the design principles and criteria of HRCS such as (Olesen 1997b, Babiak 2007, Uponor 2011, and ASHRAE 2012a). Generally, the cooling performance of such cooling system involves the determination of key parameters such as system specification (pipe's length, diameter, spacing, thermos-physical properties of building fabric) and system operating conditions (surface temperature, water temperature, flow rate, and indoor temperature).

Therefore, parametric studies were performed to determine the most efficient system design. A model of the retrofitted case study building with the passive design measures in place was developed comprising a space volume of 45 m^3 surrounded by thermally insulated clay block wall and covered by insulated TermoDeck® slabs with PEX pipe embedded in the floor (U-value 0.41) (Figure 5.30). Computational simulations using DesignBuilder was carried out on four different parameters to determine the optimum values of each parameter for ' best fit ' design of the system. The standard values of each parameter were set at 0.10 m for pipe spacing, 0.005 m for pipe diameter, 16ºC for inlet water temperature and 2 l/s for water flow, thus at every simulation process, only one variable was changed while the other variables were maintained at standard values (Table 5.26). The parametric study was conducted on a typical summer day 28th July 2016 at an average ambient temperature of 34.8°C and 65% relative humidity while the indoor setpoint temperature was fixed at 28ºC (upper thermal comfort limit). The model was numerically calculated by EnergyPlus software based on the embedded weather data profile of the selected location.

Parameter	Standard	Variables
Spacing	0.10 m	0.05 m.0.10 m.0.15 m.0.25 m
Inner diameter	0.005 m	0.0025 m, 0.005 m, 0.008 m, 0.01 m
Inlet water temp	16ºC	10ºC, 16ºC, 20ºC, 25ºC
Water flow rate	2 l/s	1 l/s, 2 l/s, 4 l/s, 8 l/s

Table 5.26: Key parameters and variables of the parametric study of HRCS design.

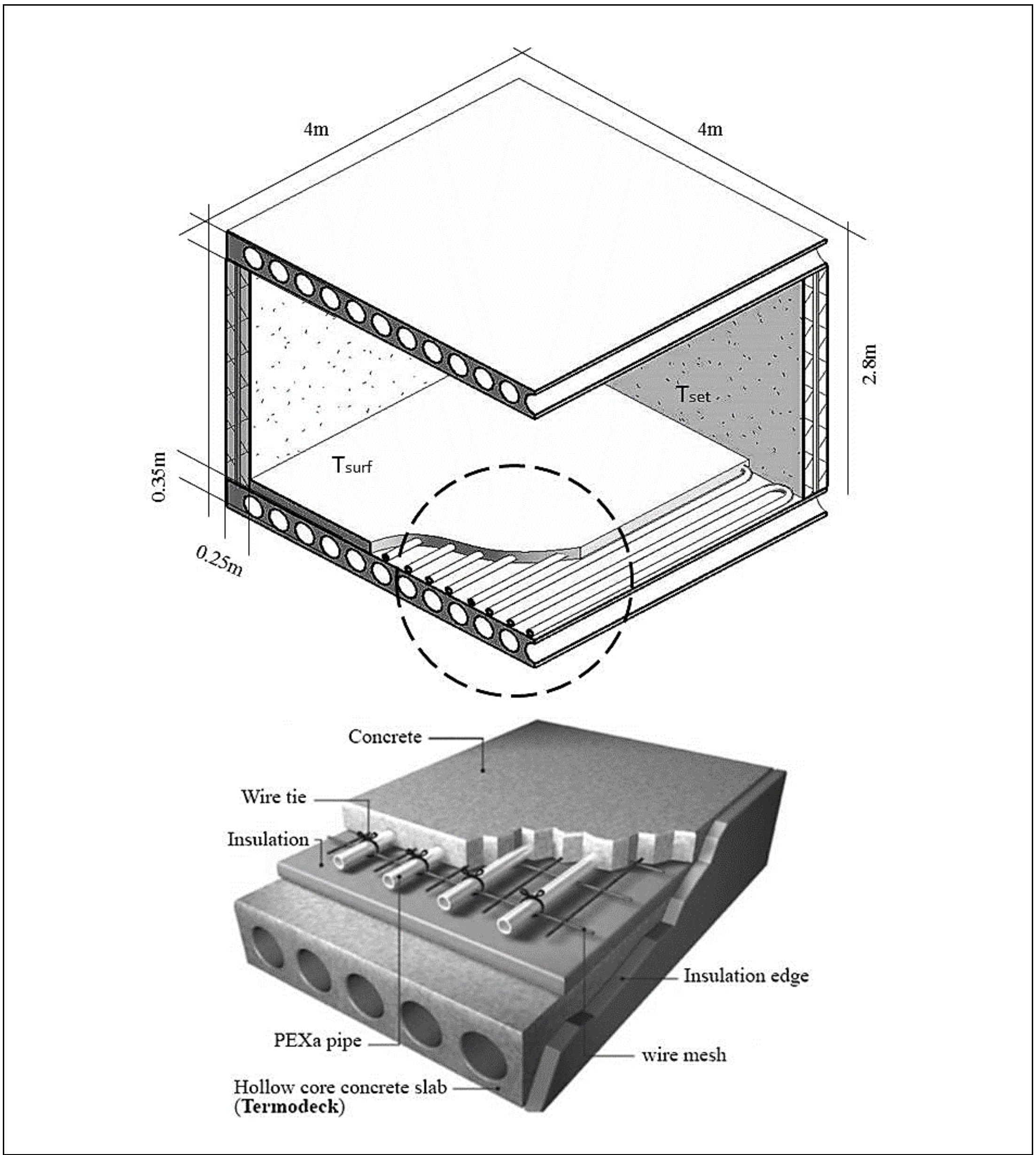


Figure 5.30: Design and specifications of the proposed HRCS simulation model.

The primary simulation results determined the impact of embedded pipe spacing on indoor operative temperature which is average of the mean floor radiant and indoor air temperatures. The data in Figure 5.31 shows that wider spaces between the pipe and floor surface lead to an increase in surface temperatures and thus operative temperatures. The rationale behind this is that wider spacing between embedded pipes and floor surface allows the cooling capacity of water to disperse into floor fabric. The increasing of surface temperature as a result of increasing pipe spacing was varied. For instance, by increasing the pipe spacing from 0.05 m to 0.25 m, the average indoor operative temperature increased by 2.2°C from 25.5°C to 27.7°C (Figure 5.31).

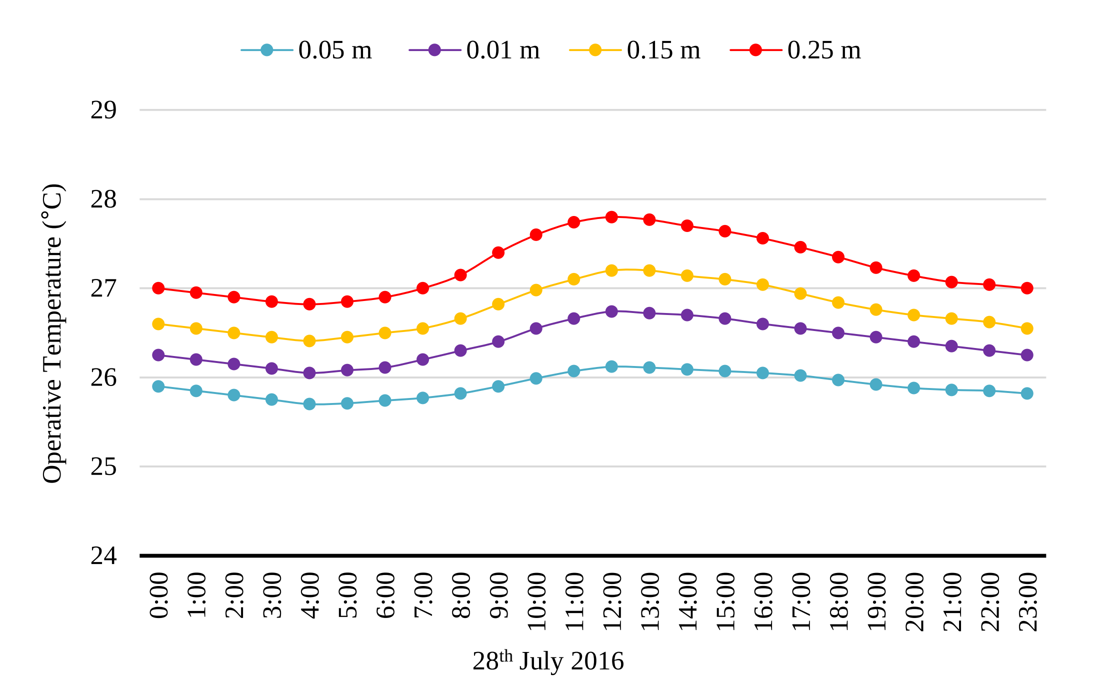


Figure 5.31: Influence of embedded pipe spacing on average indoor operative temperature

Another parameter that has an influence on the cooling performance of HRCS is the embedded pipe diameter. As illustrated in Figure 5.32 increasing the pipe diameter resulted in decreasing indoor operative temperature. The rationale behind this is that wider pipe diameter has a greater contact surface with floor fabric, allowing easier and faster heat transfer. As illustrated in Figure 5.32, increasing the pipe diameter from 0.0025 m to 0.01 m, resulted in gradual decreasing in the average indoor operative temperature by 1.3°C. However, in comparison with the other mentioned parameters, the effect of pipe diameter on floor temperature is limited.

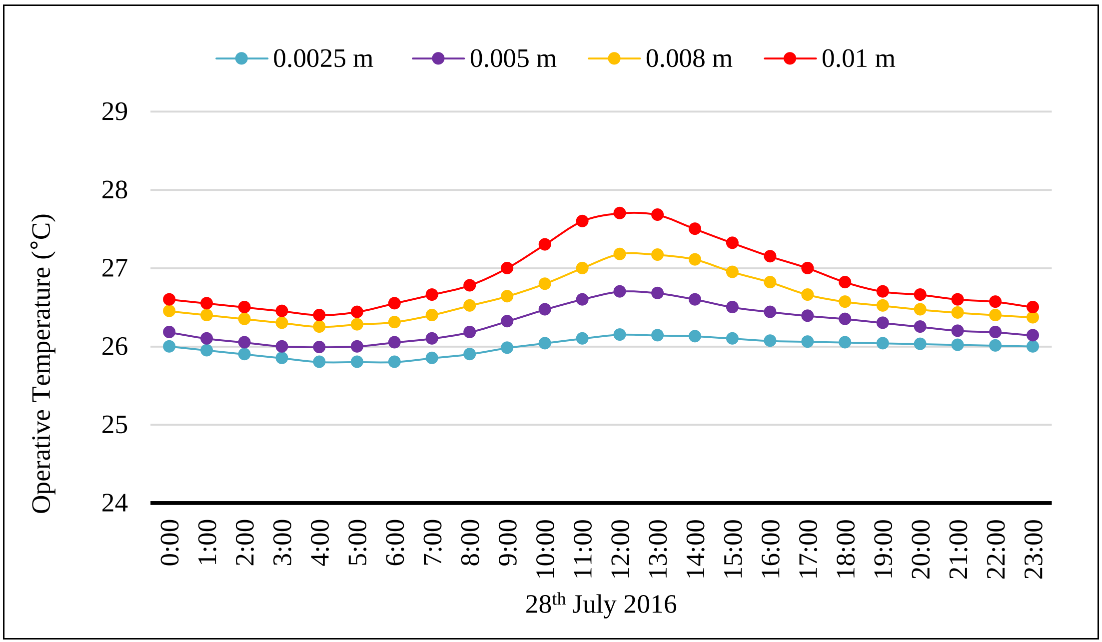


Figure 5.32: Influence of embedded pipe diameter on average indoor operative temperature.

As can be seen in Figure 5.33, water supply temperature is the key parameter that significantly affects the radiant surface temperature and thus the indoor operative temperature. Increasing water inlet temperature from 10°C to 25°C resulted in a considerable increase in the average indoor operative temperature. In the period between 10:00 am and 16:00 pm the indoor operative temperature remained constant at 28°C (the fixed set point temperature) with no radiant cooling effect due to supplying insufficient water temperature at 25°C (Figure 5.33).

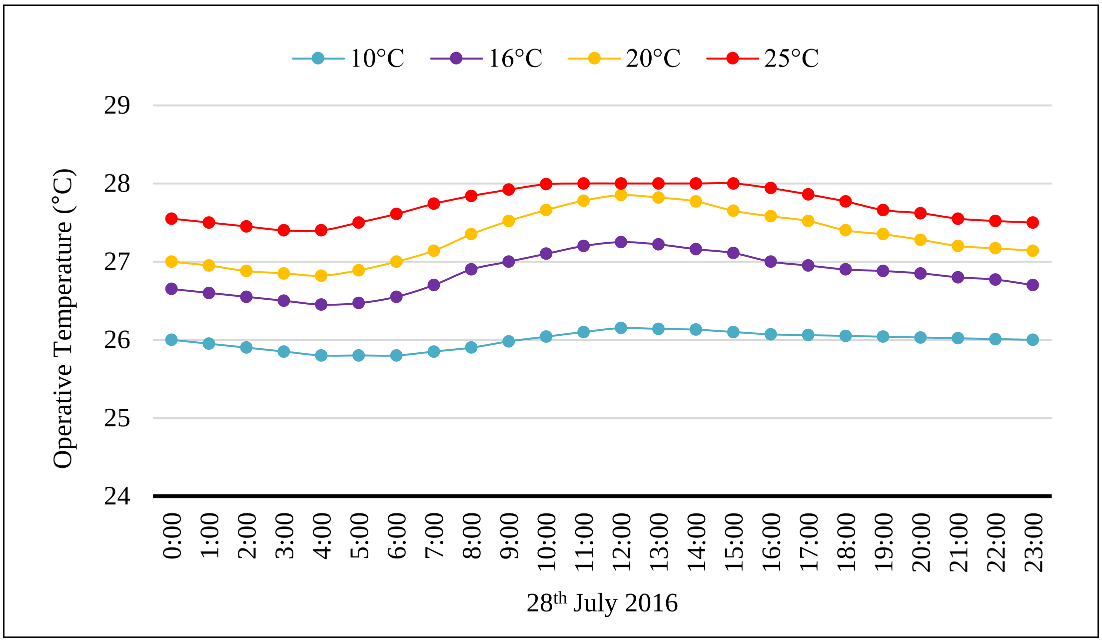


Figure 5.33: Influence of water temperature on average indoor operative temperature.

Similar to the other parameters, the water flow rate affects the cooling performance of HRCS. The findings in Figure 5.34 shows that increasing the water flow rate led to a decrease in average indoor operative temperature. The rationale behind this is the mass flow rate transfers more energy. As shown in Figure 5.34, when water flow in embedded pipe increased from 1 l/s to 8 l/s, the average indoor operative temperature decreased by 2.5°C which means that embedding the pipe with a relatively higher water flow rate improves the floor radiant cooling performance.

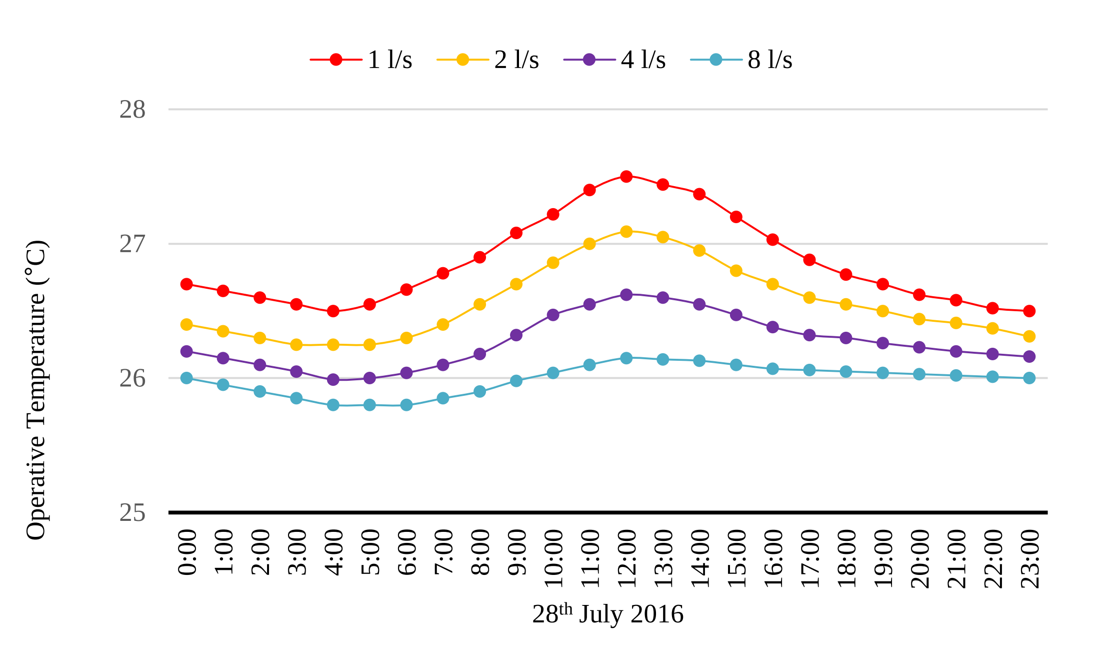


Figure 5.34: Influence of water flow rate on average indoor operative temperature.

Based on the parametrical analysis it was concluded that under optimal design conditions, the high cooling capacity of HRCS could play a significant role in achieving internal thermal comfort even under peak summer temperatures. The cooling capacity of HRCS depends on crucial factors such as, heat exchange between the surface and the space (convective and radiant heat exchange coefficient), heat conduction between the surface and embedded pipe (floor surface material, type of concrete, slab thickness and spacing between piping) and heat transfer by water (water flow rate and temperature).

g) HRCS Hybridization and Cooling Enhancement

The superior heat transfer properties of water compared to air allow the hydronic portion of the system to efficiently re-distribute heat away from the internal volumes. In addition, HRCS allows a higher space set-point temperature, compared to a traditional HVAC therefore, running the HRCS with moderate supply water temperatures allows the integration of renewable systems such as GPCS at maximum efficiencies. The two separate systems can be designed to work in tandem possibly producing a result that is greater than the sum of the parts as the hydronic system comes into its own during the peak temperature season when mid-summer skies tend to be clearer. Such a cooling system requires a ventilative cooling element as the radiant cooling system alone cannot provide ventilation and handle the latent loads. This is the rationale for integrating both ground (ventilatve) and radiant (cooling) as a hybrid system. In addition, the HRCS may require an enhancement by integrating a low energy cooling systems (chiller) in order to meet peak summer demand conditions, especially in peak summer demand.

Carpenter and Kokko (1998), Hu and Niu (2012), and Sastry and Rumsey (2014) investigated the potential of integrating conventional chillers to supply water for radiant cooling at peak demand. Another enhancement approach reported by Bourne and Hoeschele (2000) is a night roof spray water cooling system, where the cooled water is collected at roof drains and returned to a storage tank. Tank water is then circulated in floor piping throughout the spray cycle and through zoned fan coils on demand.

Budd and Lang (2014, Hu and Niu (2012), Nall (2013) have suggested in their studies combining ground source heat pumps with radiant systems for both heating and cooling. It was found that groundwater can be used for cooling through a plate-type heat exchanger instead of running the heat pump.

Tian and Love (2009) discussed in their study the use of a VAV system combined with radiant slab cooling for a seven-story building. The VAV system provides additional cooling to multiple zones. Hu and Niu (2012) suggested two radiant cooling systems applied in China, by using fan coil units as a supplemental cooling to the radiant system.

Therefore, in the current investigation of the HRCS design and potential, integrating a low energy water chiller with DC compressor as a supplementary cooling approach may provide a backup facility to manage peak cooling demand in summer days. In addition, the proposed HRCS is combined with small water pumps with a maximum flow of 3.3 l/s to regularly circulate the cooled water within radiator and to cold-water storage facility. Additionally, a full set of commercial radiant systems including water circuit controller, sensors, flow meter were installed.

In the HRCS system, a large surface area is able to exchange heat using the floor and ceilings. The coolant temperature (water) is significantly lower than the room temperature. The temperature could also be reduced by using heat pumps.

Some of the proposed low energy active mechanical systems such as fans, water pump and chiller can be totally or partly supplied by exploiting PV generated solar energy. Installing PV solar cells can efficiently reduce the grid-electricity usage of the proposed supplementary cooling systems. To estimate the energy generated in the output of a photovoltaic system, the following global formula can be used:

$$E = A * r * H * PR \qquad \text{(Equation 5.6)}$$

Where ***E*** is the generated energy in kWh, ***A*** is the total solar panel area in m², ***r*** is the solar panel yield or efficiency in (%), ***H*** is the annual average solar radiation on tilted panels (approximately 2500 kWh/m² according to Figure 5.35) and ***PR*** is the performance ratio, coefficient for losses (range between 0.5 and 0.9, default value = 0.75).

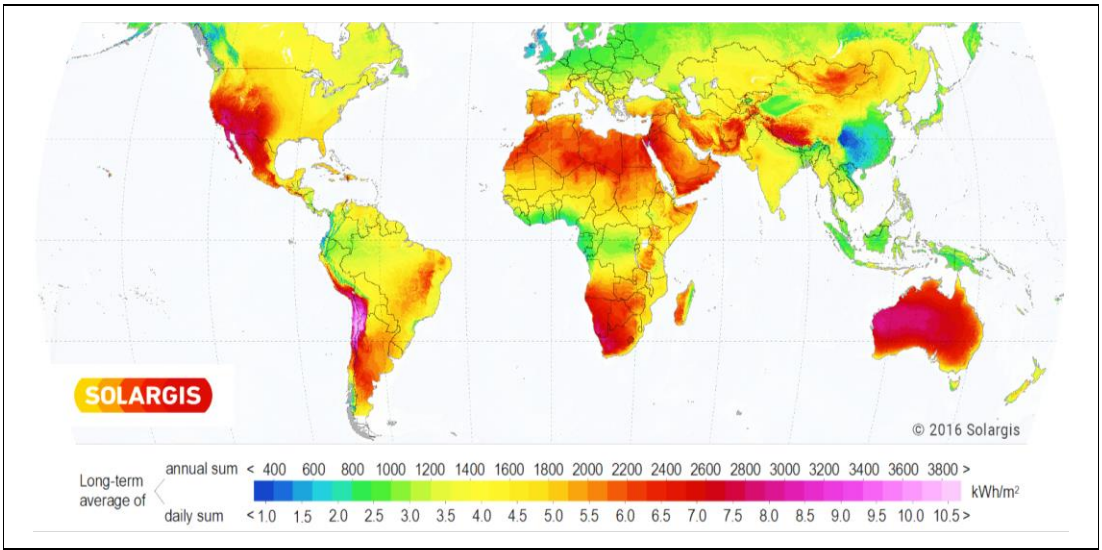


Figure 5.35: Annual average solar radiation around the globe per m² (source: solargis 2016).

Although the passive radiative cooling technique can efficiently provide a source of 'coolth' which was successfully demonstrated in many experiments, this technique can only be effective under a clear night sky. As peak cooling demand happens during the summer days, sufficient and efficient cooling of indoor spaces requires an integral hydronic radiative cooling system to be implemented in floors taking the advantage of relatively cold water that produced by the effect of night radiative cooling.

In HRCS, a large surface is able to exchange heat usually almost the whole floors, the coolant temperature (water) is just slightly lower than the room temperature. Since the coolant can be maintained at a high-temperature level, using heat pumps with high-performance coefficient values include geothermal cooling, night cooling; can reduce the required cooling demand.

2) HRCS Components and Specifications

Based on the conclusions of previous experiments and parametric studies and analysis, the proposed design and configuration of HRCS as outlined in Table 5.27 basically consists of roof-mounted water filled (420 m²) corrugated metal panels coated with high emissivity black paint as a black body radiator with 850 m long and 0.025 m diameter PVC pipe loops embedded underneath the radiator followed by a 0.15 m gap and 0.5 m thickness of rigid insulation enclosed in a box frame. Other multipurpose PVC pipes including a network of twenty 0.025 m diameter water supply pipes and 1200 m long, 0.015 m diameter of PEX a-pipe embedded in the screed on TermoDeck® hollow core concrete slabs. As can be seen in Figure 5.36, the PEX a pipes were embedded in the floor of the common circulation spaces such as main corridors and living space in each unit.

The main components and specifications of the applied low energy cooling techniques are represented in Table 5.27. The employed low-energy cooling applications include central hot water tank with a capacity of 180 liters to store the hot water circulated in radiator pipes during the day, in addition to a low energy coil chiller cold water storage with a capacity of 450 liters and chilled by a DC-Compressor are provided to store the cold water generated from the radian panels at night. A water pump with a maximum flow of 3.3 l/s and 9.0 bar pressure was also employed to regularly pump the water from the roof radiator to either cold or hot water tank and then to the embedded pipe. A mechanical water circuit controller water flow and temperature through the embedded pipe and flow meter sensors system as commercially applied in various projects.

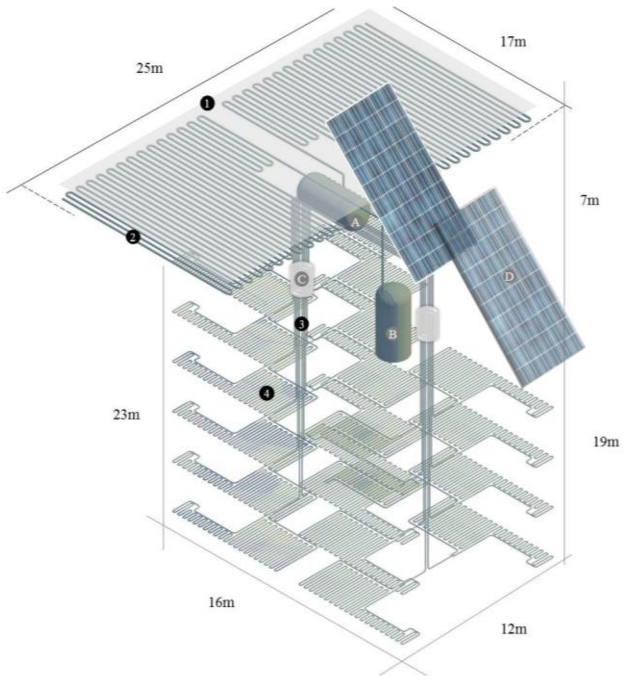
	Component and Specification	Model
1. Radiator	Material: Black painted metal corrugated panel Dimensions: 0.002 m×17 m×25m	
2. Radiator Pipes	Material: PVC Length:850 m Diameter:0.025 m Capacity: 1669 liters	
3. Horizontal supply pipe	Material: PVC Number: 20 Length: 280 m Diameter: 0.25 cm	
4. Embedded in floors Pipes	Material: Polyethylene water pipe. Number: 20 Length: 1200 m Diameter: 0.015 m Capacity: 8.4823 liters	
Solar hot water tank	Material: Metal/Steel Diameter: 71 cm Height: 150 cm Capacity: 180 litres Shape: Cylindrical	
B-Chilled water storage with compressor	Material: Metal/Steel Polyethylene. Diameter: 65 cm Height: 135 cm Capacity: 450 liters. Shape: Cylindrical Compressor Volts: 240-750 watt Load: 11 amps	
C-Water pump with a manifold set	Number: 1 Material: Stainless steel Max Flow: 3.3 liters / sec Max Pressure: 9.0 Bar 4 branch - PEX radiant floor cooling manifold set - stainless steel with an adjustable flow meter	

Table 5.27: Main components and specifications of the proposed HRCS.

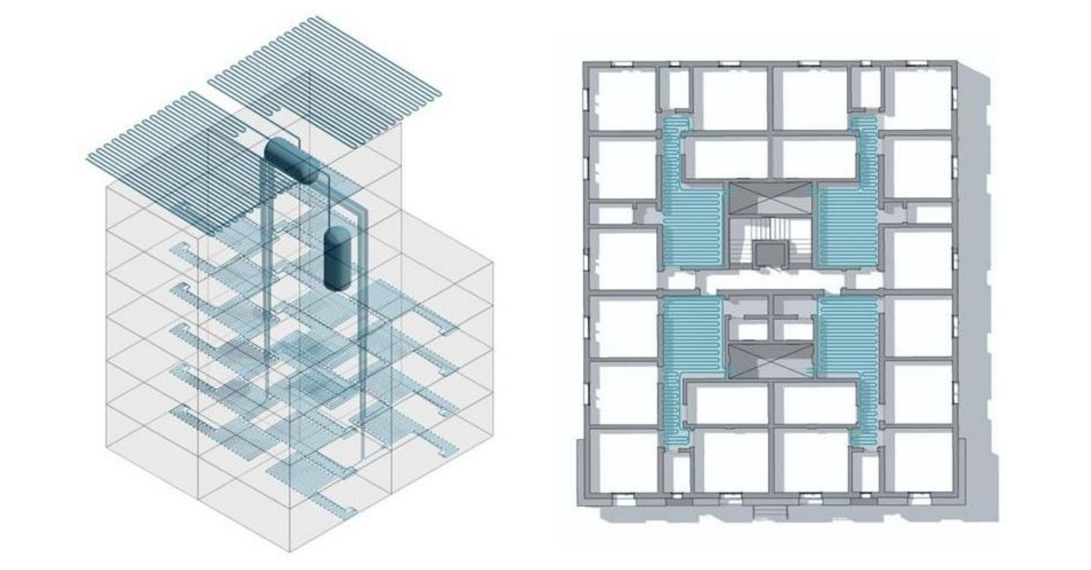


Figure 5.36: Allocation of the HRCS in building units.

5.2.3.3 Hybrid System Process and Mechanism

The HCS conceptually integrates two low-energy cooling strategies operating in tandem (GPCS and HRCS). The next task was to model the possible system interactions over stepped time frames to determine whether the ground pipe supply ventilation and radiant cooling system operating in concert with the thermal inertia of the 'fabric first' passive measures, can deliver sufficient 'coolth' to 'heat flush' and maintain internal temperatures below the upper threshold for adaptive comfort (28˚C).

The hybrid system produces a highly dynamic set of thermal interfaces that are difficult to model with any degree of accuracy. It is likely that the additional surface area and air turbulence provided by the hypocaust slabs will allow greater 'coolth' storage particularly when nights are clear. Increasing the rate of flow at these opportunities could see an increase in 'coolth' delivery, effectively chilling a large thermal mass (floors and walls) that sits at the core of the block. The simulations may, therefore, underestimate the thermal capacitance of the TermoDeck® system to store 'coolth'. Installing CO_2 sensors will also allow the ground pipe supply ventilation rate to be reduced when any flat is unoccupied. Although requiring control systems to modulate fan and pump rates, the software is unable to model such intelligent feedback loops and may, therefore, be underestimating the hybrid systems potential to suppress peak summer temperatures. As an additional power source to run the cooling systems, a 30 m² of PV panels with an estimated generation of 5936 kWh/year stored in 12

Volt Lithium battery was employed to meet the electricity demand to run in-line fans and chiller unit.

The HCS is essentially dependent on two heat sinks to absorb the heat. In HRCS mode, the clear night sky absorbs the radiant heat and cool the building by longwave radiative cooling effect at night while in GPCS mode, the ground soil absorbs the heat and disperses it to the surrounding earth layers. In this hybrid system, two mediums were used to deliver the cooling energy; water in HRCS and air in GPCS. Two time frameworks were considered to effectively perform the cooling process of the hybrid system. Since the effective longwave radiation occurred at night, the HRCS perform effectively at this time while the GPCS performs when the dwelling is occupied (Figure 5.37).

The cooling process and mechanism of the HCS as illustrated in Figure 5.37. As a result of the conductive cooling effect, the circulated water blew the black body radiator is cooled to a lower temperature close to the radiator surface temperature (range between 14ºC to 23ºC) according to the clarity of the night sky, ambient temperature, humidity level and the thermal conductivity of radiator surface and PVC pipe. This amount of cold water (450 litters) is stored in thermal storage at certain temperature (usually 18ºC which is 4ºC to 6ºC below the indoor average thermal comfort temperature) which is the ideal standard of water temperature to carry out the HRCS depending on the desired indoor set-point temperature and thermal properties of floor which was already investigated in section 5.2.3.2. Utilising passively cooled water by the effect of night radiative cooling leads to a substantial reduction in total cooling load of the HRCS. In case of peak demand that commonly happened in hot summer season especially when radiator water temperature exceeds the 18ºC and the indoor temperature exceeds the setpoint temperature at 28ºC, an auxiliary low energy DC chiller is combined with the proposed cold-water thermal storage to operate by thermostatic controller. This cold water is pumped into the embedded pipe in the slab through an integrated sensor based control system to adjust the water flow and temperature. The hot water collected in the black body radiator during the daytime is simply stored in hot water tank for domestic use with manifold switching circuits at sundown to the floor cooling loops (Figure 5.37).

The cooling process of GPCS starts usually during the day by drawing the moderate ambient air temperature which is cooled by the effect of adiabatic cooling in the semi-enclosed shaded zone on the ground floor. In this created (microclimate), the air temperature is considerably (4ºC to 9ºC) lower than the ambient outdoor temperature. The influence of adiabatic cooling leads to a decrease in the cooling load of the GPCS. The air is drawn through the ground PVC pipe through a louvred air inlet. The air circulates through the deep ground pipe following the serpentine loop which maximises the loop length for the total area footprint and thus the contact surface for thermal conductivity and heat exchange between the circulated air and the ground soil (Figure 5.37). The air is cooled to a certain temperature close to the average daily ground soil temperature (usually in the range from 25ºC to 28ºC) based on several factors including the ambient temperature, humidity and the thermal properties of ground soil and pipe. Due to the high humidity level and temperature amplitude between the ambient outdoor and ground soil temperatures, the condensation inside the ground pipe is concentrated at the lowest point in the U shape pipe loops where sloped pipes are designed to collect the condensed water in a ground tank (11.4 liter/hr equal 250 liter /day) as a source of clean and relatively cold water that can be used domestically or sprinkled on the shading zone to enhance the adiabatic cooling and irrigate the soil surface for cooling and plant growth (Figure 5.37). The air is then deposited in the plenum tank that houses an integrated chilled coil system as air to water heat exchanger by taking the advantage of the cold water produced by night radiative cooling to cool the air by convection to the desired setpoint temperature at 23ºC. The cooled air is then distributed to indoor volumes through inline central supply fans attached to each unit via supply duct and then to the internal zones through wall vents (Figure 5.37). The air is then exhausted through the hypocaust contained within the TermoDeck® floors/ceiling. The central light well is utilised to efficiently enhance the stack effect and naturally exhaust the hot air from the floors slabs at each levels using inline fans. This negative pressure drives the fresh air intake. (Figure 5.37)

The cooling load and operating time schedule of the proposed HCS is entirely dependent on the required indoor setpoint temperature and supply water temperature. Therefore, these criteria have been considered in setting up the numerical simulation of the proposed HCS, which is extensively investigated, in the following chapter.

However, substitutional scenarios can also be considered particularly for the ground pipe ventilation system by supplying the ground air to indoor spaces via hypocaust floor (TermoDeck®) and taking the advantage of its high thermal capacity. Hence, during the daytime, the cooled supply air could pass through the cores in the slab and as the concrete structure itself is cooled it absorbs the surplus heat generated during the day and the room is kept cold. While at night, the cooled supply air is recirculated in the building cooling down the slab and dissipating the surplus heat stored during the daytime. In addition, when the ambient air temperature can itself meet the cooling requirements of the building (below 28°C) the outside air can be drawn directly into the pipe inlets located at the top of the building and supplied (bypass) through a reversible fans in TermoDeck® to indoor spaces (reversing the base scenario) (Figure 5.38).

However, in some cases supplying air through TermoDeck® may require additional constructional and mechanical works which may increase the system capital cost and thus pay-back period. For instance, central air supply duct needs to be attached to the hypocaust slab with subducts linked with hollow cores where the air is circulated and passed via ceiling diffuser. In addition, this required installing suspended ceilings to aesthetically cover these duct works. Furthermore, since the air supply passes through the hollow cores of the slab, it is difficult to control the air flow and temperature of each zone.

While in the current base scenario, the ventilation system involves supplying cooled air to spaces via low-level wall outlet allows the air to contact with (chilled) floor and local heat sources such as a person and equipment. It is then warmed and rises to the top of the space where it is extracted via a high-level extract system (displacement ventilation) (Figure 5.37). Such ventilation technique relies on buoyancy-driven air movement within a space rather than forced air movement as with a conventional mechanical ventilation system. This approach ensures that the cooling capacity is supplied directly to those parts of a room where it is most needed, moreover, the temperature of the extract air at the ceiling can be allowed to rise above comfortable levels as it is above the occupied zone. The result is that to provide the same cooling capacity the supply air does not need to be cooled as much as it would be in a conventional system due to the displacement ventilation strategy is combined with other cooling systems (chilled floors) for efficient convective cooling and ventilation (Figure 5.37).

Integrating chilled floors with the ventilation system is also advantageous due to its potential to optimise such displacement ventilation approach and enhance stack effect in addition to its efficiency to chill a significant area of building fabric (floors). In fact, chilled floor has more cooling capacity compared to chilled beams or ceilings as the coolant (water pipe loops) are completely embedded in floors at 14°C - 20°C and can efficiently chill building fabric and indoor spaces by radiation and convection especially when integrated with displacement ventilation. Radiant cooling through floors or slabs also has more potential to interact with displacement ventilation than in high-ceiling spaces because it can be used to thermally stratify the space, creating an appropriately conditioned occupied zone near the floor while allowing a potentially vast upper portion of the space to "float" at a much higher temperature. As with the displacement ventilation system, thermal comfort is provided without conditioning the entire space volume. However, chilled beams usually use convective air movement to (mechanically) provide cooling while chilled ceilings transfer cooling mainly by radiation. The advantages of using chilled floor in comparison with chilled ceiling or beams were extensively discussed in section (5.2.2.2).

Additionally, night-time 'purging' can be used to passively dissipate the heat stored in the building fabric to ensure that temperatures can be reduced sufficiently for the next day's use (opening windows during the day will have little effect on the temperatures in such buildings). Purging can be achieved either passively at nighttime by (stack effect) and through ventilation of hypocaust floor voids (TermoDeck®) or mechanically by extracting the heat from (TermoDeck®) or ground pipe via the designed mixed mode inline fans (Figure 5.38).

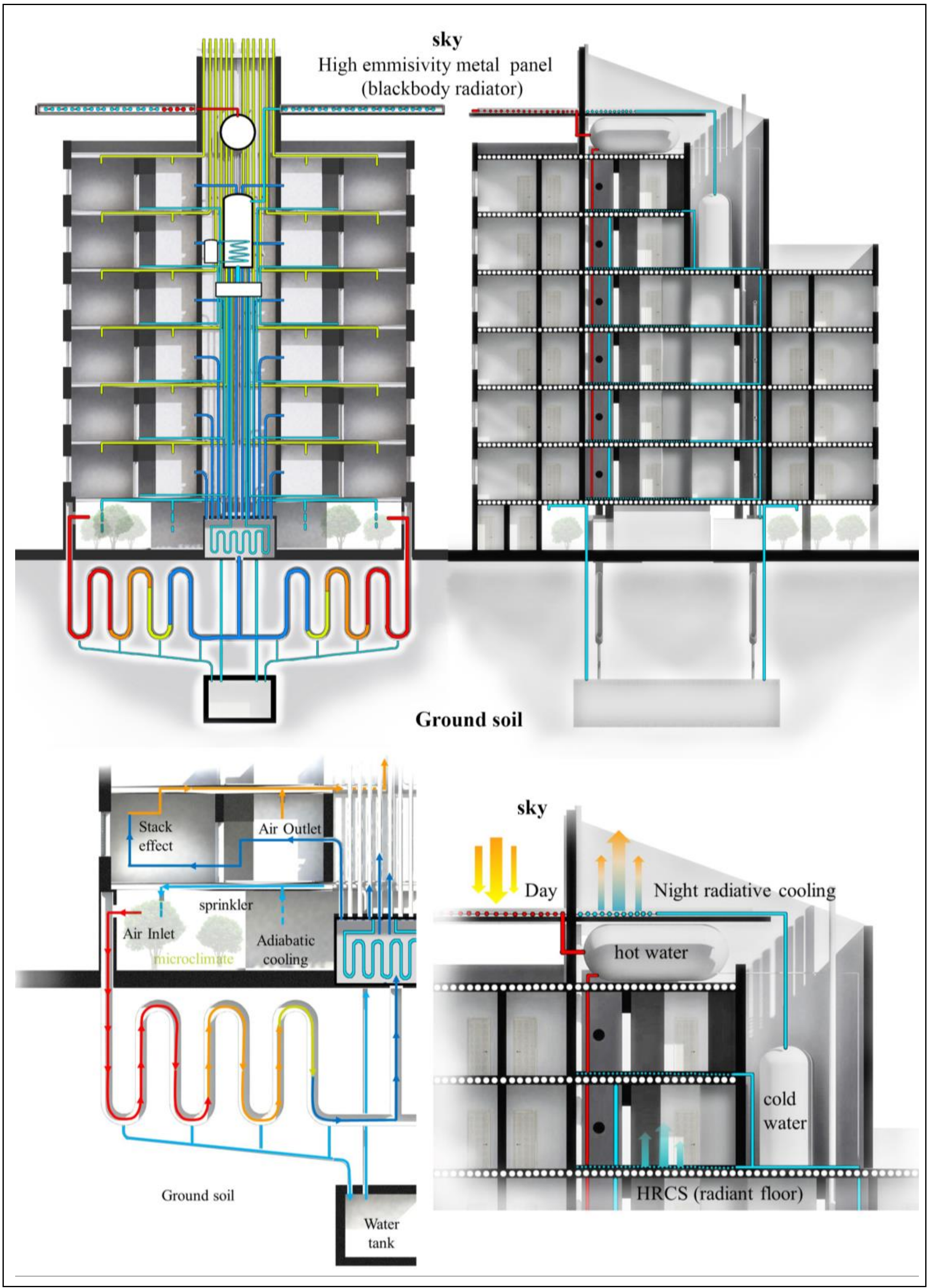


Figure 5.37: Cooling process and mechanism of the integrated HCS.

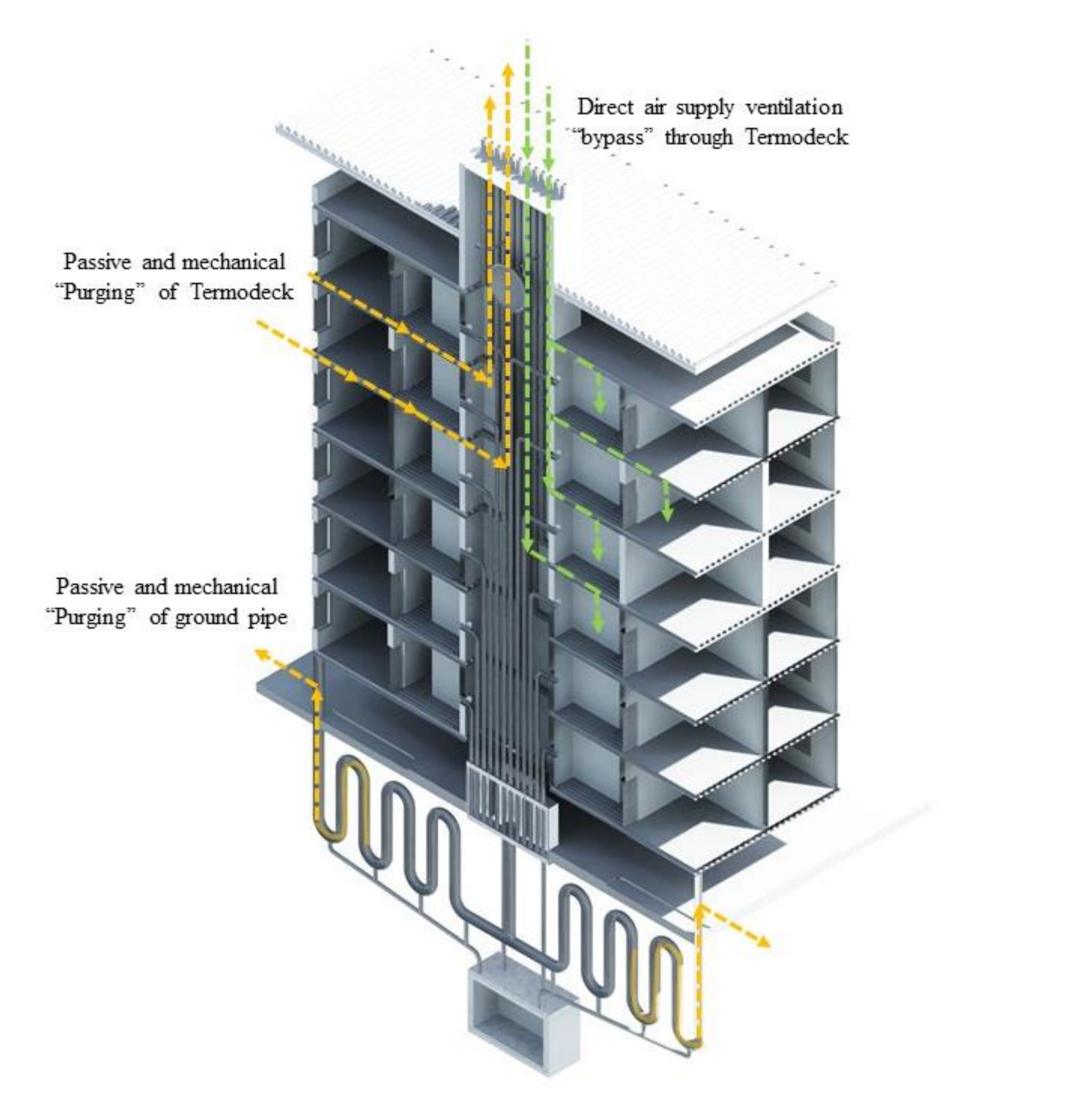


Figure 5.38: Sectional perspective illustrates the substitutional ventilation and purging scenarios of the integrated HCS.

5.3 Conclusion

Based on the analysis results of the simulated baseline thermo-physical and energy performance that conducted in chapter 4 which have demonstrated high energy consumption and cooling loads due to the poor thermal performance of the building fabric. An assessment was made of passive 'fabric first' measures to reduce external and internal heat gains and optimize the thermo-physical performance of building fabric. External walls were thermally improved by hollow clay blocks with 50 mm polyurethane foam insulation. This reduced the U-value from 2.92 to 0.41 W/m^{2}K. Floors and roofs were constructed using 200 mm of hypocaust concrete slabs (TermoDeck®) that produced a U-value of 0.31. To avoid both direct and indirect solar radiation, adjustable horizontal louvres were added to the windows combined with standard 6 mm double-glazing units produced a U-value of 2.5 and reducing heat gain by 50%. To protect the slab from solar heat, 'green' roof was added including vegetation on the ground floor to enhance the adiabatic cooling effect. For lower casual heat gains, all standard Halogen spotlights were replaced with LED lighting systems. Although such passive design and measures have a potential of reducing the latent and sensible building heat gain, PDMs on their own are unlikely to be able to cool the building during the summer months. Similarly, applying natural passive cooling strategies (PCS) such as ventilative, geothermal and radiative cooling systems were individually deficient to provide a constant source of cooling over the year and meet the peak cooling demand of hot summer.

Therefore, the key study in this chapter was focussing on hybridizing passive cooling strategy to be integrated with low energy active cooling technology towards optimising the overall cooling performance. The task involved designing ground pipe supply ventilation integrated with high emissivity blackbody radiator to displace AC system. The GPCS consist of four high-density Polethelyne ground pipes buried at an average of 4 m depth and linked with air supply and exhaust pipes, while the HRCS consist of roof-mounted water-filled corrugated metal panels with a high emissivity surface linked with water pipe loops embedded in floors. The design of such 'hybrid' system required a parametric analysis combined with testing prototypes in field trials to establish actual ground temperatures at various depths and black body emissivity ranges under different sky conditions.

The developed hybrid system design and configurations became the subject of numerical modelling and simulation using DesignBuilder software in conjunction with the EnergyPlus simulation engine to assess its cooling efficiency which was extensively discussed in the following chapter.

6 CHAPTER | Numerical Modelling and Simulation of HCS Application

6.1 Introduction

This chapter casts light on the selected modelling and simulation software DesignBuilder and reviews its features and potentials. DesignBuilder is the graphical tool used to build up the simulation model whereas the simulation engine EnergyPlus is employed to simulate the energy performance of baseline and the retrofitted case study models. The adopted modelling and simulation software provides annual, monthly and hourly data of energy use and temperature. The key inputs of setting up the simulation model include defining the simulation model zone's type, floor areas, occupancy load and environmental control. In addition, the suggested PDMs applications include external walls, floors and roof, fabric insulation together with more efficient external glazing and shading systems are applied to the simulation model in order to enhance the thermo-physical performance of the building fabric. The key inputs of the proposed GPCS and HRCS simulation models were defined including the specification of ground pipe, hydronic tubing, flow rate, chilling efficiency and operation settings, to monitor the impact of the HCS application on building thermal and energy performance. The integrated hybrid system is defined in EnergyPlus simulation model by combining the main features and specifications of the GPCS and HRCS in combination with the applied PDMs through the operation control setting in order to assess the influence of system integration on building cooling performance and indoor condition.

6.2 Overview of Modelling and Simulation Software

Most of building energy simulation programs come with a graphical user interface as well as the actual simulation engine. For instance, the current adopted simulation software DesignBuilder has a Graphical User Interfaces (GUI) where virtual buildings can be modelled with flexible geometry input and extensive material libraries and load profiles. EnergyPlus is integrated within DesignBuilder to carry out complete simulations without leaving the interface (Figure 6.1). The software provides a range of environmental performance data such as annual energy consumption, maximum summertime temperatures and HVAC component sizes (DesignBuilder, 2011).

The U.S. Department of Energy's 3rd generation dynamic building energy simulation engine EnergyPlus is used for modelling building, cooling, heating, ventilating and lighting.

Apart from energy use, the software can be used for load calculations and to model passive applications, natural ventilation, thermal comfort, water use, green roofs photovoltaic systems and it is the capability to calculate the energy savings for the purposes of building energy efficiency. The simulation outputs of EnergyPlus is validated under the comparative standard method of examination for the assessment of building energy analysis software BESTEST/ASHRAE STD 140 (DesignBuilder, 2011).

As a confirmation of its reliability and accuracy, due to limitations in field investigations, the simulation result of baseline electricity consumption and cooling demand conducted in chapter 4 was validated against energy bill data. The compared results indicate that DesignBuilder can predict building cooling load and indoor temperature with an acceptable margin of error. Besides this, referring to the comparison between simulated and measured ground soil temperature, as shown in chapter 5, EnergyPlus data was comparable to the field trial measurements. The following sections discuss DesignBuilder and EnergyPlus modelling and simulation features and capabilities.

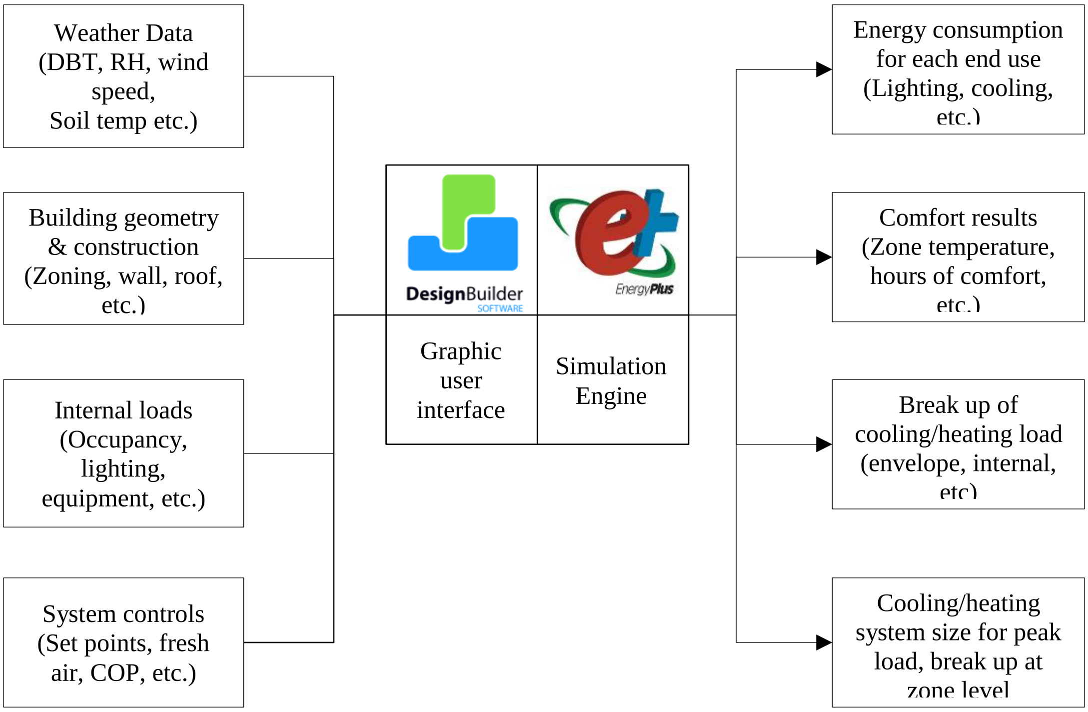


Figure 6.1: Key inputs and outputs of DesignBuilder and EnergyPlus modelling and simulation software (DesignBuilder, 2011).

6.2.1 Modelling and Simulation Features and Capabilities

6.2.1.1 Modelling Tool (DesignBuilder)

In DesignBuilder, complex building shapes can be easily created or modified. Walls, floors, roofs, partitions window constructions are all represented in 3-D. In addition, these model (including BIM models) can be imported from modelling software such as Revit, Microstation, ArchiCAD and SketchUp using gbXML file. Building geometry can be imported from 2-D CAD floor plan data and then traced over within DesignBuilder to create blocks and to partition blocks up into zones. Zone inner geometry is derived accurately from the outer zone volumes using actual construction layer thickness for individual surfaces giving accurate floor areas and zone volumes. Latest ASHRAE worldwide design weather data and locations (4429 data sets) are included with the software and over 3000 EnergyPlus hourly weather files are available free using the DesignBuilder 'Install on Demand' feature. In DesignBuilder Data entry and storage for all environmental calculations including activity, construction, glazing, lighting, and HVAC (DesignBuilder, 2011)

6.2.1.2 Simulation Engine (EnergyPlus)

The EnergyPlussoftware involves running simulations of building models using real hourly weather data to examine how the building would behave under actual operating conditions. The simulation calculates heating and cooling loads using the ASHRAE-approved heat balance method integrated into EnergyPlus algorithms and based on the design weather data profile. EnergyPlus can automatically run multiple simulations automatically adjusting up to two variables to create design curves. Design curves can be very useful at conceptual stages of the design process to understand how building performance is affected by variations. Other key features and capabilities of EnergyPlus simulation engine can be described as below (DesignBuilder, 2011).

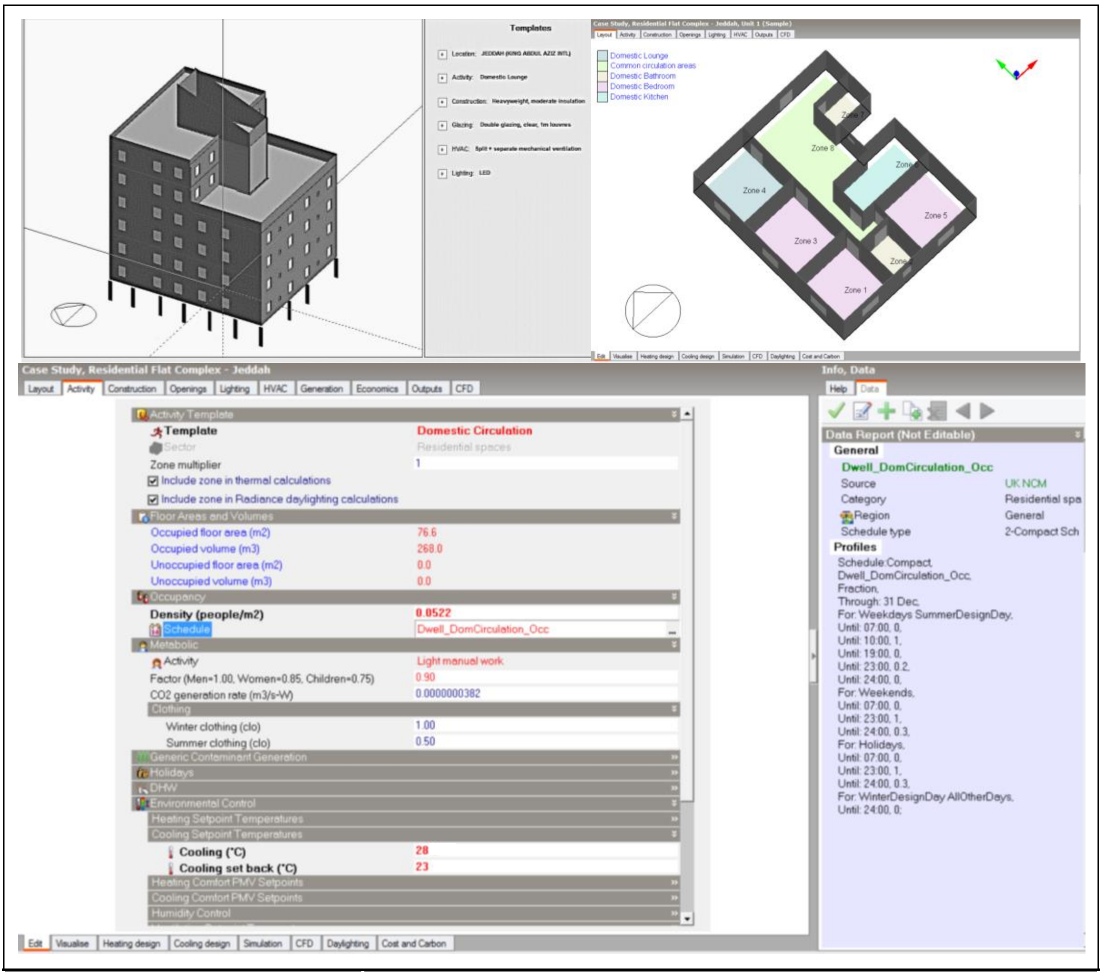
- Monitoring external and internal heat gains and heat transmission through building fabric including walls, roofs, infiltration, internal air, mean radiant and operative temperatures and humidity calculated ventilation.
- Calculating building energy consumption and carbon savings through control of electric lights according to the availability of natural daylight.
- The application of mixed-mode systems with integrated control of mechanical and natural ventilation and thermal simulation of naturally ventilated buildings.

- Dedicated outside air systems (DOAS) can be included with all zone-based systems such as fan coil units, active/passive chilled beams, hot water radiators etc.
- The application of Hybrid hydronic/air systems, radiant chilled/heated floors, ceilings, and panels.
- Examine the effects of design alternatives on the key design parameters such as annual energy consumption, overheating hours and CO_2 emissions.
- Thermal Comfort output based on ASHRAE 55 comfort criteria, Fanger PMV, Pierce PMV ET, Pierce PMV SET, Pierce Discomfort Index (DISC), Pierce Thermal Sens. Index (TSENS) and Kansas Uni TSV.

6.3 General Description of Simulation Model

Building is a complex thermodynamic object that accommodates constantly changing energy flows between the different thermal zones within the building and the outside. The two main components of the building energy simulation model are the building fabric include (walls, floors, ceilings, occupants, and equipment) and the plant components (HAVC equipment and other active or passive condition control systems). Due to the complexity of virtually applying and examining the effect of PDMs and HCS in the current study, computer simulations can analyse the effects of such applications and their complex interactions more efficiently, comprehensively and accurately than any other available method. Therefore, simulation is an appropriate tool to understand what it would be like to live in a building that has not yet been built. Simulation tools can examine how different design decisions will interact and affect outcomes. This knowledge can be used to refine the design and systems.

Since the current baseline case study model of a residential block in Jeddah is relatively large and complicated to be simulated as one model, it was appropriate and more accurate to examine the thermal and energy performance of each flat as an individual case study and then multiply the results by the number of flats in the building. As illustrated in Table 6.1, the eight zones flat layout was computationally modelled by DesignBuilder. The primary setting up of the simulation model required the definition of activity level (Table 6.1). Activity templates are used as a source of default activity data for building models which allow the operator to define the activity of the zones including data covering zone type, floor areas, occupancy, metabolic rates and environmental controls including cooling set-point and set-back temperatures which are set up according to the adaptive thermal comfort level in mixed or naturally ventilated buildings outlined in section 2.3.3 of chapter 2.



Key inputs	Data
Location	Jeddah – Saudi Arabia
Floor Area	76.6 m^2
Volume	268 m^3
Zone Number	8 Zones
Occupants	5 people – density (0.065 per m²) (Occupancy time schedule as illustrated in the description above)
Activity	Residential unit – light manual work
Metabolic factor	Factor average (0.9) (Mon 1.0 – women 0.85 – children 0.75)
Indoor environmental control	Cooling temperature (set-point 28ºC – set-back 23ºC)

Table 6.1: key data inputs and definitions of the retrofitted case study building model.

6.4 Key Features and Specifications of HCS Simulation

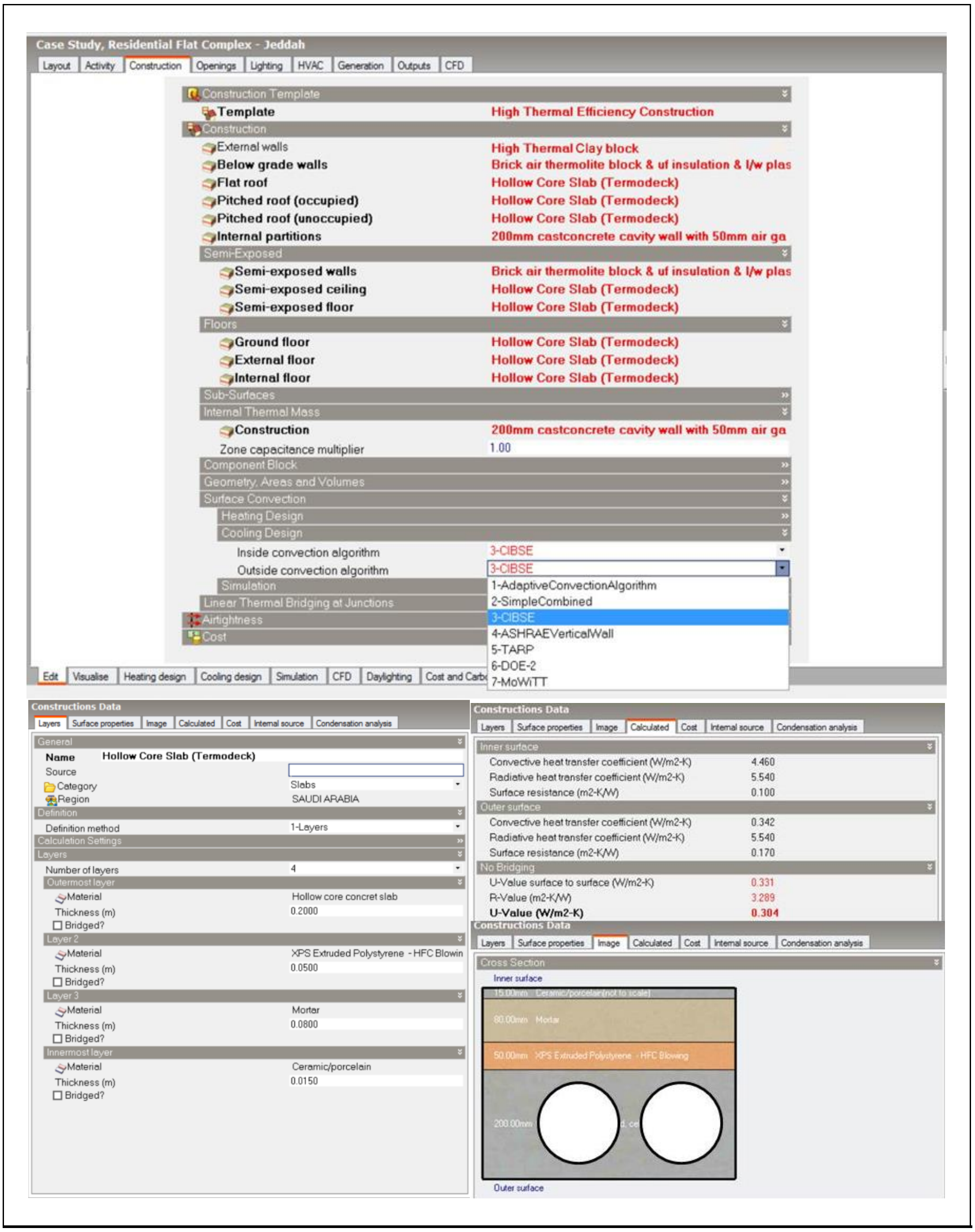
6.4.1 PDMs Simulation Model Setting-up

The applied PDMs involve improving the thermal insulation of external walls, floors, and roof, together with more efficient external glazing and shading systems to efficiently minimise the indoor heat gains and optimise the cooling potential of the applied cooling system. The following sections involved computationally setting up the proposed PDMs in EnergyPlus simulation model.

6.4.1.1 Building Fabric and Thermal Mass

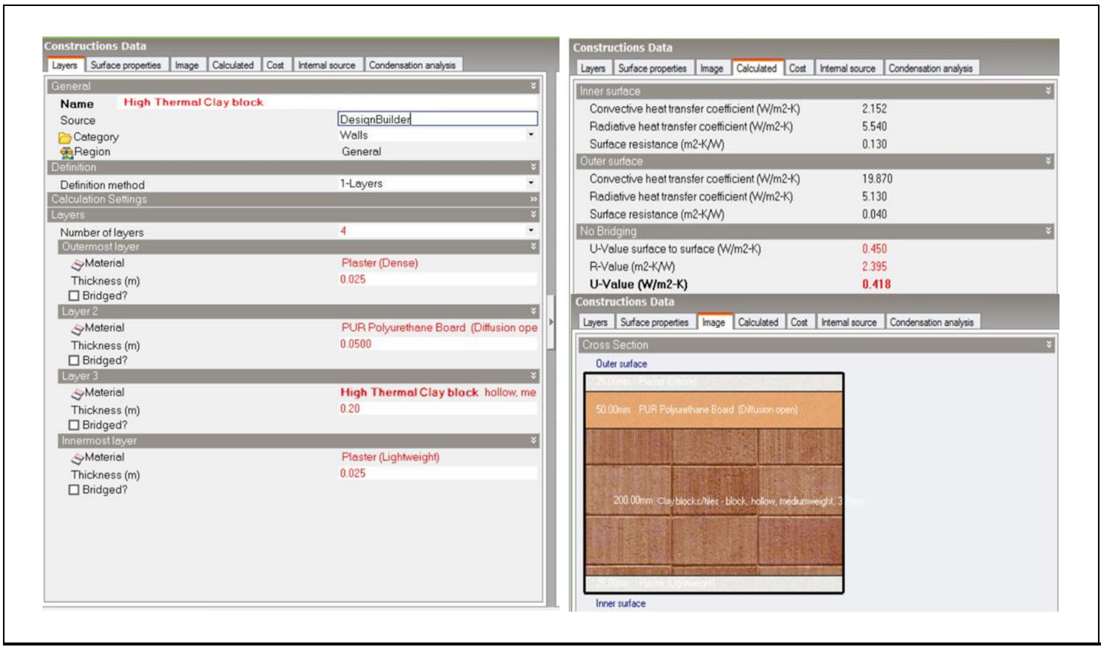
DesignBuilder uses construction components to model the conduction of heat through walls, roofs, ground and other opaque parts of the building envelope. As illustrated in Table 6.2, the proposed specification of building construction incorporating PDMs was set up in the DesignBuilder software system as the data input of the simulation model. According to the suggested PDMs application in section 5.2.1.6 of chapter 5, The wall specification was retrofitted to 50 mm Polyurethane Foam Board (PUR) insulation on 200 mm hollow clay blocks (Ziegel) with a 25 mm lightweight polymer render and heat reflective white mineral paint to increase the Albedo effect. This reduced the U-value from 2.92 to 0.41 W/m^{2}K. Floors and roof construction used 200 mm hollow core pre-cast concrete slabs (TermoDeck®) topped with 80 mm of the concrete screed, 50 mm of Polystyrene Insulation Boards (XPS) insulation and 20 mm white ceramic tiles, that produced a U-value of 0.31 W/m^{2}K, representing an improvement in thermal resistivity of 87%. (XPS) insulation was also added to the roof deck and the soffit of the ground floor ceiling (Table 6.3).

As a part of the influence of the thermal mass, green roofs have been shown to have a significant effect in reducing building solar heat gain. EnergyPlus provides a physical and quantitative building energy simulation tool that represents the influence of the construction of green roof and facilitates the fast spread of green roof technique and account for green roof benefits in related energy efficiency standards such as LEED. Green roofs can be modelled in DesignBuilder by creating a roof construction using a green roof material as the outer layer. Thermally, the model of a green roof in EnergyPlus considers the long and short wave radiative exchange within the plant canopy, the effects of Plant canopy on convective heat transfer, the evapotranspiration from the soil and plants, and heat conduction in the soil layers (DesignBuilder, 2011).



	Components	Thickness (m)	Density (Kg/m³)	Thermal transmittance (U-value -W/m²K)
Floor and Roof	Ceramic Tiles	0.015	2300	78.66
	Mortar	0.08	1800	14.40
	Extruded Polystyrene Boards (XPS)	0.05	38	0.760
	Hollow Core Concrete Slab	0.20	1550	6.50
	Total			0.304

Table 6.2: Basic setting of floors and roofs construction specification and thermal properties of the retrofitted simulation model.

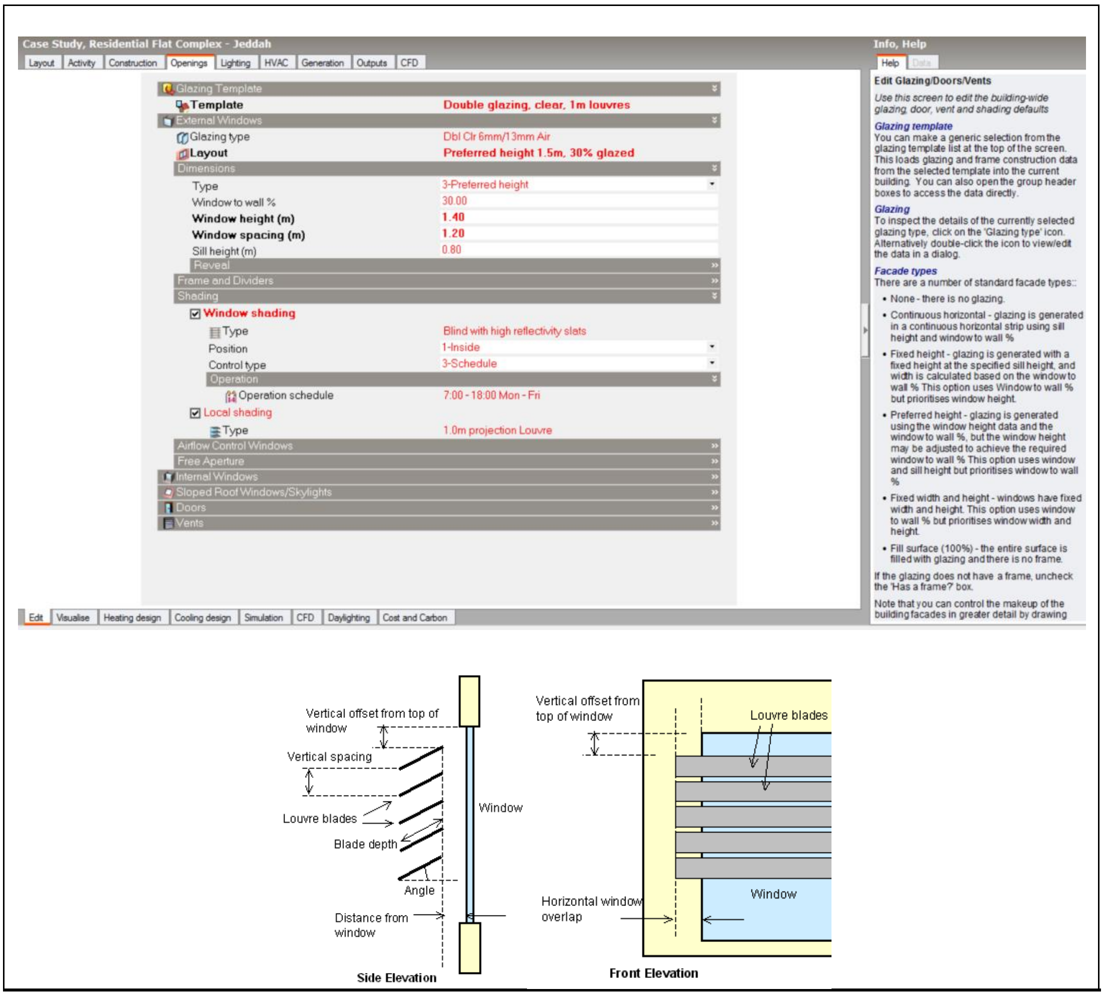


	Components	Thickness (m)	Density (Kg/m³)	Thermal transmittance (U-value -W/m²K)
External Walls	Plaster	0.025	1600	24
	Hollow clay blocks (ziegel)	0.20	1400	4.5
	Polyurethane Foam Board (PUR)	0.05	0.75	0.89
	Plaster (dense)	0.025	2600	24
	Total			0.418

Table 6.3: Basic setting of walls construction specifications and thermal properties of the retrofitted simulation model.

6.4.1.2 Window Glazing, Shading, and Lighting Systems

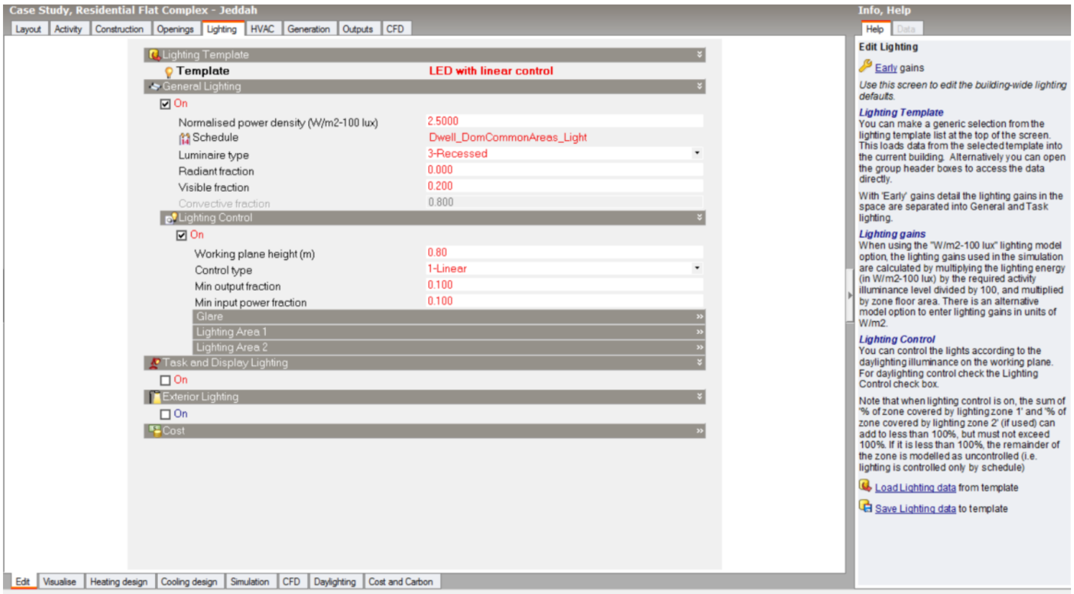
In DesignBuilder, the key specifications of window modelling including dimensions, frame, glazing, shading, and operation schedule. According to the suggested PDMs, to avoid direct, indirect and low-angled sun radiation and solar heat from different directions, an adjustable horizontal louvred shading device (0.10 SC) was employed to automatically control sunlight level and providing privacy and security for the interior while protecting heat gain. In addition, standard 6 mm thick double clear glazing window units with a U-value of circa 2.5 W/m^{2}K were incorporated to shield the interior from the direct solar heat (Table 6.4).



Components	Specifications
Opening size	1.5 m heights × 1.0 m width
Glazing	Double – 30% clear - U-value of 2.5
Shading	Louvres – 0.5 projection -0.10 SC
Operation Schedule	(Daily from 7.00am – 18.00pm)

Table 6.4: Basic setting of window glazing and shading systems of the retrofitted simulation model.

According to the proposed PDMs outlined in chapter 5, in a current simulation model of the modulated case study building all floodlight lamps (Halogen and Fluorescent) were replaced with LEDs (Table 6.5). The actual lighting heat gain can be calculated by dividing the W/m^2/100 lux data by the required luminance level as detailed on the activity tab. The operation control of lights is according to the availability of natural daylight. When lighting control is switched on, luminance levels are calculated at every time step during the simulation and then used to determine the savings in lighting energy, however, the reduction of lighting energy depends on daylight luminance level, luminance set point, a fraction of zone controlled and type of lighting control (Table 6.5).



Standards	Specifications
Lighting type	LED lighting system
Lighting power density (W/m²-100 Lux)	2.5000
Lighting control	Linear
Minimum input and output fraction	0.1

Table 6.5: Basic setting of the lighting systems of the retrofitted simulation model.

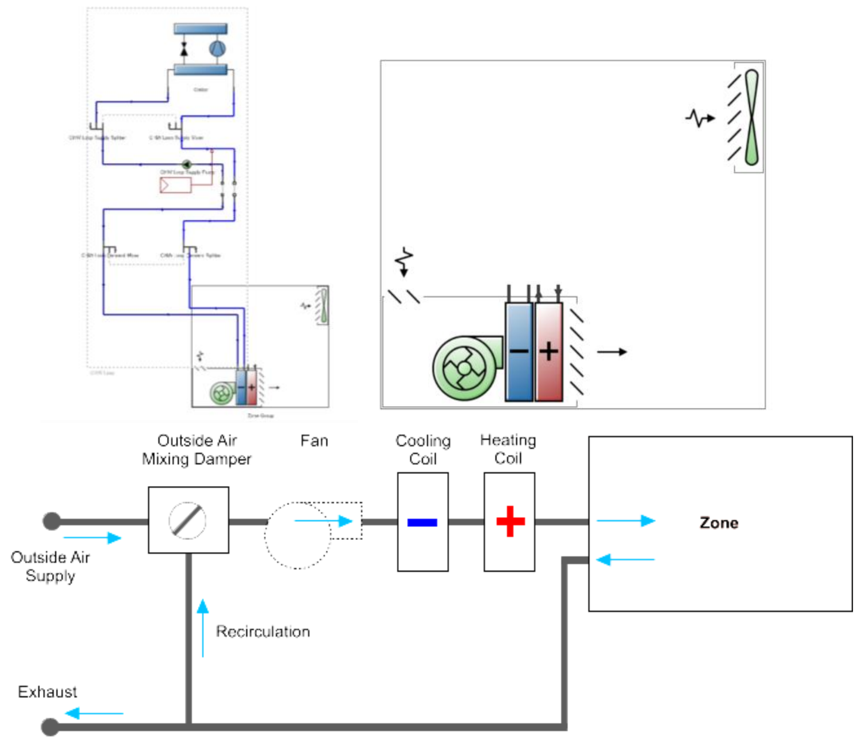
6.4.2 GPCS Simulation Model Setting-up

The GPCS simulation model which originally coupled with PDMs was set based on the results of the analytical and parametrical study of the proposed GPCS design discussed in chapter 5. The key specification of the main components of GPCS was applied and set up in EnergyPlus simulation model in order to examine the thermal impact and of GPCS application on the energy and thermal performance of baseline simulation model. As shown in Table 6.6, the setting up of GPCS simulation model includes defining the cooling operation control including the set-point and set-back temperatures of the selected building zone simulation model and other key inputs related to GPCS such as soil condition and the physical and thermal specifications of the ground pipe and air flow coefficient (Table 6.7).

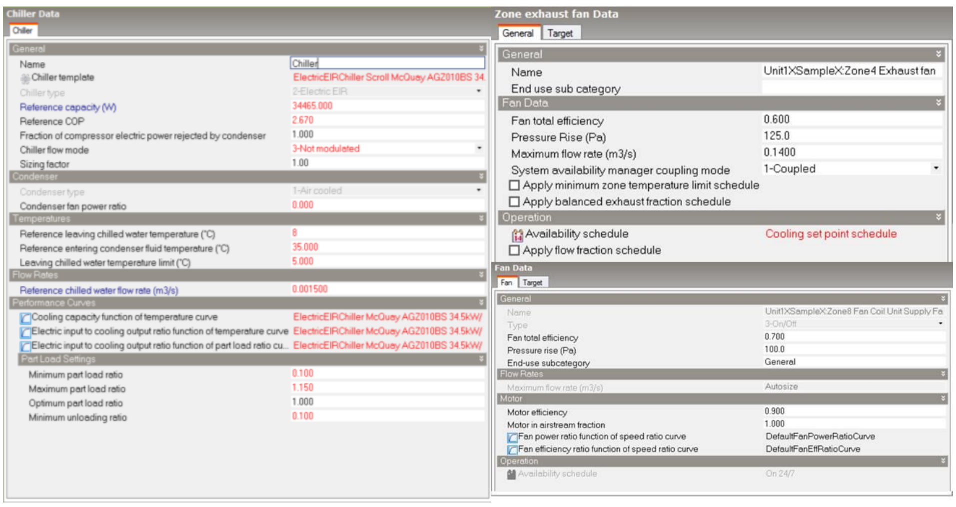
Setting up the simulation model of the proposed GPCS application considered the application of the fan coil unit with operation control to represents the proposed plenum air tank with chilled water coils (thermal storage) in EnergyPlus simulation model. The employed fan coil unit is connected to chilled water loop through its cooling coil and linked to supply and exhaust fans (Table 6.6). As illustrated in the schematic design of the GPCS, the central supply inlet is placed in the living zone of each flat. This open common space, which links the internal spaces with each other through the corridor that allows the air to smoothly circulate through the flat zones via doors and wall vents. In addition, each flat zone has an exhaust fan to extract the air via the hypocaust floor slabs to vertical ducts in the lightwell/central service duct. The cooling operation schedule was used in conjunction with the cooling set-point and set-back temperatures that sit on the activity tab to define the timeframe of cooling set-point schedule in the zone. Controlling the operation of the GPCS through a schedule and through the specification of minimum, maximum, and delta temperatures (the temperature difference in °C between the indoor and outdoor air dry-bulb temperatures). Chiller automatically runs when the zone air temperature is above 28°C, however, if the zone air temperature drops below 23°C, then the chiller is assumed to be automatically turned off. Also, the chiller operates when the supply water temperature is above the 8ºC temperature difference required to cool the space.

In EnergyPlus the ground pipe system can be defined in various ways. Options include "Natural" ground pipe where outside air naturally flows through the pipe into the building with no fan energy consumption as opposed to the "intake" option that allows a fan to be employed to draw the air through the ground pipe with a defined set of values based on the required air volume and flow rate.

The proposed GPCS simulation model comprises four high-density polyethylene pipes with a diameter of 0.4 m, 32 m in length and buried to an average depth of 4 m. Four air intake fans with fitted dust filters can deliver up to 2000 l/s; over twice the recommended air intake rate of 800 l/s for 100+ occupants. Setting up the key specifications of the ground pipe such as pipe radius, thickness, length, and depth plays a significant role in determining the amount of heat transferred from the surrounding soil to the pipe and the air passing through the pipe. As illustrated in Table 6.7. Two input fields that relate to the ground soil condition and soil temperature are required to be defined in order to determine the thermal diffusivity and thermal conductivity of the surrounding soil thereby determine the cooling efficiency of the GPCS. For soil conditions, the actual condition of the soil is defined as heavy and saturated while the annual average soil surface temperature was set at 27ºC with seasonal temperature amplitude of 5.6°C according to the result of the field experiments reported in chapter 5.

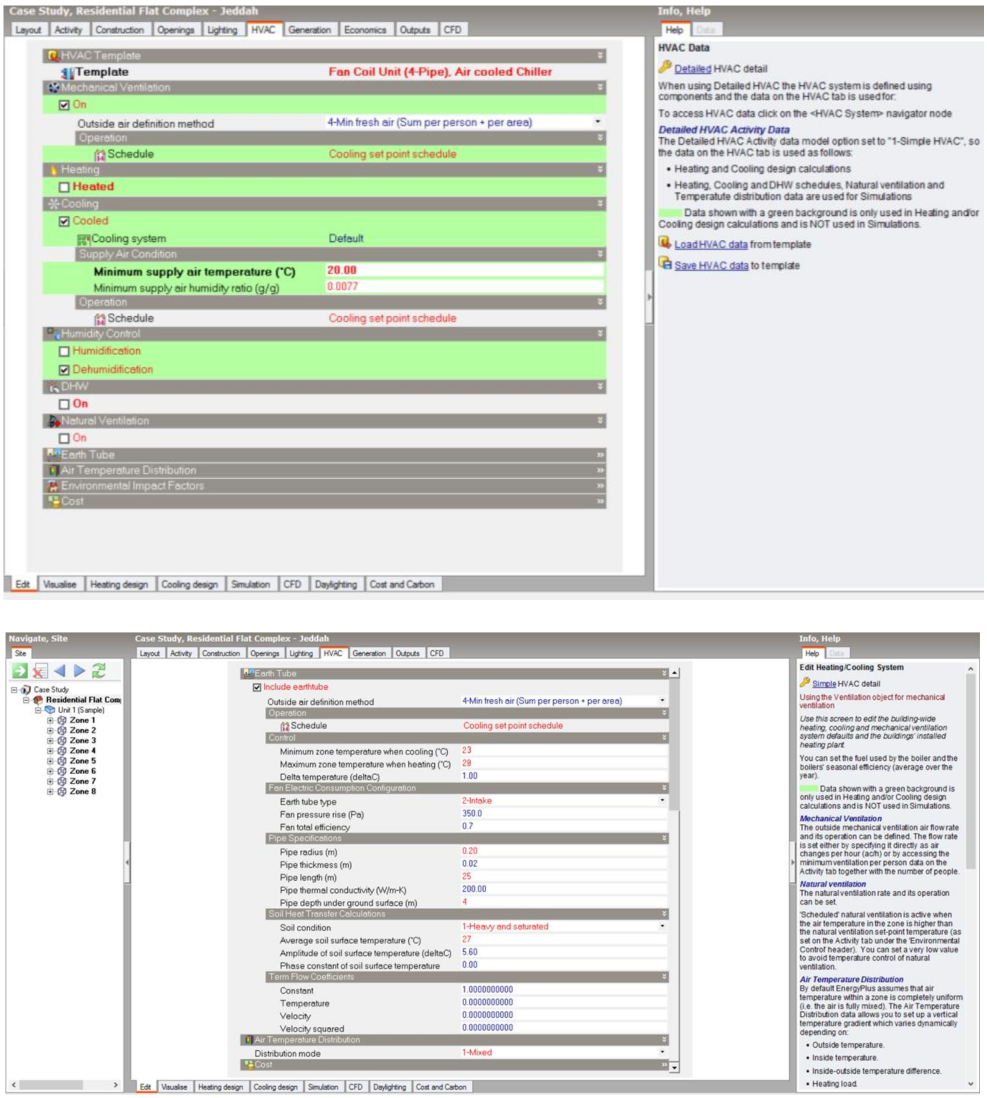


The proposed fan coil unit specification and air flow schematic.



Standard	Inputs	Standard	Inputs	
Chiller capacity (W)	34465	Fan systems	Supply	Exhaust
Chiller (COP)	2.67	Pressure rise (Pa)	100	125
Leaving chilled water temperature (°C)	8	Maximum flow rate (m^3/s)	0.25 (Autosize)	0.14
Entering condenser fluid temperature (°C)	35	Efficiency	0.7	0.6
Chilled water flow rate (m^3/s)	0.0015	Operation control	Cooling set-point schedule	

Table 6.6: Setting up the fan coil-cooling unit of the GPCS simulation model.



Standards		Specifications
Cooling setpoint temperature (ºC)		(set-point 28ºC – set-back 23ºC)
Earth tube type		Intake
Central Supply fan flow, pressure and efficiency (Pa)		0.15 m³/s - 350Pa - 0.7
Pipe	Pipe radius (m)	0.10
	Pipe thickness (m)	0.02
	Pipe length (m)	25
	Pipe thermal conductivity (W/m-k)	200 (PVC pipe thermal properties)
	Pipe depth (m)	4
Soil	Soil condition	Heavy and saturated
	Average soil temperature (ºC)	27
	Amplitude of soil temperature (ºC)	5.60
	Phase constant of soil temperature (ºC)	0
Air Flow	Constant	1
	Temperature (ºC)	0
	Velocity (m/s)	0

Table 6.7: Basic setting of GPCS simulation model components and specifications.

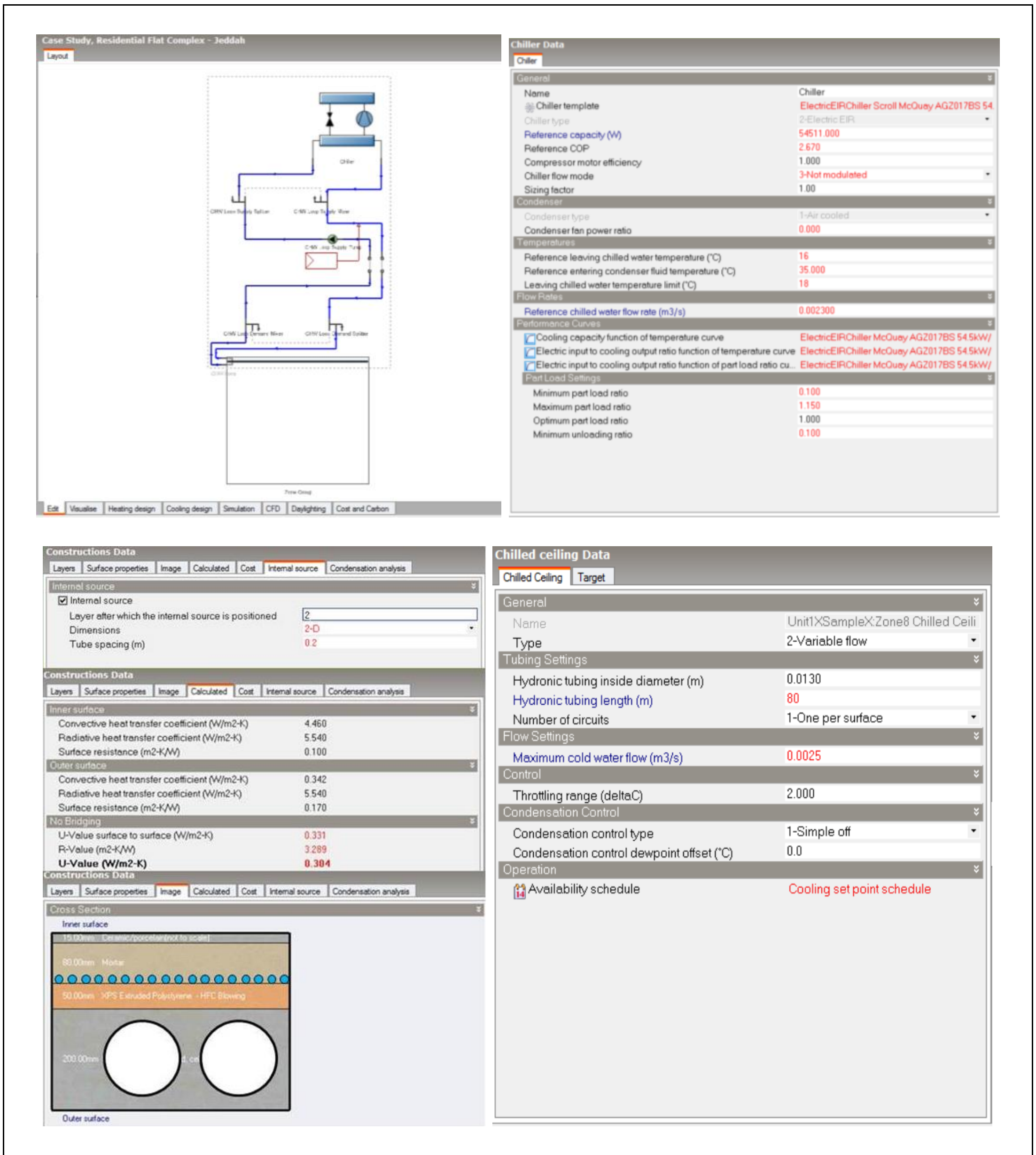
6.4.3 HRCS Simulation Model Setting-up.

The task was then to model the HRCS system coupled with PDMs. The suggested system is a low temperature hydronic radiant system with chilled water pipes embedded in the floor construction (Table 6.8). In DesignBuilder, two types of chilled floor or ceiling are available in HVAC, which is, constant flow and variable flow. In the chilled floor constant flow, the water flow rate is kept constant by the use of a local circulation pump and varies with the water temperature. This is achieved using a mixing valve controlled by a sensor (Table 6.8). In addition, this type of chilled floor has a built-in secondary loop to recirculate the flow coming out of the system and mixes this with the flow from the loop to arrive at the required inlet temperature.

This chilled floor model has the temperature sensor positioned after the local secondary pump to ensure appropriate inlet temperature to the floor. The hydronic pipe setting involves defining the inside diameter through which water is circulated to determine the convective heat transfer from the water to the inside surface of the pipe in addition to the total length embedded to determine the effectiveness of heat transfer from the fluid being circulated through the tubes and the tube/surface. Longer tubing lengths result in more heat transfer from the radiant surface to the circulating fluid.

Another key input is the number of circuits to allow the program to divide the surface into multiple parallel hydronic circuits based on the circuit length. The corresponding options are one per surface to model the system as a single circuit or calculate from circuit length to model the system as multiple circuits the water flow setting in EnergyPlus includes the maximum flow rate of water through the chilled floor or ceiling. This flow rate is constant by the local component pump; however, there is an option of manipulating the pump efficiency value in decimal form (0 = 0%, 1 = 100%) (Table 6.8).

As proposed in the schematic design of HRCS, the hydronic pipe is embedded in the floor of the living zone and the corridor of each unit. The system was set up as shown in (Table 6.8) which illustrates the properties of the main components that include chiller and tubing model. Setting up the system operation control is based on the set-point (control) and water schedules; this setting allows specifying how the chilled floor is to be controlled. The temperature denoted in the set-point schedule can refer to one of five different temperatures include the zone mean air temperature, mean radiant temperature, operative temperature, outdoor dry-bulb temperature, or the outdoor wet-bulb temperature (Table 6.8). The system operation is controlled by the set-point temperatures that set up based on the indoor operative temperature, which is the average of air temperature, and radiant temperature. When the control temperature is higher than the set point (operative 28°C) temperature, then the inlet water temperature is set to be low water temperature. While if the control temperature is below the set point (operative) temperature, then the system will be turned off and the water mass flow rate will be zero. If the control temperature is within the comfort zone between the set point and set back temperatures (23 to 28°C), then the inlet water temperature is linearly interpolated between the high and low water temperature (Table 6.8).



Standards	Specifications
Chiller capacity (W)	54511
Chiller (COP)	2.67
Leaving chilled water temperature (ºC)	16
Entering condenser fluid temperature (ºC)	35
Chilled water flow rate (m^3/s)	0.0023
Water flow type	Constant flow
Pump flow rate schedule	Cooling set-point schedule (operative temperature)
Pump head (Pa)	75000
Pump power consumption (W)	50
Motor efficiency	0.9
Hydronic tubing diameter (m)	0.013
Hydronic tubing length (m)	80
Number of circuits	1-One per surface as a single circuit

Table 6.8: The basic setting of HRCS simulation model specifications and water flow schematic.

6.4.4 HCS Simulation Model Setting-up

Setting up the simulation model of the hybrid system involved the integration of both ground pipe and hydronic radiant systems modules and operation control settings and in combination with the suggested PDMs. As a result of the hybridization process, the system produces a highly dynamic set of thermal interfaces that are difficult to model with any degree of accuracy. It is likely that the additional surface area and air turbulence provided by the hypocaust slabs will allow greater 'coolth' storage particularly when nights are clear. Increasing the rate of flow at these opportunities could see an increase in 'coolth' delivery, effectively chilling a large thermal mass (floors and walls) that sit at the core of the block. The simulations may, therefore, underestimate the thermal capacitance of the hypocaust TermoDeck® system to store 'coolth'. Installing CO_2 sensors will also allow the ground pipe supply ventilation rate to be reduced when any flat is unoccupied. Although requiring control systems to modulate fan and pump rates, the software is unable to model such intelligent feedback loops and may, therefore, be underestimating the hybrid systems potential to suppress peak summer temperatures

As illustrated in Figure 6.2, the recommended integrated system specification and the cooling process schematic considering the operation control of both cooling systems. Setting up the proposed HCS in EnergyPlus as a mixed mode cooling system by integrating both the GPCS and HRCS scenarios alongside with the applied PDMs system (Figure 6.2). In order to computationally define and set up the process and mechanism of the HCS as proposed in chapter 5, a few modifications in the system components and simulation model were required.

The cooling capacity of HRCS relies on the radiative night cooling effect of the blackbody radiator, which determines the water temperature, thereby affecting the chiller operating hours. Setting up and modelling such a technique in DesignBuilder is a complicated process, however, this cooling energy can be mathematically calculated based on theoretical equations as carried out in chapter 5, which found that the circulated water below the radiator is relatively close to the radiator surface temperature (range between 14ºC to 23ºC approximately 7ºC to 12ºC below the night ambient temperature) according to the clarity of the night sky, ambient temperature, humidity level and the thermal conductivity of radiator surface and PVC pipe. The inlet water temperatures determine the actual chiller load. The cooling process of the GPCS is reliant on the chilled water coil system, as the air to water heat exchanger takes advantage of the cold water produced by either the HRCS night radiative cooling effect or the chiller coupled with the hydronic cooling system in case of peak demand.

Therefore, the chiller load is combined with both systems to ensure that a backup system is available during temperature peaks.

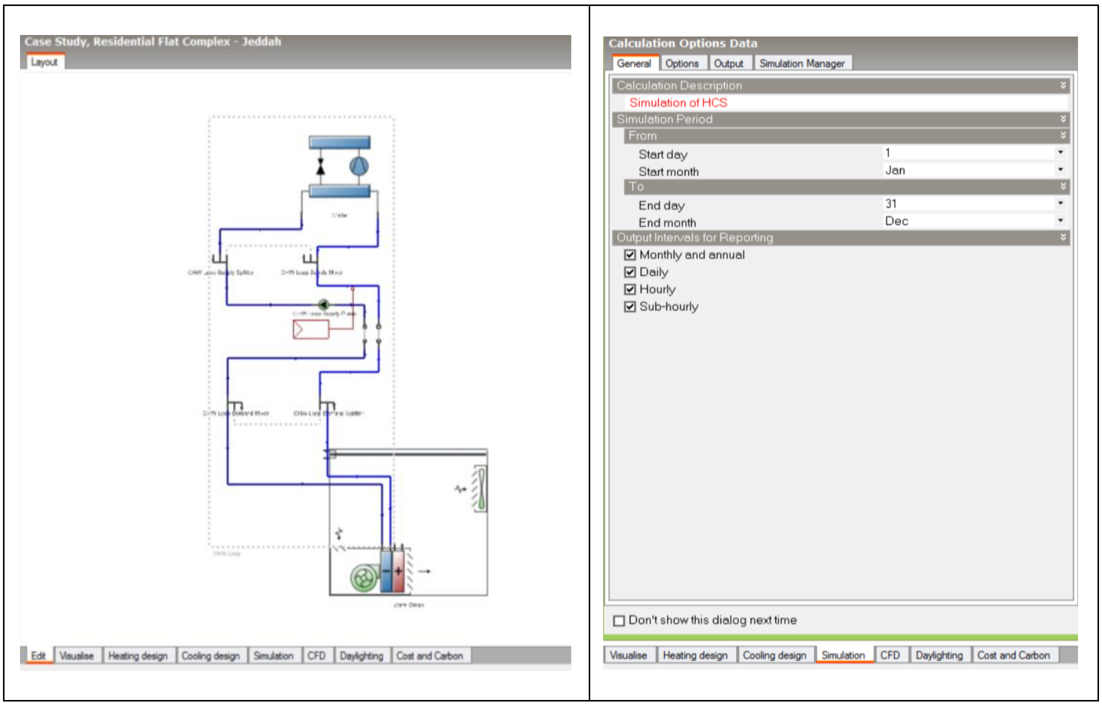


Figure 6.2: Basic setting and schematic simulation model of the integrated HCS.

6.5 PDMs Applications Simulation Results

6.5.1 The Effect of Thermal Capacitance and Retrofitting Insulation

Based on the simulation results of the retrofitted case study model, the following analysis represents the impact of implementing PDMs on the floors and roofs cooling loads in comparison with the baseline case. The simulation results of the PDMs demonstrate their effectiveness in reducing the cooling load. The outcome shows that the cooling loads were substantially minimised due to the effect of PDMs. Figure 6.3 illustrates the hourly cooling load of the simulated building on a typical summer day (15^{th} - 18^{th} July 2016). The outcome shows that the cooling load was considerably reduced especially in the peak time between (07.00 am to 19.00 pm). The maximum hourly cooling load reduction was from 21.4 kW to 12.9 kW (39.72%) monitored at 13.00 pm (15^{th} of July), while the total daily cooling load reduction was 83 kW/day (33.66%) with an average hourly load of 6.93 kW/h compared to 10.35 kW/h in the baseline.

Figure 6.4 represents the monthly cooling load saving of the simulated floors and roofs model in comparison with baseline. The findings demonstrate the thermal influence of the applied PDMs on total building thermal performance. The major reduction was predominantly demonstrated in the peak summer period between May and October with an annual reduction of 28947 kWh/year (32.60 %) and an average monthly reduction of 2412.25 kWh/month. Since the floor thermal performance represents a key factor in domestic cooling load, optimising the thermal capacity results in a substantial saving of total building cooling energy.

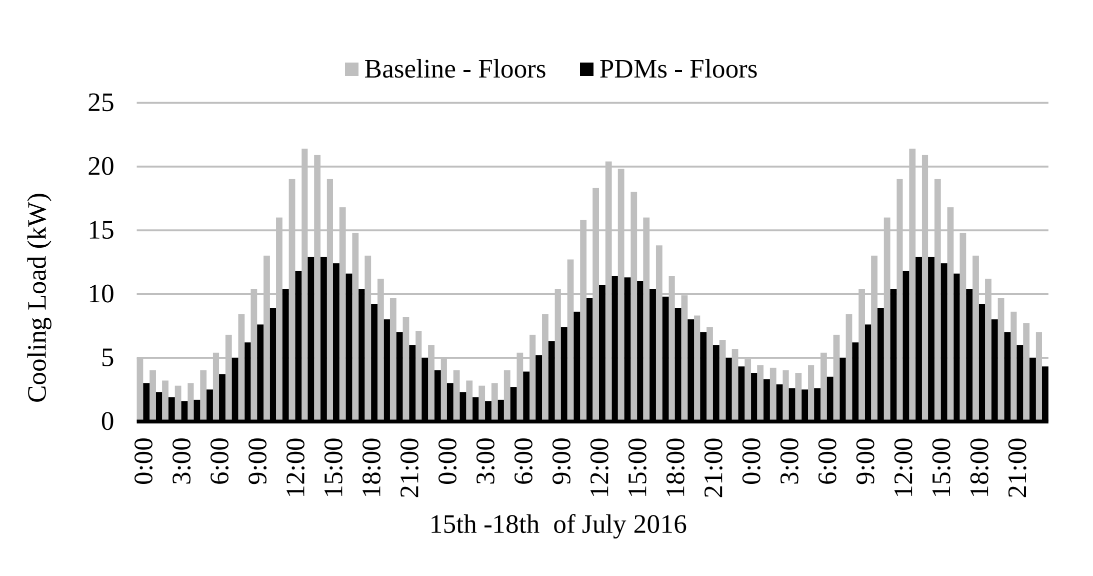


Figure 6.3: Hourly cooling load of floors and roofs PDMs compared to baseline

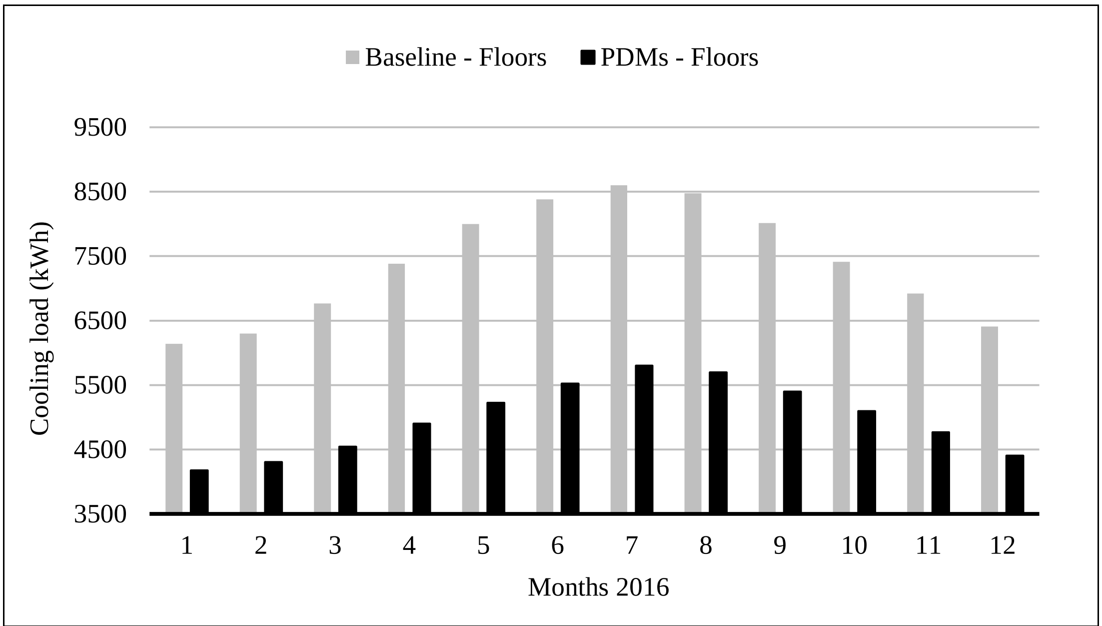


Figure 6.4: Average monthly cooling load of floors and roofs PDMs in comparison with baseline.

According to the simulation results which demonstrate the impact of the applied wall's PDMs on cooling load in comparison with the baseline, PDMs demonstrates its efficiency in minimizing the wall's cooling load. Figure 6.5 shows the hourly cooling load of the simulated building in typical days of the mid-summer (15th - 18th July 2016). The outcome records indicate that the walls cooling load were expressively reduced particularly in the peak daytime between 07.00 am to 18.00 pm. The uppermost reduction rate in cooling load was monitored in the period between 10.00am and 14.00 pm due to the high temperature and heat gain with total daily reduction of 316.2 kW/day (32.45%) and an average hourly cooling load of 28.60 kW/hour compared to 40.68 kW/hour in the baseline.

Figure 6.6 illustrates the monthly cooling load saving of the simulated PDMs wall model in comparison with baseline. The results emphasize the thermal impact of the proposed PDMs on walls thermal performance in comparison with baseline. The reduction predominantly occurred in the peak summer period between May and September with an annual reduction of 49840 kWh/year (26.70%) with monthly average reduction of 4153.33 kWh/month. Since the baseline simulation results have indicated that, walls formed around 40% of the total cooling load, the current thermal retrofitting of walls as a result of PDMs application consequently influence the total building cooling load.

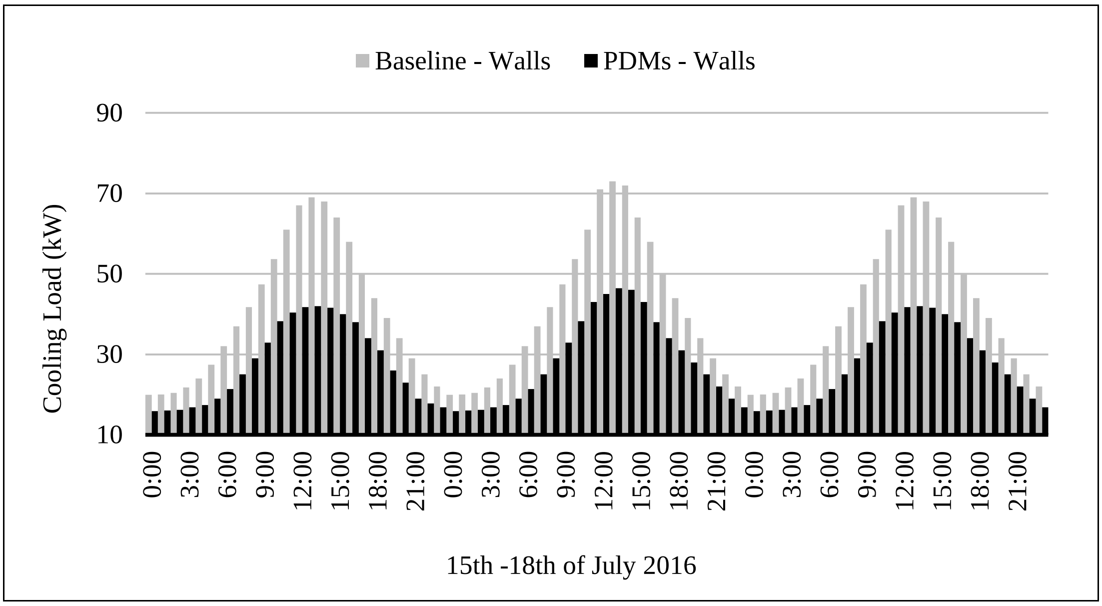


Figure 6.5: Average hourly cooling load of wall's PDMs compared to baseline.

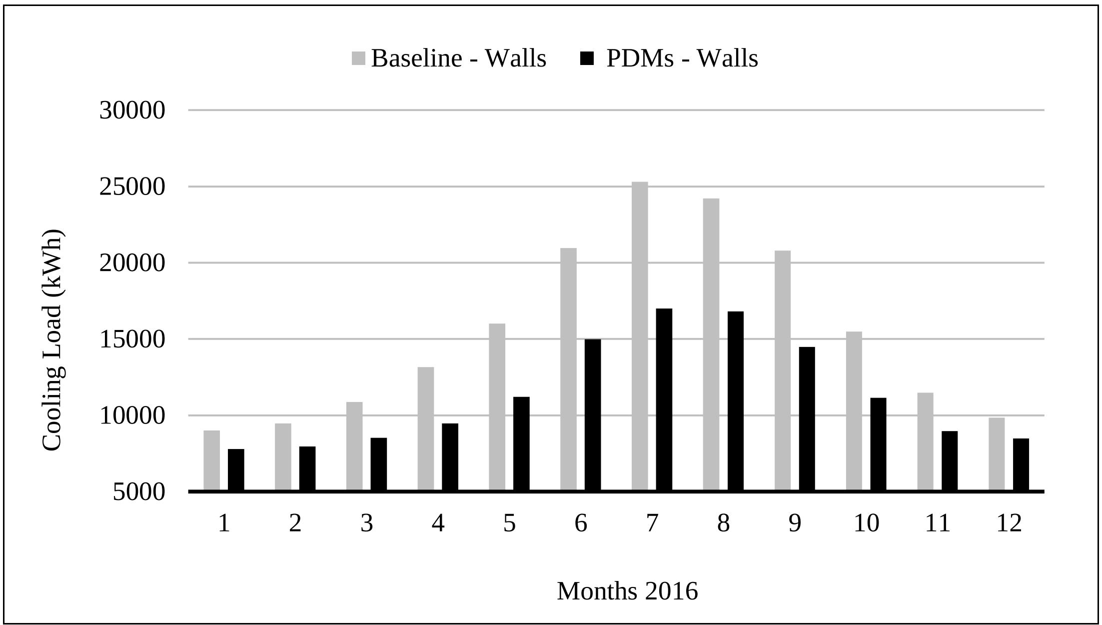


Figure 6.6: Average monthly cooling of wall's PDMs load in comparison with baseline.

6.5.2 The Effects of Window Glazing and Shading

The simulation results of the proposed window PDMs confirm their influence on lowering heat gain. The simulation findings highlight the influence of optimising window thermal performance through glazing and shading systems which show a significant reduction in cooling load. Figure 6.7 illustrates the hourly monitored cooling load of the simulated building in typical days of the mid-summer (15th- 18th July 2016). The results demonstrate that window driven cooling load was reduced in the peak time period between 07.00 am to 18.00 pm due to the high daylight solar radiation and heat gain. The maximum reduction level in cooling load was monitored during the period between 10.00 am and 14.00 pm with daily total reduction of 55 kW/day (27.75%) and an average hourly load of 5.23 kW/hour compared to 7.25 kW/hour in the baseline.

Figure 6.8 illustrates the average monthly cooling load saving of the simulated window PDMs model in comparison with baseline. The results demonstrate the thermal effect of the suggested PDMs on window thermal performance in comparison with baseline. This produced an annual total reduction of 15164 kWh/year (27.20%) and an average monthly reduction of 1263.66 kWh/month. The thermal performance of window glazing and shading has a significant impact on reducing heat gain and cooling load and consequently the total building cooling energy used.

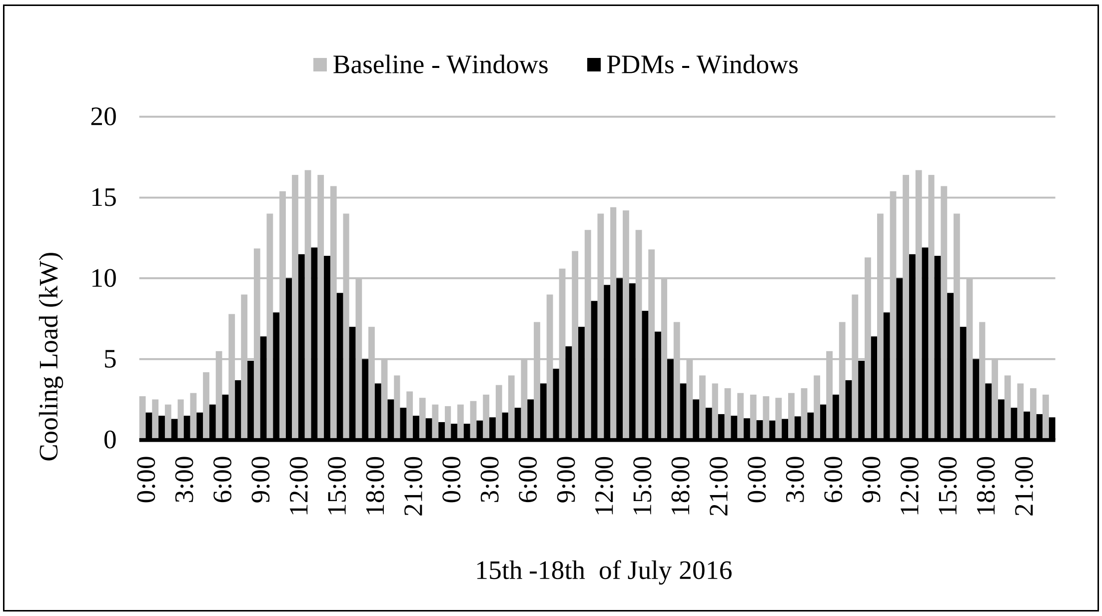


Figure 6.7: Hourly cooling load of the simulated windows PDMs model in comparison with baseline.

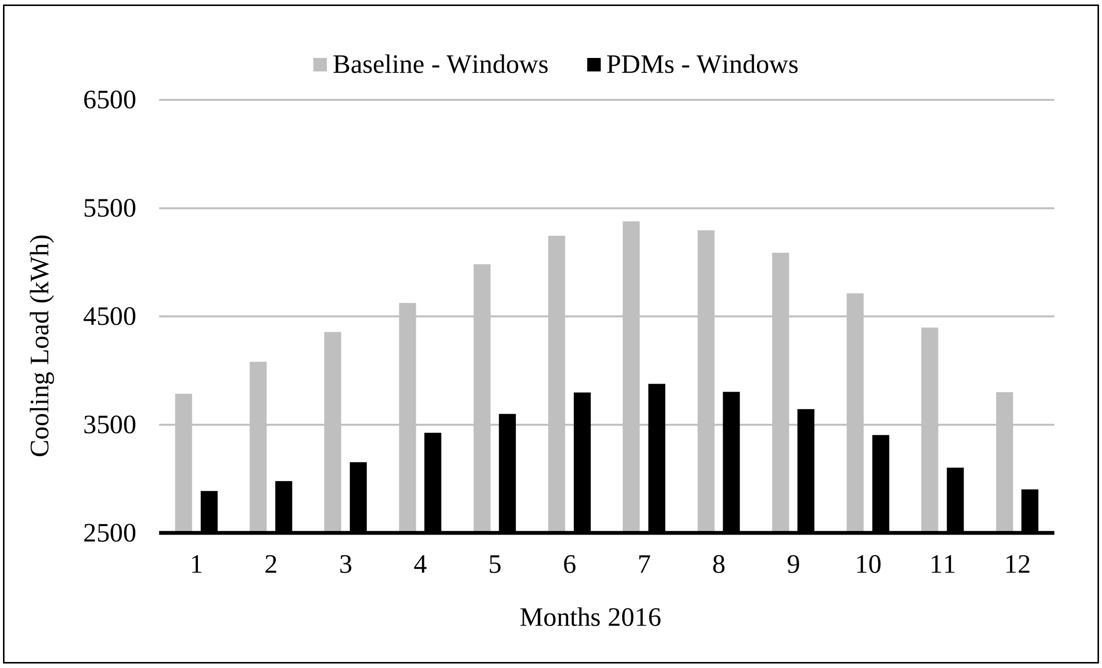


Figure 6.8: Average monthly cooling load of the simulated windows PDMs model in comparison with baseline.

6.5.3 The Effects of Lighting System Modification

The simulation results of the retrofitted model with an LED lighting system, demonstrated a significant thermal influence in reducing cooling load. The findings emphasise that utilising the LED lighting system enhanced the thermal performance of lighting system, which led to a significant saving in lighting associated cooling load. Figure 6.9 indicates the hourly cooling load of the retrofitted LED lighting cooling load in comparison with baseline Halogen lamps in typical summer days (15th - 18th of July 2016). The results show that the monitored lightings cooling load was reduced during the peak occupancy between 14:00 pm until 23:00 am. The uppermost reduction level in cooling load was observed at 15:00 pm with daily recorded total reduction of 64 kW/day (44.44%) and an average hourly load of 3 kW/hour compared to 5.7 kW/hour in the baseline.

Figure 6.10 illustrates the average monthly cooling load saving of the applied LED lighting simulated model in comparison with baseline. The results demonstrate the thermal effect of the proposed LED on indoor thermal performance in comparison with baseline due to its lighting efficiency with lower heat gain. The total annual saving of lighting cooling load as result of upgrading the traditional Halogen lighting system with highly efficient LED lighting is approximately 18954 kWh/year (40.60%) with an average monthly reduction of 1579.5 kWh/month. The thermal performance of the applied LED lighting system has a significant effect in reducing lighting cooling load.

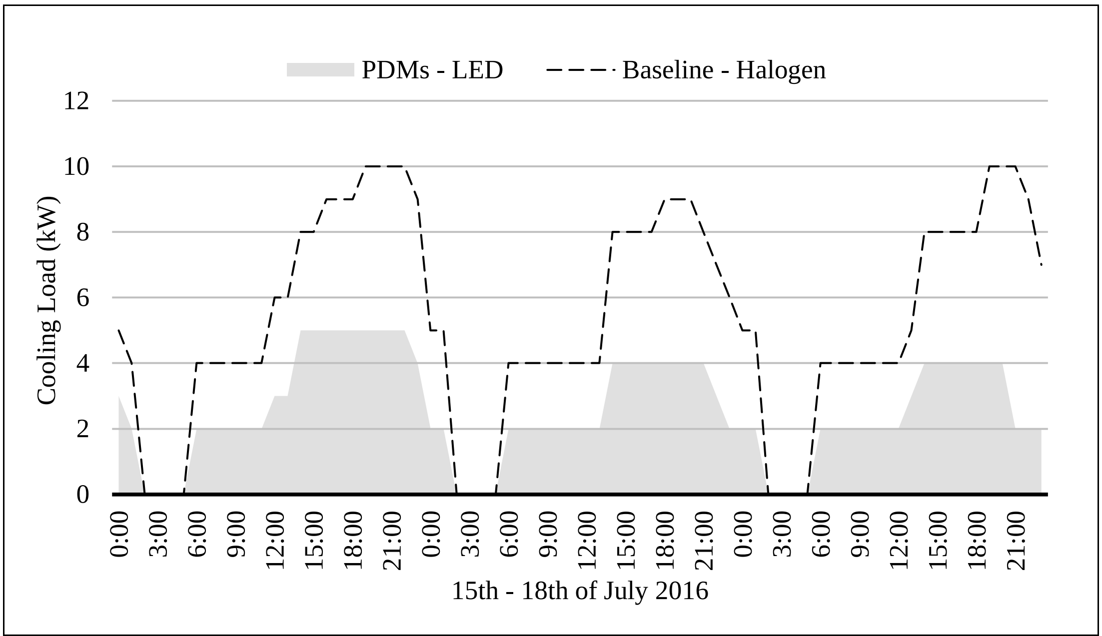


Figure 6.9: Average hourly cooling load of LED lighting system in comparison with baseline Halogen.

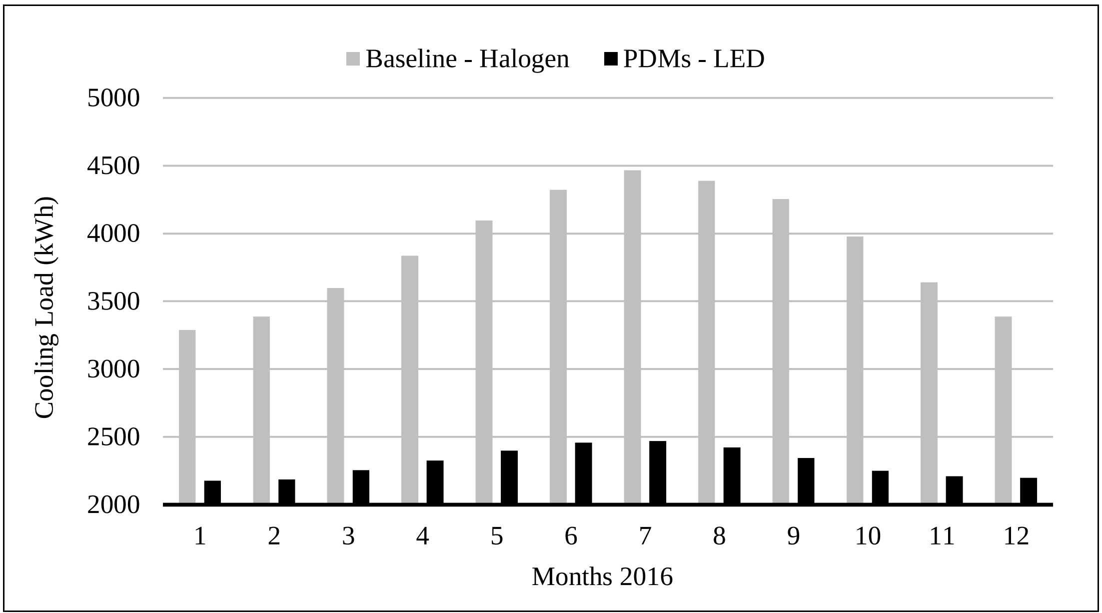


Figure 6.10: Average monthly cooling load of LED lighting system in comparison with baseline Halogen.

6.5.4 PDMs Energy Saving Potential

Overall, enhancing the thermal performance of building fabric through adopting 'fabric first' thermal retrofitting approach and PDMs such as external insulation, solar shading, additional vegetation, increasing the 'Albedo' effect and a high level of thermal inertia using hypocausts encapsulated in the concrete floors TermoDeck® were able to save a substantial percentage of the baseline cooling load. Figure 6.11 indicates the hourly cooling load of the retrofitted model in comparison with baseline in typical summer days (15th - 18th of July 2016). The results show that cooling load was significantly reduced during the peak occupancy hours between 14:00 pm until 23:00 am. The uppermost reduction level in cooling load was observed between 12:00 to 15:00 pm with daily recorded total reduction of 26 kW/day (40%) and an average hourly load of 39 kW/hour compared to 65 kW/hour in the baseline (Figure 6.11).

The holistic comparison of PDMs against baseline as tabulated in Figure 6.12 shows that PDMs were able to save around 36.60 % of the baseline AC cooling demand. This displaced over 170946 kWh/year of AC cooling energy with a peak monthly saving during July of around 40% and an average monthly reduction of 14245.5 kWh/month (Figure 6.12).

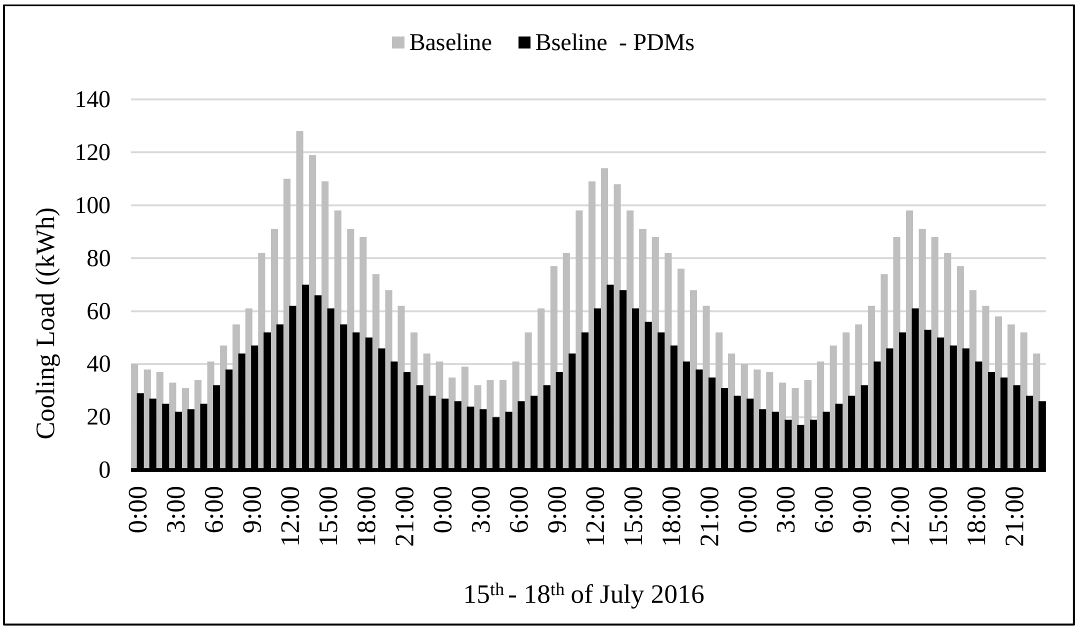
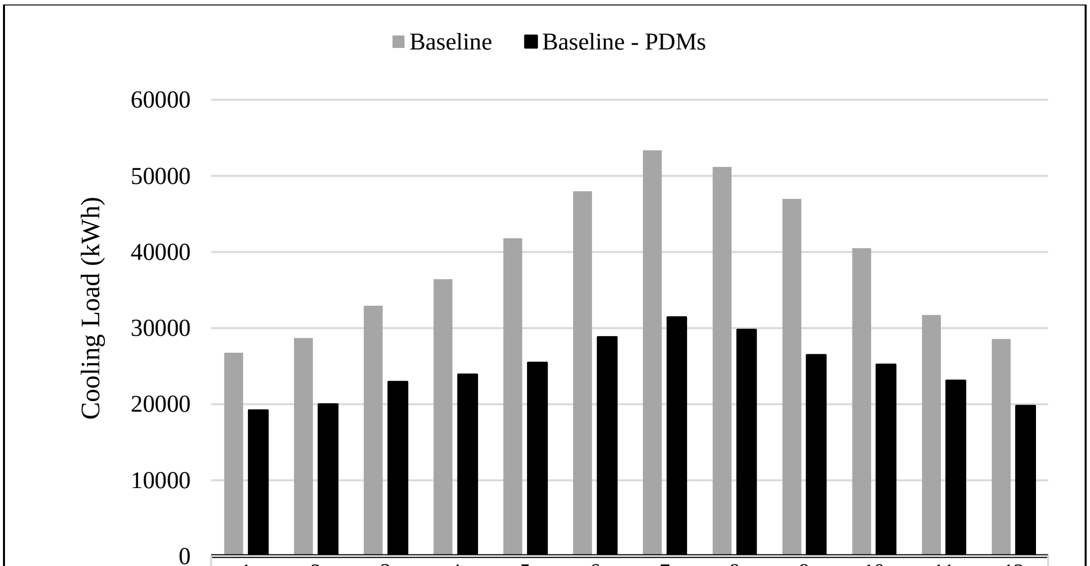


Figure 6.11: Hourly cooling load of the simulated PDMs model in comparison with baseline.



	1	2	3	4	5	6	7	8	9	10	11	12
Baseline	26754	28701	32955	36428	41820	47986	53363	51172	46990	40501	31715	28582
Baseline - PDMs	19180	19978	22947	23894	25440	28798	31440	29797	26470	25187	23091	19799

Figure 6.12: Monthly cooling load of the simulated PDMs model in comparison with baseline.

Although PDMs were able to save a considerable percentage of the baseline AC cooling energy, such passive measures can also enhance the thermal capacity and performance of the applied hybrid cooling system (GPCS and HRCS). However, before considering hybrid system application, an assessment was made of PDMs combined with 420 m^2 of roof-mounted PV panels. The intention of proposing such scenario was to determine the AC energy saving potential as result of applying such integrated simple system (PDMs with PV) compared to the baseline model. As observed in section 5.2.3.2 of chapter 5, the estimated energy supply of the current 30 m² PV panels is around 5936 kWh/year, hence, installing 420 m^2 of PV panels (circa 70% of the roof area) could generate an average annual energy of 83104 kWh/year. This generated solar energy represents only around 18 % of the total baseline AC annual cooling energy use (466967 kWh) beside the accounted PDMs energy savings percentage, the total annual AC cooling demand can be reduced by 55 % from 466967 kWh/year in the baseline to 212921 kWh/year (Figure 6.13).

Although, such integrated system might be simple and has a potential to reduce more than half of AC cooling demand, however adopting such system means that the total dependency on active mechanical air conditioners will continue without considering the initial cost, thermal comfort and air quality. This gives greater justification for adopting other passive and hybrid cooling systems that have a higher energy saving potential and provide sufficient year-round thermal comfort condition with acceptable air quality.

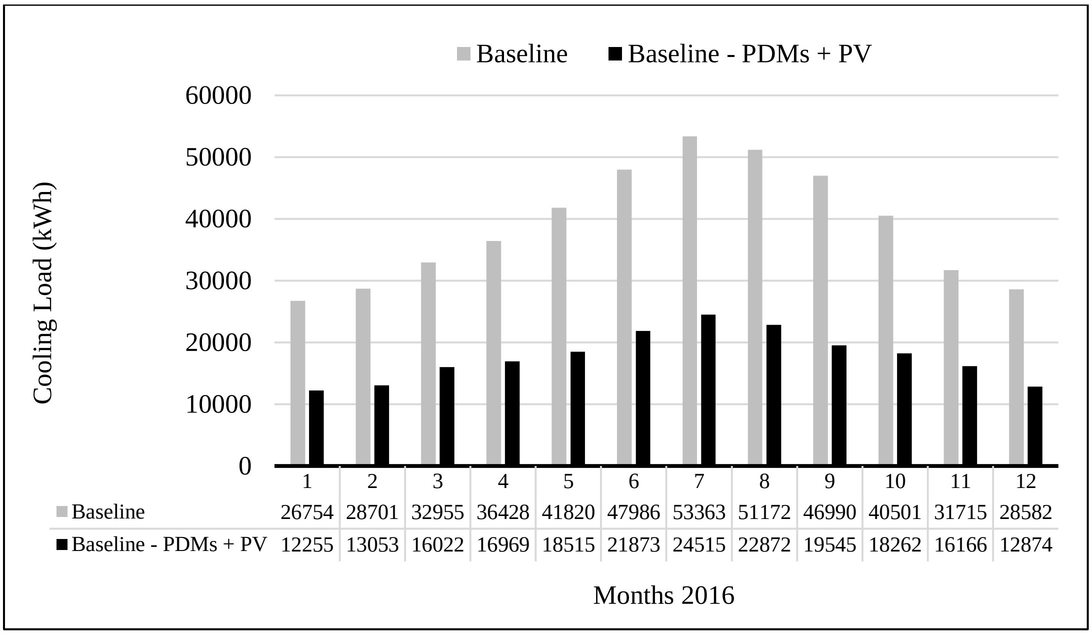


Figure 6.13: Monthly cooling load of the simulated model of PDMs integrated with PV in comparison with baseline.

6.6 HCS Applications Simulation Results

6.6.1 The Effect of GPCS Application

The task of the following assessment is to determine whether the ground pipe supply ventilation operating in concert with the thermal inertia of the 'fabric first' passive measures, can deliver sufficient 'coolth' to 'heat flush' and maintain internal temperatures below the upper threshold for adaptive comfort (28°C). As previously noted in chapter 5, the GPCS simulation model is initially coupled with the proposed PDMs. Also, low energy chiller system was incorporated to run at peak demand to supply the fan coil system. The chiller runs automatically when internal temperatures exceeded the required thermal comfort level. The cooling load of the proposed chiller is calculated as shown in the graph (Figure 6.14).

Based on the numerical simulation process of the applied GPCS model, the initial findings of the applied system demonstrate its efficiency in cooling the building and maintaining the desired indoor thermal comfort condition throughout the year.

As illustrated in Figure 6.14, the primary results of the simulated GPCS on a typical mid-summer day (15^{th} July 2016) show that the hourly cooling energy of the simulated system was varied according to the indoor and ambient temperatures. The total cooling energy use of the applied system including the utilised chiller load was determined according to the setting of GPCS operation control and set-point and set-back temperatures. The peak daily cooling energy usage recorded was 28.50 kW recorded at 13.00 pm while the lowest load was 5.7 kW monitored at 05.00 am. The total daily cooling load including chiller load was 314.88 kW and an average hourly cooling load of 13.12 kW with the high intensity of cooling load in the period between 08.00 am and 19.00 pm, which synchronizes with the chiller operating hours (Figure 6.14).

Correspondingly, on monthly scale, the cooling load of the simulated system including chiller load varies based on the seasonal temperature amplitude between summer and winter. As can be seen in Figure 6.15, the total annual cooling energy usage of the applied GPCS system is almost 66909 kWh/year and an average monthly load of 5575 kWh/month with high intensity of chiller load in the summer period between May and October. As a result, the highest monthly cooling load monitored was in July at 7966 kWh, while the lowest load was in January at 3970 kWh.

Since the GPCS inlet pipe was placed in the shaded area, the GPCS air inlet temperature was considerably lower than the actual ambient temperature, especially during the daytime peak period between 07.00 am to 19.00 pm during the hot summer season, due to shading from the sun angle. Consequently, this decrease was reflected on the outlet and indoor temperatures and system cooling load. Figure 6.14 shows the hourly minor temperature amplitude between pipe outlet and indoor temperatures (0.5ºC) at early morning periods with a gradual increase of 3.2ºC in the afternoon and early evening due to the effect of solar and internal gains. The indoor temperature was maintained over the day within the thermal comfort range between 23ºC and the upper limit at 28ºC indicated by the dotted line in the graph. The maximum hourly indoor temperature recorded was 27.9ºC at 13.00 pm while the minimum temperature was 26ºC at 00.00 am with an average daily temperature of 27ºC (Figure 6.14).

On monthly scale, the figures show that the seasonal temperature amplitude was maintained over the year within the thermal comfort range. The maximum average monthly indoor temperature was in July at 27.80ºC while the average minimum indoor temperature was in January at 24.5ºC with an average monthly temperature of 26.16 ºC (Figure 6.15).

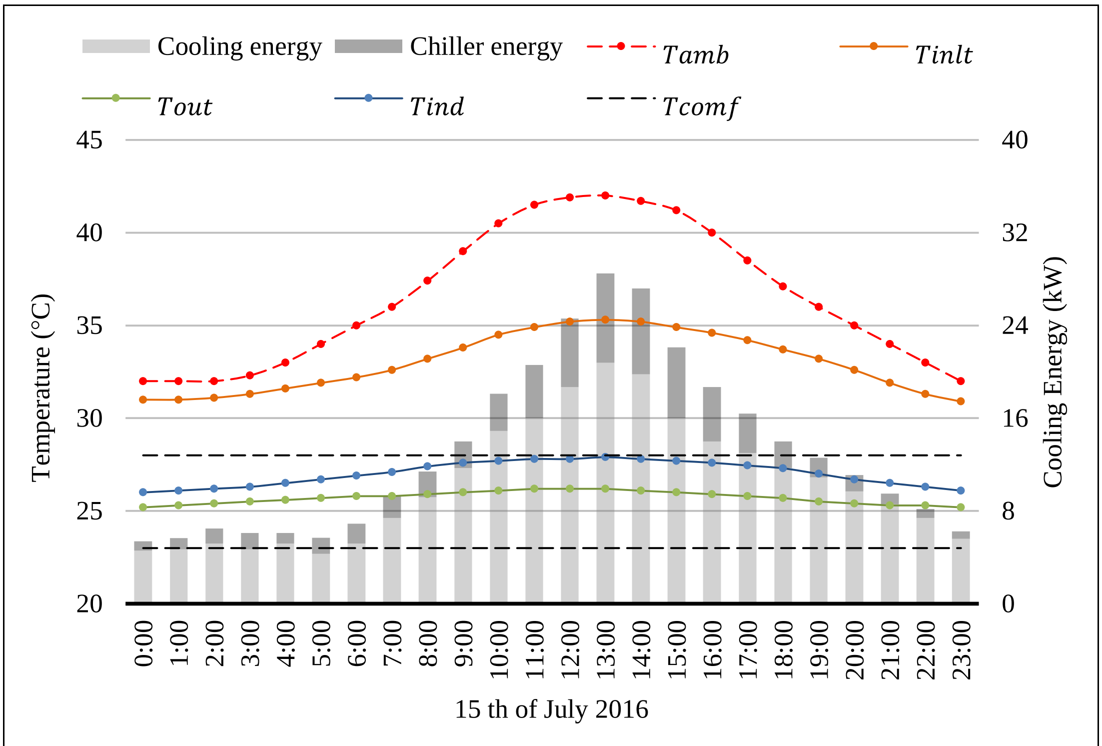


Figure 6.14: Average hourly cooling energy use and indoor condition of the simulated GPCS model.

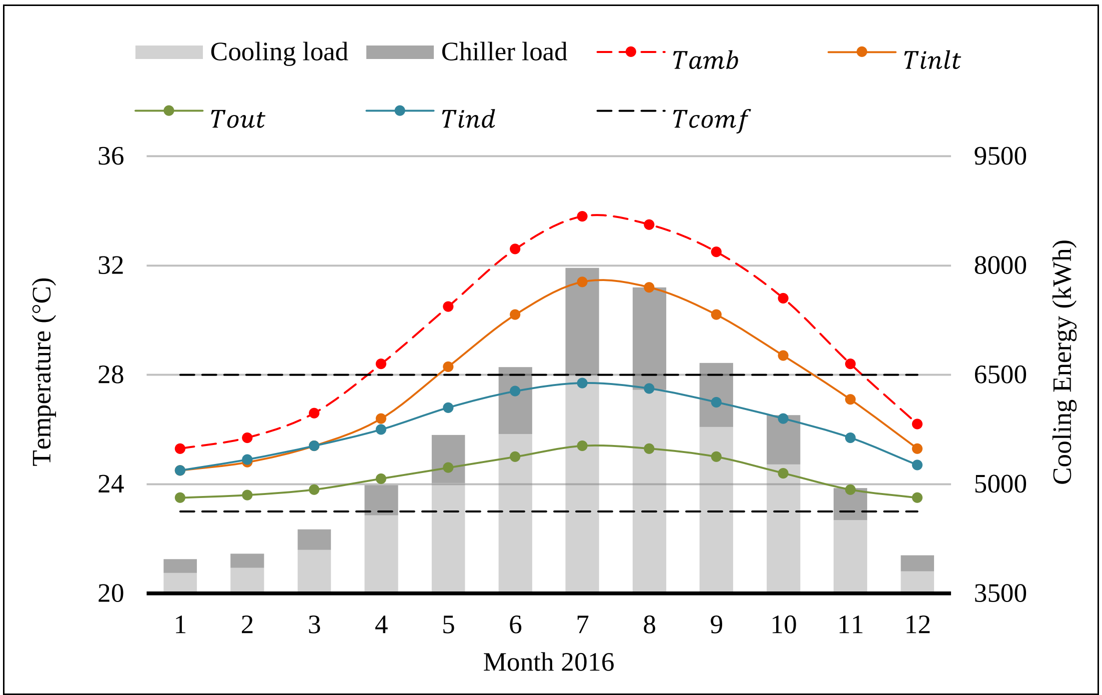


Figure 6.15: Average monthly cooling energy use and indoor condition of the simulated GPCS model.

6.6.2 The Effect of HRCS Application

The task of this evaluation is to determine whether the hydronic chilled floor (slab) operating in concert with the thermal inertia of the 'fabric first' passive measures, can deliver sufficient 'coolth' to 'heat flush' and maintain internal temperatures below the upper threshold for adaptive comfort (28°C). Despite the fact that the cooling energy of HRCS is primarily relying on the night radiative cooling of the black body radiator, without the need for any active chiller, utilising such a cooling technique work more effectively at low to medium temperatures differences, while during summer, the high temperatures can limit the cooling effect and the system might be insufficient to maintain the desired thermal comfort level as theoretically and experimentally investigated in chapter 5. The low energy chiller system was therefore coupled with HRCS to chill the water to a specified comfort temperature to provide a backup system. The chiller cooling energy and operation control depend on the supply water temperature that is derived from the radiator at 16ºC. The chiller runs automatically in case of the supply water temperature exceeded the specified water temperature, while the operation of the hydronic radiant system is controlled by the indoor set-point temperature as indicated in HRCS simulation model settings. Based on these scenarios, the HRCS cooling energy usage including chiller load was numerically calculated as shown in (Figure 6.16).

The key findings of the simulated HRCS demonstrate its efficiency in cooling the building and maintaining the desired indoor thermal comfort condition. As illustrated in Figure 6.16, the primary results of the simulated HRCS in typical mid-summer day (15^{th} July 2016) show that the hourly cooling energy use of the simulated system varies according to the ambient and indoor temperatures. The highest daily cooling energy was monitored at 13.00 pm by 20.4 kW, while the lowest was 1.69 kW at 00.00 am. The total daily cooling energy was 204.37 kWh with an average hourly cooling load of 8.51 kW and high load intensity in the period between 07.00 am and 18.00 pm, which specifically synchronizes with the chiller running hours (Figure 6.16).

Likewise, on a monthly scale, the cooling energy usage of the simulated HRCS including chiller load was varied according to the seasonal temperature amplitude between summer and winter. Figure 6.17, illustrates the total annual cooling energy use of the applied system which was almost 55609 kWh/year with an average monthly use of 4634.08 kWh/month with the chiller only operating between April and October. The highest monthly cooling energy use was monitored in July at 6392 kWh, while the lowest was in January at 3141 kWh.

Figure 6.16 shows the hourly temperature amplitude between radiant surface, indoor and operative temperatures. The figures indicate that the surface temperature of the hydronic radiant floor is slightly lower (2-3ºC) than the indoor temperature due to the effect of heat convection and internal warming. The operative temperature that is the average between the surface and indoor temperature, reflect the actual comfort temperature standard to determine the cooling efficiency of the applied radiant cooling system and comfort condition. The maximum daily operative temperature recorded was 27.17ºC at 13:00 hrs while the minimum operative temperature was 25.57 ºC at 23:00 hrs with an average hourly operative temperature of 26.44ºC (Figure 6.16).

On the monthly scale, the figures show that, despite the seasonal temperature amplitude, the operative temperature was efficiently maintained within the thermal comfort range. The maximum average monthly operative temperature recorded was in July at 26.35ºC while the minimum average operative temperature was in January at 23.85ºC with an average monthly temperature of 25.85ºC (Figure 6.17).

From an energy efficiency perspective, the sensible part of the HRCS is associated with tepid fluid temperatures in the range of 13°C to 21°C with high thermal performance of building fabric to optimise the radiative cooling effect of night sky radiation and promote the possibility of passive cooling systems; or at the very least the potential to bypass the chiller for peak loads, with around 16°C of cold water circulating in the concrete hollow core slab. The indoor and operative temperatures were efficiently maintained within the comfort range between 23ºC and 28ºC throughout the year (Figure 6.17).

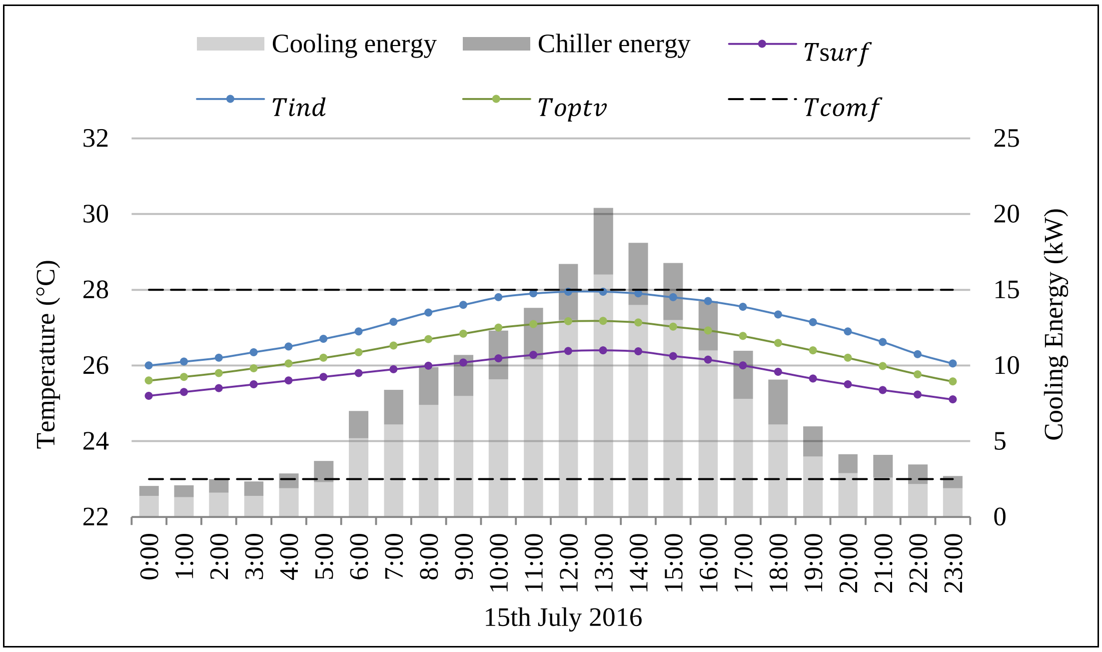


Figure 6.16: Average hourly cooling energy use and indoor condition of the simulated HRCS model.

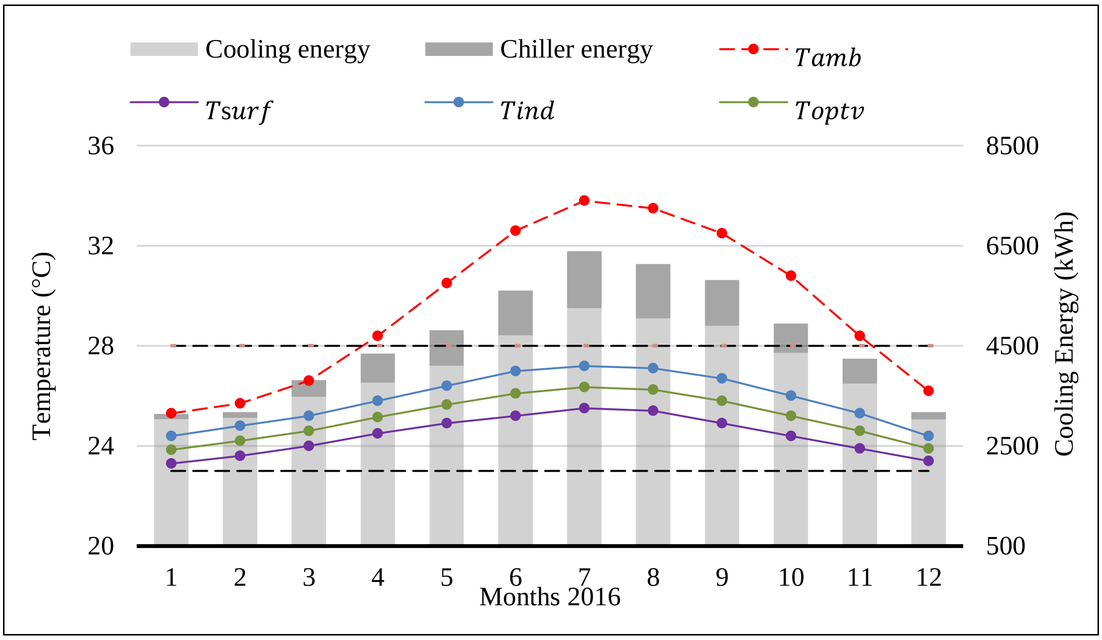


Figure 6.17: Average monthly cooling energy use and indoor condition of the simulated HRCS model

6.6.3 The Effect of the Integrated HCS Application

The task of this assessment was to determine whether the ground pipe supply ventilation and radiant cooling system operating in concert with the thermal inertia of the 'fabric first' passive measures, can deliver sufficient 'coolth' to 'heat flush' and maintain internal temperatures below the upper threshold for adaptive comfort (28°C).

The primary results of the simulated HCS model demonstrate the effectiveness of the hybrid system as an efficient integrated low energy mixed mode cooling strategy capable of maintaining the desired indoor thermal comfort condition all year round. As illustrated in Figure 6.18, the key findings of the simulated HCS on a typical mid-summer day (15^{th} July 2016) illustrate that the hourly cooling energy use of HCS was fluctuating through the day according to the indoor set point temperature and cooling demand. The highest daily cooling energy usage observed was 27.23 kW at 13.00 hrs while the lowest energy use was 5.90 kW at 00:00 hrs. The total daily cooling energy was 340.75 kW with an average hourly cooling energy use of 14.20 kWh with high cooling intensity in the period between 07:00 am and 19:00 pm (Figure 6.18).

On a monthly scale, the cooling energy use of the simulated HCS including chiller load varied according to the seasonal temperature amplitude between summer and winter. Figure 6.19 shows that the total annual cooling load of the HCS was almost 90754.07 kWh/year with an average monthly cooling energy of 7562 kWh/month with chiller loading in the summer period between April and October. The highest monthly cooling energy usage recorded was in July at 10635 kWh while the lowest was in January of 5267.40 kWh.

Figure 6.18 indicates the hourly indoor temperatures along the day. The recorded maximum daily indoor temperature was 27.9ºC at 13:00 pm while the minimum temperature was 24.5ºC at 23:00 pm with an average hourly indoor temperature of 26ºC (Figure 6.18)

On a monthly scale, the figures demonstrate that, despite the seasonal temperature amplitude, the indoor temperature was thermally maintained within the comfort range. The maximum average monthly temperature recorded was in July at 26.2ºC while the minimum average indoor temperature was in January at 24.3ºC with an average monthly indoor temperature of 25.22ºC (Figure 6.19)

Accordingly, the applied HCS has demonstrated its potential to significantly reduce the cooling energy use and sustain the indoor condition within the comfortable thermal condition between 23 to 28 ºC throughout the year (Figure 6.18). The HCS cooling energy use was reduced by up to 35% as the fan coil system that coupled with GPCS utilised the cold water produced by night radiative cooling or the chilled water from the HRCS chiller.

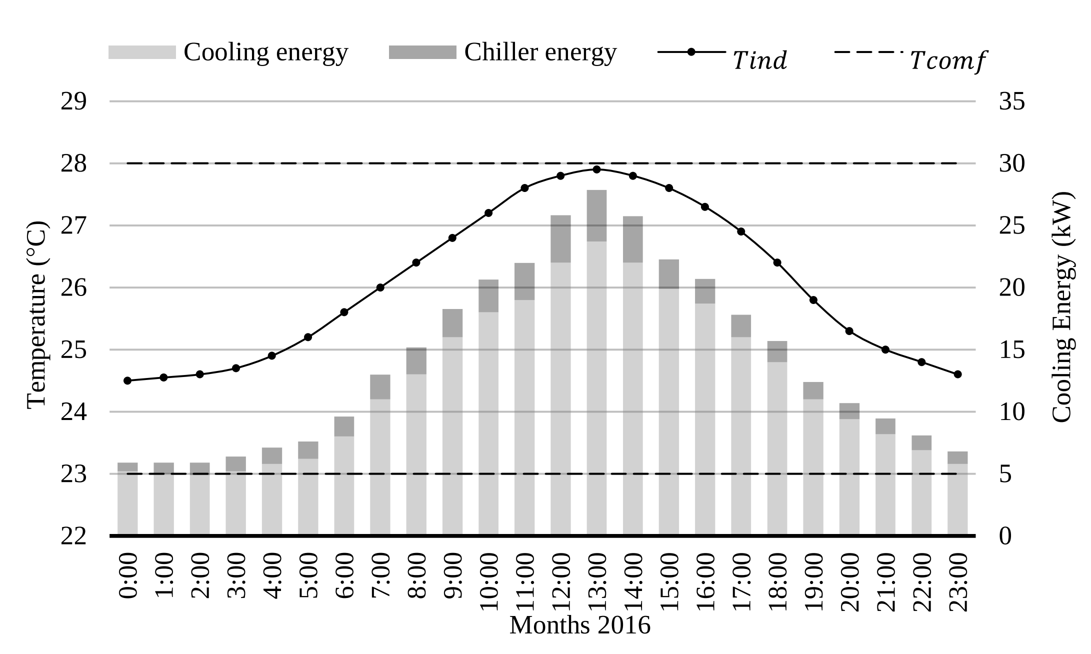


Figure 6.18: Average hourly cooling load and indoor condition of the simulated HCS model.

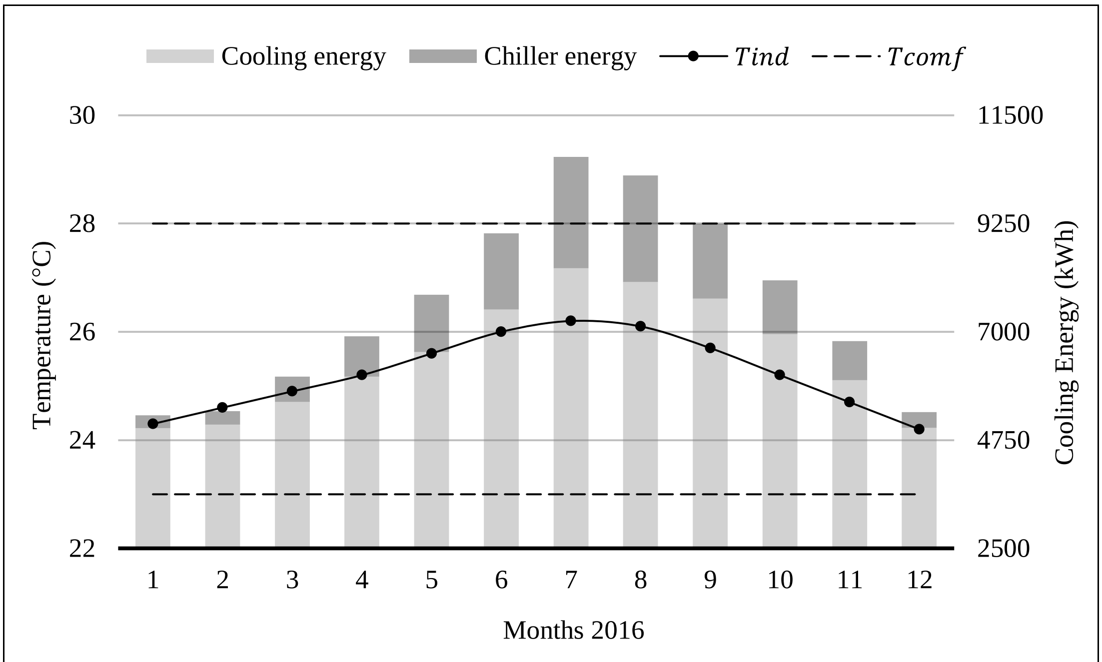


Figure 6.19: Average monthly cooling energy use and indoor condition of the simulated HCS model.

6.7 Conclusion

This chapter highlighted that the selected modelling and simulation software DesignBuilder including the key features and capabilities of the simulation engine EnergyPlus was able to build a representative model and simulate a range of scenarios comparing the base case with the new retrofitted block fitted with a hybrid cooling system applied. The modelling and simulation software provided monthly and hourly energy use and temperature data.

The primary setting up of the simulation model included the definition of model zones, floor areas, occupancy, metabolic rates and environmental control, which involve setting cooling set-point and set-back temperatures. In addition, the suggested PDMs include external walls, floors, and roof thermal retrofitting together with more efficient external glazing and shading systems were applied to the simulation model to optimise the thermo-physical performance of the building fabric and promote the cooling efficiency of the applied cooling system.

The proposed GPCS simulation model was set up including soil and ground pipes thermal specifications and operation setting in order to determine the thermal influence of such novel cooling strategy on the building cooling energy use and indoor conditions. The main inputs of the HRCS simulation model were defined including the hydronic piping specification, flow rate, chilling efficiency and operation settings, to thermally test the influence of the hydronic radiant system application on building thermal and energy performance. The hybrid integrated system was set up in EnergyPlus as a mixed mode cooling system by integrating the features and specifications of both the GPCS and HRCS with specific time frames and operation control settings to assess the effect of cooling system hybridization on the overall building energy and thermal performance.

The simulation results were obtained for comparative assessment with baseline. From an energy efficiency perspective. The results demonstrated the efficiency of the applied cooling systems in reducing electricity demand while being able to maintain the indoor temperature within the desired comfort conditions at all times.

7 CHAPTER | Efficiency Validation of HCS Application

7.1 Introduction

This chapter discusses and assesses the simulation results of various passive and hybrid cooling systems reported in chapter 6 in terms of their energy efficiency and cost-effectiveness. This involves comparing the additional cost of the measures and systems against the likely energy savings in use. The assessment will also include life cycle economic analysis and the estimated payback period.

7.2 Critical Assessment of HCS Energy Efficiency

7.2.1 Cooling Performance and Energy Saving Potential

As observed from the energy simulation results of the baseline case study building, the high domestic cooling energy consumption resulting from the excessive use of the mechanical AC systems was clearly attributed to the low thermal capacity of building fabric in conjunction with the rise of outdoor temperature when the ambient temperature reaches 45°C in July and August (Figure 7.1). However, enhancing the thermal performance of building fabric through adopting 'fabric first' thermal retrofitting approach and PDMs were able to save a substantial percentage of the baseline cooling energy usage. The preliminary analysis suggested that passive 'fabric first' design and measures such as external insulation, solar shading, additional vegetation, increasing the 'Albedo' effect and a high level of thermal inertia using hypocausts encapsulated in the concrete floors TermoDeck® could produce a reduction in AC cooling energy use of (36.60%). This displaced over 170946 kWh/year of AC cooling energy with a peak monthly saving during July of around 40% and an average monthly reduction of 14245.5 kWh/month (Figure 7.1). These energy saving results are in line with the findings of the studies discussed in the literature review; (chapter 2) by Abdelrahman (1993), Al-Naimi (1989) Budaiwi (2011), Al-mofeez (2007) that addressed the effect of PCM and fabric thermal measures on building energy performance.

Figure 7.1 illustrates the cooling energy use of the applied passive and hybrid cooling systems that demonstrated a significant reduction in cooling demand over the baseline case. In the GPCS scenario that is basically coupled with PDMs, the total annual cooling energy use was 66909 kWh, which is almost 85.67 % lower than the baseline (AC) energy use with an average monthly energy use of 5575.75 kWh/month compared to an average consumption of 38913 kWh/month in the baseline.

Likewise, as a result of applying HRCS which is essentially integrated with PDMs, the annual cooling energy usage was remarkably minimised by 88% with an average monthly energy use of 4634 kWh/month, however, this figure did not factor in ventilation gains in the peak summer required to maintain 'healthy' indoor air quality.

In HCS scenario which combined the GPCS and HRCS and coupled with PDMs, the annual cooling energy use was expressively reduced by over 80.56% of the baseline AC energy use with an average monthly cooling energy consumption of 7562.84 kWh/month compared to around 38913.91 kWh/month in the baseline (Figure 7.1). Although the proposed HCS was predicted to displace lower percentage of cooling energy (80%) compared to HRCS (88%) and GPCS (86%), the thermal capacity of the integrated HCS was able to sustain the indoor temperature at lower and more constant temperature over the year compared to GPCS and HRCS (Figure 7.2). Since cooling energy represents 74% of the total baseline electricity consumption, saving 80% of the cooling energy by applying HCS could produce a significant reduction of total electricity use by around 62%.

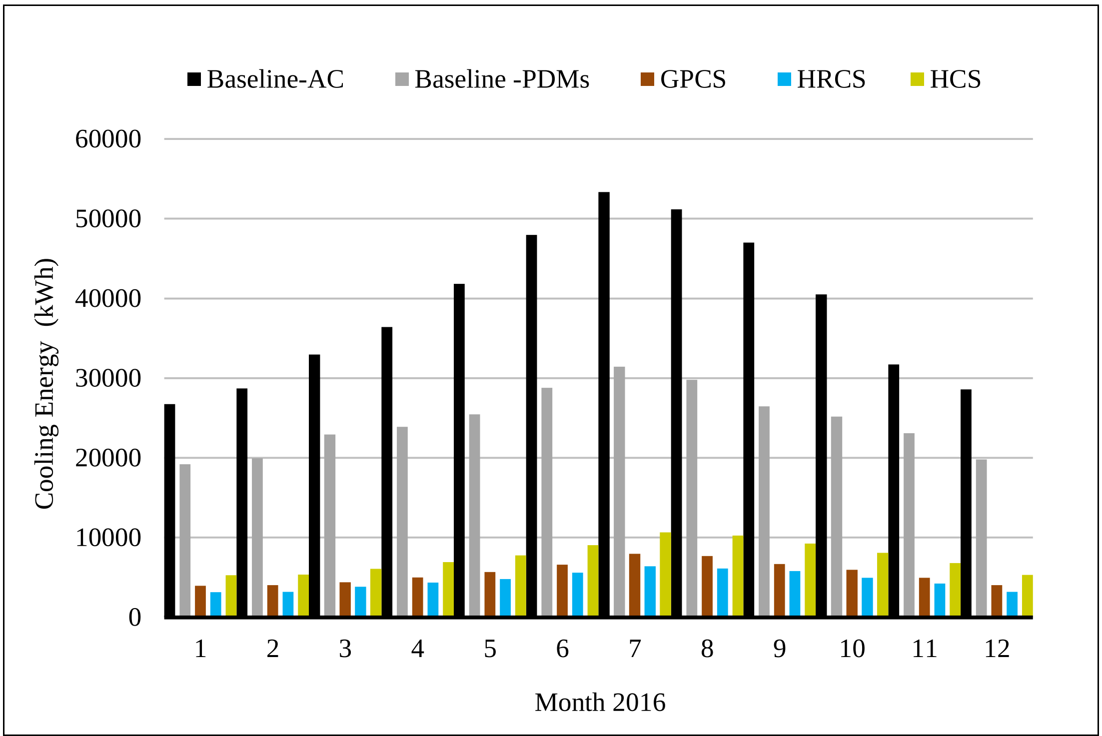


Figure 7.1: Comparison between cooling energy use of various cooling systems applications.

The Coefficient of Performance (COP), is the basic parameter used to define the efficiency of the cooling system application including fan chiller and compressor energy. COP is the ratio between useful energy acquired and energy applied which can be expressed as:

$$\textbf{System COP} = \frac{\textbf{Energy output in (W)}}{\textbf{Energy input in (W)}} \quad \text{(Equation 7.1)}$$

However, Energy Efficiency Ratio EER which is a measure of how efficiently a cooling system operates in a steady state (over time) when the outdoor temperature is at a specific level (outdoor conditions commonly used are 35°C). The higher EER the more energy efficient is the system. EER was calculated based on the following equation:

$$\textbf{System EER} = \frac{\textbf{Output cooling energy (W)}}{\textbf{Input energy use (W)}} \quad \text{(Equation 7.2)}$$

Based on the cooling capacity of the applied low energy mechanical systems include chillers, pumps, and fans and the cooling energy used in the applied passive and hybrid cooling systems. As a result of applying the above equation, the annual COP and EER of the HCS including GPCS and HRCS calculations were indicated in Table 7.1

Cooling system	Annual cooling capacity (kWh)	Annual cooling consumption (kWh)	COP	EER
GPCS	107266	66909	1.60	5.46
HRCS	96418	55609	1.73	5.90
HCS	203684	90754.09	2.24	7.64

Table 7.1: Annual COP and EER of the implemented HCS including GPCS and HRCS.

Figure 7.2 shows a comparison of the annual cooling load between different cooling system applications. The figures clearly demonstrated a significant saving in baseline AC cooling energy resulted from applying passive/hybrid cooling systems. For instance, the total annual cooling energy use of HCS was approximately 90754.09 kWh, which formed less than 20% of the baseline AC annual cooling energy use of 466967 kWh (Figure 7.2)

In this comparative assessment, the energy consumption of each applied cooling system was classified into three main categories. These categories include the cooling energy of mechanical pumps, fans and chillers. The comparison shows that the cooling energy consumption of each of these categories was wide-ranging according to the applied system cooling strategy and capacity (Figure 7.2). For instance, chiller load formed around 60% of the total annual energy usage of the baseline mechanical AC system which formed approximately 25%, 47% and 22% of the GPCS, HRCS and HCS respectively duo to utilising passive cooling strategies and reduced chiller cooling loads (Figure 7.2).

Likewise, mechanical pumps consumed around 14% of the total annual energy use of the baseline whilst it consumed 10%, 53% and 26% of the total annual cooling usage of GPCS, HRCS and HCS respectively. The energy use of mechanical fans and air distribution system formed around 26% of the baseline AC energy, whereas it dominates the total annual energy used in the GPCS (65%) as it is the key component of the GPCS process while the HRCS does not use fans power. (Figure 7.2).

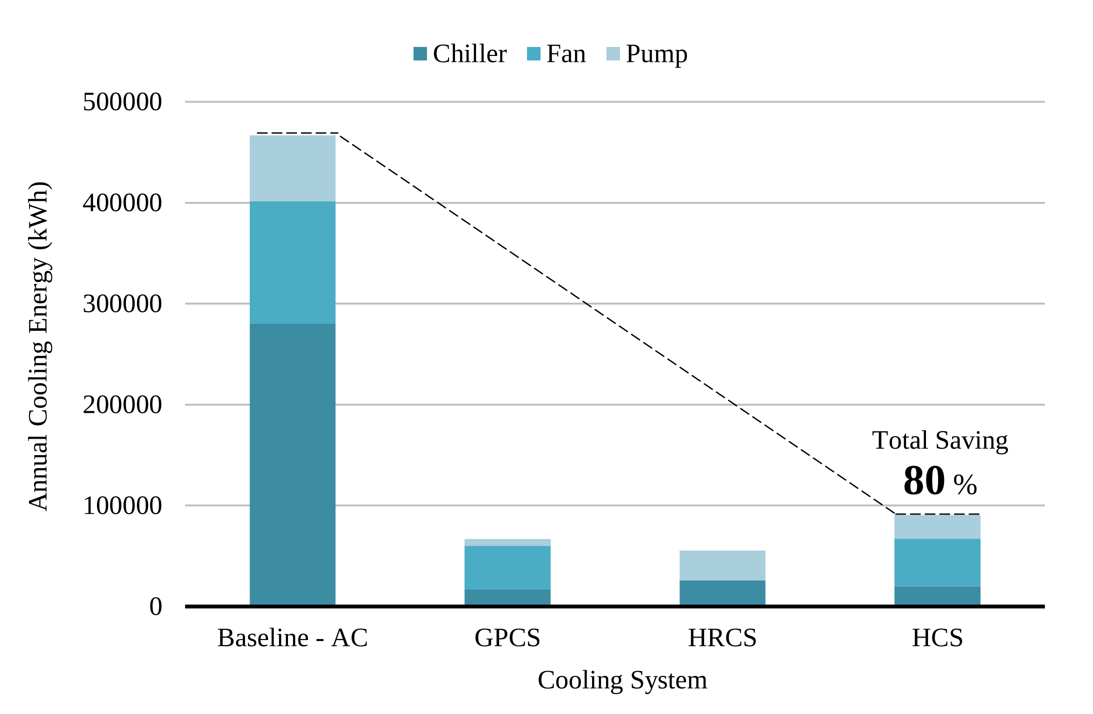


Figure 7.2: Annual cooling energy use breakdown of various cooling systems.

7.2.2 Indoor Condition and Thermal Comfort

Maintaining the indoor temperature within the thermal comfort and acceptable standard of air quality is a significant indicator to determine the efficiency of the implemented cooling system. Figure 7.3 shows the average monthly indoor temperature of the applied GPCS and HRCS and when both systems are operating in tandem (HCS) compared to baseline. As shown in the graph, the baseline (AC) annual indoor condition remained constant throughout the year with an average temperature of 24.74°C which is within the adaptive comfort zone between 23°C and 28°C. Although PDMs application can efficiently displace almost 37% of AC cooling energy usage, PDMs on their own are unable to maintain internal temperatures below the upper threshold (28°C) for around 180 days of the year (from mid of April until mid of October) (Figure 7.3). In GPCS and HRCS modes, the indoor temperature reached its peak in July at an average temperature of 27.2°C and 26.3°C respectively. However, the HCS is considered as an optimum low energy cooling scenario in terms of energy saving and its capability to sustain the average indoor temperature invariably within the comfort level in a range between 24.2°C to 25.7°C throughout the year despite the monthly ambient temperature amplitudes (Figure 7.3). In the hybrid cooling mode, any shortfall in comfort was of course met by the installed chiller unit to cope with peak summer demand. Based on the recorded indoor temperatures of the applied GPCS, HRCS and HCS, the thermal comfort range of the applied cooling systems was illustrated in the psychometric chart. The comfort zones were specified within the thermal comfort range of the mixed mode and naturally ventilated building according to ASHRAE (2004) Standard 55 (Figure 7.4).

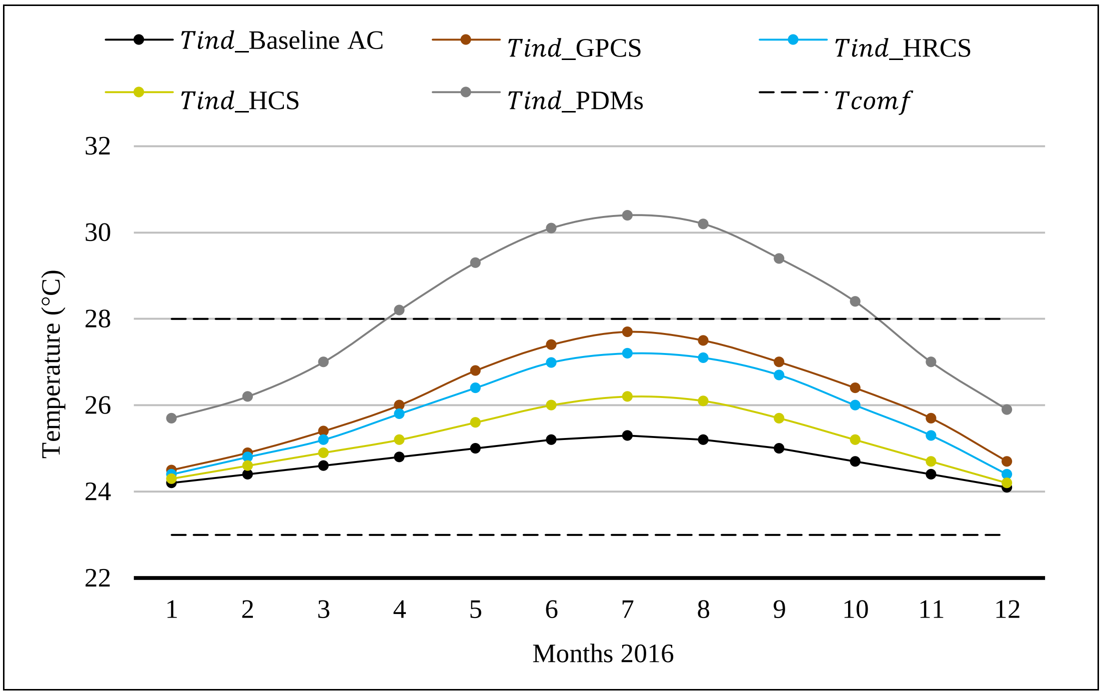


Figure 7.3: Average monthly indoor temperatures of various cooling scenarios.

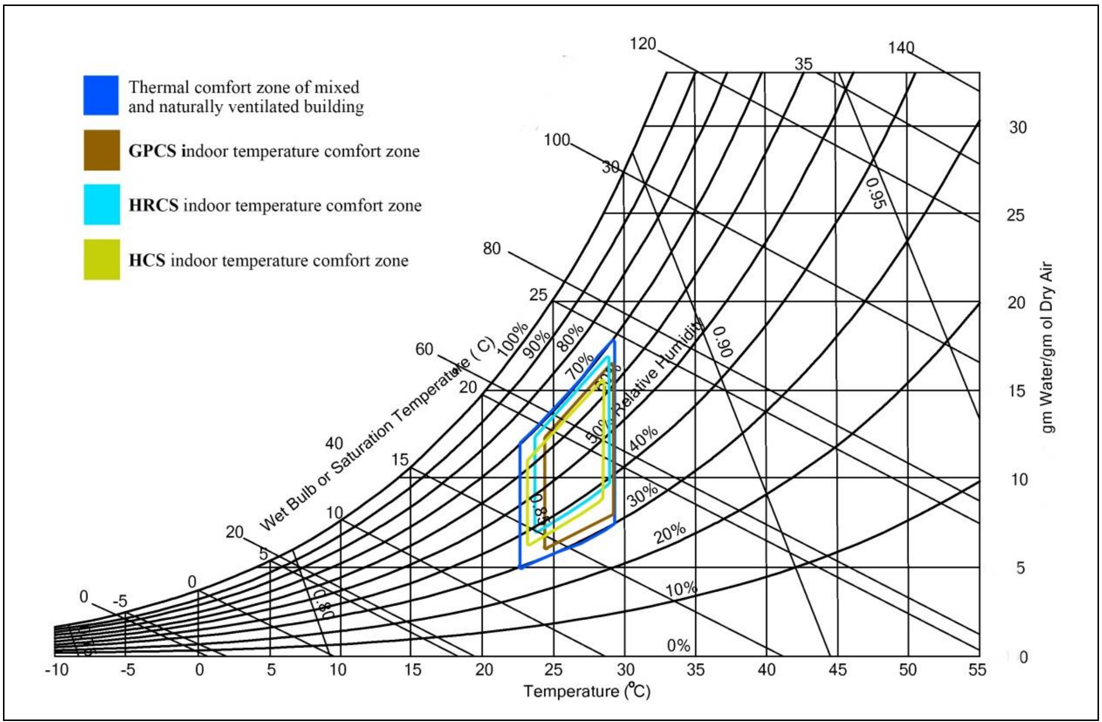


Figure 7.4: Psychometric chart shows indoor temperature and thermal comfort zones of various mixed mode and naturally ventilated cooling systems (ASHRAE, 2004).

7.2.3 Air Quality Enhancement and CO_2 Level

Besides the considerations of thermal comfort, indoor air quality is a significant indicator of providing 'healthy' indoor air quality. Carbon dioxide concentration in air is an important factor and can be a proxy for overall air quality. The acceptable indoor air quality is basically determined by specifying the required outside air supply rate and indoor air changes per hour–on the presumption that the outdoor air contains relatively little pollutants.

ASHRAE, the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., has a standard called ASHRAE 62 ―Ventilation for Acceptable Indoor Air Quality. This standard recommends a minimum amount of fresh air per person for defined spaces. For example, the minimum amount of fresh outdoor air recommended for residential spaces is 25 CFM/person (12.1 l/s/person) (Table 7.2). While the air supply rate recommended by CIBSE is 8 l/s per person to maintain CO_2 below 1000 ppm (CIBSE, 2005a). This standard was considered in calculating the actually required air ventilation rate and CO_2 concentration in indoor air in chapter 6, which result in Figure 7.5.

Parameter	Limit/Range	Reference
Air temperature	Summer (23 – 28°C) Winter (20 – 25.5°C)	ASHRAE Standard 55-2010 - ISO 7730
Relative humidity	30 – 65%	ASHRAE Standard 55-2010 - ISO 7730
Air movement	0.25 m/s	WHO - ISO 7730
Ventilation (fresh air)	15 – 60 CFM/person 7-28 L/s /person	ASHRAE Standard 62.1- 2010
Ventilation (CO_2)	700 ppm over outdoor ambient	ASHRAE Standard 62.1- 2010

Table 7.2: References to the recommended indoor condition, ventilation and air quality standards (ASHRAE, 2013).

Figure 7.5 shows the distinction between the carbon dioxide levels in different cooling and ventilation designs. The main contributor to the carbon dioxide concentration inside the building was the rate of air circulation. In the baseline scenario, the average monthly concentration of CO_2 in the internal air was 807 ppm, which classified according to ASHRAE 62 as a medium to low air quality. This figure, however, relies on fresh air being introduced into the system with little recirculation occurring. To boost the coefficient of Performance (COP) of the AC system the temptation is always to increase recirculation rates and minimise fresh air input –particularly when the temperature of that air may be as high as 45°C. This figure may therefore underestimate the actual CO_2 level in many dwellings where windows are habitually closed for over five months (summer months May – September). For instance, the highest average monthly CO_2 concentration in air was recorded in July and August at 952 and 926 respectively as a result of intensive use of mechanical AC system while during winter season the indoor CO_2 concentration was decreased to an average of 718 ppm as a result of taking the advantage of the outdoor temperate air.

In contrast to the AC system, since the ground pipe cooling in GPCS relies on delivering relatively high levels of 'fresh air' that in turn reduced the CO_2 concentration to average 712 ppm; however, the reduction level was varied from month to month according to the ambient temperature and system usage. In direct contrast to AC use, the maximum average CO_2 concentration was 744 ppm predicted in January as a result of the lower cooling demand. In comparison with baseline, high temperatures in peak summer have increased the airflow rate of the HCS which resulted in a lower concentration of CO_2 in internal spaces. The HCS also lowered the internal RH falling within the accepted comfort parameters of 44 % - 65 %. This is due to the mixing ratio of the supply air falling as water condenses in the ground pipes (Figure 7.5).

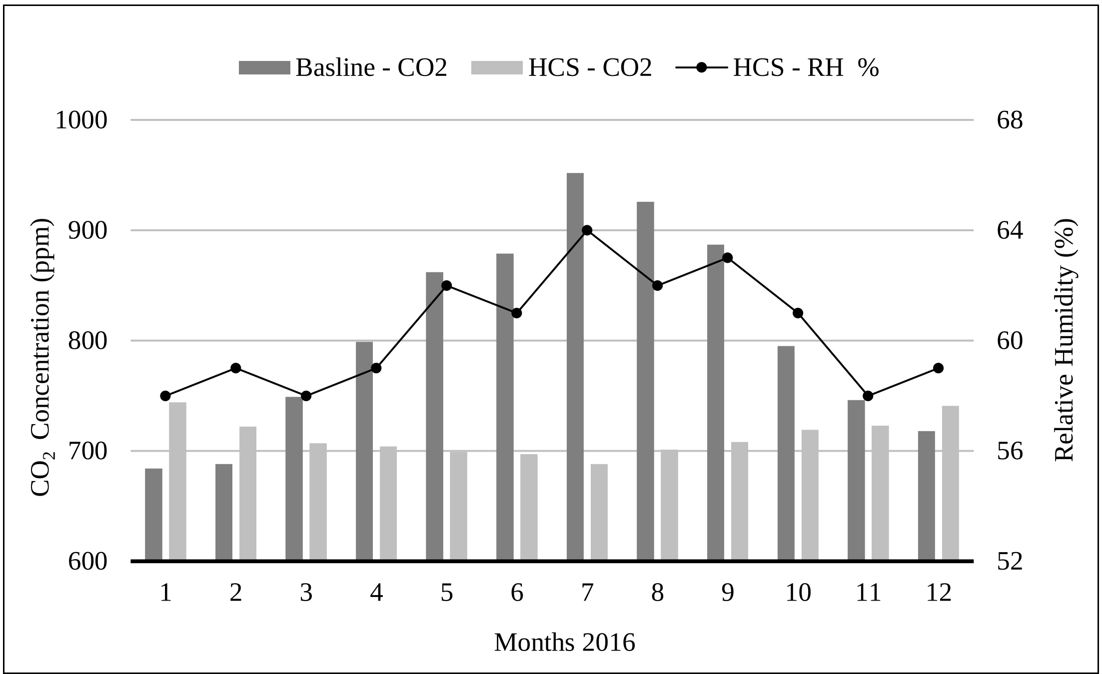


Figure 7.5: Comparative assessment of HCS and baseline indoor condition and air quality.

7.2.4 CO_2 Emission from Electricity Generation

Additionally, the CO_2 emissions from electricity consumption were calculated by applying an emission factor to the amount of electricity consumed in baseline mode. Specific emission factors for grid electricity are published for various countries, for example, Defra/DECC publish factors for the UK, and the Environmental Protection Agency publishes factors for the US (EPA 2010). However, for Saudi Arabia, the best available factors are the composite electricity/heat factors in CO_2 emissions from fuel combustion published by the IEA (IEA 2010). Table 7.3 shows the results for CO_2 emission per kWh of electricity generated using the electricity-specific method, and the composite of electricity/heat factors from the IEA. Additionally, the differences between the two factors in gCO_2/kWh including the difference percentage were also indicated.

Based on the calculated CO_2 emission of the baseline conducted in chapter 4, Figure 7.6 illustrates the monthly average CO_2 emission of the retrofitted case study model a result of applying HCS in comparison with the baseline. The results have emphasized the major reduction of CO_2 emissions as a result of minimizing the cooling energy use and in turn the total electricity consumption. The CO_2 emission of the developed hybrid cooling application model was decreased by 75% compared with baseline. The monthly average was CO_2 emission 9744.642 kg/month compared with an average of 38978.57 kg/month (Figure 7.6).

Country	Electricity-specific factors (kg CO_2/kWh)	IEA composite electricity/heat factors (kg CO_2/kWh)	Difference (g CO_2/kWh)	Difference (%)
India	1.333174843	0.9682265	0.36495	37.7%
Indonesia	0.684693977	0.726138	-0.04144	-5.7%
Japan	0.443356848	0.436453	0.00690	1.6%
United Arab Emirates	0.938297499	0.8420557	0.09624	11.4%
Kuwait	0.637316929	0.6136518	0.02367	3.9%
United States	0.547096737	0.535031	0.01207	2.3%
Portugal	0.400151316	0.383544	0.01661	4.3%
Qatar	0.596345388	0.533875	0.06247	11.7%
United Kingdom	0.508501975	0.486949	0.02155	4.4%
Saudi Arabia	0.795591395	0.7541919	0.04140	5.5%
Singapore	0.57904595	0.5310437	0.04800	9.0%
South Africa	1.069026617	0.8349481	0.23408	28.0%
Spain	0.34287509	0.325878	0.01700	5.2%
Sweden	0.023033883	0.039939	-0.01691	-42.3%
Switzerland	0.003177437	0.027385	-0.02421	-88.4%
Turkey	0.865664547	0.495279	0.37039	74.8%

Table 7.3: International factors of CO_2 emissions calculations (IEA, 2010).

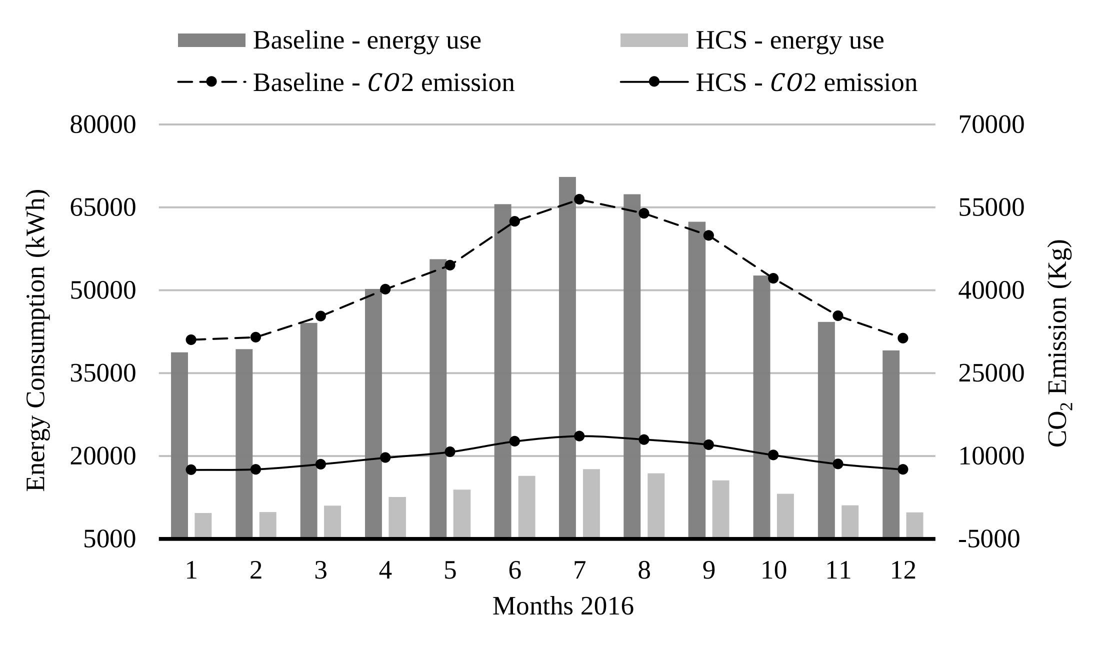


Figure 7.6: Impact of HCS application on baseline electricity consumption and associated CO_2 emission.

7.3 Feasibility Study and Payback Analysis

Based on the comparative assessment of the retrofitted hybrid cooling energy and the actual cooling energy of the AC system (baseline), this section presents a detailed estimation of capital and running cost of the implemented cooling systems and the predicted payback period as a result of energy saving. Two factors were considered when determining the cost-effectiveness of the proposed passive and hybrid cooling applications. The capital cost of the passive and active interventions measured against energy cost savings in use.

To calculate the actual running costs of the applied systems, an energy consumption tariff was used. The Saudi Electricity Company average tariff for residential buildings is currently 0.17 SR/kW, which is approximately £0.034/kW of electricity. Since the average annual cooling energy consumption is circa 466967 kWh hence, according to the current domestic electricity consumption tariff, the estimated cooling energy cost of the baseline is £15876/year. PDMs reduced the baseline energy cost by around 37% to £10064/year. However, the estimated energy cost of the hybrid system including GPCS and HRCS is almost £3085/year due to an average energy saving of 80%. The graph demonstrates the contrast between the baseline AC energy cost and the other cooling system applications (Figure 7.7).

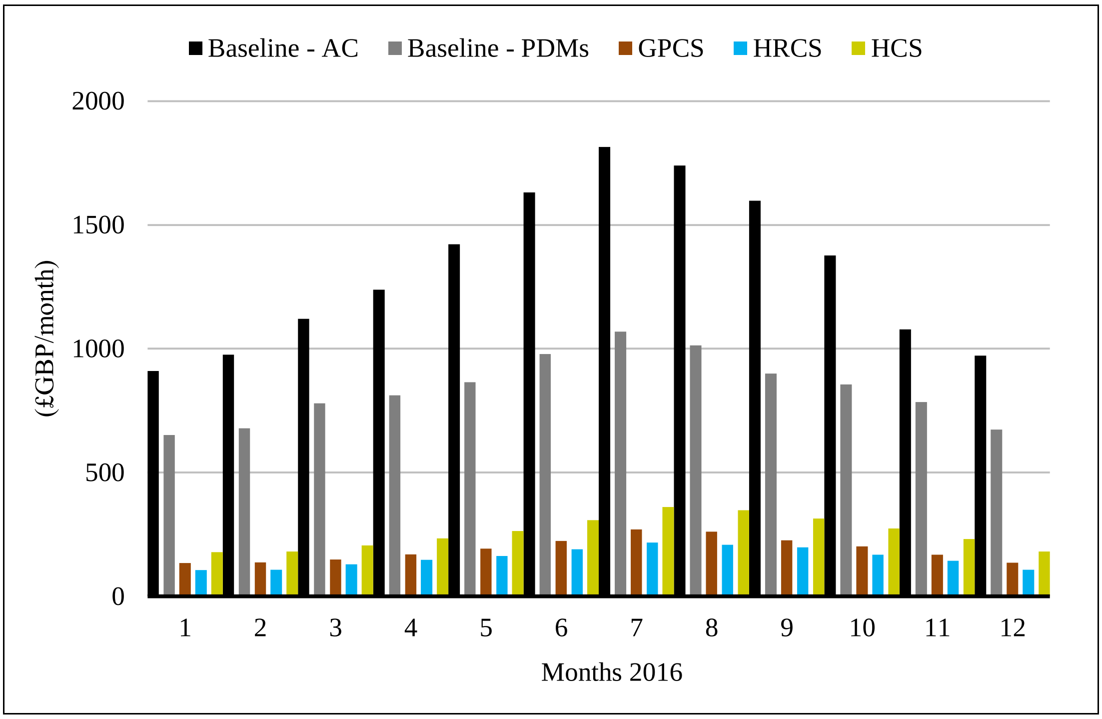


Figure 7.7: The average monthly estimated cooling energy cost of various cooling systems.

Since the suggested PDMs are combined with the retrofitted designs of the GPCS, HRCS and the integrated HCS, the initial cost of PDMs was added to the total initial costs of the applied cooling systems. Due to the fluctuation of construction materials and thermal insulation prices in KSA and in order to estimate the actual cost of PDMs applications, the study considered the current average cost of PDMs components and materials in the current Saudi construction market. The price usually starts from a few pounds per m², ending up at around £20/m² for the best performing options/thicknesses. According to the space measurements and current market price, Table 7.4 shows the estimated cost (GBP/ m²) of the proposed PDMs including walls and floors thermal insulation and window shading and double glazing, was approximately £12002 (including the installation cost).

PDMs applications	Thickness (m)	Area (m²)	Price (GBP/ m²)
Extruded Polystyrene Boards (XPS)	0.05 m	1825	4.0
Polyurethane Foam Board (PUR)	0.05 m	650	4.0
Window Shading	Louvre– 0.5 projection	280	5.0
Window glazing system	Double – 30% clear	260	2.7
Total cost			£12002

Table 7.4: Cost estimation of the proposed PDMs applications.

With regard to the actual capital cost of the HCS that include GPCS and HRCS systems, in fact it is quite difficult to obtain the cost of such novel technology particularly in Saudi Arabia due to that the industry of such systems in KSA is still plagued with a lack of detailed information on the estimated cost associated with implementing such hybrid systems into Saudi dwellings including installation and maintenance costs. However, a reasonable cost estimation was made of elemental (include pipes, fans, pumps, chillers, and PV panels), installation, and maintenance costs of the integrated system and taking into consideration the domestic and international market rate and labour cost in KSA.

Due to their market penetration, the cost of ground and radiant cooling systems was estimated under four categories: the cost of the components, installation, operation and maintenance. The cost estimation of the applied cooling systems was based on a survey of current Saudi market price. For instance, the estimated cost of PVC piping works which forms almost 70% of the ground and radiant system configurations and the electrical and mechanical works related to fans and chillers installation (25%) were compared to the current cost of plumbing and electrical works in building construction (components and installation).

Besides the capital costs, the calculations also covered the total operating cost for the baseline case study building (total 20 flats in the residential block). In addition, the solar energy which can contribute 5936 kWh/year generated from 30 m of PV panels was also considered within the total annual capital and energy usage costs of the applied hybrid cooling system (Table 7.6).

Based on the design and configuration of the applied cooling systems (GPCS, HRCS and the integrated HCS) that extensively discussed in chapter 5, a detailed elemental, installation and maintenance cost estimation of the applied cooling systems was made and tabulated in Table 7.5. while the calculations of total costs (capital, maintenance and operating) of the applied cooling systems including PDMs were summarised in Table 7.6.

A comparison was made between the elemental, installation, maintenance and operating costs of the applied GPCS, HRCS and baseline AC (Table 7.5). As can be seen from Table 7.5, There was a disparity in the capital costs of the applied hybrid and current conventional AC system, however, the capital costs of GPCS was higher than the HRCS. This can be attributed to the extensive pipework GPCS along with the high cost of drilling and ground pipe installation. However, among all the applied cooling systems the HRCS is considered as the most cost-effective cooling system in terms of capital, maintenance and operating costs. The operating costs as summarized in Table 7.5 was obtained based on the energy simulation results of the applied cooling systems as discussed earlier in this section and illustrated in Figure 7.7.

As discussed in chapter 5 section 5.2.3.3, in order to control the operating cost of the applied hybrid cooling system, a thermostatic controller was incorporated in HRCS to adjust water flow and temperature based on a set point temperature to control the pump and chiller running hours and thus system operating cost. In addition, a CO_2 sensor was incorporated in GPCS to allow the ground pipe supply ventilation rate to be reduced when any zone is unoccupied.

Maintenance cost data has been the most difficult to obtain and was available for only limited cooling systems. However, the maintenance cost of window air conditioners is relatively high which involves regular treatments of refrigerant leaks, sensor and drainage problems. Usually, such conventional systems include a warranty which covers any maintenance might be required. In contrast, ground and radiant cooling systems have longer life spans and require less upkeep than conventional cooling systems as the main elements of the system such as pipes are already embedded in floors or buried in deep ground soil while some components, such as chiller and fans have a relatively moderate maintenance cost. Generally, based on this cost comparison it appears that HCS can offer significant savings in capital, operating and maintenance costs over conventional AC systems.

System type	Components	Capital cost (£)		Maintenance cost (£/year)	Energy use cost (£/year)
		Element	Installation		
Baseline (AC)	100 x window air conditioner units (12000 BTU /3500W)	£25000	£2000	£3000	£15876
Ground Pipe Cooling System (GPCS)	ground Polyethylene HDPE pipe (128 m /dia: 0.35 m)	£550	£350	£140	(n/a)
	Polyethylene PVC pipe (440 m /dia: 0.20 m)	£1460	£550	£250	(n/a)
	4 x inline fan (intake) 115V/335W (495 l/s)	£450	£120	£50	£250
	40 x Inline fan (mixed) 115V/65W (138 l/s)	£1600	£650	£160	£900
	2 x air tank (plenum) with refrigerant compressor (1.2 m^3) 3.7 kW/230V	£1470	£250	£120	£815
	Water pump max head: 8 m 230V / 450W 300 lpm	£265	£75	£80	£310
Hydronic Radiant Cooling System (HRCS)	140 x metal panels (radiator) (3 x 0.95 x 0.003 m)	£650	£125	£125	(n/a)
	Polyethylene PVC pipe (850 m/ dia 0.025 m)	£1650	£180	£150	(n/a)
	Polyethylene PVC pipe(Supply) (280 m – dia 0.025 m)	£550	£160	£110	(n/a)
	PEX water pipe loops / manifold with adjustable flow meter (1200 m – dia 0.015 m)	£2250	£650	£210	(n/a)
	Central hot water tank (180 liters)	£450	£120	£90	(n/a)
	Chilled water storage/ compressor (450 liters) / 240V-750W	£1250	£160	£125	£1440
	Water pump max head: 9.5 m 230V / 500W 350 lpm	£285	£75	£80	£450
PV system	24 x Photovoltaic panels (30 m^2) (1480 x 670 x 35 mm)(160W / battery: 12V)	£2400	£450	£150	(n/a)

Table 7.5: Detailed cost estimation of various cooling systems.

Total Cost (£)	AC	GPCS	HRCS	HCS
Capital cost	£27000	£11990	£8555	£20545
Capital cost with maintenance	£30000	£12790	£9445	£23395
Capital cost with PDMs	£39002	£23992	£20557	£35397
Energy use cost	£15876	£2274.90	£1890.70	£3085.63

Table 7.6: Comparison of total costs by system type.

However, there are some constructional and operational limitations and challenges my associated with the application of such hybrid cooling systems. For instance, installing GPCS may require excavating a large area for horizontal pipes or drilling holes in the ground for vertical pipes which could take several days to several weeks depending on the size of the system and the composition of the ground. Therefore, for many existing buildings, converting to a geothermal system may not be an option due to space restrictions. The high upfront cost of converting to a geothermal system for existing buildings makes payback very long and renders the investment unfeasible. Therefore, it is crucial to consider the application of GPCS at early stages of building design and construction process.

In terms of HRCS, due to the potential for condensate formation on the cold radiant surface (resulting in water damage, mould), radiant cooling systems may have not been widely applied in such hot and humid climate. Condensation caused by humidity is a limiting factor for the cooling capacity of a radiant cooling system. Therefore, surface temperature should not be equal or below the dew point temperature in the space. Some standards suggest a limit for the relative humidity in a space to 60% or 70%. An air temperature of 26°C would mean a dew point between 17°C and 20°C. There is, however, evidence that suggests decreasing the surface temperature to below the dew point temperature for a short period of time may not cause condensation. Also, the use of additional systems, such as a dehumidifier, can limit humidity and allow for increased cooling capacity. Another challenge is that, in Saudi Arabia, many contractors are not familiar with the installation of such system. in addition, it is difficult to install retroactively after a home or room has been built.

However, according to the above cost assessment, applying HCS is a long-term cost-effective, this system which cost approximately £35397 GBP can significantly reduce the cooling energy consumption and cut down the electricity bill up to 80%. Based on the presented cost analysis, Figure 7.8 clearly shows the life cycle saving and estimated payback period which is the number of years after which the initial applications cost of PDMs, GPCS, HRCS and HCS will be retrieved due to energy savings in use compared to baseline AC system energy cost.

Although the estimated energy cost of the baseline (AC) is almost £15876.88, PDMs has considerably reduced the annual cooling energy cost of baseline up to 36.6% from 15876 GBP/year to approximately £10064 GBP/year and are able to recoup the initial investment within two years. Likewise, the estimated capital cost of the suggested GPCS and HRCS (£23992 and £20557 respectively); can be retrieved within less than two years (20 months) as a result of energy saving of 86% and 88% respectively. Although the integrated HCS is marginally more expensive in capital outlay (£35397), this hybrid system has a short payback period of less than three years (34 months) (Figure 7.8).

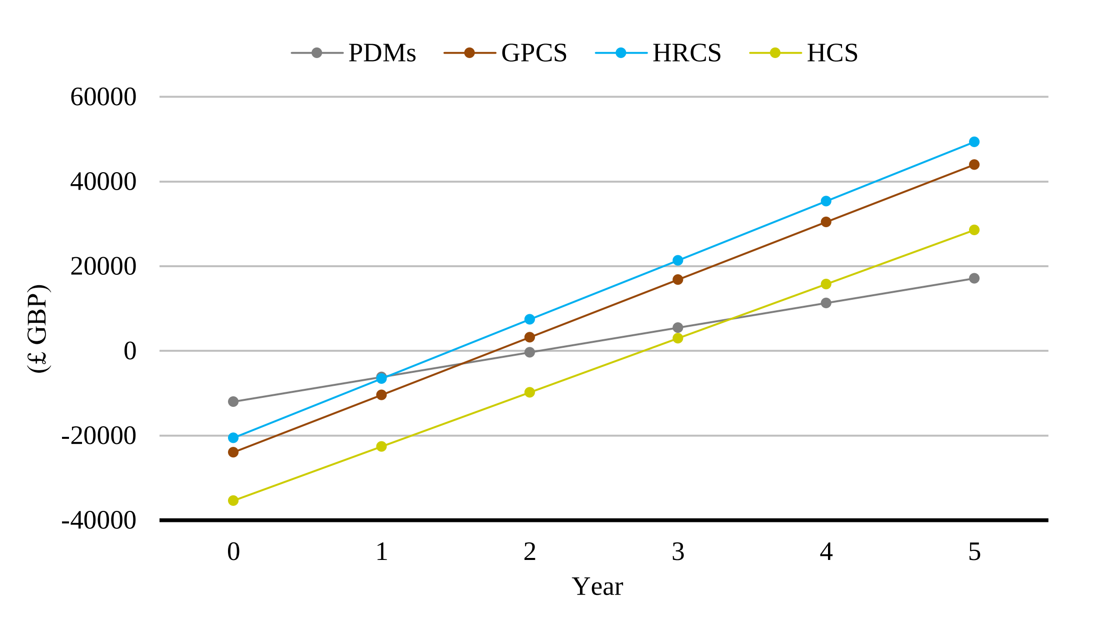


Figure 7.8: Life cycle analysis and payback estimation of various passive and hybrid cooling systems.

7.4 Conclusion

As remarked from the baseline energy simulation outcomes, the high domestic cooling energy consumption resulting from the excessive use of the mechanical AC systems was clearly attributed to the low thermal capacity of building fabric in conjunction with the rise of outdoor temperature especially in peak summer (45°C).

However, the application of 'fabric first' passive designs and measures (PDMs), combined with night hydronic radiant cooling (HRCS) and supply ventilation via ground pipes (GPCS), can negate the necessity for a standard AC system by displacing a substantial percentage of cooling demand and lower the carbon footprint of a typical housing block.

The analytical assessment and validation conducted in this chapter clearly demonstrated the energy and economic efficiency of the applied passive and hybrid cooling systems. The assessment of simulation results proved that PDMs such as external insulation, solar shading, additional vegetation, increasing the 'Albedo' effect and a high level of thermal inertia using hypocaust flooring were able to reduce the baseline annual energy use by 37%.

GPCS was capable to save around 86% of the cooling energy compared to 88% with HRCS and 80% with the integrated hybrid mode.

Despite their energy saving potential, PDMs on their own were unable to maintain indoor temperatures below the upper thermal comfort limit for all summer season (April to October), however, the indoor temperature was maintained within the comfort zone as a result of applying GPCS and HRCS with an average annual temperature of 27°C. While in HCS scenario, the indoor temperature was maintained at lower and more constant temperature throughout the year with an average annual temperature of 26°C.

As a result of applying HCS the assessment of indoor air quality showed that, in the baseline scenario, the average monthly concentration of CO_2 reaches its peak in July at 952 ppm due to excessive use of AC systems. In contrast, as the ground pipe ventilation relies on delivering fresh air, that in turn reduced the average monthly CO_2 concentration to 725 ppm.

According to the current domestic electricity consumption tariff, the estimated energy cost of the baseline is £15876/year. PDMs reduced the baseline energy cost by 37% to around £10064/year. However, the estimated energy cost of the hybrid system (including GPCS and HRCS) is almost £3085/year due to an average energy saving of 80%.

To determine the cost-effectiveness of the applied cooling systems, two factors were considered, the capital cost against energy cost savings in use. As a result, the estimated payback period of applying PDMs is around 24 months compared to 20 months in GPCS and HRCS mode. Although the integrated HCS is marginally more expensive in capital cost, the system has a short payback period of less than 34 months.

8 CHAPTER | Conclusion and Implication

8.1 Introduction

This research primarily aimed to investigate the potential of developing low carbon and energy HCS to displace the current employment of mechanical AC in current modern Saudi housing blocks. The aim was to investigate and evaluate techniques and systems that could reduce cooling loads and CO_2 emissions and maintain the desired thermal condition. The intention was to produce a new low carbon house model for hot and humid climates that could also be highly cost-effective.

The study suggests that a combination of passive design measures combined with two active cooling systems (hydronic radiant cooling in tandem with ground pipe supply ventilation) can reduce AC demand in KSA by around 80%. 'fabric first'passive measures reduce the demand by 37%, however, the hybrid system contributes an additional 43% reduction in the baseline total annual cooling demand.

Since the cooling energy dominates domestic energy costs, applying such a strategy to all new developments could reduce the overall electricity use in the domestic sector by 62%. As the KSA housing program plans to build around million housing units by 2020, applying such low carbon measures may save around 1900 GWh/year. This represents 5% of the total new housing budget, allowing an additional 50000 units to be built from the savings. It could also reduce the carbon footprint of the citizens living in these new blocks from 17.9 to 8.9 metric tonnes of CO_2 per annum. The following conclusions can be drawn from the present study findings.

In this research study, six research questions were established and presented in the introduction chapter, each question contributing to guiding the research study to meet its objectives. This chapter concludes the research works by presenting the research key findings as answers to the research questions that were raised at the starting point of the research. In addition, this chapter combines the conclusions of the research chapters and presents the final product and contribution to the body of knowledge. This chapter offers recommendations to stakeholders in the construction industry and energy efficiency organisations, including guidelines for the relevant government sectors and future researchers working in this field. Finally, this chapter will propose potential future work and further investigation to be undertaken. In order to address these subjects, this chapter is divided into three main sections that include the key findings of the study, some general recommendations and guidelines, and further studies for potential future research.

8.2 Key Findings of the Study

The current research has attempted to meet the primary aims and objectives. The main aim of this research was to present an investigation into the viability of 'fabric first' intelligent architectural design measures, in combination with a hybrid cooling system with specific aim to displace air conditioning and reduce carbon emissions, while maintaining thermal comfort, in a typical urban housing block in Saudi Arabia.

Chapter One The introductory chapter presented the general background and an overview of the research field, with a clear statement of the research problems that related to building energy use, cooling demand and corresponding carbon emissions. This chapter considered issues of sustainability and excessive cooling energy consumption common in Saudi dwellings. It presented the hypothesis, aims and objectives and research questions. Finally, it highlighted some unique aspects of the research programme and the potential contributions to the body of knowledge were outlined alongside a brief description of the challenges and potential limitations.

Chapter Two involved reviewing relevant studies of low-energy cooling strategies in hot humid climates. Initially, this chapter presented the general background of KSA including the geographic location and climatic conditions followed by a review of the typical current cooling approaches in Saudi buildings. Thermal comfort parameters were reviewed as were the key factors that affect adaptive thermal comfort. A review of literature addressed the cooling approaches in hot humid climates houses and moved towards the potential for developing low carbon hybrid cooling systems.

As a result of literature review, it was found that although many types of research carried out to investigate the potential optimization of current mechanical HVAC system, the result was limited potential in conserving energy use. Additionally, the review has emphasised that energy-efficient cooling systems are needed to replace the current conventional air conditioners used in most current residential buildings. Many researches have demonstrated that applying PCS has a potential to save a considerable amount of cooling energy and provide good thermal comfort without causing much pollution to the surroundings. Such passive cooling strategies in hot humid regions are difficult to accomplish due to the high temperature and relative humidity. Whilst many authors argue measures such as orientation, planning, material selection, window shading and fabric thermal insulation have a significant impact on lowering the building’s cooling energy consumption it became clear that PDMs on their own could not maintain thermal comfort all year round. Some form of active systems will be necessary if thermal comfort is to be achieved in the peak summer months. Based on the findings of this chapter, the following research objective was achieved:

- To investigate the potential implementation of a range of viable passive design measures aimed at reducing heat gain and cooling load.

Chapter Three involved reviewing and developing paradigms, approaches, methods and strategies. The first section of this chapter outlined some concepts and philosophies. The second section presented the research rationalisation and illustrated a possible approach and methodology. The third section presents the adopted research method and strategy in each research stage and described their appropriateness while the fourth outlined the research stages, process and flowchart which described a quantitative method in data collection and analysis.

The interrogation of the hypothesis was addressed in three stages. The initial stage was to generate the actual thermo-physical and energy performance of the selected block typology in Jeddah as a baseline case study. The second stage involved developing a viable low energy HCS which combined hydronic radiative cooling strategy via hypocaust TermoDeck® floors integrated with ground pipe ventilation systems and ‘fabric first’ intelligent architectural design. Such hybrid system designs were subject to parametric analysis combined with testing prototypes in field trials to validate simulations. The third stage involved validating the efficiency of the developed HCS associated with PDMs through numerical modelling and simulation of the retrofitted HCS model DesignBuilder taking into consideration the specific thermal and climatic conditions. The definitive findings of the simulation process were generated and compared with the baseline results for efficiency and comparative assessment.

Chapter Four conducted a general background review of energy use within Saudi context. Additionally, an analytical study was carried out to identify and observe the actual thermo-physical and energy performance of current residential block to establish a baseline case study. The selected case study building was computationally modelled and simulated. The study outcomes include the thermo-physical performance of building fabric and construction and a detailed description of total building heat gains, electricity consumption and carbon emissions. The primary findings demonstrated high-energy consumption and cooling loads due to the poor thermal performance of the building fabric and envelope that led to high usage of AC with an associated cost and CO_2 emission penalty. Based on the findings of this chapter, the following research objectives were achieved:

- To assess the current energy use and mechanical cooling approaches in existing dwelling typologies.
- To identify the reasons for the high cooling energy demand in current dwellings.
- To determine the actual thermo-physical performance of a housing block's envelope and fabric in current house typologies in Saudi Arabia.

Chapter Five provided a rationale for the adoption of passive and low energy cooling strategies, establishing 'fabric first'passive design measures (PDMs) as a starting point for reducing cooling loads. The thermal efficiency of the proposed PDMs in controlling heat gain and cool loss were investigated and their potential quantified. It becomes clear that although they could make a significant contribution on their own they could not address peak summer demands, therefore, the key requirement was an evaluation of GPCS and HCRS – possibly in hybrid combination – to address the comfort gap. These systems were assessed both separately and in hybrid combination using parametric analysis. Based on the findings of this chapter, the following research objectives were achieved:

- To investigate the potential implementation of a range of viable passive design measures aimed at reducing heat gain and cooling load.
- To develop viable HCS combined and model their performance when combined with passive low energy measures as measured against the current employment of AC systems.

Chapter Six performed an overview of the employed modelling and simulation software DesignBuilder including the key features and capabilities of the simulation engine EnergyPlus that has extensively discussed. The graphical instrument in DesignBuilder was used to build up the simulation model while EnergyPlus simulation engine was employed to simulate the energy performance of the baseline and the developed case study building models. The sophisticated modelling and simulation software provided hourly, daily and monthly energy use and temperature data, which lets the user closely examine the performance of the building. The primary setting up of the simulation model included the definition of model zone type, floor areas, occupancy, metabolic rates and environmental control, which involve setting cooling set point and setback temperatures. In addition, the key proposed PDMs include external walls, floors, and roof, thermal insulation together with more efficient external glazing and solar shading systems were applied to a simulation model to optimise the thermo-physical performance of the building and promote the cooling efficiency of the applied cooling system. Furthermore, the proposed GPCS simulation model was set up to include its main components, specifications and operation settings in order to examine the thermal effect of GPCS application on the building cooling performance and indoor condition. Similarly, the main inputs of the developed HRCS simulation model were defined including the hydronic tubing specification, flow rate, chilling efficiency, and operation setting to thermally test the influence of the hydronic radiant system application on building performance. The hybrid integrated system HCS set up in EnergyPlus as a mixed mode cooling system by integrating the features and specifications of both the GPCS and HRCS alongside with the applied PDMs system within the operation control setting toward determining the effect of cooling system hybridization on building cooling performance and indoor temperature. The simulation results of applying the developed PDMs, GPCS, HRCS and HCS into to the baseline model was obtained for comparative assessment with baseline. The simulation results statistically and mathematically validated for results comparison. From an energy efficiency perspective, the results remarkably demonstrated the efficiency of the applied system in considerably reducing the building cooling energy consumption alongside with its potential to thermally maintain the indoor temperature within the desired comfort conditions. Based on the findings of this chapter, the following research objective was achieved:

- To develop viable HCS combined and model their performance when combined with passive low energy measures as measured against the current employment of AC systems.

Chapter Seven has carried out an analytical assessment and validation that clearly demonstrated the energy and cost-effectiveness of the PDMs, GPCS, HRCS and HCS applications to efficiently perform as an alternative low energy cooling system to the current AC system. The comparative study proved the energy efficiency and cost-effectiveness of the proposed HCS application and its basic components PDMs, GPCS and HRCS in saving cooling energy, carbon emissions and enhancing indoor thermal comfort and air quality. The applied PDMs have controlled and sustained the internal temperature and reserved any cooling loss or infiltration which reflect on minimizing the cooling load of AC, GPCS, HRCS and HCS and consequently reduced its energy consumption. In addition, the analysed results of the simulated baseline case-study of AC system in comparison with various cooling systems applications demonstrated the potential to save up to 80% of the total cooling load and energy usage cost. The results demonstrated the cost efficiency of applying PDMs, GPCS, HRCS and

HCS with an estimated payback period of 34 months. Based on the findings of this chapter, the following research objectives were achieved:

- To validate and assess the influence of the proposed HCS application in reducing cooling energy consumption, CO_2 emissions while ensuring indoor comfort is maintained throughout the year.
- To estimate the capital and life cycle running cost of the applied PDMs and HCS and calculate the payback timeframe.

According to the research key findings, the current study was satisfactorily and sufficiently answered the research leading questions that raised at the beginning of this thesis and emphasized the research hypothesis. These answered questions are summarized as follows:

Question 1: What strategies and/or systems can be adopted to minimise the energy use in the domestic sector?

This question was extensively answered in chapter 5 when PDMs include external walls, floors, and roof, thermal insulation together with more efficient external glazing and solar shading systems were applied to a simulation model to optimize the thermo-physical performance of the building and promote the cooling efficiency. The simulation results of the retrofitted model conducted in chapter 6, demonstrated that AC annual cooling energy use can be decreased by 37% as a result of applying a range of PDMs in comparison with the baseline model.

***Question 2*:** To what extent can passive strategies be applied to existing house typologies and will their performance be able to provide the desired thermal condition for its occupants particularly in peak summer?

The answer to this question was indicated in chapter 2 through the review of the relevant research studies that conducted to investigate the potential application of low energy passive cooling systems in hot and humid climate houses. The investigations reported that although that passive designs and cooling strategies have the potential to save a considerable amount of energy, such passive strategies in current houses typologies in hot humid regions are difficult to accomplish and insufficient to meet the peak cooling demand in hot summer when the temperature reaches 45°C with high humidity level. This finding was confirmed in chapter 5 through field experiments when the measured ground pipe outlet air temperature and black body radiator temperatures in hot summer were above the thermal comfort level. In addition, these findings were also validated in chapter 6 when the simulation results demonstrated that the applied PDMs on their own were unable to maintain internal temperatures below the upper threshold (28°C) for around 180 days of the year (summer season)

***<u>Question 3</u>*:** What is the possibility of hybridizing passive techniques with low energy active cooling system to perform a viable mixed mode or Hybrid Cooling System (HCS) to substitute the current employment of AC towards limiting cooling energy usage while ensuring a degree of thermal ‘safety’?

The answer to this question was stated in chapter 5 by designing the proposed GPCS, HRCS and the HCS which combined the passive cooling essence of geothermal and radiant cooling strategies with low energy cooling technologies such as fan coil and DC-chiller to optimise the cooling performance of the developed systems, particularly in the summer peak demand. Based on the simulation results conducted in chapter 6 that were validated in chapter 7, the suggested hybrid system demonstrated its cooling efficiency to substitute the current employment of AC and save up to 80% of cooling energy usage while maintaining the indoor temperatures within the comfort range throughout the year.

***<u>Question 4</u>*:** To what extent can HCS be integrated with the current thermo-physical performance of building’s fabric and envelope and what additional measures are required to be taken to ensure that such strategies are both efficient and cost-effective?

The carried out studies suggested a thermal retrofitting of current building fabric and envelope in order to ensure the cooling efficiency of the applied hybrid cooling systems. In addition, the thermal influence of the passive ‘fabric first’ thermal retrofitting design and measures PDMs was validated in chapter 7. The key findings of the PDMs simulation model demonstrated the thermal impact of such passive measures on reducing the cooling load of the applied cooling systems (GPCS, HRCS and HCS and controlling the indoor temperature which consequently led to minimizing the running hours of the applied HCS. In addition to thermal mass, the hybrid system combines low energy chiller unit to meet peak summer cooling demand and sustain the desired indoor comfort over the year. As a result of energy saving the applied HCS proved its cost-effectiveness compared to the baseline with an estimated short pay-back period.

Overall, the most remarkable finding to emerge from this study is that the integration of passive design measures and two active cooling systems (hydronic radiant cooling in tandem with ground pipe supply ventilation) can displace around 80% of AC demand in KSA and reduce over 75% of the CO_2 footprint. Passive 'fabric first' designs and measures (PDMs) can constrict the demand by 37% against the baseline housing block. However, the hybrid cooling system is predicted to contribute an additional 43% reduction with an estimated short pay-back period.

8.3 Critical Review of the Study

This section critically reviews the barriers and potential challenges that may hinder the implementation of the suggested passive and hybrid cooling systems particularly in KSA such as system costs, buildability, complexity social acceptability and building policy.

Reducing cooling demands and moderating indoor condition in challenging climate such as in Saudi Arabia-Jeddah requires a substantial reduction in heat and solar gain and an optimization of cooling through a combination of passive and active cooling strategies to achieve acceptable comfort levels. This combination often creates 'radical' designs that pose additional programmatic and cost challenges, and occasionally produce design forms that are unwelcome by some developers and occupants in the KSA especially after a long time of complete reliance on mechanical AC systems. Integrating a mixed- mode "hybrid" cooling and ventilation strategy has associated capital costs that might not be appropriate for every project's funding model. Likewise, while it is an established fact that in order to reduce solar heat gain it is preferable to add thermal mass and limit the use of wide glazing surface, many developers and occupants in Saudi Arabia are unwilling to accept any design form that requires additional thermal insulation and does not feature excessive glazing. As a result, it has become common for designers to abandon their ambitious sustainability aspirations during the design process, occasionally resigning themselves to the use of standard mechanical systems.

Although the hybrid and passive cooling strategies have demonstrated its efficiency to displace the current use of conventional AC systems, implementing such novel technology in Saudi context may encounter various limitations and barriers while still the major restriction and limitation is that, until now, there is no actual implementation of such innovative passive and hybrid systems in Saudi buildings due to the absence of companies and contractors specialized in such systems applications or even attempt to import this technology from international companies specialized in this field to be applied in Saudi buildings. Also, there are other limitations and barriers that may face the application of such technology in current modern building. Most of these limitations and barriers are attributed to the incompatibility with spatial availability (availability of sources, topography, soil characteristics and allowable built area). For instance, implementing GPCS to the current residential building requires considering the soil condition and water table level to reach the optimum depth to bury the ground pipe. Such soil characteristic differs from location to another and thus the installation and maintenance work and cost will be different as well.

In addition, there are some economic barriers such as the high initial cost of the passive and hybrid cooling techniques itself, the durability of the passive technique over time and maintenance cost. For instance, implementing PDMs or hybrid cooling and ventilation system may result in additional initial cost, however, this additional cost can be retrieved in short time period due to significant energy saving. Moreover, there are some limitations and barriers relevant to planning and architectural legislations such as building codes or local housing laws. For example, in HRCS application, embedding water pipe loops in floor or slab necessitate a specific requirement of floor thickness and insulation layers for optimum thermal performance. Likewise, in GPCS the piping design through floors and walls require a clear specification of wall and floor thickness and material.

Additionally, there is a limitation relevant to the socio-cultural dimensions, which assess the acceptability of such technology according to socio-cultural factors. In fact, imposing such novel cooling strategy after a long time of complete dependency on a mechanical cooling system with a specific level of thermal comfort is a real challenge requires a community awareness campaign and strong support from the public, government and the housing industry. One of the main obstacles for implementing passive and hybrid cooling technology is the lack of public awareness of the environmental benefits of using this technology. The cheap electricity supplies from the conventional process in the region depend on fossil fuel. In addition, there is a lack of information available on the performance of hybrid cooling technologies and their economic benefits. In fact, energy efficiency is not being considered seriously in buildings in Saudi Arabia. The designs of buildings in this region are not taking into account the harsh climate and application of new technologies in the buildings. In addition, there is a lack of familiarity and information from the involved parties, users, and Government decision-makers in Saudi Arabia that the application of such low carbon cooling strategy has economical and environmental advantages. Therefore, the following section presenting key guidelines and recommendations targeting, decision makers and future researchers in the field of energy efficiency and construction.

8.4 General Recommendations and Guidelines

The following recommendations and guidelines are intended for both existing and future residential buildings in Saudi Arabia, in order to fulfil the requirement of achieving low-carbon energy houses targets. Therefore, based on the research outcomes the key recommendations for the energy and mechanical engineers, architects and construction industry workers are summarized as follows:

a) During the design process, it is advantageous to integrate the work of building designers and physicists to consider the thermo-physical performance with an efficient design of cooling system application. This task must start with the provision of an efficient building envelope that uses 'fabric first' design measures to shade and insulate.
b) Design an efficient external use landscaping to cool the surrounding environment and ground soil to enhance the adiabatic cooling effect and optimise the cooling efficiency of the GPCS.
c) Utilizing on-site natural renewable energy generation systems, such as PV, to generate electricity and to reduce the cooling system energy use, thereby reducing CO_2 emissions.

The Key recommendations for the decision makers include:

a) Adopting policies and regulations in the construction industry to promote low-carbon and energy houses in Saudi Arabia that can provide many environmental and economic benefits.
b) Review and update conditions for approving housing permits to add energy consumption requirements to the building design.
c) Implement the established energy consumption standards to control the energy use of future residential buildings.
d) Promote the idea of adopting passive and hybrid cooling strategies in residential buildings and support developments with grant aid.
e) Invest in passive cooling applications and renewable energy resources in Saudi Arabia, for future use across various sectors.
f) Raise public awareness about the deleterious impacts of high energy consumption in the residential sector, and educate the public on the economic benefits to both state and individuals.

g) Establish legislation in Saudi Arabia to develop and approve plans for future homes, taking into account the proposed low carbon cooling techniques and strategies. Energy efficiency targets should be set before warrants are granted.

The key recommendations for future researchers are as follows:

a) Since the current study aimed to achieve low-carbon energy houses, it is recommended for future research to upgrade the target to achieve Zero energy and CO_2 emissions building.
b) Expanding the field of study and investigation to cover the energy consumption patterns in commercial and governmental building sectors.
c) Developing passive or hybrid cooling systems by integrating different passive cooling strategies and implementation techniques.
d) Investigating energy saving potential and cooling approaches in different climatic conditions.
e) Applying different design parameters to develop the cooling system.
f) Adopting different approach of investigation and case study scale and context.
g) Develop and manufacture new construction materials from local raw materials with lower thermal transmission.
h) Incorporate various renewable energy resources such as PV solar panel and wind turbine systems that deliver high-performance energy generation utilising natural resources.
i) Any future implementation of HCS will have to take into account the size of the variation between theoretical and mathematical models and actual real-time building performance on a given site.

8.5 Further Studies and Potential Future Research

It is self-evident that, researchers build upon each other's work. New studies are usually built based on former studies; therefore, it is advantageous to highlight the potential of this research in order to motivate future studies.

In light of the current research findings and the situation in Saudi Arabia in terms of cooling approach and energy consumption in residential buildings, there is a demand for a transition process, leading from the current situation to a low energy sustainable environment.

Therefore, the future researches objective is to design strategies to ensure the implementation of a low carbon residential design framework within the Saudi housing sector.

The project will require cooperative researches and studies with organisations associated with the construction industry in Saudi Arabia; such as the ministry of the municipality, the ministry of housing, the ministry of electricity, Saudi energy efficiency centre, engineering consultants and construction companies.

This research has attempted to evaluate the potential impact of ground pipe supply ventilation in combination with diurnal heat flushing using black body emitters in hot and humid climates. In fact, most of the available energy simulation software packages cannot accommodate the novel passive and hybrid cooling strategies and systems under consideration. The only viable method of progress was to use a combination of modelling and simulation with physical scale models in an attempt to provide further validation or at least, quantify the margin of error. The outcomes of any simulation software have to be treated with care and a degree of scepticism, however, the data generated by prototype testing and field measurements go someway to underpinning the hypothesis and support the view that these techniques in additive hybrid combination, are at least worthy of further investigation.

If these simulations and test results prove to be a good facsimile of reality (a full-scale ground pipe prototype requires to be built and tested), the impact on KSA's electricity demand will be significant. Although it is difficult to retrofit the hybrid cooling strategies into the existing stock, most of the 'fabric first'passive measures could be applied, and this would reduce AC use by over a third in the existing stock.

Therefore, the next stage will be to construct full-scale prototypes of the ground pipe and hydronic panel with enhanced thermal interfaces and test these for their cooling potential, particularly in 'high' summer. If these tests provide data of the same order as the simulation results, the building industry in KSA should have the confidence to produce a prototype housing block for full-scale trials.

Further researches and studies can also adopt different cooling approach and schematic. For instance, the developed HRCS can be integrated with building fabric (floor, roof, wall and beams) while the cooling effect of the radiator can be used as water to air heat exchanger by taking the advantage of the night radiative effect to cool air by convection and blow it to indoor spaces via hypocaust slab (TermoDeck®). Likewise, the cooling performance of the GPCS can be enhanced by controlling the pipe outlet temperature and using ground source heat pump (GSHP), or can be integrated with building structure to perform as "thermal labyrinth". Additionally, based on climatic patterns, other passive cooling systems such as evaporative and ventilative strategy can be incorporated.

Potential future work could focus on building with zero energy and carbon emissions by upgrading the cooling capacity of the hybrid system and integrating additional passive cooling strategies and low energy cooling applications. Such cooling application might be designed injunction with renewable energy resources such as PV solar panels or wind turbine to passively run the developed hybrid cooling system. Moreover, researchers can test such hybrid or low energy cooling system on real physical model rather than a simulation (virtual) model.

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Appendix (A): Simulation input data modelling – (EnergyPlus) – Residential Block –Jeddah – KSA

Location templates	
Data Report (Not Editable)	
General	
Name JEDDAH (KING ABDUL AZIZ INTL)	
Country	SAUDI ARABIA
Source	ASHRAE/ETMY
WMO	410240
ASHRAE climate zone	1B
Koppen classification	BWh
Latitude (°)	21.70
Longitude (°)	39.18
Elevation (m)	17.0
Standard pressure (kPa)	101.1
Time and Daylight Saving	
Time zone	(GMT+03:00) Nairobi
Start of Winter	Oct
End of Winter	Mar
Start of summer	Apr
End of summer	Sep
Energy Codes	
Legislative region	SAUDI ARABIA
Heating 99.6%	
Outside design temperature (°C)	15.2
Wind speed (m/s)	11.8
Wind direction (°)	0.0
Heating 99%	
Outside design temperature (°C)	16.8
Wind speed (m/s)	10.3
Wind direction (°)	0.0
Yearly	
Cooling Design Weather (0.4% based on dry-bulb temp.)	
Max DB temperature (°C)	41.0
WB temperature at Max DB (°C)	23.5
Min night design temperature (°C)	30.8
Cooling Design Weather (1% based on dry-bulb temp.)	
Max DB temperature (°C)	39.8
WB temperature at Max DB (°C)	24.2
Min night design temperature (°C)	29.6
Cooling Design Weather (2% based on dry-bulb temp.)	
Max DB temperature (°C)	38.8
WB temperature at Max DB (°C)	24.5
Min night design temperature (°C)	28.6
Cooling Design Weather (0.4% based on wet-bulb temp.)	
Max DB temperature (°C)	35.0
WB temperature at Max DB (°C)	29.9
Min night design temperature (°C)	24.8
Cooling Design Weather (1% based on wet-bulb temp.)	
Max DB temperature (°C)	34.4
WB temperature at Max DB (°C)	29.1
Min night design temperature (°C)	24.2
Cooling Design Weather (2% based on wet-bulb temp.)	

Max DB temperature (°C)	38.8
WB temperature at Max DB (°C)	24.5
Min night design temperature (°C)	28.6
Cooling Design Weather (0.4% based on wet-bulb temp.)	
Max DB temperature (°C)	35.0
WB temperature at Max DB (°C)	29.9
Min night design temperature (°C)	24.8
Cooling Design Weather (1% based on wet-bulb temp.)	
Max DB temperature (°C)	34.4
WB temperature at Max DB (°C)	29.1
Min night design temperature (°C)	24.2
Cooling Design Weather (2% based on wet-bulb temp.)	
Max DB temperature (°C)	33.9
WB temperature at Max DB (°C)	28.5
Min night design temperature (°C)	23.7
Cooling Design Weather (0.4% based on dew-point temp.)	
Max DB temperature (°C)	33.6
WB temperature at Max DB (°C)	28.8
Min night design temperature (°C)	23.4
Cooling Design Weather (1% based on dew-point temp.)	
Max DB temperature (°C)	32.8
WB temperature at Max DB (°C)	27.9
Min night design temperature (°C)	22.6
Cooling Design Weather (2% based on dew-point temp.)	
Max DB temperature (°C)	32.3
WB temperature at Max DB (°C)	27.1
Min night design temperature (°C)	22.1
Monthly	
0.4% Monthly Design Dry Bulb and Mean Coincident Wet Bulb Temperatures	
Monthly Design Dry Bulb Temperatures	
January (°C)	32.2
February (°C)	33.2
March (°C)	36.2
April (°C)	39.1
May (°C)	42.0
June (°C)	43.2
July (°C)	42.1
August (°C)	41.2
September (°C)	41.2
October (°C)	41.1
November (°C)	36.2
December (°C)	33.2
Mean Coincident Wet Bulb Temperatures	
January (°C)	20.4
February (°C)	21.0
March (°C)	21.8
April (°C)	22.7
May (°C)	24.0
June (°C)	23.8
July (°C)	23.6
August (°C)	23.8

November (°C)	21.9
December (°C)	21.5
2% Monthly Design Dry Bulb and Mean Coincident Wet Bulb Temperatures	
Monthly Design Dry Bulb Temperatures	
January (°C)	31.0
February (°C)	31.9
March (°C)	34.1
April (°C)	37.0
May (°C)	39.1
June (°C)	40.0
July (°C)	40.6
August (°C)	39.9
September (°C)	38.2
October (°C)	38.1
November (°C)	34.8
December (°C)	32.1
Mean Coincident Wet Bulb Temperatures	
January (°C)	21.2
February (°C)	21.6
March (°C)	21.7
April (°C)	23.0
May (°C)	24.3
June (°C)	23.7
July (°C)	23.9
August (°C)	25.2
September (°C)	26.3
October (°C)	23.8
November (°C)	23.0
December (°C)	22.1
5% Monthly Design Dry Bulb and Mean Coincident Wet Bulb Temperatures	
Monthly Design Dry Bulb Temperatures	
January (°C)	29.9
February (°C)	30.5
March (°C)	32.2
April (°C)	35.8
May (°C)	37.3
June (°C)	38.2
July (°C)	39.2
August (°C)	38.8
September (°C)	37.1
October (°C)	36.2
November (°C)	33.5
December (°C)	31.1
Mean Coincident Wet Bulb Temperatures	
January (°C)	20.9
February (°C)	21.9
March (°C)	21.6
April (°C)	23.3
May (°C)	24.3
June (°C)	24.4
July (°C)	24.1
August (°C)	25.6
September (°C)	26.9

October (°C)	25.0
November (°C)	23.3
December (°C)	22.0

10% Monthly Design Dry Bulb and Mean Coincident Wet Bulb Temperatures

Monthly Design Dry Bulb Temperatures

January (°C)	28.2
February (°C)	29.0
March (°C)	30.9
April (°C)	34.1
May (°C)	36.0
June (°C)	37.0
July (°C)	38.2
August (°C)	37.3
September (°C)	36.1
October (°C)	35.1
November (°C)	32.3
December (°C)	30.0

Mean Coincident Wet Bulb Temperatures

January (°C)	20.0
February (°C)	21.0
March (°C)	21.4
April (°C)	23.2
May (°C)	24.4
June (°C)	24.9
July (°C)	24.4
August (°C)	26.4
September (°C)	27.1
October (°C)	25.4
November (°C)	23.3
December (°C)	21.9

0.4% Monthly Design Wet Bulb and Mean Coincident Dry Bulb Temperatures

Monthly Design Wet Bulb Temperatures

January (°C)	24.7
February (°C)	25.2
March (°C)	25.8
April (°C)	27.2
May (°C)	29.1
June (°C)	29.0
July (°C)	29.7
August (°C)	31.1
September (°C)	30.6
October (°C)	29.2
November (°C)	27.0
December (°C)	25.6

Mean Coincident Dry Bulb Temperatures

January (°C)	28.9
February (°C)	30.1
March (°C)	31.6
April (°C)	33.7
May (°C)	36.5
June (°C)	35.9

July (°C)	35.5
August (°C)	36.1
September (°C)	35.9
October (°C)	34.1
November (°C)	32.1
December (°C)	30.0
2% Monthly Design Wet Bulb and Mean Coincident Dry Bulb Temperatures	
Monthly Design Wet Bulb Temperatures	
January (°C)	23.7
February (°C)	24.1
March (°C)	24.5
April (°C)	26.1
May (°C)	27.4
June (°C)	27.9
July (°C)	28.8
August (°C)	30.2
September (°C)	29.3
October (°C)	28.1
November (°C)	26.0
December (°C)	24.6
Mean Coincident Dry Bulb Temperatures	
January (°C)	28.0
February (°C)	29.1
March (°C)	30.5
April (°C)	32.4
May (°C)	34.5
June (°C)	34.7
July (°C)	34.3
August (°C)	34.9
September (°C)	34.6
October (°C)	33.1
November (°C)	31.1
December (°C)	29.3
5% Monthly Design Wet Bulb and Mean Coincident Dry Bulb Temperatures	
Monthly Design Wet Bulb Temperatures	
January (°C)	22.8
February (°C)	23.2
March (°C)	23.6
April (°C)	25.2
May (°C)	26.5
June (°C)	27.2
July (°C)	28.0
August (°C)	29.3
September (°C)	28.9
October (°C)	27.4
November (°C)	25.2
December (°C)	23.9
Mean Coincident Dry Bulb Temperatures	
January (°C)	27.1
February (°C)	28.0
March (°C)	29.6

April (°C)	31.7
May (°C)	33.6
June (°C)	33.7
July (°C)	33.8
August (°C)	34.2
September (°C)	34.1
October (°C)	32.5
November (°C)	30.3
December (°C)	28.7
10% Monthly Design Wet Bulb and Mean Coincident Dry Bulb Temperatures	
Monthly Design Wet Bulb Temperatures	
January (°C)	21.9
February (°C)	22.4
March (°C)	22.8
April (°C)	24.5
May (°C)	25.8
June (°C)	26.7
July (°C)	27.2
August (°C)	28.7
September (°C)	28.2
October (°C)	26.9
November (°C)	24.7
December (°C)	23.1
Mean Coincident Dry Bulb Temperatures	
January (°C)	26.5
February (°C)	27.0
March (°C)	28.5
April (°C)	31.1
May (°C)	32.8
June (°C)	33.2
July (°C)	33.5
August (°C)	33.9
September (°C)	33.3
October (°C)	32.0
November (°C)	29.8
December (°C)	27.8

Appendix (B): Simulation key inputs and outputs – (EnergyPlus) Hybrid Cooling System (HCS)

The developed hybrid cooling system (HCS) was defined in the EnergyPlus simulation model by integrating the main features and specifications of the proposed hydronic radiant cooling (HRCS) in tandem with the ground pipe supply ventilation (GPCS). The key inputs of the proposed HCS simulation model include the specification of ground pipe, hydronic tubing, flow rate, fans and chiller coefficient, and operational setting while the key outputs include. energy use and thermal conditions.

Ground heat exchanger template

Data Report (Not Editable)

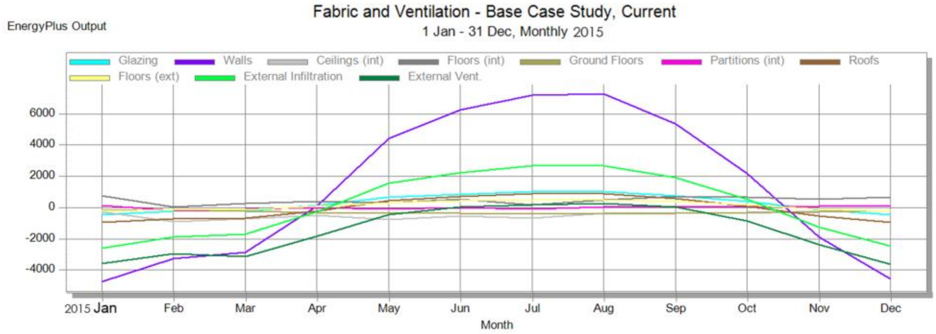
General	
Ground Pipe Cooling System (GPCS)	
Source	User defined
Category	Vertical ground heat exchanger
Ground Heat Exchanger - Vertical	
Ground temperature (°C)	27.200
Flow rate	
Design flow rate (m3/s)	0.00390
Maximum flow rate (m3/s)	0.00390
Borehole and Pipe Geometry	
Number of boreholes	24
Borehole length (m)	76.0
Borehole radius (m)	0.063508
Pipe outer diameter (m)	0.4000000
U-tube distance (m)	0.0253977
Pipe thickness (m)	0.00241285
Ground, Grout and Pipe Properties	
Ground thermal conductivity (W/m-K)	0.692626
Ground thermal heat capacity (J/m3-K)	2347000.00
Grout thermal conductivity (W/m-K)	0.692626
Pipe thermal conductivity (W/m-K)	0.391312
Others	
Maximum length of simulation	1
G-function reference ratio	0.000836
Ground Heat Exchanger - Pond	
Pond depth (m)	2.00
Pond area (m2)	1000.00
Hydronic tube inside diameter (m)	0.02

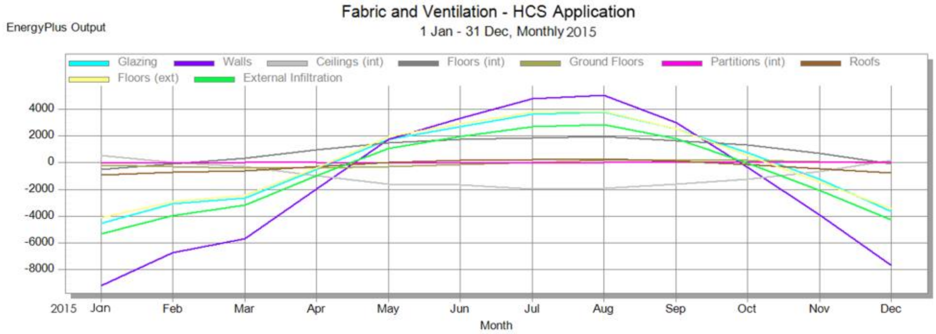
Chillers

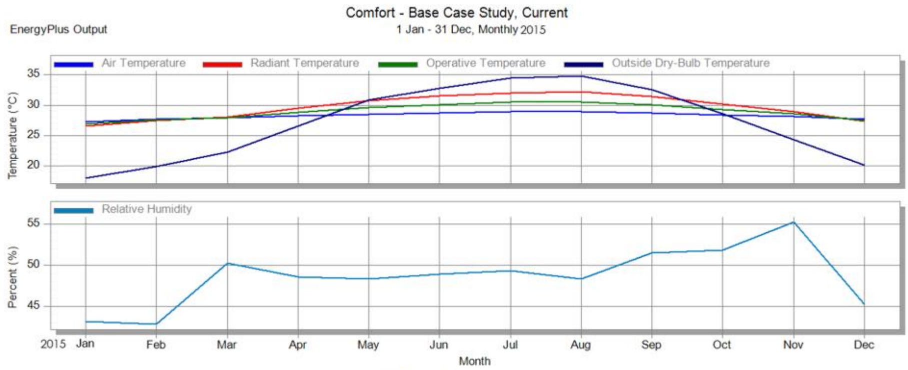
Data Report (Not Editable)

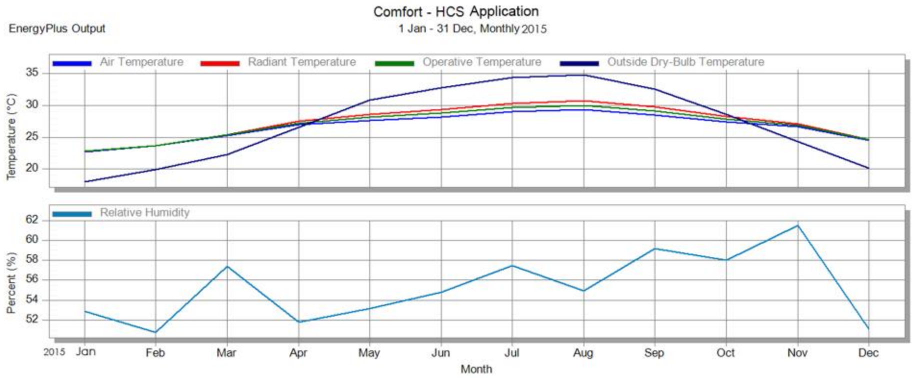
General	
ElectricEIRChiller Scroll McQuay AGZ010BS 34.5kW/2.67COP	
Source	EnergyPlus
Category	Air Cooled
Chiller type	2-Electric EIR
Nominal capacity (W)	autosize
Nominal CoP	5.500
Reference COP	2.670
Reference leaving chilled water temperature (°C)	6.670
Reference entering condenser fluid temperature (°C)	35.000
Reference leaving condenser water temperature (°C)	
Design chilled water flow rate (m3/s)	autosize
Design condenser water flow rate (m3/s)	autosize
Performance Curves	
Cooling capacity function of temperature curve	ElectricEIRChiller McQuay
Electric input to cooling output ratio function of temperature curve	ElectricEIRChiller McQuay
Electric input to cooling output ratio function of part load ratio curve	ElectricEIRChiller McQuay
Basin Heater	
Basin heater capacity (W/K)	0.000
Basin heater setpoint temperature (°C)	2.000
Basin heater operating schedule name	

HVAC templates	
Data Report (Not Editable)	
General	
Chilled floor (HRCS)	
Source	
Category	Project
Region	SAUDI ARABIA
Simple	
Auxiliary energy (kWh/m2)	9.00
Colour Shading in Model	
Floor shade colour	
NCM HVAC system type	
NCM HVAC system type	Chilled floor (HRCS)
Natural Ventilation	
On	Yes
Rate (ac/h)	5.00
Mixed mode on	No
Mechanical Ventilation	
On	No
Heating	
On	No
Cooling	
Cooling On	Yes
Precool (hr)	1.0
Cooling system seasonal CoP	0.80
Supply Air Condition	
Minimum supply air temperature (°C)	23.00
Minimum supply air humidity ratio (g/g)	0.009
Humidification	
Humidification	No
Dehumidification	
Dehumidification	No
Air Temperature Distribution	
Distribution mode	1-Mixed
Interpolation mode	2-Inside temperature
Upper Conditions	
Temperature (°C)	28.00
Heat rate (W)	1.00
Temperature gradient (°C/m)	1.00
Lower Conditions	
Temperature (°C)	21.00
Heat rate (W)	0.00
Temperature gradient (°C/m)	1.00
Heights	
Thermostat height (m)	1.50
Return air height (m)	3.50
Cost	
Cost per area (GBP/m2 GIFA)	65.00


Fabric and Ventilation - Base Case Study, Current
1 Jan - 31 Dec, Monthly 2015
EnergyPlus Output
Glazing
Walls
Ceilings (int)
Floors (int)
Ground Floors
Partitions (int)
Roofs
Floors (ext)
External Infiltration
External Vent.
6000
4000
2000
0
-2000
-4000
2015 Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month


Fabric and Ventilation - HCS Application
1 Jan - 31 Dec, Monthly 2015
EnergyPlus Output
Glazing
Walls
Ceilings (int)
Floors (int)
Ground Floors
Partitions (int)
Roofs
Floors (ext)
External Infiltration
4000
2000
0
-2000
-4000
-6000
-8000
2015 Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month


Comfort - Base Case Study, Current
1 Jan - 31 Dec, Monthly 2015
EnergyPlus Output
Air Temperature
Radiant Temperature
Operative Temperature
Outside Dry-Bulb Temperature
Temperature (°C)
35
30
25
20
Relative Humidity
Percent (%)
55
50
45
2015 Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month


Comfort - HCS Application
1 Jan - 31 Dec, Monthly 2015
EnergyPlus Output
Air Temperature
Radiant Temperature
Operative Temperature
Outside Dry-Bulb Temperature
Temperature (°C)
35
30
25
20
Relative Humidity
Percent (%)
62
60
58
56
54
52
2015 Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month