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TOWARDS A NET-ZERO ENERGY HOUSE ADAPTING VERNACULAR AND PASSIVE TECHNIQUES IN JEDDAH CITY

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The thesis study titled "TOWARDS A NET-ZERO ENERGY HOUSE ADAPTING VERNACULAR AND PASSIVE TECHNIQUES IN JEDDAH CITY" is submitted by Ghayda NYAZI in partial fulfilment of the requirements for the degree of Master of Science in the Department of Architecture, Gazi University by the following committee.

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(M.S.Thesis)

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ABSTRACT

The high energy consumption rates in Saudi Arabia are alarming and as a country that depends mostly on oil as a source of energy, which is a non-renewable and a pollutant source, solutions must be found to reduce the high consumption and to start shifting to the use of renewable energy resources. The fact that the major consumption in the country comes from the building sector and predominantly from the residential buildings, makes enhancing the houses' energy performance a priority target. The purpose of this study is to evaluate and enhance the residential buildings' energy performance in Saudi Arabia, to reduce the high energy consumption and the CO_2 emissions, by achieving a net-zero energy prototype house adapting the Passive House standards for hot climate and suitable natural ventilation solutions from the vernacular architecture of Jeddah. Based on energy simulation analysis obtained from DesignBuilder software tool, this study compares the energy performance results of an average contemporary Saudi house in Jeddah city, west of Saudi Arabia, before and after applying the Passive House principles and passive techniques from the vernacular architecture. This study proposes a potential net-zero energy prototype house that achieves a 66.80% reduction in annual energy consumption through combining the Passive House Standard and the vernacular techniques, along with on-roof solar panels that cover up the remaining energy demand. Future studies can investigate the cost of constructing net-zero energy houses in Saudi Arabia.

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CİDDE KENTİNDE YÖRESEL VE PASİF TEKNİKLERİ UYARLAYAN SIFIR ENERJİLİ KONUTA DOĞRU

(Yüksek lisans Tezi)

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ÖZET

Enerji kaynağı olarak çoğunlukla petrole bağımlı olan Suudi Arabistan'daki yüksek enerji tüketim oranları endişe verici düzeylere ulaşmıştır. Petrol, yenilenemez ve kirletici bir kaynak olduğundan ülkede yüksek enerji tüketimini azaltacak ve yenilenebilir enerji kaynaklarını devreye sokacak çözümler üretilmelidir. İnşaat sektörünün ülkenin en çok enerji tüketen sektörü olması gerçeği ve özelikle de konut binalarının yaygın olması sebebiyle bu yapıların enerji performansının arttırılması öncelikli bir hedeftir. Bu çalışmanın amacı, Suudi Arabistan'daki konut binalarının enerji performansını değerlendirmek ve arttırmaktır. Bu amaçla konut binalarının yüksek enerji tüketimini ve CO_2 emisyonunu azaltacak, Pasif Ev standartlarını ve Cidde'nin yerel mimarisinden uygun doğal havalandırma çözümlerini uyarlayacak sıfır enerjili prototip bir ev tasarlanmıştır. Çalışmada, DesignBuilder programından elde edilen enerji simülasyonu analizine dayanarak, Suudi Arabistan'ın batısındaki Cidde kentinde çağdaş ortalama bir Suudi evinin mevcut durumu ile Pasif Ev prensipleri ile yerel mimariden gelen pasif tekniklerin uygulanmasından sonraki enerji performansı sonuçları karşılaştırılmıştır. Sonuç olarak çalışmada, yıllık enerji tüketiminde %66.80 azalma sağlayan Pasif Ev Standardı ve yerel teknikleri birleştirerek potansiyel bir sıfır enerjili prototip ev elde edilmiş, kalan enerji talebini karşılamak için çatıya yerleştirilecek güneş paneller önerilmiştir. Gelecekteki çalışmalar için ise Suudi Arabistan'da inşa edilecek sıfır enerjili evlerin yapım maliyetlerinin araştırılmasının önemi vurgulanmıştır.

Bilim Kodu	:	80103
Anahtar Kelimeler	:	Sıfır enerjili ev, sıcak iklim, pasif tasarım teknikleri, yöresel mimari, bina enerji simülasyonu.
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SYMBOLS AND ABBREVIATIONS

The symbols and abbreviations used in this study are presented below along with explanations.

Symbols	Explanations
cm	Centimetres
h	Hour
km^2	Square kilometre
kW	Kilowatt
kWh	Kilowatt hour
$kWh/(m^2a)$	Kilowatt hours per year
m	Meter
mm	Millimetres
m^2	Square meter
n_{50}	(ACH) @50Pa
W/m2	Watt per square meter
&	And
°C	Celsius
$	Dollar
%	Percentage, a number or ratio as a fraction of 100

Abbreviations	Explanations
am	Ante Meridiem
ACH50	Air changes per hour at 50 pascals (Pa) pressure
BC	Before Christ
BIM	Building Information Modelling
CFD	Computational Fluid Dynamics
CO_2	Carbon dioxide
CSP	Concentrated Solar Power
DXF	Drawing eXchange Format

Abbreviations	Explanations
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EPS	Expanded Polystyrene
Epw	EnergyPlus Weather
GCC	Gulf Cooperation Council
GCS	General Commission of Survey
GW	Gigawatt
HVAC	Heating Ventilating and Air Conditioning
i.e	That is
IES	Integrated Environmental Solutions
IPHA	International Passive House Association
K●A●CARE	King Abdullah City for Atomic and Renewable energy
KAUST	King Abdullah University for Science and Technology
LEED	Leadership in Energy and Environmental Design
MBRSC	Mohammed Bin Rashid Space Centre
MW	Megawatt
NREP	National Renewable Energy Program
OSB	Oriented Strand Board
PDF	Portable Document Format
PH	Passive House
PER	Primary Renewable Energy
PHI	Passive House Institute
PHPP	Passive House Planning Package
pm	Post Meridiem
PV	Photovoltaic
PVC	Polyvinyl Chloride
REPDO	Renewable Energy Project Development Office
SEEC	Saudi Energy Efficiency Centre

Abbreviations	Explanations
SHGC	Solar Heat Gain Coefficient
UAE	United Arab Emirates
U.S	United State
U-Value	Thermal transmittance
XPS	Extruded Polystyrene
2-D	Two-Dimensional
3-D	Three-Dimensional

1. INTRODUCTION

Scope of the study

The high energy consumption rates in Saudi Arabia are alarming and as a country that depends mostly on oil as a source of energy, which is a non-renewable and an environmental pollutant source, solutions must be found to reduce the high consumptions. Moreover, the integration of renewable energy must be approached. The fact that the major energy consumption in the country is coming from the building sector and mostly from the residential buildings makes enhancing the houses' energy performance as a priority target for architects.

Background

The environmental crises that the world is facing today such as global warming are due to the greenhouse gases emissions that are produced by our dependence on burning fossil fuels for energy. Saudi Arabia is one of the countries that depend completely on oil as a source of energy therefore it's facing environmental and economic issues that are going to become more serious in the near future. Since the discovery of oil in Saudi Arabia, economic growth has invaded the country, shifting its lifestyle to the modern concept thus resulting in the abandonment of the vernacular architecture by the building sector. New buildings have emerged which were in contrast with the vernacular ones that addressed the local climate and the culture of the region. The modern buildings lacked identity and have lost their connection and adaptation to the local climate through design and construction by relying completely on mechanical air conditioning which represents the highest energy consumption rates by buildings.

Since energy and environment-related challenges became a serious global issue, the concept of sustainability has become a wide platform for research, studies, and applications. Many approaches in architecture are adopting the concept of sustainability through green standards and zero energy approaches which have been studied but have limited applications.

In fact, vernacular architecture has introduced the concept of sustainability long ago, in the way it was formulated with reactions to the local climate and culture in mind. Vernacular architecture in Saudi Arabia has adapted many solutions and techniques especially for natural ventilation in order to adapt to the hot climate, which has potential to propose innovative solutions addressing the energy issues in the built environment of today.

Research objective

The purpose of this study is to evaluate and enhance the residential buildings' energy performance in Saudi Arabia by taking the typical contemporary detached villa as a case study. In order to reduce the high energy consumption and the CO_2 emissions, this study aims to achieve a net-zero energy prototype house adapting the concept of the Passive House for hot climate merged with suitable passive solutions from the vernacular architecture of Jeddah.

Research questions

This study has been designed to investigate the following research question: How can the net-zero energy residential buildings in Jeddah city be achieved? This question is answered through answering the following sub-questions: Will the Passive House standards prove its efficiency under Jeddah's climate? How can we learn from the vernacular housing in the region? What kind of vernacular passive cooling techniques can be applied to modern houses together with passive house standards?

Research method

Based on energy simulation analysis obtained from DesignBuilder software tool, this study has analyzed the energy performance results of an average conventional Saudi house in Jeddah city. A compression between the energy consumption and cooling loads in particular of the conventional house before and after applying the Passive House principles has been obtained. In addition, the effect of introducing passive vernacular ventilation techniques on reducing cooling loads has been examined. Finally, this study has proposed a potential net-zero energy prototype house by combining Passive House standards with vernacular techniques.

With this regard, the second chapter of this thesis is the literature review which is based on a review of the problem of high energy consumption and some potential solutions such as renewable energy, PH standard, vernacular architecture, as well as the analysis of case studies of related issues. The third chapter discusses the method used to achieve the results of this study, which is building energy simulation, and data related to the simulation process (location and climate). The fourth chapter includes designing the Base-Case house and the simulation results of applying PH standard and vernacular solutions. The fifth and final chapter discusses the achieved results and future remarks of this study.

Significance of the study

Saudi Arabia is a country of high energy consumption rates with the building sector being responsible for 75% of the total national electricity consumption (SEEC, 2017). It is crucial for the country to move towards sustainable housing solutions that include adapting energy-efficient and environmentally friendly concepts and changing its outlook towards the use of renewable energy.

2. LITERATURE REVIEW

The literature review section analyses the causes and the potential solutions for the high energy consumption by the residential building sector in Saudi Arabia. In addition, it explores the passive techniques that can be adapted in order to reach the goal of this study, through the examination of successful examples. Table 2.1 lists some studies and researches done related to energy consumption and building energy issues in Saudi Arabia between 2009-2018.

Table 2.1. Energy related studies in Saudi Arabia.

Author (Year)	Type of publication	Description
Prins (2018)	Master Thesis	This study exposes the effects of renewable energy projects on the rentier state of the Kingdom of Saudi Arabia.
Al Surf (2017)	Book	This book reveals the challenges for the application of sustainability to housing in Saudi Arabia, discussing the current energy consumption situation.
Ratikainen (2017)	Master Thesis	This thesis analyses the national political context and factors shaping Saudi Arabia's renewable energy policies through a multi-level perspective analysis.
Alkhathlan and Javid (2015)	Journal Article	This study analyzes the effect of oil consumption on the environmental quality of Saudi Arabia from 1971 to 2013.
Almasoud and Gandayh (2015)	Journal Article	This article compares between the cost of solar energy and fossil fuel energy in Saudi Arabia taking the environmental and health damages into account.
Alrashed and Asif (2015)	Journal Article	This study explores the residents' views towards applying renewable energy systems in Saudi dwellings.
Atieh and Alshariff (2015)	Journal Article	This study investigates powering up a typical house in Madina using hybrid solar and hydrogen fuel-cell energy system.
Olayan (2011)	Master Thesis	This study suggests the use of adaptive façade systems in Saudi Arabia that harvest the sun's energy to produce clean electrical power.
Lahn and Stevens (2011)	Book	This book examines Saudi Arabia's energy consumption problem and the role of energy prices, discussing current approaches to addressing the energy challenges.
Al Saleh (2009)	Journal Article	This paper represents a set of renewable energy scenarios for Saudi Arabia developed using the Delphi technique.

2.1. Energy Consumption in Saudi Arabia

Saudi Arabia is the world's second-largest holder of proved oil reserves as it holds according to the EIA statistics, roughly 16% of total reserves in the world. It is the largest exporter of petroleum liquids in the world, and maintains the world's largest crude oil production capacity at roughly 12 million barrels per day. Saudi Arabia was ranked the 6th in the world regarding the total petroleum consumption in 2015 and the number one in the Middle East with a total consumption of 3.9 million barrels per day of oil in 2016, oil consumption grew between 2006 and 2016 by an average of 7% per year, mainly as a result of strong economic growth and government-subsidized energy prices. Saudi Arabia's economy depends heavily on petroleum exports, which is nearly 75% of total Saudi export value in 2016. In 2016 as well, Saudi Arabia announced that it will adapt a national transformation called Vision 2030, including cultural, governance, and economic aspects of the Saudi society. This Vision 2030 plans to lower the dependence on oil production for income, by broadening the economic base. According to the BP Statistical Review of World Energy 2017, Saudi Arabia was ranked the world's 10th largest consumer of total primary energy in 2016 about 63% was crude oil and petroleum liquids-based (EIA, 2017). As fossil fuel use is the primary source of CO_2, in 2014 Saudi Arabia was the number 8 in the ranking of the world's countries total CO_2 emissions from fossil-fuel burning, cement production, and gas flaring (EPA, 2017).

2.1.1. Energy consumption in building sector in Saudi Arabia

The Building sector represents the largest energy consumer in the world, and responsible for over one-third of total final energy consumption as well as the main source of carbon dioxide (CO_2) emissions (IEA, 2013). The building sector (residential, governmental, and commercial) represents roughly about 23% of the energy consumption in Saudi Arabia, which represents more than 75% of the total produced electrical energy by the Kingdom, noting that the residential sector is recording the highest consumption (Figure 2.1), with an annual growth rate of about 7%. This is due to two main reasons: first, the low energy efficiency in electrical appliances; second, the lack of thermal insulation in most buildings, as more than 70% of the residential buildings are not insulated which has led to increase the consumption of energy used in refrigeration equipment (SEEC, 2017).

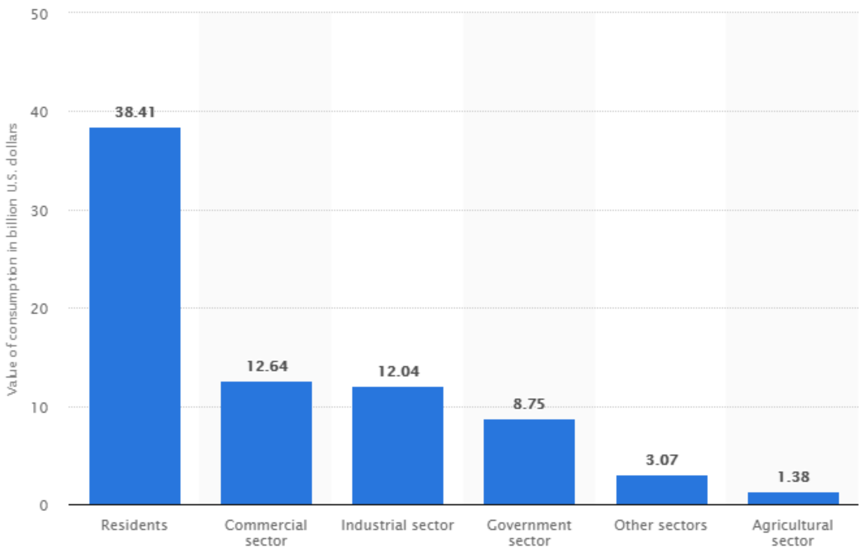


Figure 2.1. Electricity consumption in Saudi Arabia in 2015, by sector (in billion U.S. dollars) (Statista, 2018)

Some other reasons behind the high consumption by the building sector in Saudi Arabia can be summarized as:

- The lack of the vernacular architecture principles that adapt passive and low-energy strategies for cooling and lighting in the modern houses in Saudi Arabia.
- The complete dependence on burning of fossil fuel for electricity generation in Saudi Arabia and ignoring the utilization of the renewable energy resources as Saudi Arabia is an oil-rich country.
- The absence of regulations and building codes that includes the principles of sustainable architecture.
- The focus on luxurious style of living, and the relatively large residences caused the negligence of the sustainability issues (Taleb and Sharples, 2011).

Although Saudi Arabia can still depends on oil as a source of energy for many coming years. The fact that it’s non-renewable, unreliable and the cause of serious environmental crisis, realistic governmental efforts have been done for utilizing the renewable energy sources.

2.1.2. Sustainable energy usage in Saudi Arabia

As Saudi Arabia maintains a rapidly growing population which causes an ever-increasing pressure on the country's non-renewable hydrocarbon resources. Thus, it was urgent to introduce alternative, sustainable and reliable sources of energy for generating power and generating desalinated water, as it will reduce consumption of the nation's fossil fuel reserves. In April 2010, K●A●CARE (King Abdullah City for Atomic and Renewable Energy) was established with the essential goal of building a sustainable future for the country by developing an alternative energy capacity fully supported by world-class local industries (K●A●CARE, 2018).

The anticipated demand for electricity in the country is expected to exceed 120 GW in 2032 according to governmental estimate, except if alternative energy and energy conservation measures are applied. K●A●CARE aims to utilize a balanced mix of economically feasible and technically achievable atomic and renewable energy in a sustainable way in order to generate power and preserve the Kingdom's resources of oil and gas for the future. Ensuring longer-term availability of hydrocarbons for export, will ensure the long term prosperity and maintain energy security of the country. The economic viability of the renewables sector is evident considering Saudi Arabia's year-long high solar intensity, such renewable resources are subjected to fluctuation in supply, it is recognized they are best used in combination at times of peak demand whereas the other alternative, atomic energy, can provide an uninterrupted source of electricity throughout the year. To meet the required demand K●A●CARE is recommending the introduction of renewable and atomic energy gradually, by the time of 2032, 50% of all electricity generated will be from non-fossil fuels (K●A●CARE, 2018).

The fact that Saudi Arabia has a high solar intensity, solar energy was the most efficient renewable energy source to be utilized, second comes wind energy.

2.1.3. Solar and wind energy in Saudi Arabia

Saudi Arabia is blessed with an abundant sunlight all over the year, with one of the world's highest insolation rates. In addition to the availability of empty desert spaces and the vast deposits of sand that can be used in the manufacture of silicon photovoltaic cells (Ouda, 2017). For that reason K●A●CARE's aims for the implementation of clean, cost-effective solar energy technologies that could meet the peak demands, particularly in the summer, which will be achieved by two forms of solar energy – Photovoltaic (PV) and Concentrated Solar Power (CSP), (K●A●CARE, 2018).

Saudi Arabia Solar Industry Association is a non-governmental organization dedicated to helping Saudi Arabia realizes its enormous solar potential. It has initiated many solar power stations in many universities around the kingdom, by collaboration with international leader companies in the field. The association encourages the development of expertises and reduces the need for foreign labor in the renewable energy sector (Saudi-sia, 2017).

Applications of solar energy in Saudi Arabia have been growing since 1960, starting with small-scale research activities for university projects, and since 2010 many larger solar energy projects have been implemented. In 2017 and in line with vision 2030 The Renewable Energy Project Development Office (REPDO) within the Ministry of Energy, Industry and Mineral Resources was established to deliver the goals of the National Renewable Energy Program (NREP) which aims to get the best out of the potential of renewable energy in Saudi Arabia. (Figure 2.2) shows the renewable energy projects that will be deployed in 35+ parks across the country, and 4 of them will take concentrated solar power (CSP) technology.

In 2018 two renewable energy projects were launched in the northern region of Al-Jouf: Sakaka, a 300 MW solar PV powerplant, and the Dumat Al-Jandal 400 MW onshore wind project. which will be Saudi Arabia's first utility-scale wind farm. The growth of a wind energy industry in Saudi Arabia is an important factor for diversifying the industry. The $500 million Dumat Al Jandal wind farm will generate enough power to supply up to 70,000 Saudi households when it connects to the Northern electricity grid," said the Minister of Energy, Industry and Mineral Resources (KSA Climate, 2018).

11 solar projects with a combined capacity of 2,225 MW were set to be tendered in 2019. The goal is to achieve over 25GW of wind and solar power generation in the next five years, and close to 60GW over the next decade; of which 40GW will be generated from

solar energy, with a further 16GW of onshore wind. With a combined generation capacity of 1.51 GW, the latest seven projects will supply energy to power 226,500 households. The total investment in the projects is expected to be worth $1.51 billion, creating over 4,500 jobs during construction, operations and maintenance. The projects include Qurrayat (200 MW), Madinah (50 MW), Rafha (45 MW), Alfaisaliah (600 MW), Rabigh (300 MW), Jeddah (300 MW) and Mahad Duhab (20 MW) (Figure 2.3). The Kingdom aims to create over the next decade a global hub of renewable energy capability upwards of 200 GW (Powersaudiarabia, 2019)

Renewable energy can supply our buildings with a sustainable, environmental friendly energy but the amount of energy we consume must also be reduced in order to raise the percentage of our dependence on those resources until we cut the support of fossil fuel energy completely. Buildings can consume less energy by changing their design and construction; in fact, the vernacular architecture of Saudi Arabia has introduced many techniques to adapt to its harsh weather with minimum energy use.

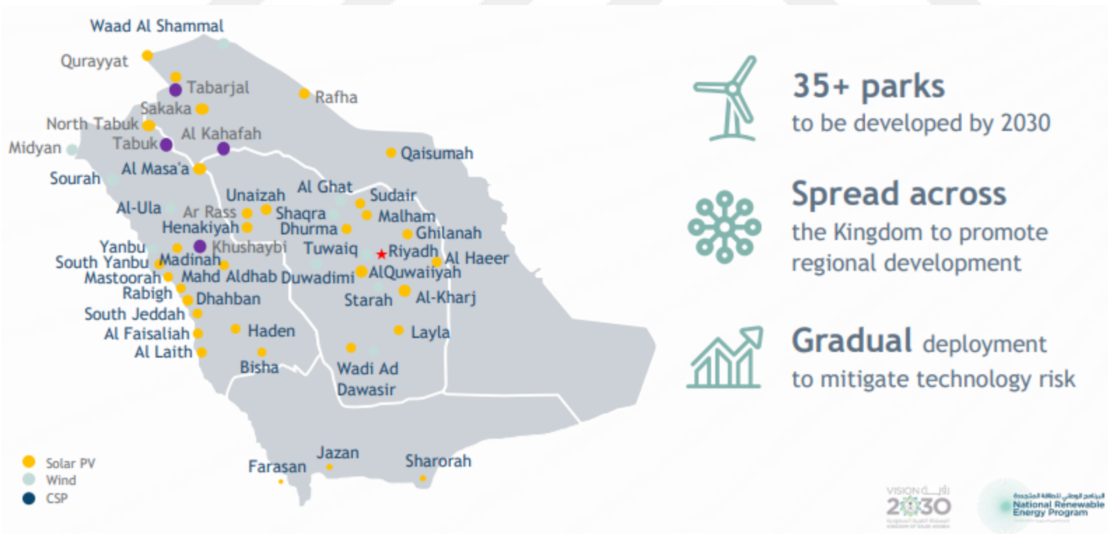


Figure 2.2. Renewable energy projects that will be developed across Saudi Arabia (Powersaudiarabia, 2019).

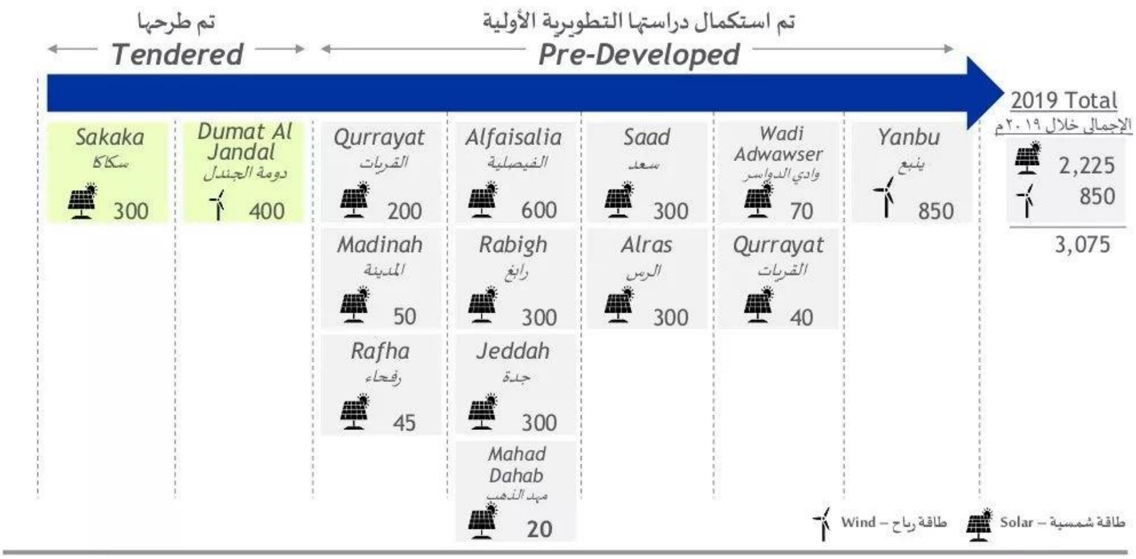


Figure 2.3. Tendered and Pre-developed Projects in 2019 with a total capacity of 3.1 GW (Powersaudiarabia, 2019).

2.2. The Vernacular Architecture of Jeddah

The city of Jeddah was established as a fishing settlement in 350 BC. It gained its importance in the Islamic era due to its location as a coastal city on the Red Sea shores which has made it the Islamic port for the two holy cities of Mecca and Medina for thousands of years. This connection played a great role on influencing the traditional buildings materials and construction techniques. The diverse ethnic backgrounds in the city have enriched the architecture of Jeddah and the Hejaz region in general. As pilgrims came from various parts of the world, they transported and exchanged their skills with the local people. The construction skills of the people of Hejaz were also influenced by the building activities in Egypt, an evident example of that are the *Rowshans* or *Mashrabiyas* (projected screened windows). The traditional architecture of Jeddah responded to the climate in terms of form, construction techniques, material selection and the application of passive design features that maintained thermal comfort within the building in the hot humid climate (Kamal, 2014).

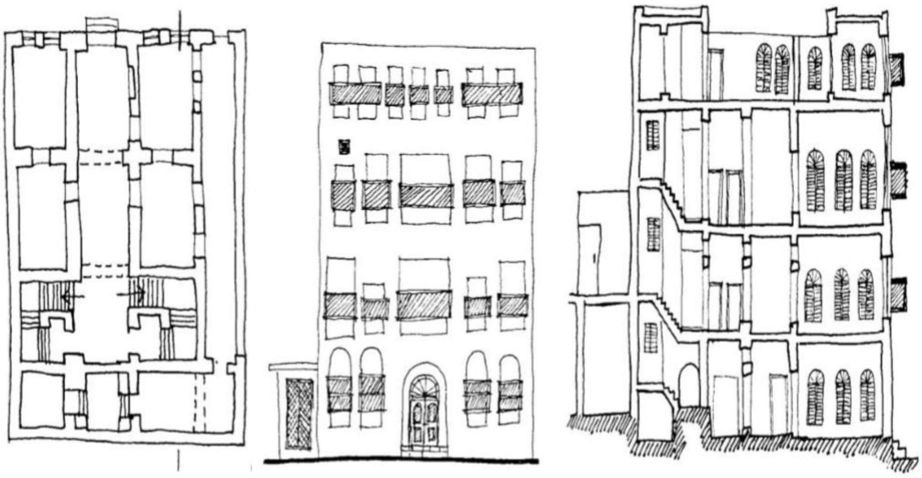
The old settlement of Jeddah that is called *'Al Balad'*, which means a town, or referred to as Historic Jeddah today was inscripted as a world heritage site by the UNESCO in 2014. This contributes to the preservation of the distinctive architecture tradition of Jeddah including the traditional tower houses that were built in the late 19th century by the rich merchants and still exist today as some of the last major surviving examples of the Red Sea Coast vernacular Architecture (UNESCO, 2018).

The vernacular architecture of Jeddah is responsive to climate in terms of design and layout, material, construction techniques, and the application of passive design elements.

2.2.1. Design and layout

The traditional houses in Jeddah were built as narrow and multi-story buildings in order to catch the breeze and to fit in the limited space within the old city wall (Bagader, 2016). The house form was designed with three main considerations: privacy, tradition norms and the response to the hot humid climate. The socio- economic status of inhabitants played a role as well in the development of three types of the vernacular residential buildings. Which are: the simple house for small family, the large house which is a tall structure for rich people mostly merchants. Finally, the Multiple Unit, consisting of more than one house combined together which is like a palace for the very rich people (Kamal, 2014).

The traditional buildings can be up to seven storeys high generally 15-18 meters high, airy structures allowing cross ventilation. The ground floor at street level is usually used for men and reception of guests while upper floor is reserved for women or family members. Sleeping and family rooms are located on upper floors to take advantage of on-shore and off-shore breezes. Large houses have vertical shaft called '*manwar'* which allows natural light and ventilation into internal rooms (Isteeaque, 1990). The projected bay windows (rowshans) are enclosed with decorative wood screens which provide cross ventilation as well as privacy for family (Figure 2.4) (Kamal,2014).



(a) (b) (c)

Figure 2.4. Ground floor plan (a), elevation (b) and section (c) of a typical traditional house in Jeddah (Talib,1984).

In addition to the spatial arrangement of the traditional house, material use and construction techniques came also as a result of regional conditions.

2.2.2. Material and construction techniques

The vernacular architecture of Jeddah has a distinctive structural system that is also popular in some other towns along the Red Sea coast of Saudi Arabia, as well as on the Sudanese coast at Swakin. These traditional buildings follow a structural system that consists of imported wooden courses known as *gandal* used to reinforce local coral blocks (King, 1989).

The main structure of the 5-6 storey traditional buildings in old Jeddah were possible to be built due to the use of coral stone and timber technology by special engineers and artisans (Pint, 2005). The coral stones that were cut from the Red Sea shore were known locally as *Hajar al manqabi* after *Al-Manqabah* lagoon at Jeddah (King, 1989). *Mangabi* stone is a coquina (seashell) limestone, quite easy to cut and work with, especially when freshly excavated because it is likely to get harder when exposed to air. *Mangabi* stone is porous, relatively light and has good insulation properties against the salty air of the Red Sea coast (Figure 2.5) (Bagader, 2016).

Figure 2.5. Mangabi Stone (Akbaş, 2018)

While Jeddah was a trading port for centuries this has allowed importation of building materials not available locally. Hard timber which was transported from Africa and Indonesia was used for beams (Kamal, 2014). The floors and roofs construction consisted of wooden boards laid over wooden joists. The type of wood used for reinforcement and flooring was imported from India and known as *gandal* which was a major factor behind the possibility of constructing multistory houses. Another type of wood was imported from Java, usually used for front doors, *rawshan* and windows, known as *Jawi, i.e. Teak.* It was favored by local craftsmen despite it is harder to work with; it has more resistance to insects and humidity. In addition to *Teak* wood, *mahogany* and *sisam* wood were also used for doors and windows. Houses were usually whitewashed or painted in pastel shades of yellow, cream, blue and pink (Kamal, 2014, Bagader, 2016).

The traditional buildings in Jeddah follow a structural system that consists of *gandal* wooden courses which are used horizontally to reinforce the coral block walls at every 1.20 m. or so (King, 1988). The construction process starts with one meter deep excavation for footings and wall foundations that were made out of compact, firmly bound coral stone and clay layer. Load-bearing walls were constructed approximately 50-60 cm thick, starting thicker then reduced in thickness on upper floors, reinforced with horizontal wooden members spread out vertically leaving a one-meter gap between each one. The last and uppermost tier of the wooden reinforcement were tied to the cross joists of the floors, to form a firm structural frame. The reinforcing members were visible on both external and internal faces of the walls (Figure 2.6) (Al-Lyaly, 1990).

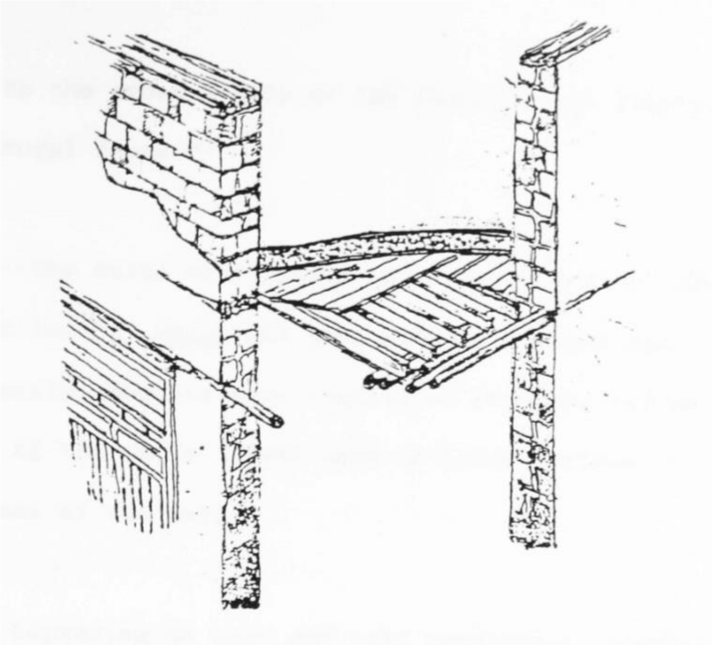


Figure 2.6. Structural detail of coral stone structure (Al-lyaly,1990)

The floor structure consists of timber boarding laid on timber joists, which are about 15 centimeters in diameter, covered with straw mats, followed by layers of four centimeters wet earth, three centimeters dry earth, three centimeters mixture of pulverized pebbles and lime bonded with lime mortar, finally covered with floor tiles. As for Roofs they were constructed in a similar way but with an addition of a thick bed of limestone below the wet earth layer, and water-resistant lime plaster on the top (Figure 2.7) (Al-Lyaly, 1990).

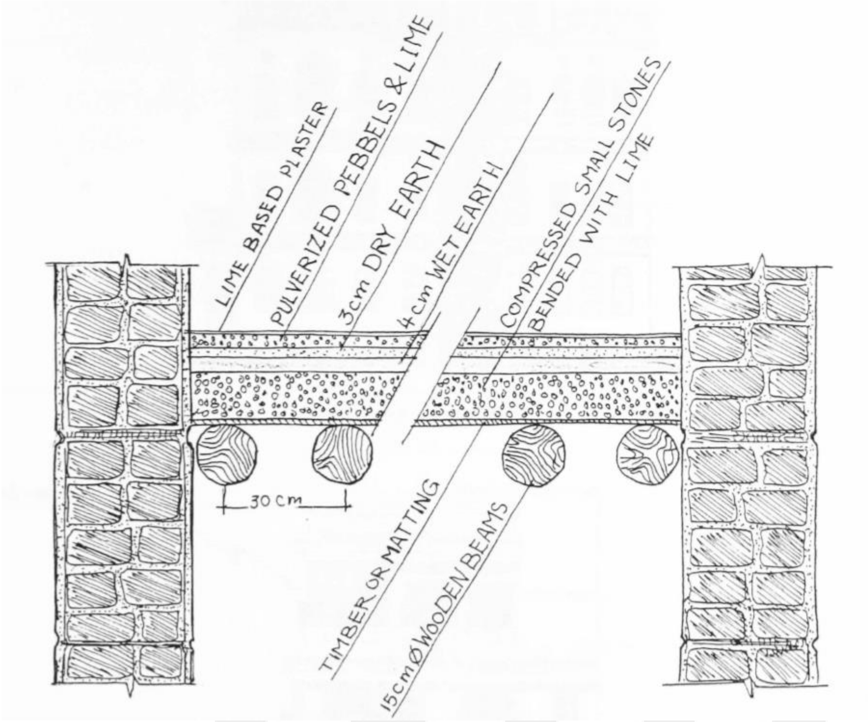


Figure 2.7. Typical section showing roof and ceiling construction in the traditional coral building (Al-lyaly,1990)

The staircase was one of the contributors to the strength of the traditional coral tower house. It was looped around a central pier enclosed throughout its height by thick walls, acting as a massive hollow column. The steps of the stair were also constructed of coral blocks, and then plastered by a five by five centimeters wooden log at the front edge, rested on top of three long wooden sticks. The openings consisted of timber lintels or masonry arches, depending on the span and loads. The common practice was to use lintels of stout parallel timbers across the thickness of the wall, tied into the masonry on both sides of the opening allowing a good length by distributing the high concentration of stresses that are settled at the corners of the opening (Al-Lyaly, 1990).

Lime-based white or ochre plaster layer painted by lime wash is commonly used for covering the wall of the coral rocks buildings (King, 1988). The material used in the traditional buildings has a major contribution in protecting, ventilating and cooling the traditional house.

2.2.3. Energy based concerns and solutions in the traditional architecture of Jeddah

Material

The materials that construct this traditional structure were also used effectively by the builders against the climate. As the 50-60 cm. thick coral stone walls (Figure 2.8) at the lower floors provide a considerable resistance to the passage of heat due to the low thermal conductivity of the material. The considerable thickness of the construction is capable of absorbing heat and delaying its passage to the interior. The heavy roof construction retains high heat insulating qualities and heavy thermal mass to ensure less consumption of solar heat and the least heat flux entering the living spaces beneath. As Earth is a good insulator of heat, 7 cm layer of pressed dry earth was placed below the top layer of pulverized pebbles to reduce the amount of heat penetrating to the limestone layer during the day. The thick coat of plaster covering the walls and the roof of the whole building (Figure 2.9) shields the coral stones from humidity, heat and salinity's effects (King, 1988) and reflects 80% or more of solar radiation received, reducing the heat transmission through the walls and roof structure during the day (Al-lyaly, 1990). In addition of protecting the coral stones, plaster was used sometimes to decorate houses' exteriors by carving elaborate patterns with geometries and floral motifs (Figure 2.10) (King, 1989).

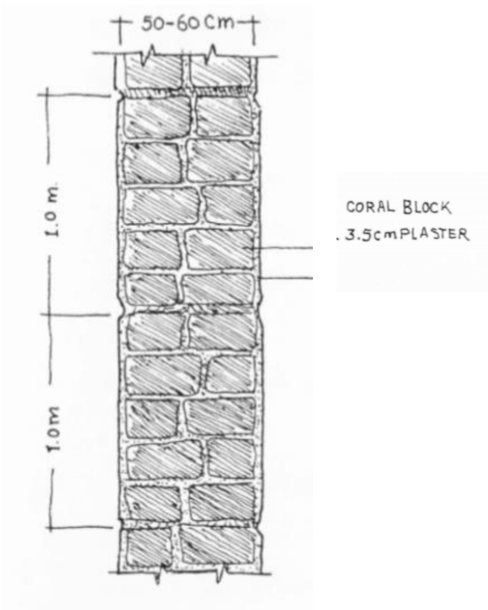


Figure 2.8. Typical section in the load bearing external wall of the traditional coral building (Al-Lyaly, 1990)

Figure 2.9. Salloum House Exterior, Historic Jeddah 2018 (Nyazi's archive)

Figure 2.10. Al-Jukhdar House decorative plaster, Historic Jeddah 2018 (Nyazi's archive)

Floor plan arrangement

The traditional houses floor plans responded to the local climate and prevailing breezes by the allocation of living-rooms in the north and west parts of the house taking advantage of the north and sea breezes while reserving the southern and eastern parts for the service areas such as the stairway, latrines, storages, *etc.* (Figure 2.11). The north and west facades were also main exposed and have the *rowshans* that allow maximum flow of breezes (Figure 2.12). While east and south facades have few windows, and only light or ventilation apertures (Al-Lyali, 1990).

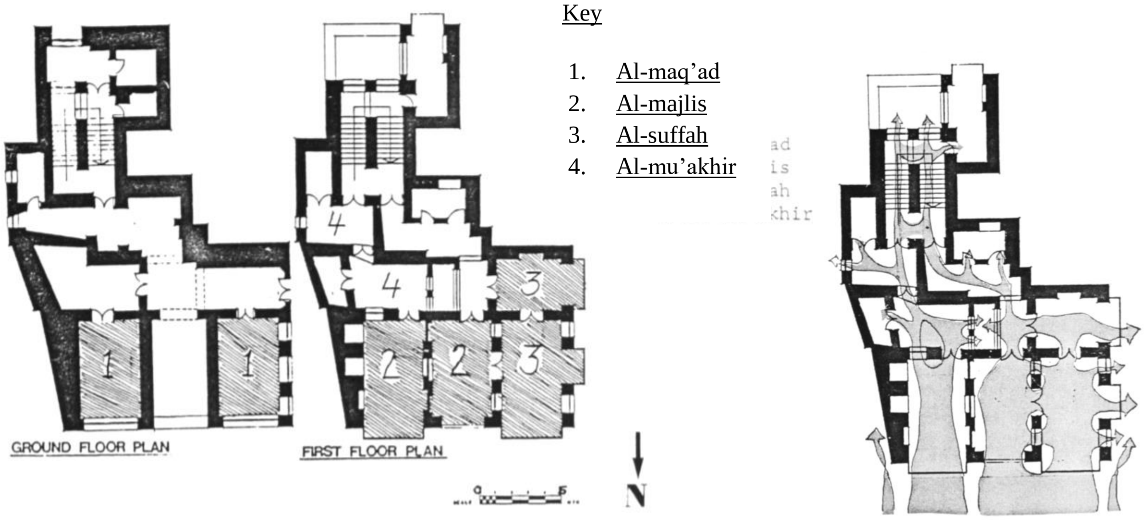


Figure 2.11. The living spaces located in the northern and western parts of the traditional house (Al-lyali, 1990)

Figure 2.12. North elevation of the traditional house (Al-lyali, 1990)

Mashrabiya-Rowshan

Mashrabiya or what is known as *Rowshan* in Jeddah (Figure 2.13, 2.14), is the Arabic term for the type of window enclosed with carved wood latticework (Feeney, 1974). The name is originally derived from the Arabic word '*sharbah'* which means 'drink' and referred to 'a drinking place'. As it was a cantilevered space covered with a lattice opening, where water jars were cooled there by evaporation effect as air moves through the opening (Fathy, 1986). *Mashrabiya* usage in buildings windows came as a response for climate and privacy conditions. They provide the cross-ventilation required in buildings located in a hot humid climate like Jeddah and has a cooling effect at day by increasing the humidity of air, through releasing the moisture absorbed from the wind passing at night (Figure 2.15). The Mashrabiya works as well to maintain the desired privacy as you can see from inside without being seen from outside. The *Mashrabiya* were constructed by cantilevered timber framework and was often prefabricated with some decorations and finish and then installed over the opening. In some cases, the wood of *Mashrabiya* was painted but mostly it was left exposed (Kamal, 2014).

The *Mashrabiya's* design was developed to fulfill five functions; each design can address all or some of them. The *Mashrabiya* can control the passage of light, control the air flow, reduce the temperature of the air current, increase the humidity of the air current and ensure privacy. In order to control the amount of light and air as well as graduating the contrast between shade and light, the size of the interstices and the diameter of the balusters must be adjusted (Fathy, 1986).

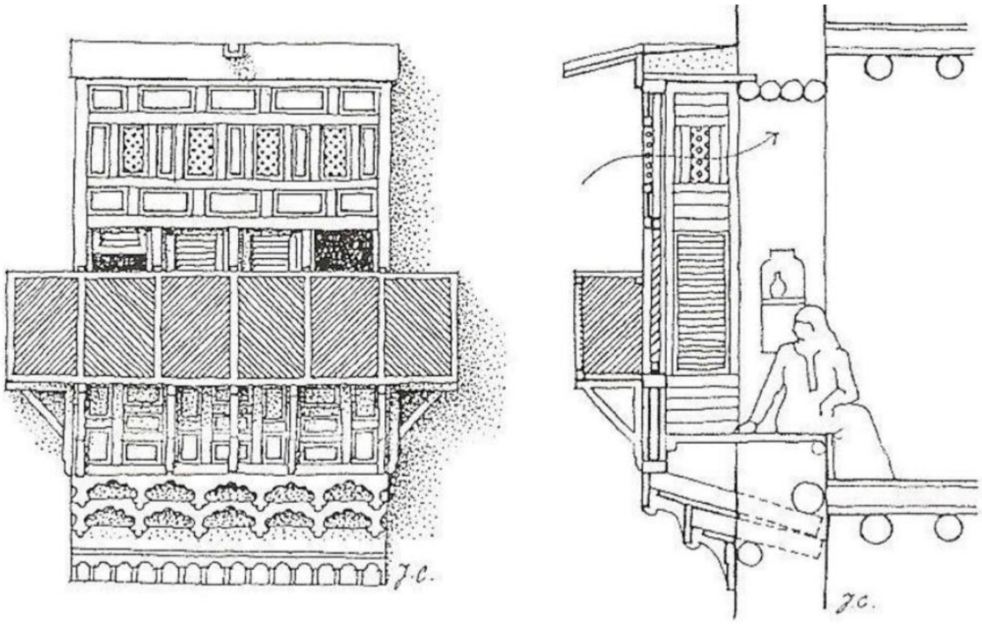


Figure 2.13. Mashrabiya in elevation and section (Ragette, 2006)

Figure 2.14. Salloum House Historic Jeddah 2018 (Nyazi's archive)

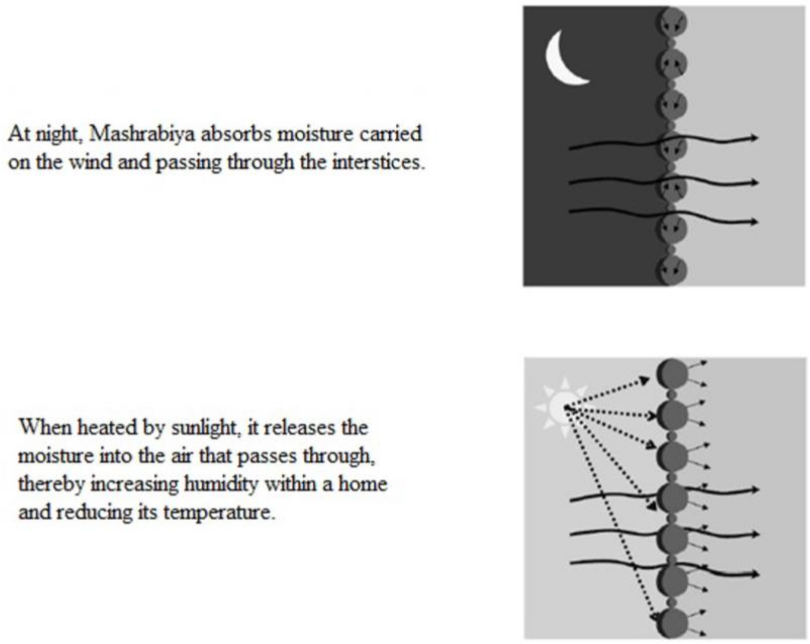


Figure 2.15. The cooling effect of Mashrabiya through the evapo-transpiration process (Fathy,1986, illustration by Gelil, 2014)

The Stairwell or Airshaft

The living parts of the traditional house were usually arranged around a vertical stairwell or airshaft called *Manwar* (Figure 2.16), which acts as a chimney conducting the hot air out of the house (stack effect). The mouth of the airshaft is opened to the sky with no operable flaps to control the air flow, while the top of the stairwell, however, has louvered openings that allow wind flow (Figure 2.17). The air flow creates a low-pressure area which pulls air into the house from higher pressures below and through the airshaft or stairwell (Melaragno, 1982).

Figure 2.16. Salloum House’s Air shaft (Nyazi’s archive)

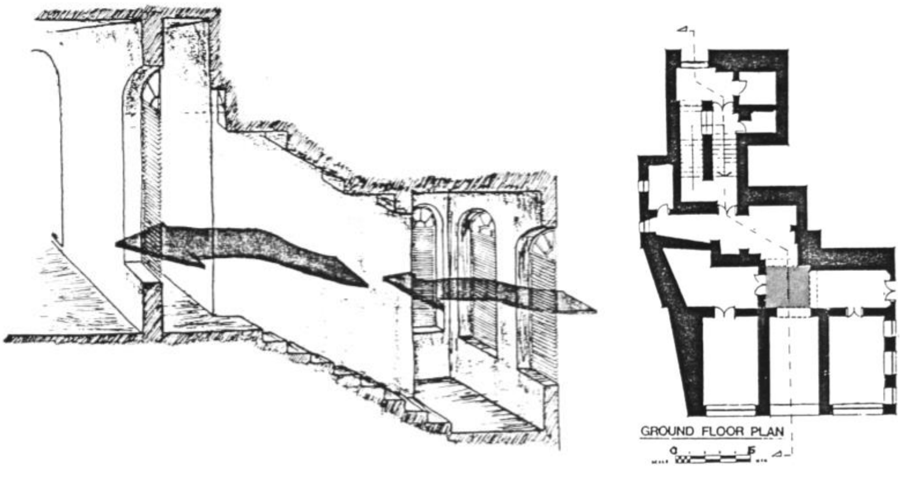


Figure 2.17. Air shaft in traditional houses (Al-Layaly, 1990)

Al-Mabit

Due to the land limitation in old Jeddah the courtyard was replaced with the open space at the roof that sometimes contained an architectural feature called *al-mabit* (Figure 2.18, 2.19) which is a room that was constructed of panelled woodwork with movable louvers, and a light roof, in contrast with the massive lower floors that stay cool during the daytime in the summer but tend to warm up in the late night. *Al-mabit*, would be warm during daytime but tends to cool down quickly at night, therefore it was used for sleeping in hot summer days (Al-Lyaly, 1990).

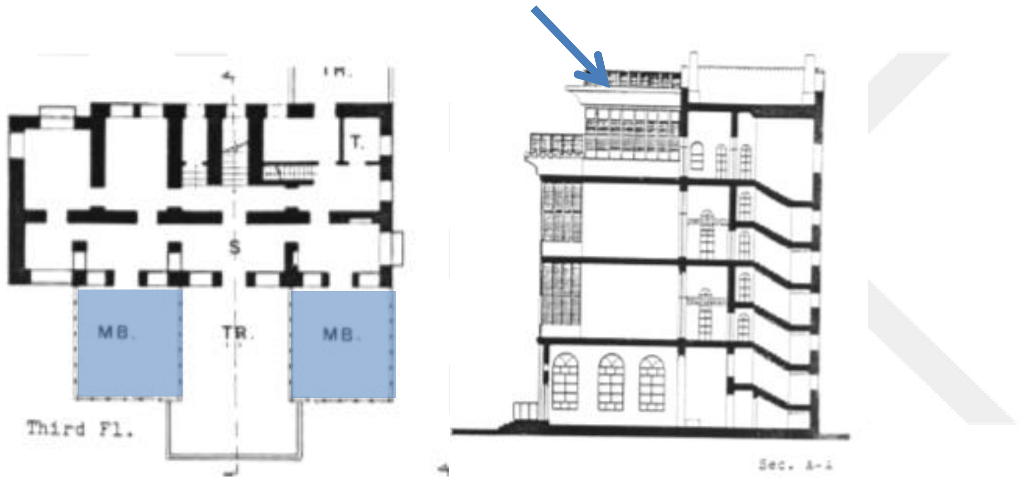


Figure 2.18. Al-mabit in Al-Jukhdar House third floor plan & section (Al-lyali,1990)

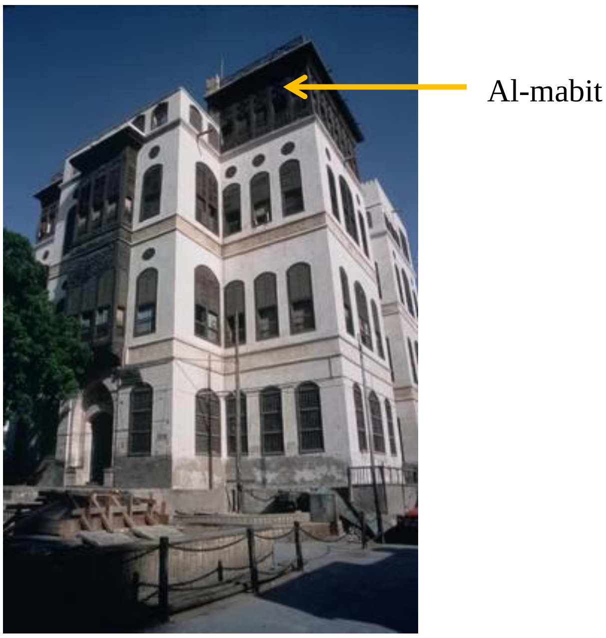


Figure 2.19. Beit Nassif in Historic Jeddah (Osborn, 1982)

2.2.4. Modern applications of vernacular systems

Mashrabiya, is one of the vernacular features that has been widely interpreted in modern architecture for many purposes and in different ways. Some projects introduced the concept of Mashrabiya as an adaptive skin for buildings, forming an envelope that can response to sun exposure and change incidence angles during the different days of the year with the help of high technology Daylight responsive systems. Other projects focus on the shape of Mashrabiya to reflect the Islamic identity, the cultural values and reviving the heritage. Mashrabiya was also used as a structural pattern in some other projects (El Semary, Attalla, & Gawad, 2017). The air-shaft or wind-catcher is another vernacular feature that was interpreted in contemporary architecture sometimes mixed with mechanical systems to provide ventilation for buildings.

The Mashrabiya House, Palestine

The project is located in the Palestinian village Beit Safafa between Jerusalem and Bethlehem. The house is designed by the architect Senan Abdelqader and it was completed in 2011 (Figure 2.20). The Mashrabiya in this project was interpreted to provide a floating effect, replacing the wooden lattice of the traditional Mashrabiya by a stone layer that covers the whole house. The semi-transparent effect was achieved by positioning the stones slightly apart, with irregular spacing, to create an effect of lightness and porousness. The stone envelop is structurally separated by a narrow gap from the actual apartment building behind (Figure 2.21).

Figure 2.20. The Mashrabiya House (Giron, 2011)

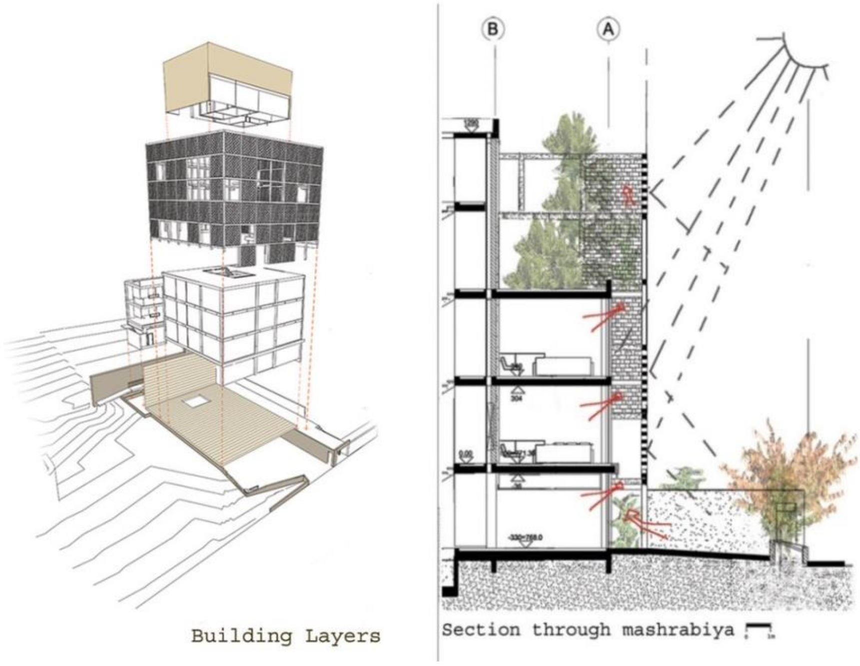


Figure 2.21. Illustrations of Mashrabiya House (Abdelqader, 2011)

The design of the façades that created small and large openings ensured views from inside to outside while maintaining the required privacy. The Mashrabiya at the top of the building becomes a 'garden wall' for the roof top garden which forms a sheltered place of tranquility and privacy. The Mashrabiya was considered in this project to be an environmental element as the stone layer which surrounds the whole building works as a climatic buffer as the architect has described it "The gaps between the stones ensure a constant flow of fresh air. A further element of passive cooling is the 1m gap between outer and inner envelop. Not only does it ensure constant circulation of fresh air around the building the fact that it remains open towards the top of the building generates a suction effect like that of a chimney: Hot air travels upwards and fresh air is sucked into the gap from below." (Abdelqader, 2011).

By comparing the stone pattern modern mashrabiya in this house to the traditional Mashrabiya, the daylight is reduced in irregular ways, unlike the traditional Mashrabiya which creates an effective reduction of glare and blocks direct light by specific calculation of the spaces between the balusters. Although those irregular spacing between the stones in the modern Mashrabiya provides airflow movement, it is still can't provide the appropriate, comfortable airflow in the traditional Mashrabiya with its studied spacing between the balusters. In addition, wood is more efficient than stone in absorption and evaporation (Alothman, 2017).

King Abdullah University for Science and Technology (KAUST)

King Abdallah University for Science and Technology (KAUST) (Figure 2.22) is an example of a project that aimed to reflect some of the vernacular architecture features in an advanced way and with coordination with the LEED standards. KAUST is a private institution established in 2009, located in the town of Thuwal, which is 85 kilometres north of Jeddah. The campus is Platinum rated on the Leadership in Energy and Environmental Design (LEED) scale that is produced by the U.S. Green Building Council. KAUST is considered as Saudi Arabia's first LEED certified project and the world's largest LEED Platinum project (KAUST, 2017).

The campus design includes a pedestrian spine that functions as an active outdoor courtyard connecting between research buildings and housing conference, meeting, office and retail spaces, the spine emphasizes that KAUST is one continuous building. The design imitated some passive solutions from the local architecture to provide natural ventilation for the spine, along with water and vegetated area to help clean the penetrated air (American Institute of Architects, 2010).

The design of the campus has adapted five strategies from the local traditional architecture in order to solve some environmental issues:

1. The campus was planned like traditional Arabic cities, compressed as possible in order to minimize the amount of exterior exposure to the sun and reduce outdoor walking distances. The finger-shaped floor plans allow natural daylighting in order to reduce lighting demand. Buildings' orientations as well limit harsh eastern and western sun exposure while taking advantage of prevailing Red Sea winds.

2. The design introduced some shaded and passively cooled circulation accesses and social spaces which were inspired by the traditional souk, or Arabic market.

3. The Arabic Bedouin tent inspired the creation of a monumental roof system that spans across building masses to block sun on building facades and into the pedestrian spine, to facilitate natural ventilation and to filter light. Solar panels covering the surface capture the sun's energy.

4. Mashrabiya's concept was interpreted in the shaded windows and skylights that reduce heat loads while creating dramatic dappled light (Figure 2.23).

5. Passive ventilation techniques of the traditional Arabic architecture have inspired the design of iconic, solar-powered wind towers which use the energy from the sun and the prevailing Red Sea winds to create natural ventilation. Approximately 1 million square feet of conditioned space through the pedestrian spine is conditioned through passive means for most of the year.

The wind towers can encourage natural ventilation during the day even in the absence of wind by absorbing solar heat by a dark surface at the top of the tower. This hot dark surface heats the air around it then makes it rise through an opening at the top of the tower, which makes cooler air moves from below to replace it. This creates an air movement in the circulation spines (Figure 2.24) (American Institute of Architects, 2010).

Figure 2.22. King Abdullah University for Science and Technology KAUST (American Institute of Architects, 2010)

Figure 2.23. Shaded windows and skylights inspired by Mashrabiyya in KAUST (American Institute of Architects, 2010)

Figure 2.24. Passive design techniques in KAUST (American Institute of Architects, 2010).

2.3. The Contemporary Single Family House in Jeddah

The mid 1950s mark the beginning of the major changes in the housing industry in Saudi Arabia. By the introduction of the gridiron street pattern and the detached villa-type dwelling which this study will focus on, the new Saudi house held new design and organization concepts, as well as the great changes in the construction techniques and the building materials (Al-Hathloul, 1981). The economic boom, the new building practices, and the sociocultural changes, are all factors that contributed to the introduction of the modern design of the contemporary Saudi villa (Bahammam, 1998). The contemporary dwellings were built as a final product according to the design adopted by municipal rules and regulations, which contrast the traditional dwelling design that addressed the immediate needs of the family (Al-Hathloul, 1981). A Common trending practice in Saudi Arabia is the residential building complexes that contain villa-type dwellings with over services (Figure 2.25).

Figure 2.25. Masharef Residential Complex in Jeddah (Kinan, 2014)

2.3.1. Design and layout

The contemporary Saudi villa is a two-storey or two and a half-detached dwelling with yards on the four sides, large in size, compared to the traditional dwelling. Western style furniture is used, which is hard to move and store which made the house loose the flexibility to use the same rooms for various functions. An example of a contemporary single family house floor plans are shown in Figures (2.26, 2.27, 2.28). A typical contemporary dwelling ground floor consist of two reception rooms one for men's and one for women's with a toilet for each, one or two guest dining rooms. One kitchen and in some houses there's an extra dirty kitchen. The house usually has one or two living rooms in ground and first floor, three or more bedrooms in the first floor with bathrooms, and several storage spaces. A second half floor is usually used for laundry room and the maid's room, while a driver room is detached from the house in the ground floor. Rooms in the contemporary dwellings are designed for special purposes incorporating the particular furniture under certain names which is another reason for building a larger villa with more space. Some villas have new features that didn't exist in the traditional dwelling, which were a result of the change in the lifestyle and the wealth of population, such as, the first floor balcony, the dressing rooms, the maid's and chauffeur's rooms. The balcony was a borrowed feature from the Mediterranean architecture which failed in its application to the Saudi villas, since it neither maintains the required level of privacy nor provides an enjoyable space in the harsh weather, so it is often found as an extra unused space (Bahammam, 1998). A widespread practice has emerged in Saudi villas by the residents who extended the houses fences by steel frame and plastic corrugated sheets, to protect their houses by being overlooked by neighbours, wither overlooking their yards surrounding the villa or their windows (Figure 2.29)(Al-Hathloul, 1996). The figure shows illustrations of Riyadh houses but similar applications are common in Jeddah's villas as well.

Figure 2.26. Ground floor plan of a contemporary Saudi villa (Kinan, 2013)

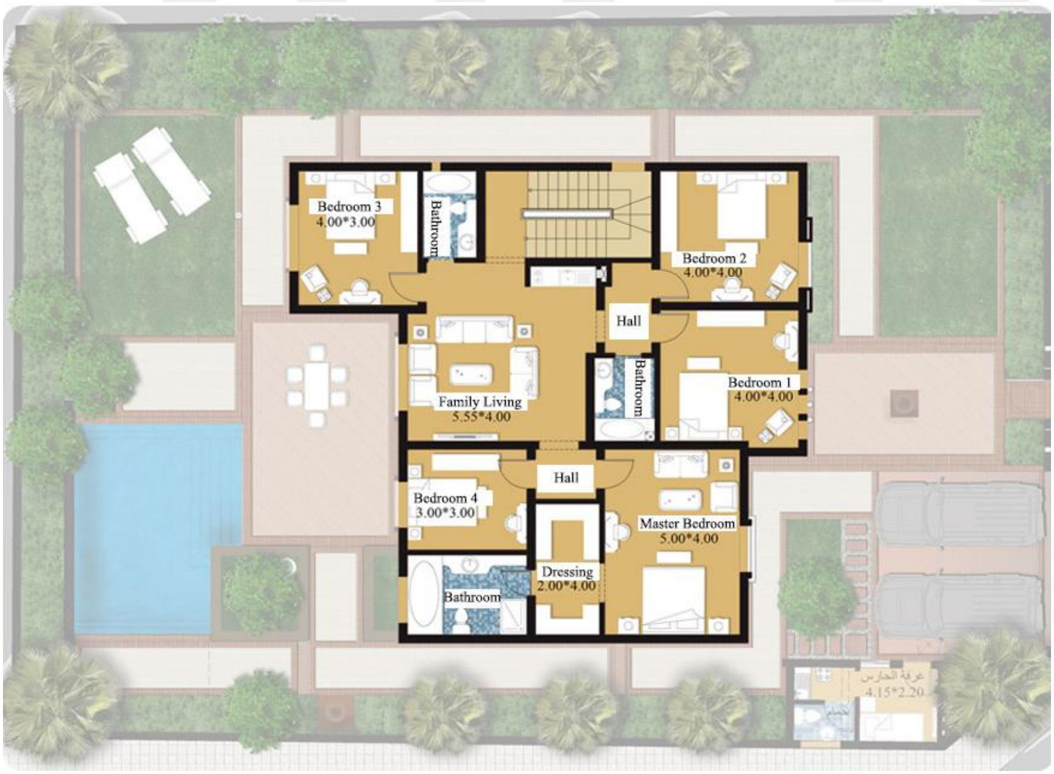


Figure 2.27. First floor plan of a contemporary Saudi villa (Kinan, 2013)

Figure 2.28. Second floor plan of a contemporary Saudi villa (Kinan, 2013)

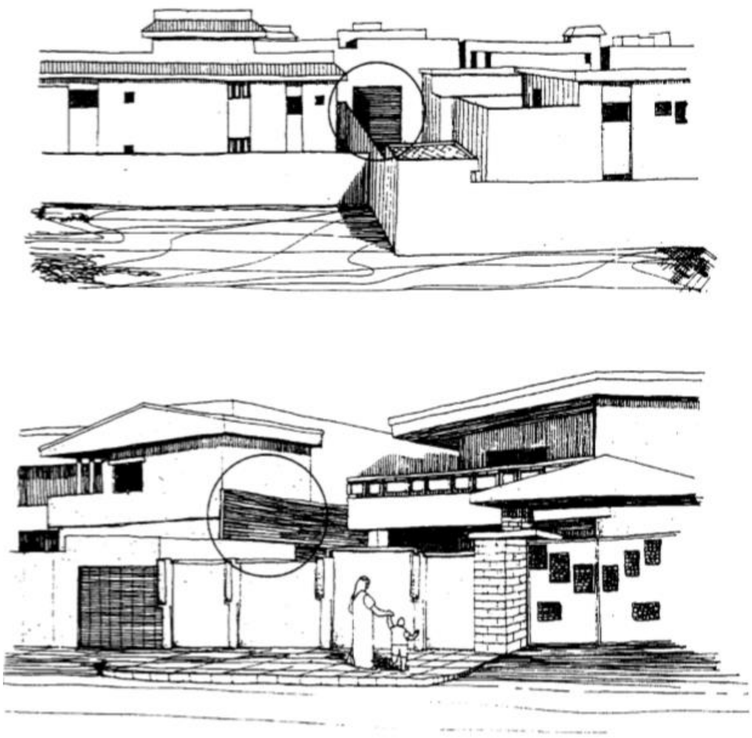


Figure 2.29. Use of plastic corrugated sheets to ensure privacy (Al-Hathloul, 1996).

2.3.2. Material and construction

In the construction of the contemporary dwellings, the use of reinforced concrete has speed up the building process and has allowed the building of wider spans and consequently larger spaces using the post and beam conventional technique (Bahammam, 1998). Concrete became the major used material roughly 70% of residential buildings are built with concrete in Makkah Al-Mukarramah region where Jeddah city is located (Figure 2.30) (Census, 2010).

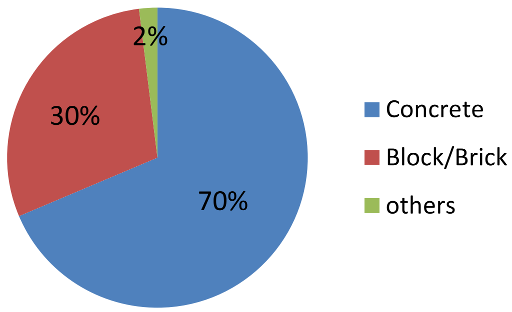


Figure 2.30. Distribution of construction material used in residential buildings in Makkah Al-Mukaramah region (Census 2010)

2.3.3. Energy based concerns and solutions in contemporary housing

According to SEEC, almost 70% of buildings in Saudi Arabia are not thermally insulated due to the absence of such regulations until a Royal Decree no. (6927 / MB) came out approving the application of thermal insulation as a mandatory manner on all new buildings, including residential, commercial and governmental facilities in the major cities in the Kingdom including Jeddah city (Saudi electricity company, 2018). Thermal Insulation will contribute in reducing the proportion of electrical energy consumed in air conditioners by almost 30 to 40% (SEEC, 2018).

2.4. Net-Zero Approaches and Passive Techniques in Hot Climate

An energy-efficient house can be described simply as a house that maintains comfortable temperature along the year with minimum energy consumption while utilizing solar power to produce its energy needs, as well as treatment and recycling of waste including gray water. Energy-efficient approaches for residential buildings have been constructed broadly in cold regions, yet it is still under experimentation in the hot and arid climates such as in the Gulf Cooperation Council (GCC) region where the primary concern is to reduce space cooling load (Alalouch, 2015).

The Passive House Standard is one of the approaches that began to be tested for applicability in hot climates, as the original concept was initiated and spreaded in the cold climate regions, as the first passive house constructed in the modern era was in Germany, Darmstadt, in 1991 (Passipedia, 2016). The term ‘‘Passive House’’ refers to a construction standard that can be achieved by using multiple technologies, designs and materials. It is basically an alteration of the low energy house standard. Passive House has to provide a comfortable indoor climate in summer as well as in winter. The Passive House is one of the leading standards in energy efficient constructions today. It stands for quality, comfort and energy efficiency, by requiring very little energy to achieve thermal comfort for occupants (IPHA, 2018).

According to (Passive House Institute, 2015) for a building to be considered a Passive House, it must meet some criteria which are:

1. The Space Heating Energy Demand must not to exceed 15 kWh per square meter of net living space (treated floor area) per year.

2. The Renewable Primary Energy Demand (PER, according to PHI method), the total energy to be used for all domestic applications such as (heating, hot water and domestic electricity) must not exceed 60 kWh per square meter of treated floor area per year.

3. In terms of Airtightness, a maximum of 0.6 air changes per hour at 50 Pascals pressure (ACH50), as verified with an onsite pressure test (in both pressurized and depressurized states).

4. Thermal Comfort must be met for all living areas during winter as well as in summer, with not more than 10 % of the hours in a given year over 25 °C.

In order to achieve all criteria, five Passive House principles must be applied for the construction of Passive Houses (Figure 2.31).

Thermal insulation

All opaque building components of the exterior envelope of the house must be very well-insulated.

Passive House windows

The window frames must be well insulated and fitted with low-e glazings filled with argon or krypton to prevent heat transfer.

Ventilation heat recovery

Efficient heat recovery ventilation is crucial, to allow good indoor air quality and to save energy. At least 75% of the heat from the exhaust air is transferred to the fresh air again by means of a heat exchanger.

Airtightness of the building

The uncontrolled leakage through gaps must be smaller than 0.6 of the total house volume per hour.

Absence of thermal bridges

All house's edges, corners, connections and penetrations must be planned and executed with excessive caution, to avoid thermal bridges. Thermal bridges that cannot be avoided must be minimized as possible.

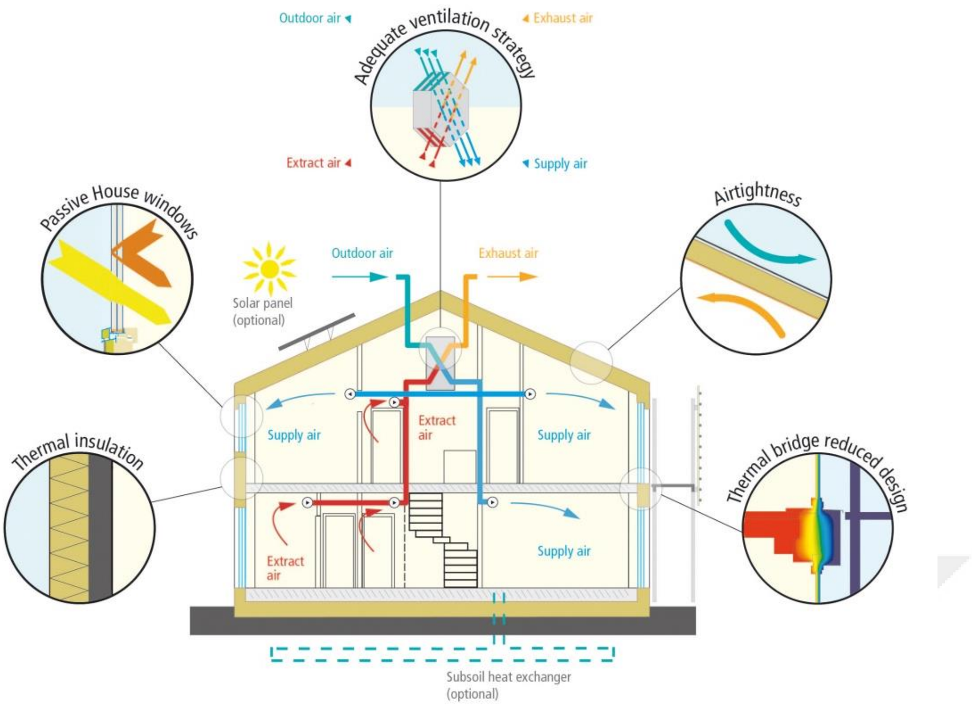


Figure 2.31. The five basic principles for the construction of Passive Houses (IPHA, 2015)

Passive House buildings allow for heating and cooling related energy savings of up to 90% compared with typical building stock and over 75% compared with average new builds. Similar energy savings have been demonstrated in warm climates where buildings require more energy for cooling than for heating (Passipedia, 2017). Although energy-efficient houses were first introduced in cold regions, the same concept and methods can be applied in hot and arid regions such as Saudi Arabia. Because the energy efficient house has a different aim in each region, where in hot climate the aim is to reduce space cooling load as opposite to reducing space heating load in cold regions, that's why the design strategies, construction details and technologies need to be customized to meet the local conditions (Alalouch, 2015).

2.4.1. Case study: *Baytna,* the Passive House in Qatar

Baytna, which means "our home" in Arabic is considered to be the first Passive house project in the Middle East, which was completed in 2013 in Qatar one of the GCC countries. Qatar is a country that has a similar hot and dry climate as Saudi Arabia, and facing similar energy consumption problems. The weather in Qatar is characterized by long hot summers and short mild winters. The average monthly temperatures range from 19°C to 37°C with a maximum temperature of 47°C in July and a minimum of 12°C in January. The average annual relative humidity is around 57%. The estimated energy performance and comfort levels for Qatar Passive House indicated that the building would successfully operate in its hot and arid climate, and in accordance with the Passivhaus Standards (Khalfan and Sharples, 2016). The project was carried out by Qatar Green Building Council as the technical and scientific adviser and in partnership with several industrial and governmental bodies. The project consists of two identical villas in terms of size, spatial arrangements and comfort requirements, (Figure 2.32). However, the two villas implemented different design specifications, as one was designed based on passive house strategies with solar panels to generate energy (Figure 2.33), while the second one was designed parallel to the conventional villas in Qatar in order to act as a control case. The aim of constructing those two villa types was to compare between passive house standards and conventional villas in terms of energy consumption, CO_2 emissions, cost effectiveness, comfort levels, and occupants' satisfaction (Alalouch, 2015).

Both villas were designed for a family of four members on a 200 m^2 floor area. They composed of three bedrooms, an open living/kitchen space and a central atrium which is an architectural feature found in the vernacular architecture of the region as well as the external colonnade. Private and public zones separation was ensured by providing two entrances (Figure 2.34). In addition, the zones are visually hidden by movable Mashrabiya panels that allow manual control (Khalfan and Sharples, 2016).

The house designed according to the Passive House Standards has the following "green" features (Amato and Skelhorn, 2014):

- Wall construction: 370 mm extruded polystyrene insulation with ¾ mm external render finish and 200 mm masonry wall (compared to 150 mm external /100 mm internal concrete block with 50 mm air gap in the twin conventional house).
- Triple glazed windows and doors.
- Skylight in atrium with louvers that open and close according to the sun angle.
- PV array with a peak power of 34 kW that would produce around 58,000 kWh of electricity per year.

- Black and grey water recycling

Although the two villas are similar in layout, the construction materials and electrical fixtures are different. The passive house villa was equipped with high efficiency fixtures and systems; on the other hand the other villa was built and equipped in accordance with the normal practices in Qatar. Table 2.1 summarizes the building materials and systems used in both villas (Khalfan and Sharples, 2016).

Table 2.2. Summary of PHV and STV building materials and fixtures.

Construction	PHV	STV
Wall	200mm block wall – 380mm Polystyrene layer	300mm block wall – 50mm cavity in between
Roof	200mm cast concrete – 380mm Polystyrene layer	200mm cast concrete – 100mm polystyerene layer
Floor	250mm cast concrete – 200mm polyfoam layer	250mm cast concrete
Glazing	Triple glazing – 6mm clear and coated glass – double 12mm cavity	Double glazing – 6mm clear float glass – single 12mm cavity
Cooling systems	High efficincy duct split cooling system with heat recovery ventilation unit	Duct split cooling system
Added features	Solar water heater – 220m^2 photovoltaics array mounted on roof – high efficiency lighting	none

The villa which adapted the Passive House Institute standards aimed to achieve at least 50% reduction in annual operational energy consumption, water usage, and CO_2 emissions when compared to the conventional twin house. The target is to achieve this reduction with no more than 20% additional capital cost compared to the capital cost of the conventional house (Alalouch, 2015). To testify the houses performances, it will undergo a period of experiment, where both homes will be occupied by the same number of people for six months period to achieve a full comparative study. The viability of Passive House concept in this region will be testified through the live-in experiment to produce more true-to-life findings than computer simulation might allow (Qatar Foundation, 2014). The estimated energy performance and comfort levels obtained through the IES dynamic simulation tool indicated that the building would successfully operate under the hot and arid climate, and in accordance with the Passive House standards (Khalfan and Sharples 2016). However, Results of occupancy experiment are not published yet.

This project will inspire the creation of energy-efficient houses in Qatar and countries that are under similar climate conditions, by achieving 50% energy reduction, as well as 50% water reduction and CO_2 emissions in comparison to a conventional house in the region. Although houses that adapted Passive House Standards in cold regions have achieved net-zero energy, this project has aimed for lower goals which indicates that the case of passive house in hot regions are still under experiment and other solutions for the massive cooling loads should be found.

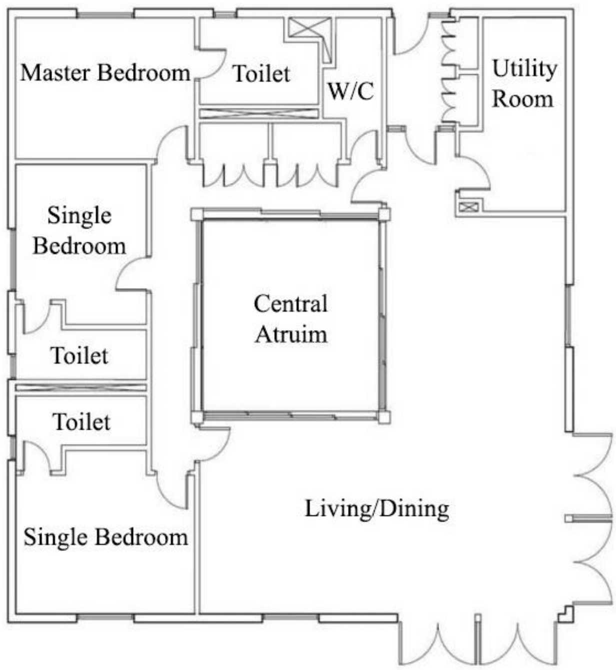


Figure 2.32. Villa typical layout (Khalfan and Sharples, 2016)

Figure 2.33. Conventional villa on left, Passive House standard villa on right (Laurie Balbo, 2014)

Figure 2.34. The villa with Passive House strategies with solar panels on roof (Qatar foundation, 2014)

2.4.2. Case study: UAE Passive House

In 2016 the new office building located in Dubai was the UAE's first sustainable autonomous house; it was realized as a pioneering “pilot project” for the governmental research body (MBRSC) (Figure 2.35). The building is considered the first one to acquire the certification by PHI (Passive House Institute) in extreme climatic conditions in the Arab world. The building was constructed within 100 days due to the use of a prefab European timber platform frame technology. For research purposes 3 different cooling systems have been installed: supply air cooling or dehumidifying, recalculated air cooling and floor cooling with the probability of coupling them to achieve the best results in the matter of efficiency as well as comfort. With extreme insulation and high energy efficient systems, a 40 kWp photovoltaic field (Figure 2.36) and a 25 kWh electric storage system were able to cover up all the building's demands. According to the PHPP the treated floor area= 411 $m^{2,}$ Building infiltration n_{50} = 0.48/h. Cooling and dehumidification demand: 50 kWh/(m^2a). Peak Cooling load: 9,7 W/m^2. The Primary energy requirement of the house is 143 kWh/(m^2a) on heating installation, domestic hot water, household electricity and auxiliary electricity calculated according to PHPP (Passivehouse database, 2019). Thermal envelope and mechanical systems of the house are summarized in (Table 2.2).

The house allows for energy savings of up to 85% compared to conventional houses. The building uses certified modern smart technology, sensors and remote sensing light fittings, to guarantee low energy consumption and adequate lighting. Smart technology also sustains indoor temperatures via controlling all shading devices (such as venetian blinds) sensors detect sunlight over windows then automatically draw shading devices and adjust them according to the sun angle to avoid solar gain temperatures. The building is also equipped with a smart alarm system to alert residents of the need to close doors and windows to maintain a moderate indoor temperature (from 20^0C to 25^0C) and humidity level with optimal 40% to 70% humidity ratio (MBRSC, 2019).

Figure 2.35. UAE Passive House (MBRSC, 2019)

Figure 2.36. UAE Passive House solar panel field (MBRSC, 2019)

Table 2.3. Thermal envelope and mechanical systems of Dubai passive house (Passivehouse database, 2019).

Thermal Envelope		
	Construction	U-value
Exterior wall	Plasterboard (12,5 mm), mineral fiber insulation (75 mm), mineral fiber thermal and acoustical insulation (75 mm), plasterboard (12,5 mm), timber frame construction with mineral fiber insulation (200 mm), plasterboard (12,5 mm), EPS-insulation (180 mm), exterior rendering	U-value = 0.076 $W/(m^2K)$
Basement floor / floor slab	Flooring screed (60 mm), XPS-insulation (20 mm), perlite added screed (155 mm), XPS-insulation (225 mm)	U-value = 0.108 $W/(m^2K)$
Flat roof	Sealing sheet (thermoplastic elastomere) XPS-insulation (200 mm), OSB (15 mm) mineral fibre insulation between rafters (280 mm), plasterboard (25 mm)	U-value = 0.076 $W/(m^2K)$
Glazing	Triple thermal protection glazing	U_g-value = 0.5 $W/(m^2K)$ g -value = 28 %
Frame	Frame Bayerwald, BW80 PVC window, thermal bridge free insulation	U_w-value = 0.89 $W/(m^2K)$
Mechanical Systems		
Ventilation	PAUL Wärmerückgewinnung GmbH, Novus 450 Central comfort ventilation system with 89 % heat recovery	
Heating	Geothermal energy / Cooling via heat pump	
Domestic hot water	Geothermal energy via heat pump	

The literature review guided the design of the Base-Case in this study, and summarised the possible passive solutions for lowering the energy consumption of the contemporary house. These solutions were found in the vernacular architecture of the city that achieved thermal comfort passively hundreds of years ago, and the Passive House standard which is the leading standard today in terms of energy efficient constructions. The experiments of the Passive House in Qatar and Dubai which have similar climate to Jeddah, indicated that reducing heat and solar gains is the essential goal for achieving reduction in cooling load which is the main concern in hot regions. The effectiveness of natural ventilation through Air-shaft and mashrabiyya which are the cooling techniques that the vernacular houses depended on will be tested for efficiency in the modern house as well.

3. MATERIAL AND METHODOLOGY

Since this study is aiming for energy efficiency in designing residential buildings, understanding the local climate and the urban context is an essential step in the pre-design stage. In addition to understanding the building simulation process and the software tool that will help in achieving the energy goals of this study.

3.1. Building Energy Simulation

It is essential for the design of zero energy buildings to be supported by an energy simulation tool which helps in making effective decisions at the early design stages (Attia, 2012). During the past 50 years, hundreds of building energy simulation programs have been established and developed. The whole-building energy simulation programs which are the basic tools in the building energy field can provide fundamental building performance meters such as: energy demands, temperature, humidity and expenses (Crawley, 2008). The determined variables by the energy simulation software can help designers to explore several design parameters and alternatives to take decisions about the best measures to apply for any building in order to reduce energy consumption and achieve thermal comfort. Those measures are mainly regarding passive design elements such as building orientation, size and function of the design, geometry/shape, building envelope materials, window-to-wall ratio, shading and daylighting (Altensis, 2015).

In addition to the energy consumption, simulation software tools can be used for calculating the following: Indoor temperatures; heating and cooling demands; HVAC systems consumption; natural lighting necessities and comfort conditions for occupants; as well as levels of ventilation. There are four essential aspects that should be considered in every building simulation: 1) the structure of the building and its organization; 2) The Physical phenomena involved in the simulation; 3) The weather conditions; 4) The building use (Sousa, 2012).

There is a wide range of energy simulation software tools used today but in general, the simulation process in any software tool is divided into three steps (Sousa, 2012):

1. Design of the building

This process can be achieved either by inserting the coordinates into the software tool or by uploading files from other softwares, such as AutoCAD or Google Sketch Up. It is important in the formation of building to identify the dimensions and geometry of the structure as well as the materials used in the building's components.

2. Building simulation

After the model is ready, variables which need to be considered in the simulation of the building should be established to run the software tool. As the thermal performance of any building differs according to its function, therefore there are few aspects that need to be specified such as: Building type (house, office, etc.), human activities carried out, existing equipment (lighting, refrigeration, air conditioning systems, furnaces, etc.), and their daily schedules.

3. Analysis of results

After running the software tool, errors or major mismatch introduced in the variables set should be checked.

<u>DesignBuilder</u>

In this study DesignBuilder was used for the building simulation, which is an EnergyPlus based software tool that offers advanced modelling with an easy-to-use interface. Through precise and reliable energy and daylighting performance data, designs can meet performance targets at the early design stages using DesignBuilder. Models can be constructed in DesignBuilder from scratch or import from BIM using DXF or PDF 2-D drawings or importing 3-D models via gbXML format. DesignBuilder provides high quality practical and rendered outputs that represent outcomes in an understandable and clear way. DesignBuilder provides main performance indicators such as: (Energy consumption, carbon emissions, thermal comfort, daylighting and costs), in both naturally ventilated and air-conditioned buildings throughout the design process (Designbuilder, 2018).

DesignBuilder has been developed to be used in many professions, in architecture, engineering, building services, and energy consultancy. Some of the purposes of usage can be summarized as following (Altensis, 2015):

- Evaluation of facade alternatives in terms of: overheating, energy consumption and shading.
- Reaching the ideal use of daylight by modelling lighting control systems and defining the savings in electricity.
- Calculating temperatures inside and outside the building, as well as velocity and pressure distribution by using the CFD (Computational Fluid Dynamics) module.
- Picturing the site plan and shading.
- Thermal simulation for naturally ventilated buildings.
- Defining heating and cooling equipment and their capacities in HVAC systems.

The energy simulation process depends on real site data. Therefore, it is important to understand the location and climate of the site.

3.2. Climatic Zones in Saudi Arabia

Saudi Arabia has a huge area of 2.3 million square kilometres with a land elevation that varies from 0 to 3000 m above the mean sea level (GCS, 2018). The huge area and variation in sea level resulted in distinctive climatic features in the different parts of the country. The climate of Saudi Arabia has been classified in many ways by scientific and administrative organizations; most of these classifications defined it either as a desert or arid region. Köppen-Geiger, for example, has classified Saudi Arabia’s climate into two climatic zones, the south-western region as a desert cold arid zone, while the remaining of the country as a desert hot arid zone. This description is found to be misleading, as it ignores the fact that there are climatic differences between the regions of the huge country (Alrashed, 2017).

Said *et al.* (2003) had classified the country into six climatic zones, which are more convenient when used by designers and researchers in the field of buildings energy conservation (Said, 2003). While taken in consideration that the Empty Quarter is an uninhabited region; five locations are selected to represent five habited climatic zones:

Dhahran, Guriat, Riyadh, Jeddah and Khamis Mushait (Figure 3.1) the climatic characteristics of these climatic zones are described in (Table 3.1).

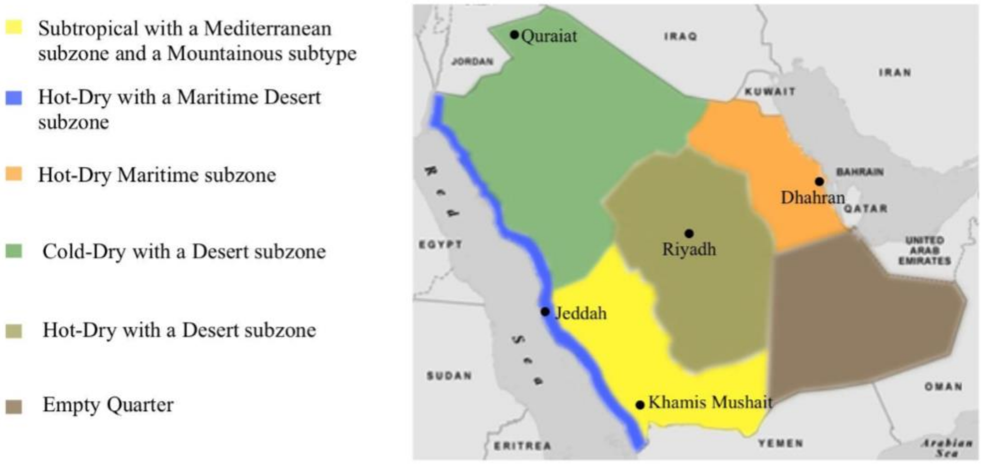


Figure 3.1. The climatic zones in Saudi Arabia (Said, 2003)

Table 3.1. Climatic parameters of the climatic zones in Saudi Arabia (Said, 2003)

Location	Geographic Coordinates			Air Temperature			Relative Humidity		
	Latitude (°N)	Longitude (°E)	Elevation (m)	Minimum (°C)	Maximum (°C)	Mean (°C)	Minimum (%)	Maximum (%)	Mean (%)
Dhahran	26.3	50.1	22	5.0	45.7	25.8	19	99	57
Guriat	31.3	37.4	502	-3.3	43.9	19.8	12	100	40
Riyadh	24.7	46.8	583	2.2	43.7	25.1	10	91	32
Jeddah	21.5	39.2	33	13.9	41.7	27.9	37	100	65
Khamis Mushait	18.3	42.7	2051	2.7	34.3	18.9	17	100	51

3.3. Geographical Location of Jeddah City

Jeddah, the second largest city in Saudi Arabia is located within 1765 km² urban boundary; with a total area of 5460 km². The population of city in 2010 has reached approximately 3.4 million, with a growth rate of 3.5% per annum. This population represents nearly 14% of the total population of the country. It is located on the west coast of Saudi Arabia (latitude 29.21 north & longitude 39.7 east), and in the middle of the eastern shore of the Red Sea south of the Tropic of Cancer. To the east there are the plains of Tihama (the low heights of the Hijaz region). To the west beside the beach there are the parallel chains of coral reefs (Jeddah Municipality, 2018).

3.4. Climate of Jeddah City

Jeddah’s climate is recognized by the high temperature and humidity during the summer. Humidity reaches its highest levels in summer because of the high temperature of sea water and it is lower in winter due to the impact of the moderate air mass associated with high pressure. Due to the city's coastal location on the shore of the Red Sea, the prevailing winds over Jeddah are North West winds. These winds are frequently light-to-moderate winds most of the year. Yet, sometimes Southern winds blow through winter, spring, and fall along with thunderstorms and heavy rain (Jeddah Municipality, 2018).

According to (Figure 3.2) the warmest month (with the highest average high temperature) is July (39.4°C). While the month with the lowest average high temperature is January (29°C). The month with the highest average low temperature is August (27.6°C), while the coldest month (with the lowest average low temperature) is February (20.1°C).

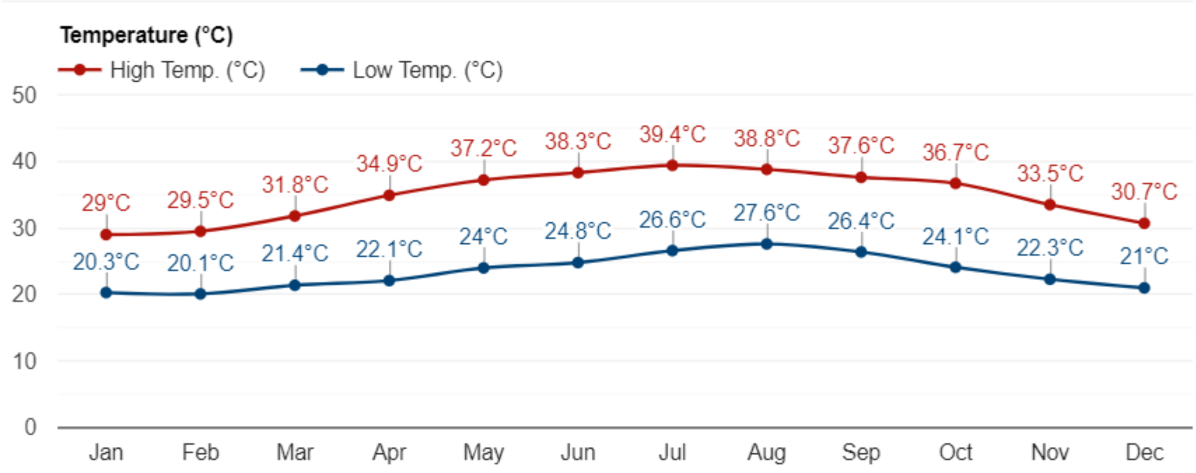


Figure 3.2. Average temperatures Jeddah, Saudi Arabia (Weather Atlas, 2018).

Figure 3.3. shows that the month with the highest relative humidity is September (67%), while July is the month with the lowest relative humidity (53%).

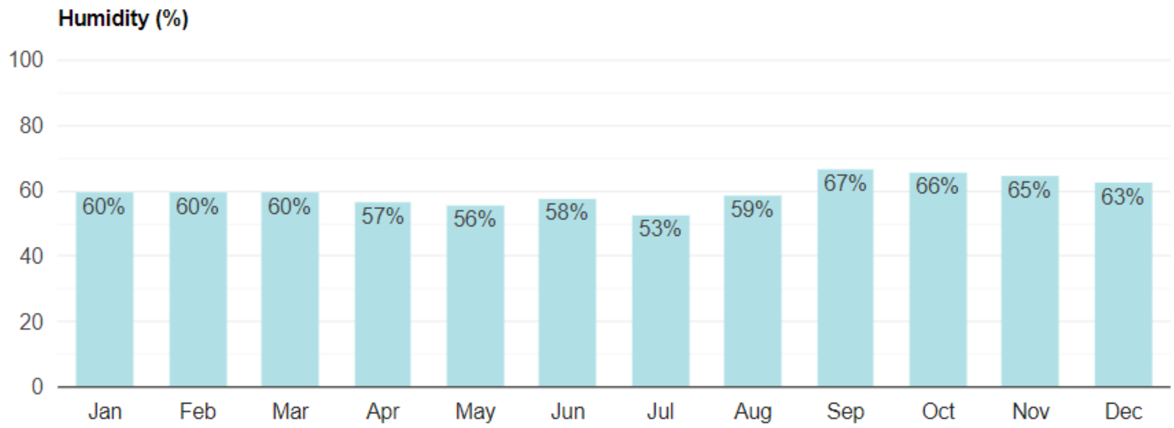


Figure 3.3. Average humidity Jeddah, Saudi Arabia (Weather Atlas, 2018).

According to Figure 3.4 the wettest month (with the highest rainfall) is November (26.4mm), while the driest month (with the lowest rainfall) is June (0mm).

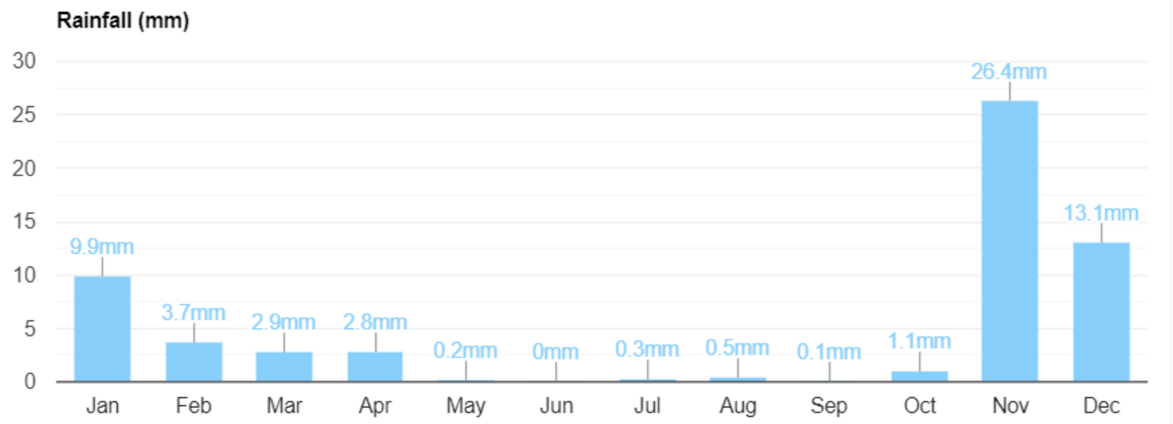


Figure 3.4. Average rainfalls Jeddah, Saudi Arabia (Weather Atlas, 2018).

(April, May, June, July and August) are the months with the longest days, with an Average daylight of (13h), while (January, February, November and December) are the months with the shortest days, with an Average daylight of (11h). Months with most sunshine are (May and June) with an Average sunshine of (11h), while months with least sunshine are (January and December) with an Average sunshine of (7h) (Figure 3.5).

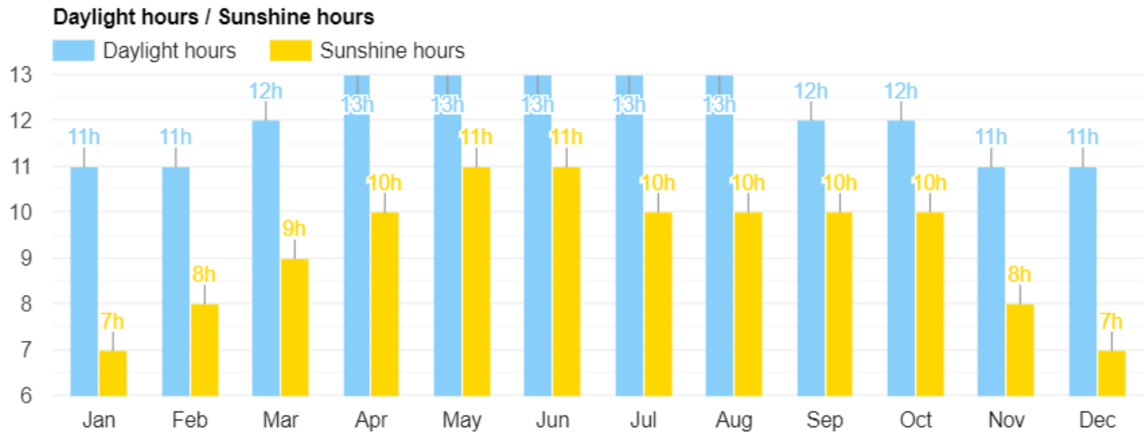


Figure 3.5. Average daylight/ average sunshine Jeddah, Saudi Arabia (weather atlas, 2018).

According to statistics that are based on observations taken between 06/2009 - 11/2018 daily from 7am to 7pm local time, (Figure 3.6) shows that the prevailing wind direction is mainly north-west in Jeddah city.

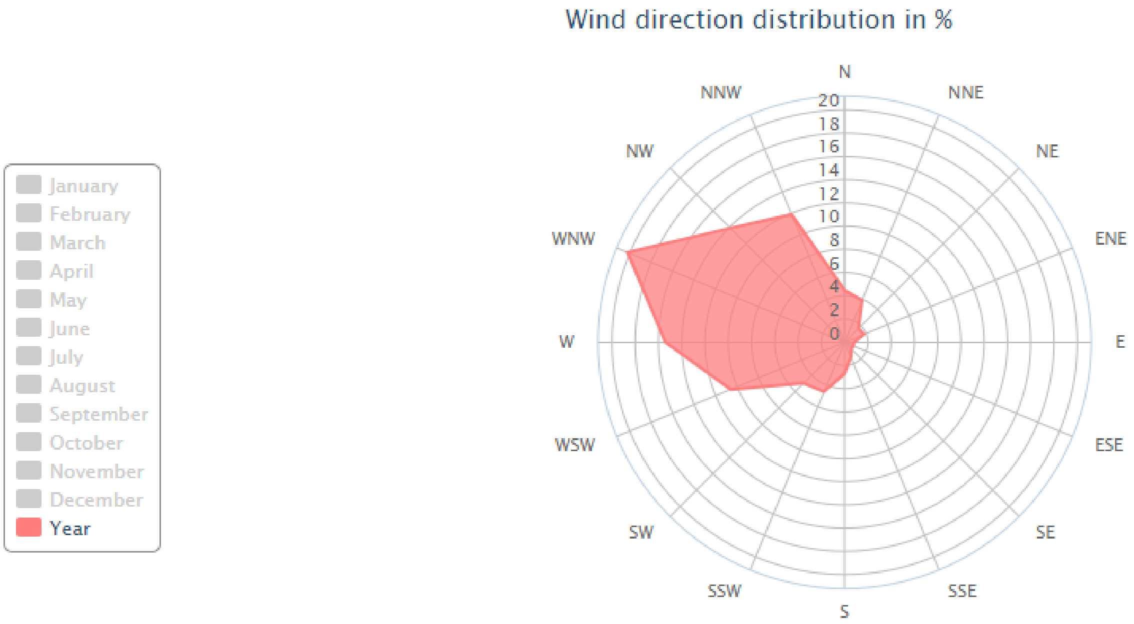


Figure 3.6. Wind distribution in Jeddah (Windfinder, 2018)

3.5. Site Location

The site was selected in the new residential grid north of Jeddah since the city is expanding towards the north (Figure 3.8). The plot size is approximately 400 m^2 which is an average size for residential villas in Saudi Arabia as the minimum is 300 m^2.

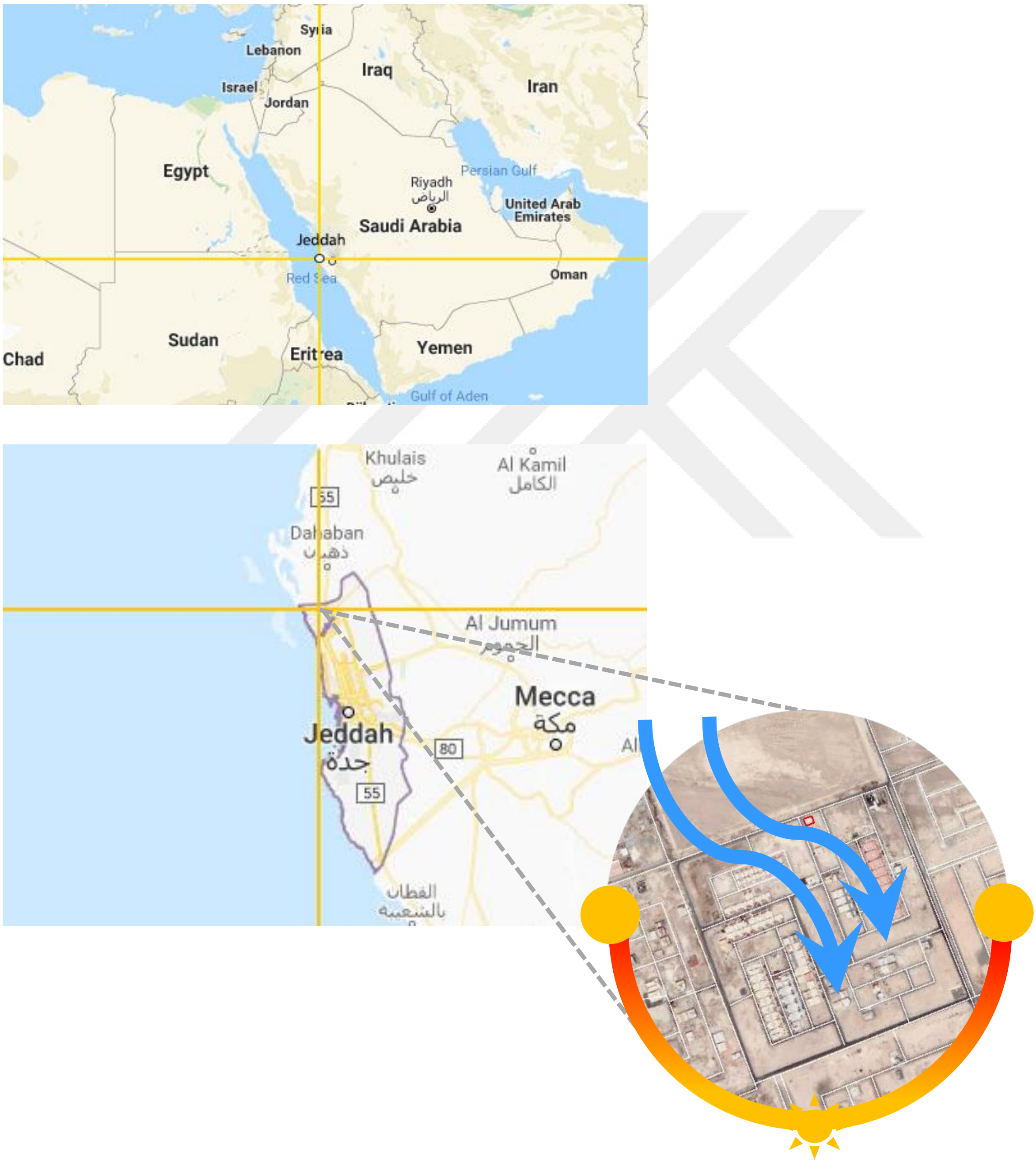


Figure 3.7. Site location (Google Map, 2019)

4. DESIGN AND SIMULATION

4.1. Base-Case Design

The base case represents a conventional design and construction of a single family house in Saudi Arabia. It's a two story house with three bedrooms; the design was adjusted according to the sun and wind direction, the house longest facades are facing the North-South axis in order to minimize the exposure to the east and west sun. As the blocks grid in Jeddah is tilted and the prevailing wind is in the North-West direction the house is tilted making the longest façade taking advantages of the wind (Figure 4.1). The ground floor is occupied by reception and living areas while bedrooms are located in the first floor. Most of the living areas are facing the wind axis while services are located to the south. The design also respects the privacy traditions in the area by having two separate zones and entrances for guests and family (Figure. 4.2). Table 4.1 demonstrates the Base-Case areas, construction materials, and cooling system.

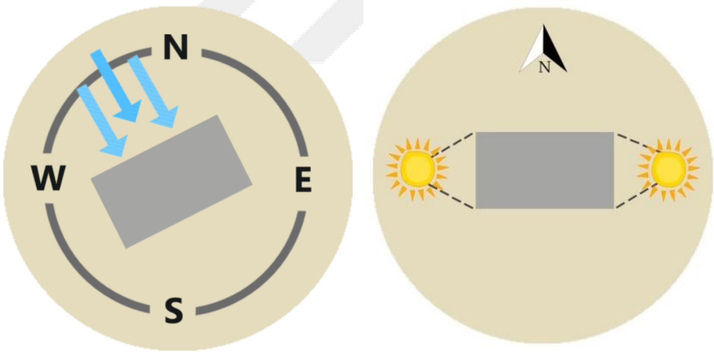


Figure 4.1. Sun and Wind direction in relation to the house (drawn by author)

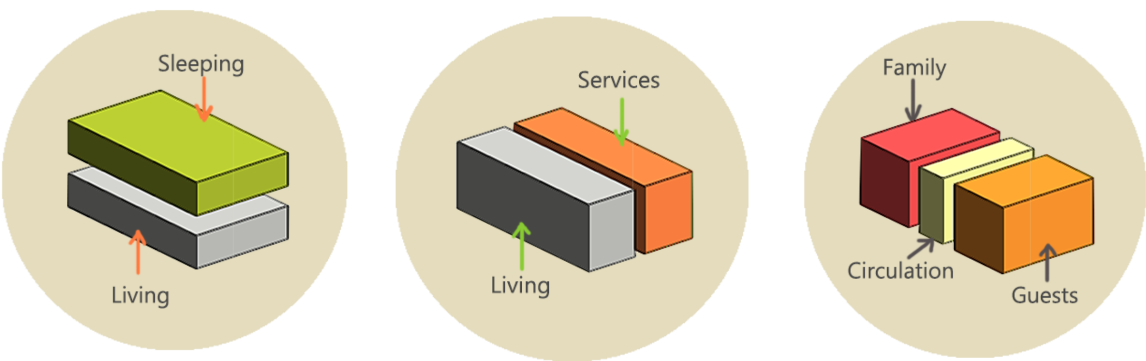


Figure 4.2. House zoning (drawn by author)

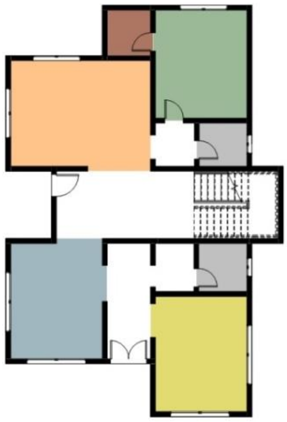
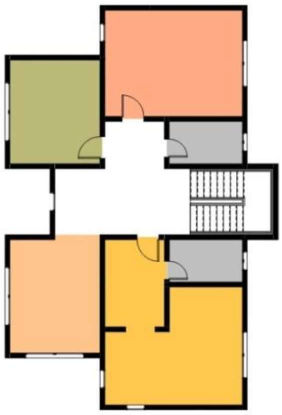
Table 4.1. Base case details schedule

Building details	Description
Plot Area	400 m^2
Built Area	295 m^2
Number of floors	2
Floor Height	3 m
Ground Floor area	151.765 m^2
First floor area	136.304 m^2
Exterior wall material	20 cm -CMU
Roof material	Reinforced concrete slab
Glazing type	Single clear glazed
Mechanical cooling system	Split system

(a) (b)

Figure 4.3.Base-case ground floor plan (a) first floor plan (b) (by author)

Table 4.2. Base Case Floor plans zones and areas

Floor	Colour	Space	Area in m^2	Plan
Ground Floor		Guest reception "Majlis"	18	
		Dining room	19	
		Living room	26	
		Kitchen	17	
		Laundry room	3	
		Toilets	8	
		Circulation	41	
First Floor		**Space**	**Area in m^2**	
		Family living	19	
		Master bedroom	33	
		Bedroom 1	26	
		Bedroom 2	17	
		Bathrooms	12	
		Circulation	31	

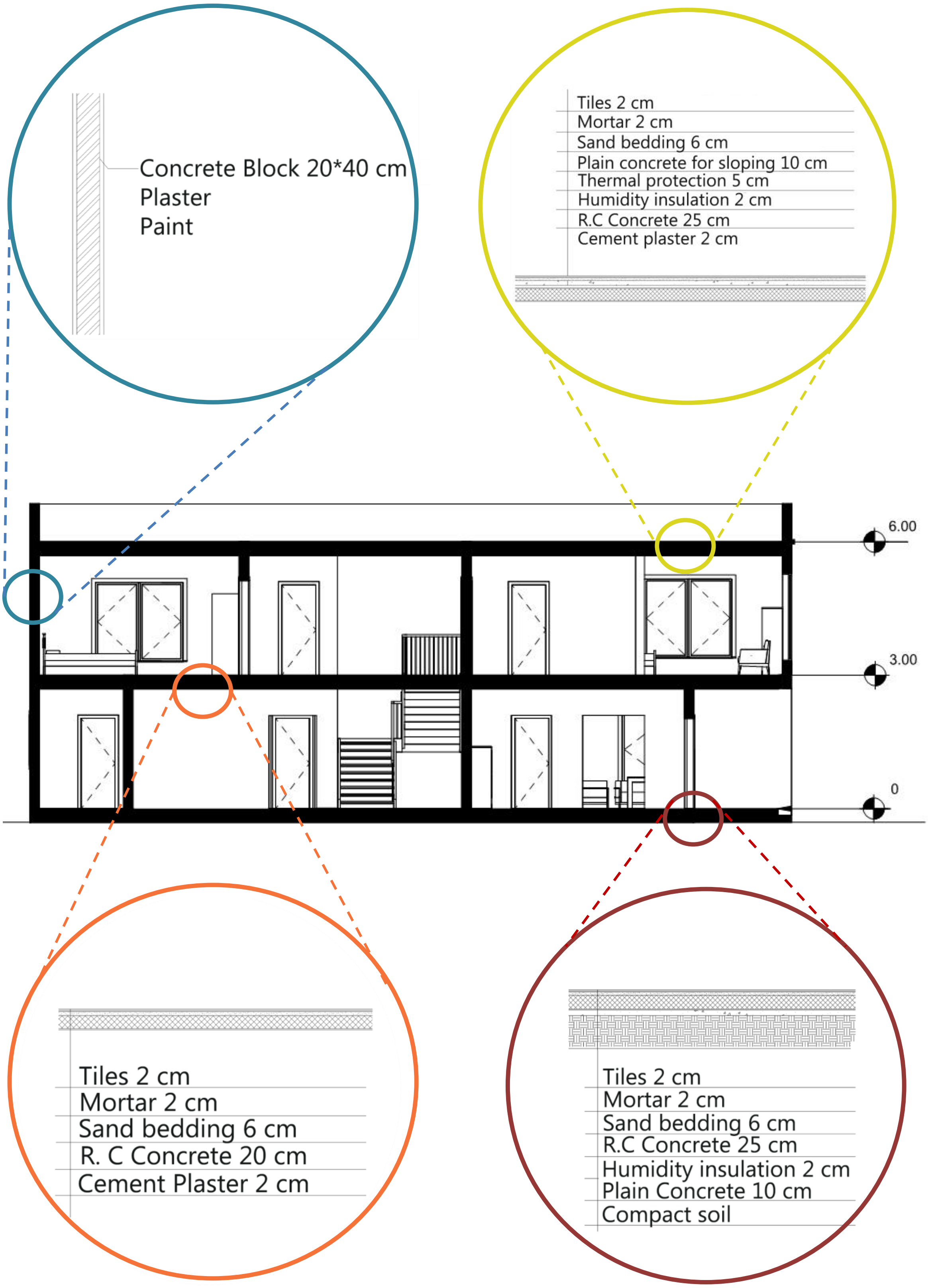


Figure 4.4. Base case section (by author)

4.2. Base-Case Simulation

The Base-Case house was modelled in DesignBuilder (Figure 4.6) according to the construction trends in Saudi Arabia, as specified in (Table 4.1 & Figure 4.5) under EnergyPlus format hourly weather data (epw file) of Jeddah. The estimated annual energy consumption of the Base-Case was 59333.63 kWh and by dividing it by the floor area of the house (295m) the result was 201.13 kWh/m2/yr. The potential annual carbon emission was 35956.13 kg/yr. The month of August recorded the heights energy consumption in summer by 6865.12 kWh (Figure 4.7) and the month of January recorded the lowest consumption by 2847.81 kWh (Figure 4.8). As the main concern in hot climates is the cooling load, simulation in summer time was the main focus in this study. The simulation results show that cooling is the main consumer of energy (electricity) and it reaches the highest in August with 4977.57 kWh (Figure 4.9) which represent 72.51% of the house's electricity consumption in August and 62% annually (Figure 4.10). By running the simulation in a summer day (July 21) results show that solar gain represents most heat gain in the house and it mostly increases near sunset as it reached its peak at 4:00 pm which makes windows facing west more critical (Figure 4.11). This data was used as a reference for testing the energy performance for the developed cases.

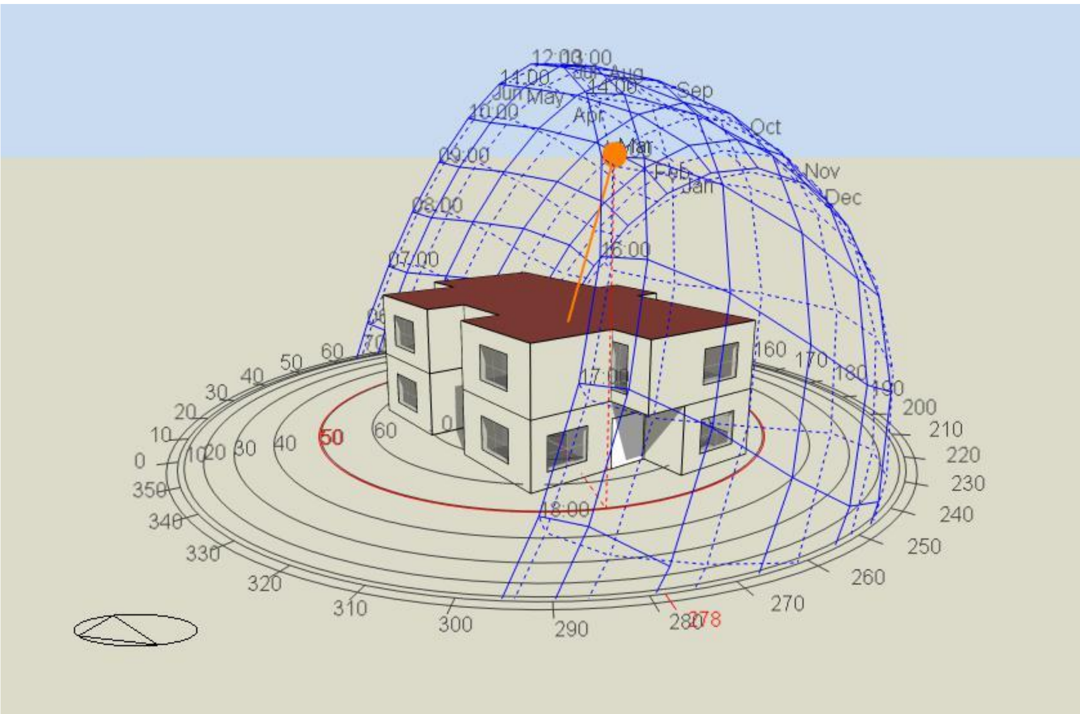


Figure 4.5. Base-Case model in DesignBuilder (by author)

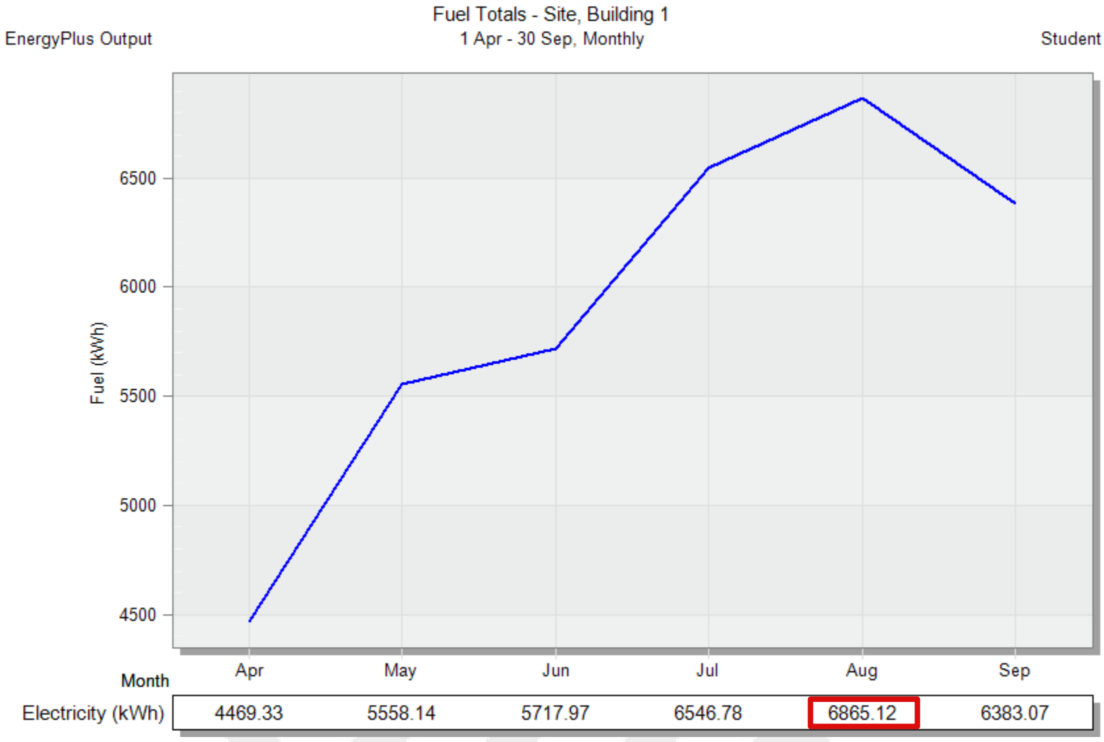


Figure 4.6. Base-Case Energy consumption all summer from 1 April – 30 September.

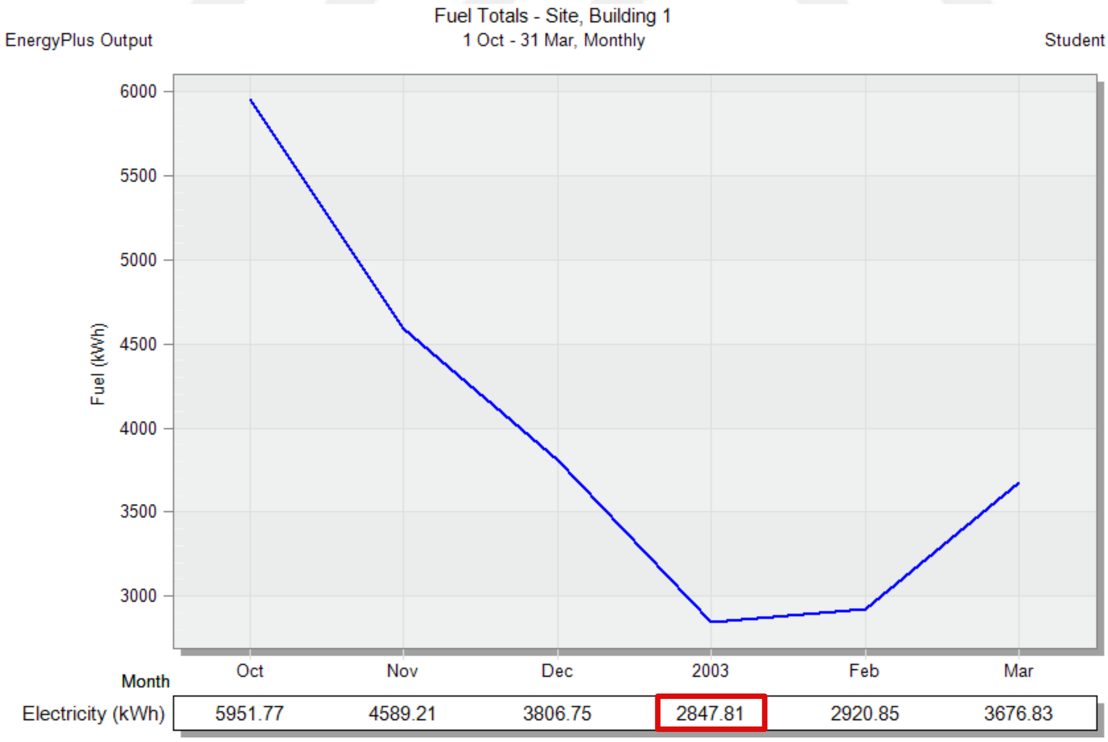
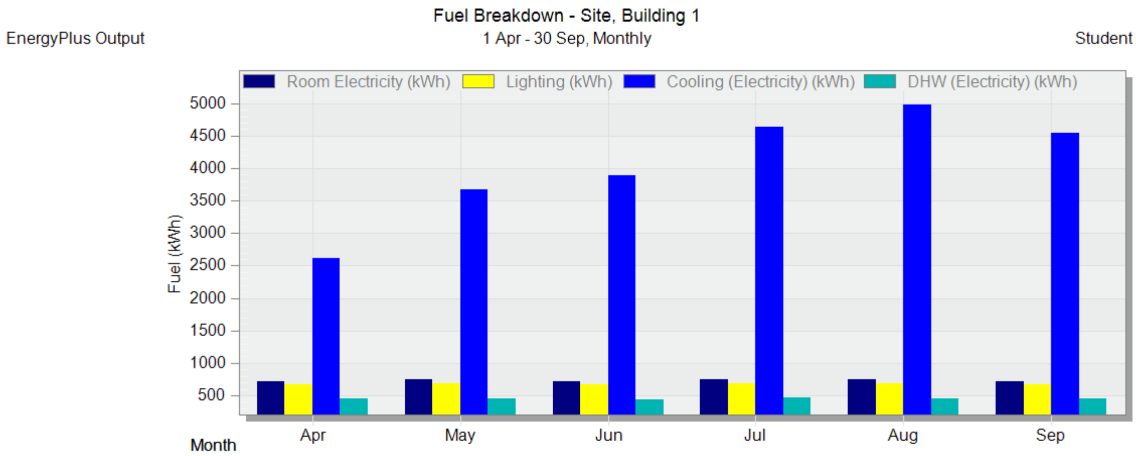


Figure 4.7. Base-Case Energy consumption all winter from 1 October– 31 March.



Month	Apr	May	Jun	Jul	Aug	Sep
Room Electricity (kWh)	722.92	745.36	721.50	746.78	745.36	722.21
Lighting (kWh)	671.75	689.67	667.92	693.50	689.67	669.83
Cooling (Electricity) (kWh)	2617.72	3670.82	3888.97	4637.96	4978.15	4543.38
DHW (Electricity) (kWh)	456.90	452.52	440.09	469.33	452.52	448.50

Figure 4.8. Base-Case fuel breakdown all summer from 1 April – 30 September.

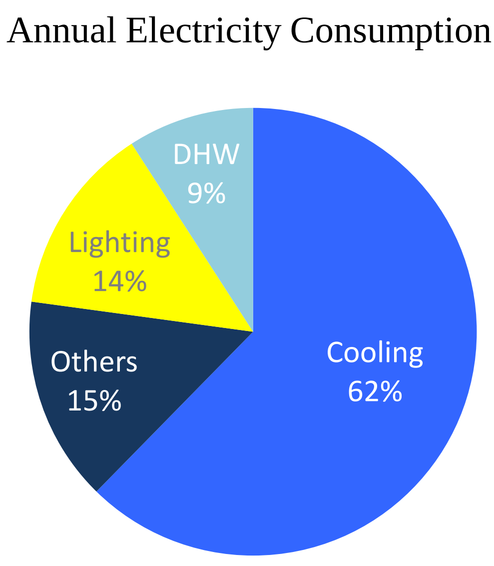
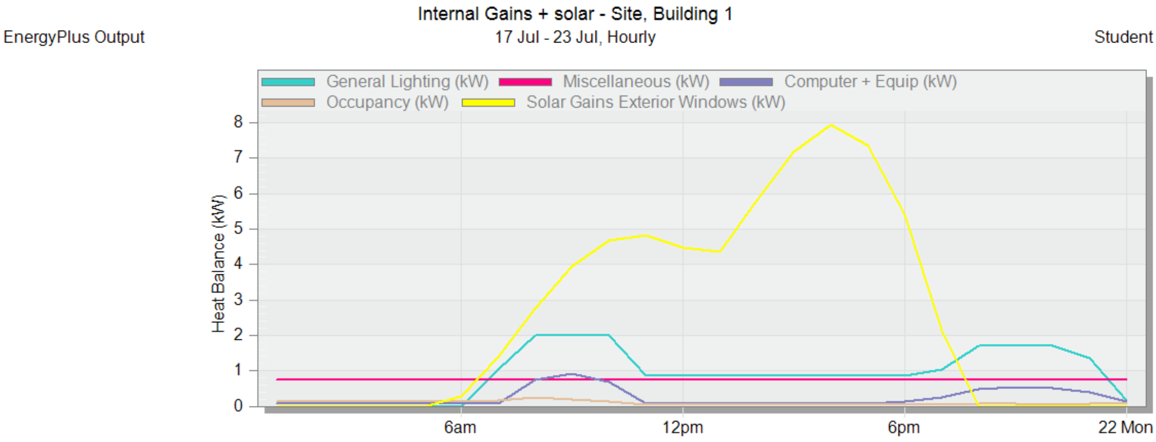


Figure 4.9. Base-Case Annual Electricity consumption Breakdown chart.



Time/Date																								
General Lighting (kW)	0.00	0.00	0.00	0.00	0.00	0.00	1.05	2.00	2.00	2.00	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	1.05	1.72	1.72	1.72	1.37	0.17
Miscellaneous (kW)	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76
Computer + Equip (kW)	0.06	0.06	0.06	0.06	0.06	0.06	0.08	0.75	0.92	0.70	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.15	0.26	0.47	0.55	0.51	0.40	0.15
Occupancy (kW)	0.13	0.13	0.13	0.13	0.13	0.13	0.15	0.24	0.19	0.14	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.06	0.08	0.08	0.05	0.07	0.10
Solar Gains Exterior Windows (kW)	0.00	0.00	0.00	0.00	0.00	0.28	1.39	2.74	3.95	4.67	4.81	4.49	4.34	5.81	7.19	7.94	7.37	5.42	2.16	0.00	0.00	0.00	0.00	0.00

Figure 4.10. Base-Case internal gains+solar in 21 July

4.3. Passive House Simulation

A Passive House refers to a building that uses very little energy in order to maintain pleasing temperature, which makes the building almost "passive" as it barely needs any active heating or cooling to stay comfortable year-round. Therefore, the Base-Case house was developed according to the Passive House standards to achieve improvement in the energy performance by decreasing the electricity consumption mainly from the cooling load. In this case the design was kept the same because the Passive House is a performance standard with no specific design or construction methods, the building should meet some specific energy demand targets, but with freedom of design and material choices (IPHA, 2014).

The Passive House five principles have been introduced in this case which are: Thermal insulation, Passive House windows, Thermal Bridge reduced design and Airtightness, and high efficient ventilation or air conditioning system. In addition to the main principles high efficiency lighting criteria was also applied. Energy simulation has been conducted for each criteria to test how much reduction in energy consumption they will achieve, at the end all the results have been collected in one model to see if the passive house standards can be achieved in Jeddah city or not.

4.3.1. Thermal insulation

According to the Passive House standards exceptionally high levels of insulation (200 mm minimum thickness insulation layer) must be applied to all the opaque building components of the exterior envelope of the house (walls-floor-roof). Thermal insulation can be achieved for any construction with no specifications such as: solid construction, timber construction, prefabricated building elements, formwork element technology, steel construction and mixed constructions. As well as it can be added to new and existing structures.

In the matter of choosing the insulation material and its appropriate thickness, Qatar and Dubai Passive Houses have been used as a guide to choose the insulation materials as they have similar climate and construction methods to this case. Polystyrene was found to be the major thermal insulator in both (Qatar and Dubai) Passive Houses, accordingly Extruded polystyrene (XPS) was chosen to be used to insulate the exterior walls and roof which is a foam insulating sheathing that is Energy-efficient, easy to install, lightweight, and has the ability to create a continuous layer of thermal and moisture protection by this means it contributes to energy efficiency (Herrenbruck, 2018). A 380 mm layer of extruded polystyrene was added to the 200 mm exterior concrete block walls of the house, (Figure 4.12) shows that insulation in passive house is usually thicker than the construction material. After applying the insulation the heat gain from the exterior walls was reduced from 12 to 2 kW in the peak hour in July 21 (Figure 4.13, 4.14). As a result cooling load was reduced from 4978.15 kWh in the Base-Case to 3075.05 kWh in the peak cooling load in August (Figure 4.15, 4.16).

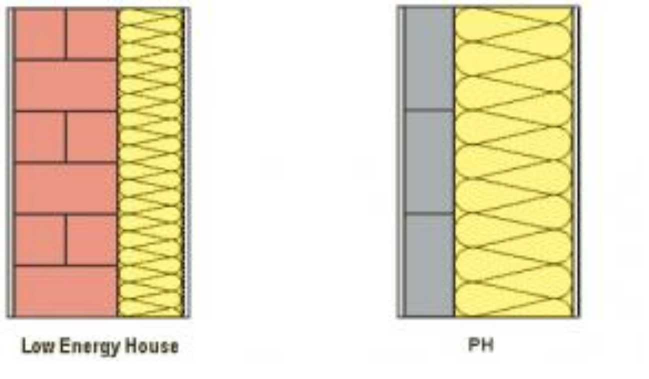


Figure 4.11. Exterior wall insulation (IPHA, 2015)

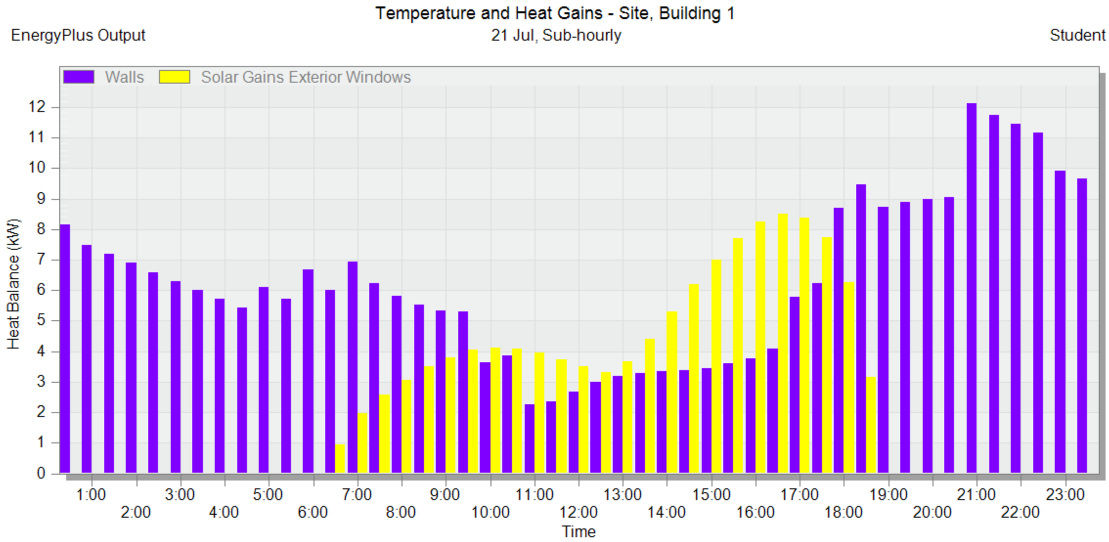


Figure 4.12. Base-Case heat gains through walls without insulation in 21 July.

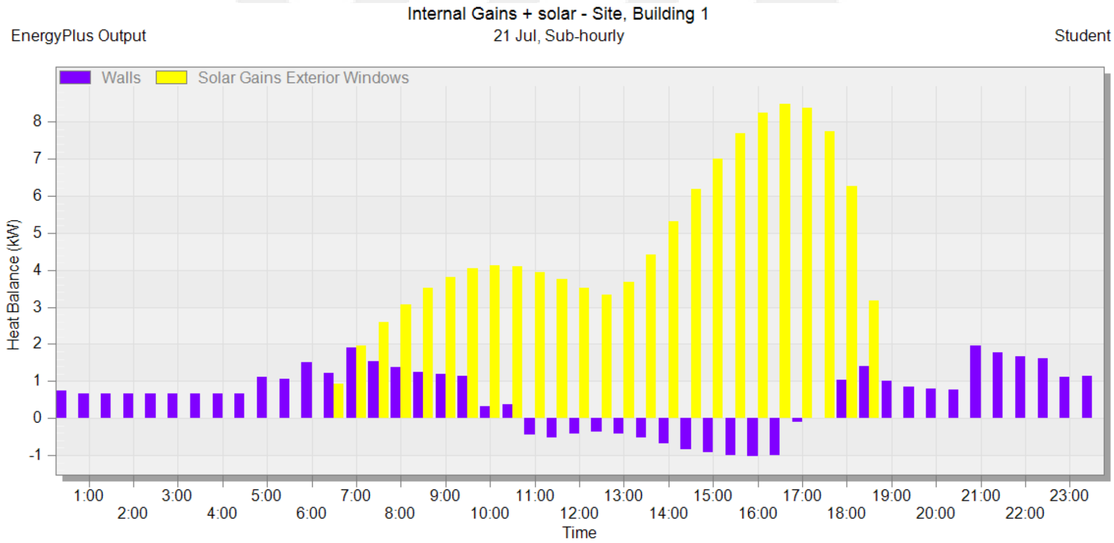


Figure 4.13. Heat gains through walls with Extruded polystyrene insulation in 21 July.

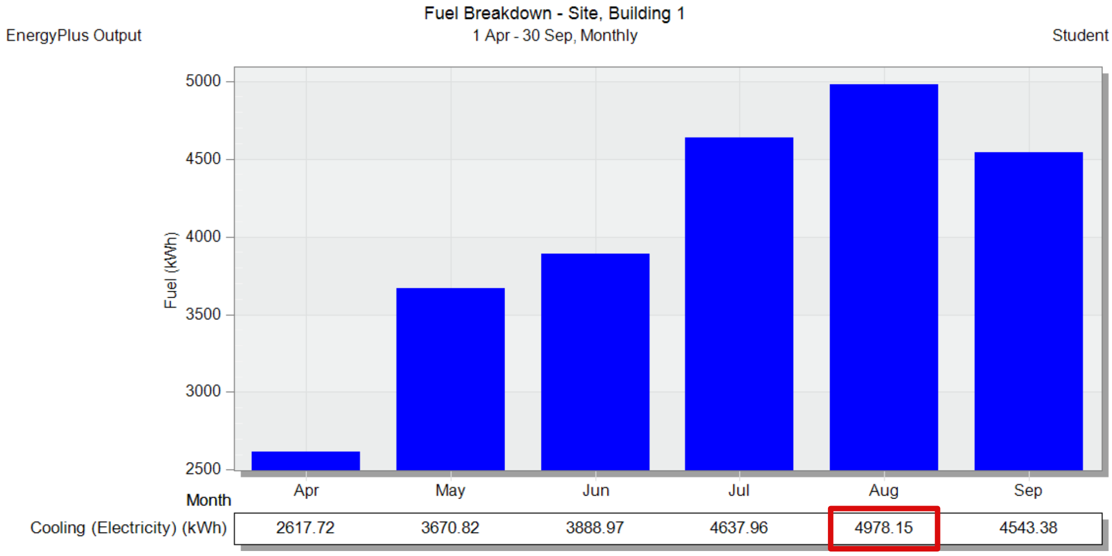


Figure 4.14. Base-Case Cooling electricity without exterior wall insulation in summer.

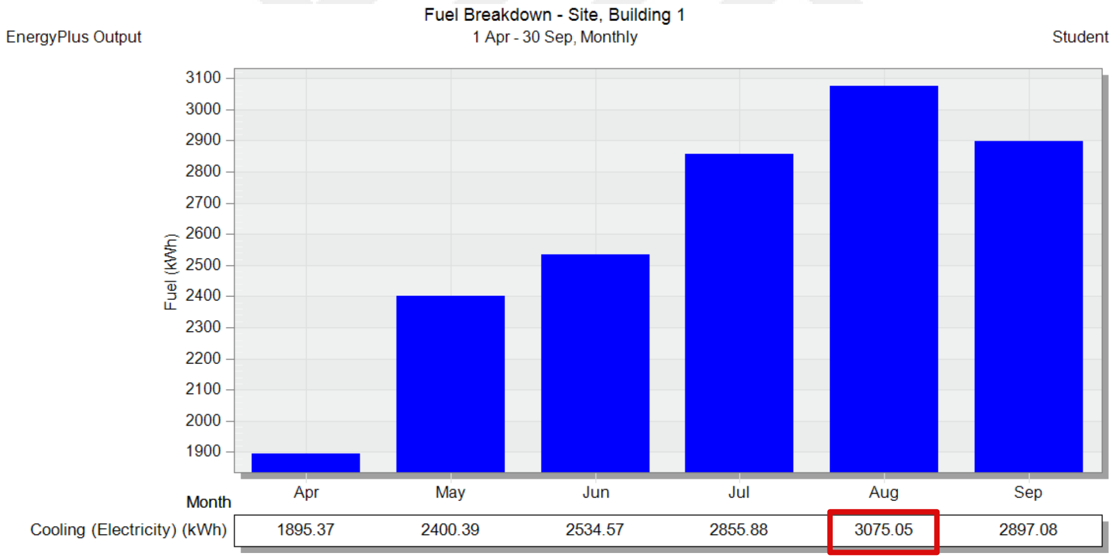


Figure 4.15. Cooling electricity after exterior wall insulation in summer.

The roof as well was insulated with 380 mm layer of polystyrene, heat gains through roof was reduced from 2.47 KW to 0.31 KW at the peak in July 21 as it show in (Figure 4.17, 4.18) and impacted as well on the cooling load by reducing it from 4978.15 kWh to 4788.62 kWh in August (Figure 4.19).

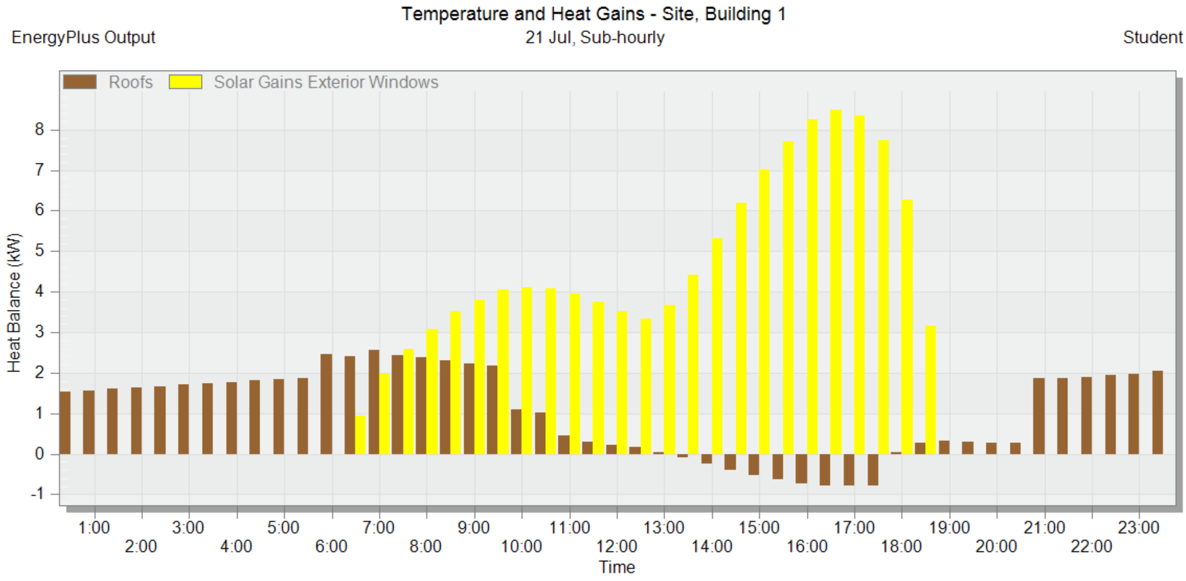


Figure 4.16. Base-Case heat gains through roof without insulation in 21 July.

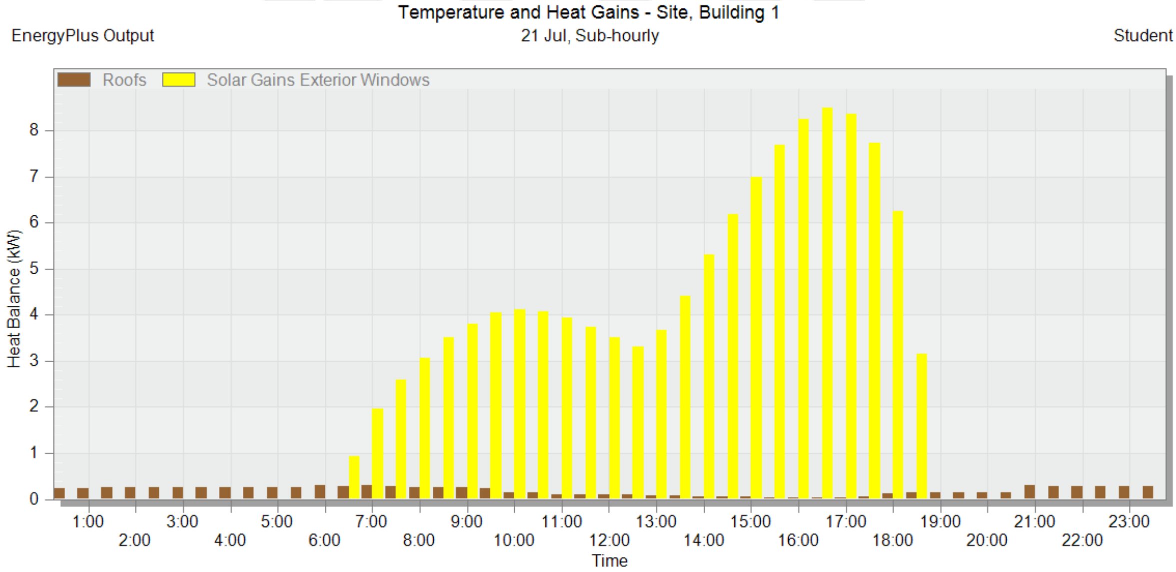


Figure 4.17. Heat gains through roof with Extruded polystyrene insulation in 21 July.

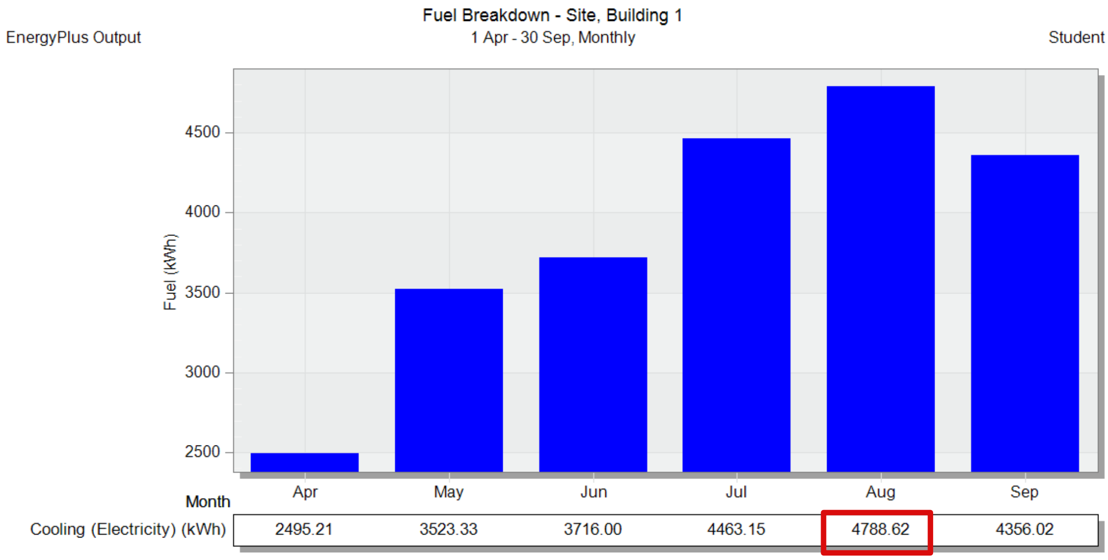


Figure 4.18. Cooling electricity after roof insulation in summer.

4.3.2. Passive House windows

The Passive House windows should be of high quality, either double or triple-paned according to the climate conditions, low-e glazing filled with argon or krypton to prevent heat transfer with U-values of less than 0.85 W/(m²K) are suggested. Exterior shading is also essential whether fixed or moveable to block solar heat gains especially during the summer period. Additionally, well insulated window frames are required, as the frame accounts for between 30% and 40% of the total window area. Thinner frames and larger glass surfaces are more preferred as the thermal performance of glass is better than the frame (IPHA, 2014).

There are two glazing specification that impact on windows performance: solar heat gain coefficient (SHGC) and U-Value, (Table 4.3) demonstrates the SHGC and U-Value for a number of glazing types, trial simulations were run to decide which type of glazing resulted in higher reduction in cooling load. Therefore, the Base-Case house's windows were modified as Triple glazed windows 6mm clear glass with double 12mm cavity filled with Krypton gas. PVC was used in frames for its low conductivity. As a result solar gain from windows was reduced from 8.25 KW to 2.96 KW at its peak in one of the hottest summer days (21 July), and after adding shading louvers it was even more reduced to 1.92 KW (Figure 4.20). And cooling load was reduced from 4978.15 KW in August to 4473.11 KW (Figure 4.21).

Table 4.3. Properties of window glazing types (Reilly, 1992).

Glazing Type	SHGC	U-Value (W/m2/K)
Single clear	0.86	6.31
Double clear air	0.76	3.23
Double clear argon	0.76	2.61
Double LoE clear air	0.60	2.47
Double LoE clear argon	0.59	1.48
Triple clear air	0.68	2.19
Triple clear argon	0.68	1.64
Triple LoE clear air	0.47	1.55
Triple LoE clear argon	0.47	0.77

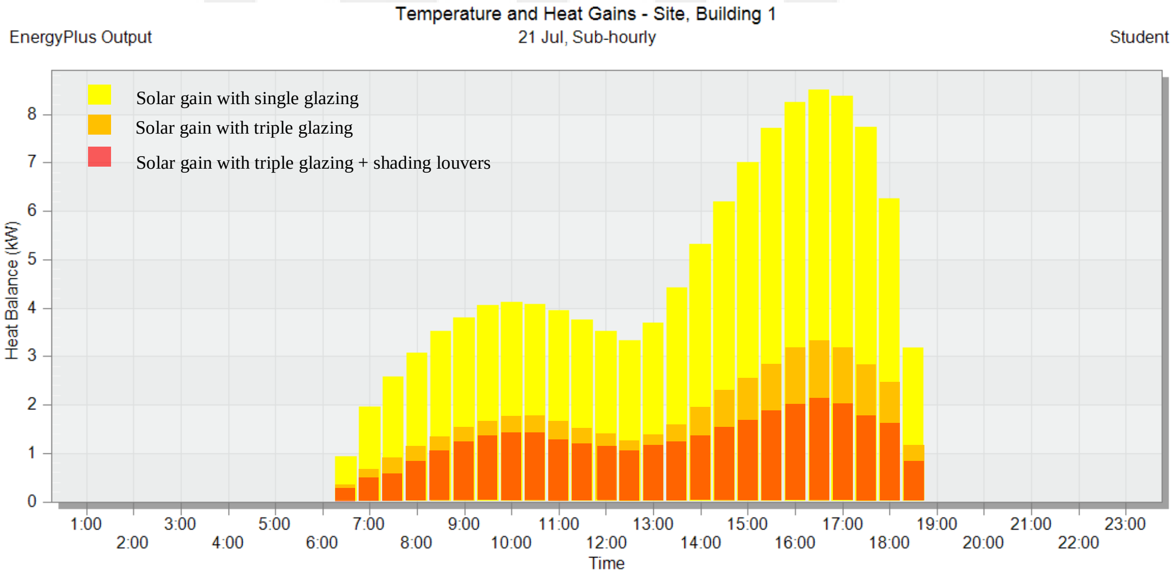


Figure 4.19. Solar gain from exterior windows in 21 July

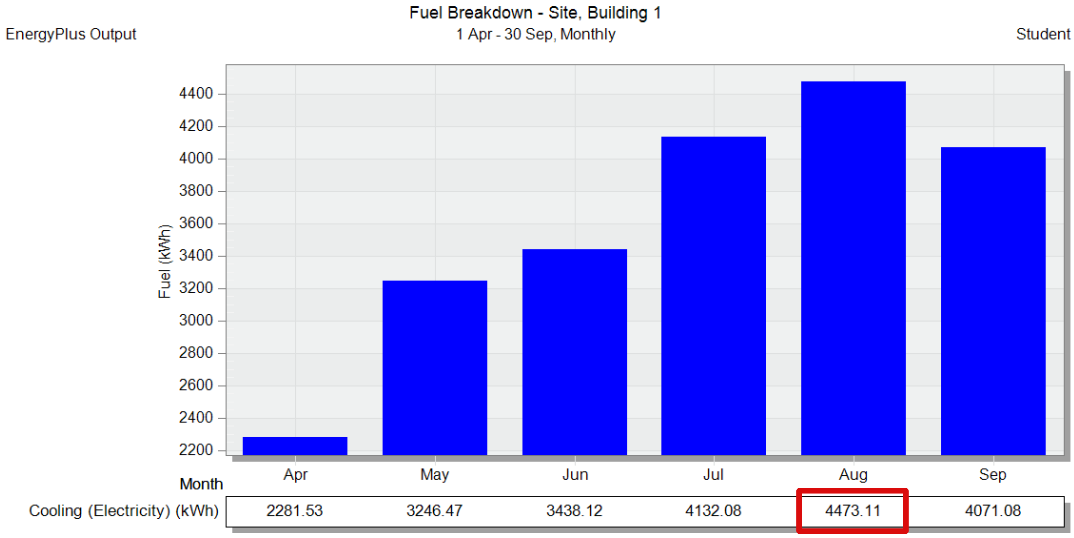


Figure 4.20. Cooling loads in summer after applying Passive House windows.

4.3.3 Thermal bridge reduced design and airtightness

Another critical principle of the Passive House is the thermal bridge free or reduced design which means that the insulation must be applied without any “weak spots” around the whole structure in order to avoid heat gain or loss. Thermal bridge means that there is a direct connection between the inside and outside through elements which are more thermally conductive than the rest of the building envelope. Therefore: thermal bridges happen at the connection of different building components, or where penetration of the insulating layer occurs. In order to achieve thermal bridge free design, the insulation of the building must form a continuous layer (Passipedia, 2019). In Addition, paying attention to some construction details at the design stage can help reducing thermal bridging, such as: window and door openings (cills, jambs and lintels) -external wall/ground floor, and wall/roof junctions (Energy Saving Trust, 2009).

As the heat loss and gain through the structure must be reduced through free thermal bridge design, air penetration through the structure must be minimized as well by achieving airtightness (Figure 4.22). An airtight building envelope must be ensured in a Passive House, by avoiding Air leakage or (infiltration) which is the uncontrolled flow of air through gaps and cracks in the fabric of a building (Energy saving trust, 2009). The infiltration rate must be smaller than 0.6 of the total house volume per hour during a pressure test at 50 Pascal (both pressurised and depressurised). An airtight building envelop reduces the risk of structural damage. Airtightness can be achieved through cautious planning and intelligent solutions such as: full interior plastering, quality workmanship and the proper installation of all windows and doors is also important (IPHA, 2014).

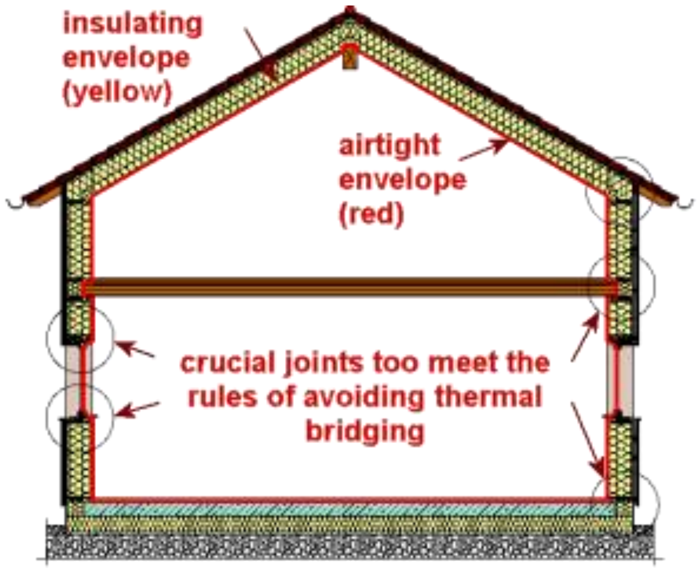


Figure 4.21. The airtight layer in a Passive House (Red line), thermal bridge insulation layer (yellow) (IPHA, 2019).

By changing the infiltration rate in the Base-Case model from 0.7 ACH50 to 0.5 heat gain from infiltration was reduced from 559.77 to 387.74 kWh in July (Figure 4.23, 4.24) cooling load was reduced from 4978.15 KW in August to 4661.38 KW (Figure 4.25).

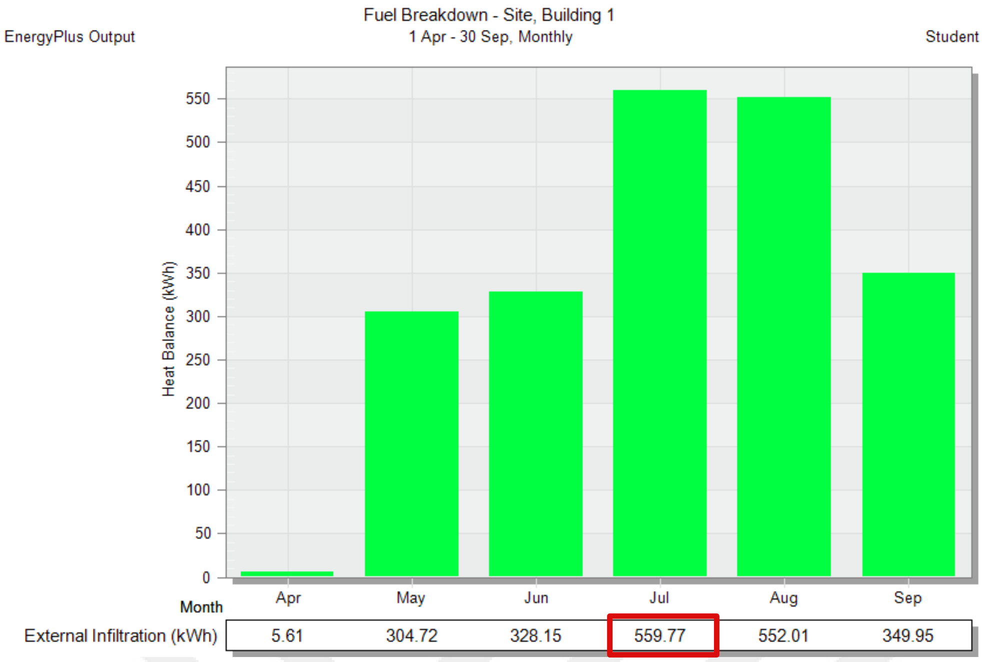


Figure 4.22. Heat gain from external infiltration in Base-Case (0.7 ACH50)

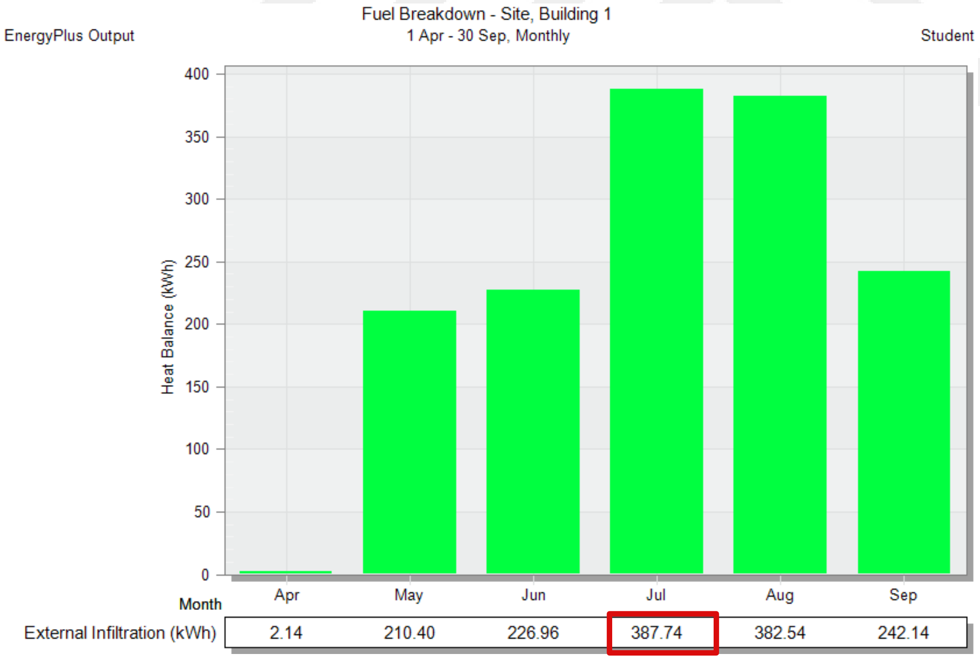


Figure 4.23. Heat gain from external infiltration in Passive House (0.5 ACH50)

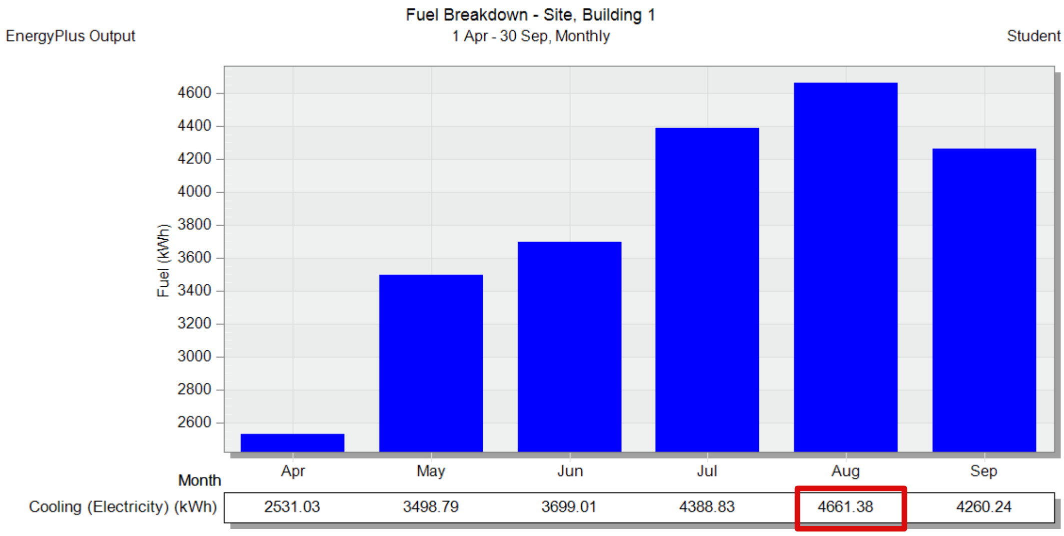


Figure 4.24. Cooling load with 0.5 ACH50 infiltration.

4.3.4. Highly efficient HVAC system

In hot climates such as Saudi Arabia, active cooling is mostly necessary. The Passive House measures aim to keep cooling needs low in order to be covered with a relatively small, highly efficient cooling system (IPHA, 2014).

Variable refrigerant flow (VRF) is a high efficiency air-conditioning system where there is one outdoor condensing unit and multiple indoor units. The system works by getting the (desired comfort temperature) from the user and from the surroundings (outside ambient temperature), and depending on this data it gets to the desired comfort conditions. Having the ability to adjust itself according to the outdoor conditions is the main factor behind the high efficiency of this system, compared to the traditional systems (Daikin, 2013).

There are three types of VRF System:

1) Cooling only systems (less popular) – those systems can only cool. Heating is not available. Fan and Dry modes are available for each indoor unit independently.

2) Heat Pump systems (most popular) – all the indoor units can either heat, or cool (not at the same time). Fan and Dry modes are available for each indoor unit independently.

3) Heat Recovery systems (less popular) – those systems are the most sophisticated ones, where cooling and heating may be available by each indoor unit, independently, at the same time.

VRF cooling only system was chosen in this case because buildings in Jeddah city don't require heating in winter as the temperature are moderate. After changing the HVAC template in DesignBuilder model from split system to VRF air cooled, the cooling load has decreased from 4978.15 kWh (Figure 4.26) to 3138.28 kWh at the peak cooling load in August (Figure. 4.27).

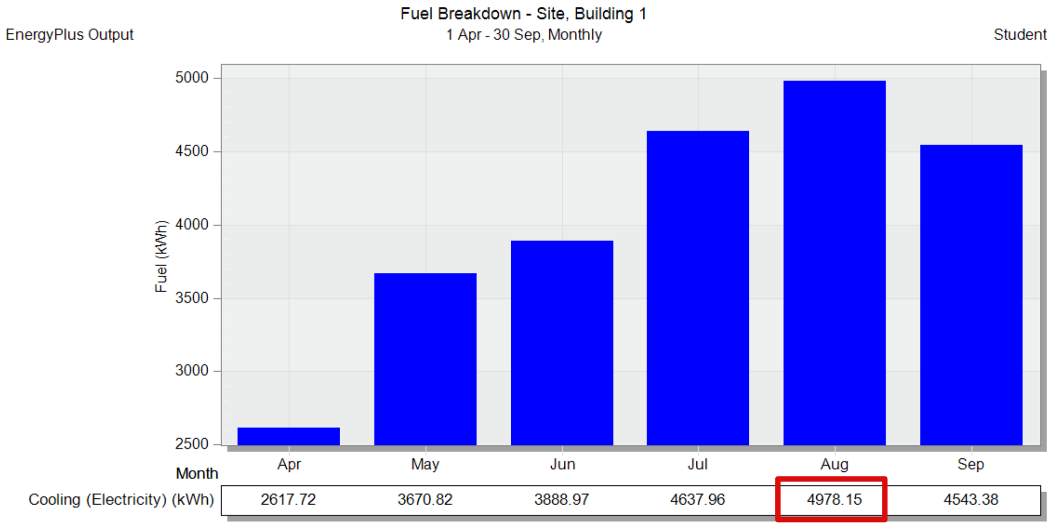


Figure 4.25. Base-Case cooling loads in summer with split system.

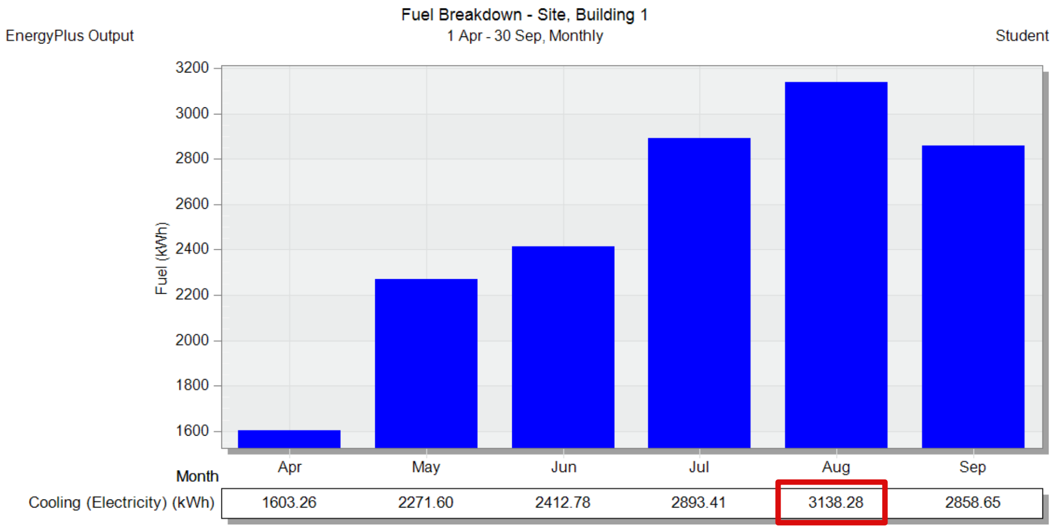
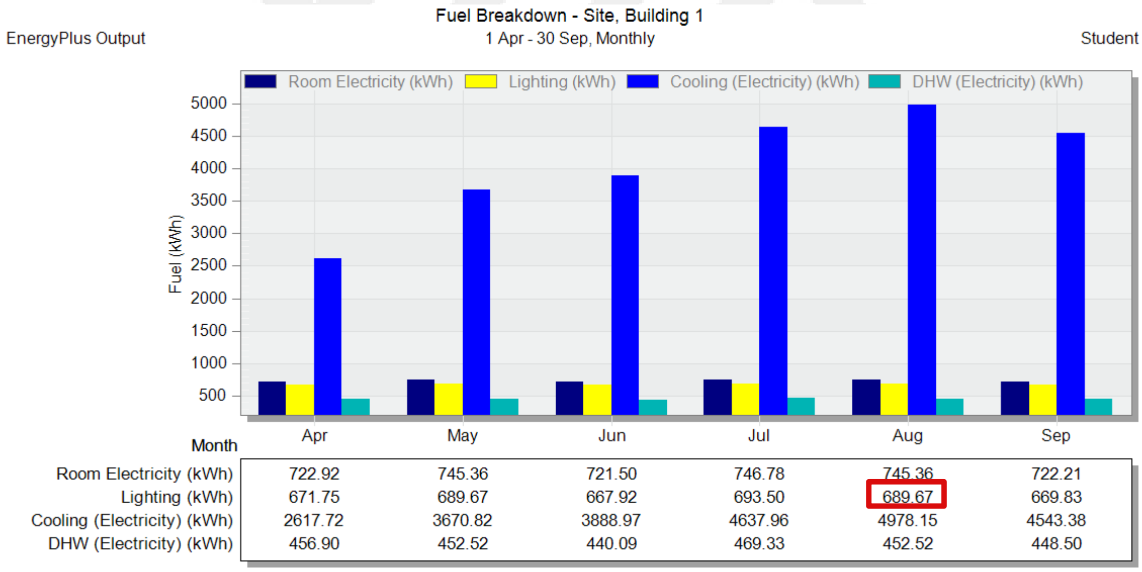


Figure 4.26. Cooling loads with VRF air cooled system.

4.3.5. High efficiency lighting

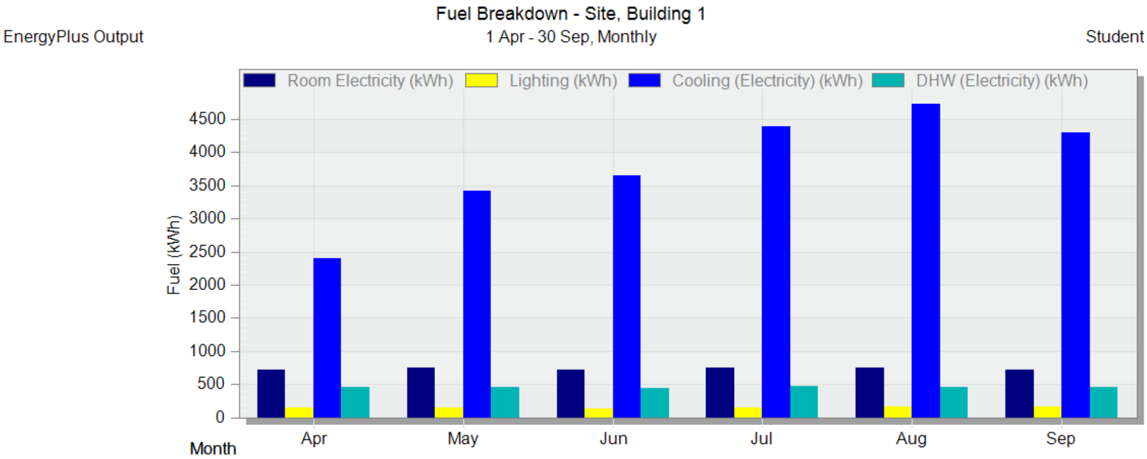
As lighting is one of the internal heat gains it should be minimized in the Passive House through the use of efficient lighting. LED lights that have an efficiency value of 65 lm/W or greater and a color rendering index (CRI) of at least 80 are recommended by the Passive House standards (IPHA, 2014).

The previous conventional “low-energy” light bulbs with 5.00 W/m2 power density lightings in the Base-Case were changed to LED with 2.50 W/m2 power density with linear control. By switching to high efficiency lighting reduction in electricity consumed by lighting was accrued. Electricity for lighting was 689.67 kWh in August (Figure 4.28) and reached 155.85 kWh (Figure 4.29). So, if we compared the results of one month electricity for lighting it was reduced by 77.40 % (Figure 4.30).



Month	Apr	May	Jun	Jul	Aug	Sep
Room Electricity (kWh)	722.92	745.36	721.50	746.78	745.36	722.21
Lighting (kWh)	671.75	689.67	667.92	693.50	689.67	669.83
Cooling (Electricity) (kWh)	2617.72	3670.82	3888.97	4637.96	4978.15	4543.38
DHW (Electricity) (kWh)	456.90	452.52	440.09	469.33	452.52	448.50

Figure 4.27. Base-Case electricity consumption breakdowns all summer.



Month	Apr	May	Jun	Jul	Aug	Sep
Room Electricity (kWh)	722.92	745.36	721.50	746.78	745.36	722.21
Lighting (kWh)	152.08	151.73	138.11	143.49	155.85	154.70
Cooling (Electricity) (kWh)	2401.74	3425.94	3645.35	4383.49	4724.58	4295.72
DHW (Electricity) (kWh)	456.90	452.52	440.09	469.33	452.52	448.50

Figure 4.28. Electricity breakdowns after applying high efficiency lighting.

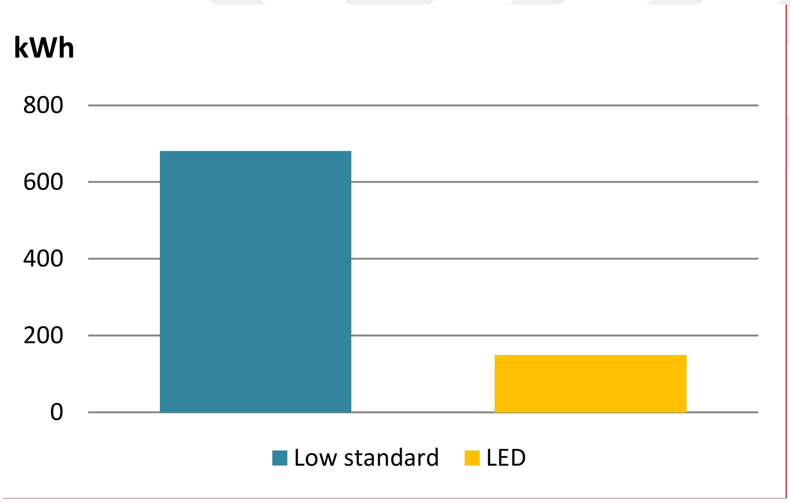


Figure 4.29. Average monthly electricity for lighting.

If we compare between all five Passive House principles applied to the Base-Case, Thermal insulation was found to be the most effective strategy on the energy (electricity) consumption rate if we compare the results in August, as it achieved 36.02% reduction compared to the conventional Base-Case (Figure 4.31)

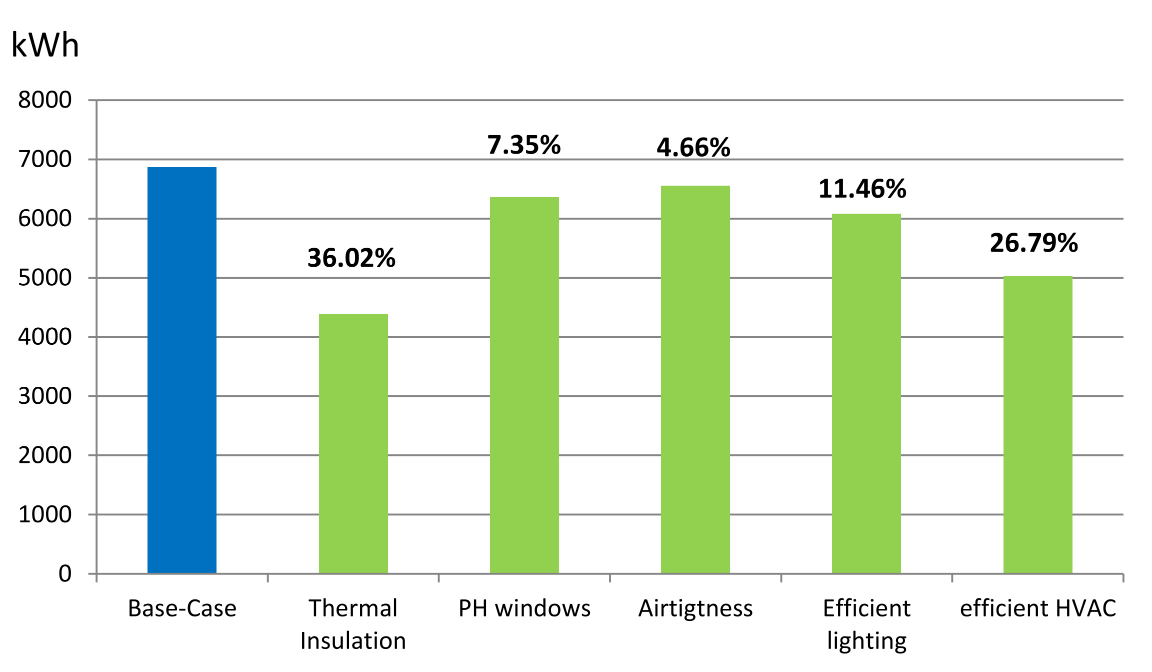


Figure 4.30. Energy consumption in August.

When we join all the principles applied before in one model which is refered to as the Passive House Case (Figure 4.32), this case achieved 63.04 % reduction in total annual electricity consumtion as it decresed from 59333.63 kWh in the Base-Case to 21927.95 kWh which means (74.33 kWh/m2/yr)(Figure 4.33). The major reduction was in the cooling load as it decreased from 4977.57 kWh in Augest to 1069.95 kWh, which means it was decreased by 78.50% in the hottest month (Figure 4.34, 4.35). The annual cooling load of the Base-case was 36989.98 kWh and it reached 8346.07 kWh (28.29 kWh/m2/yr), which means the annual reduction of cooling load has achieved 77.44% (Figure 4.36).

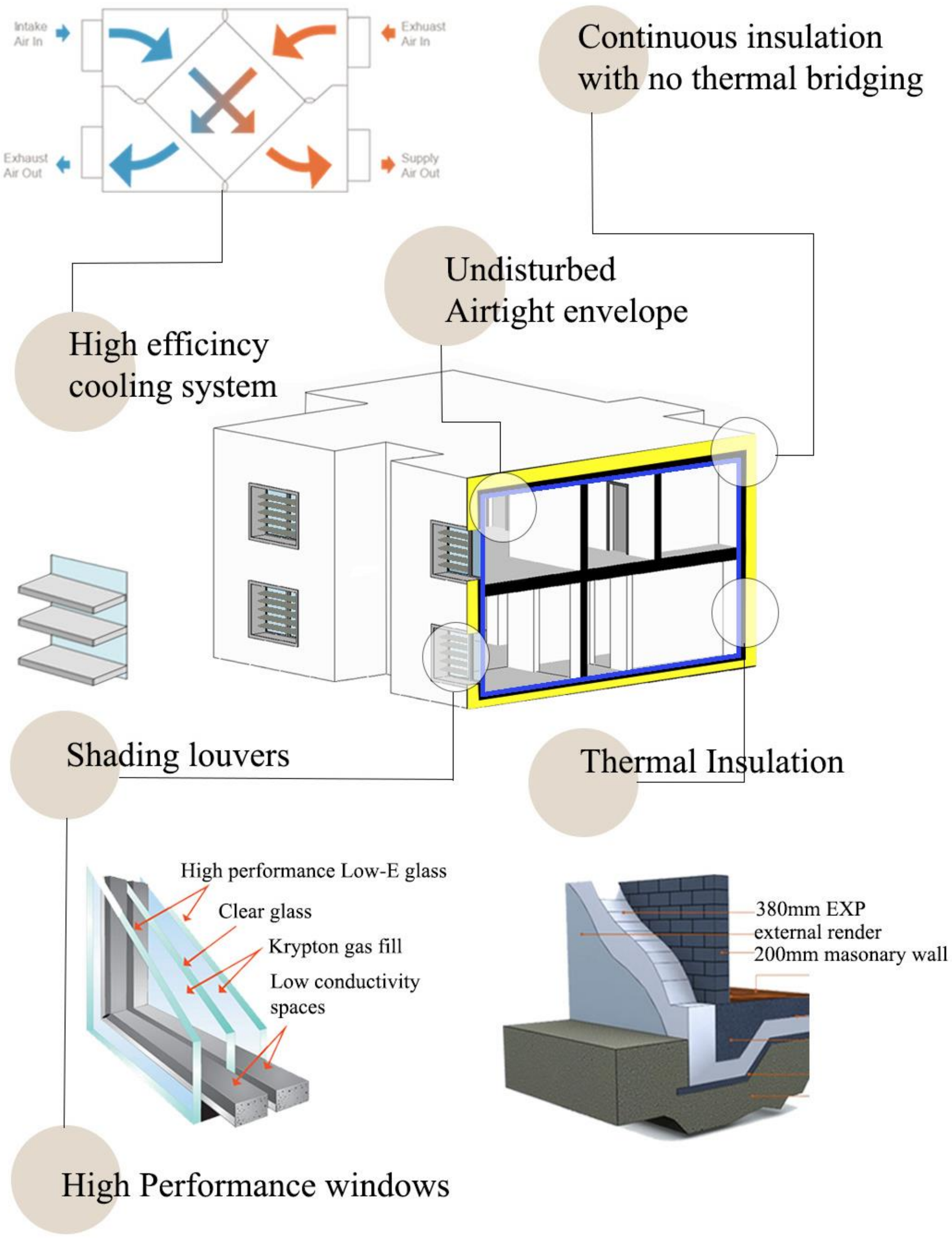


Figure 4.31. 3D section with applied Passive House features

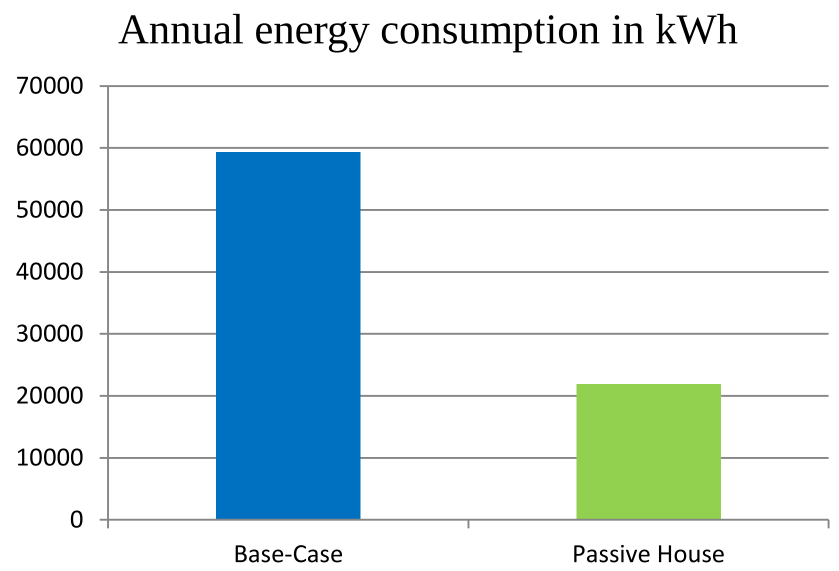
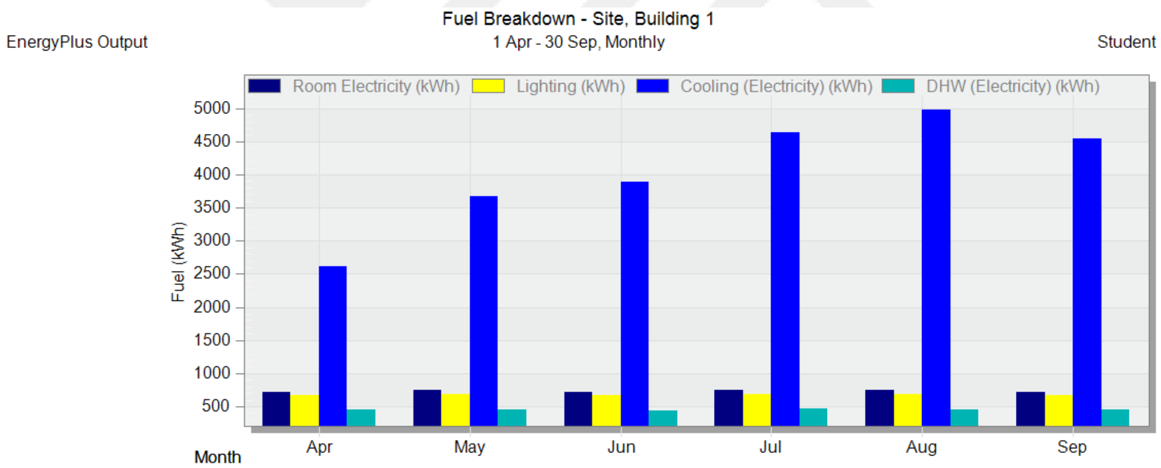
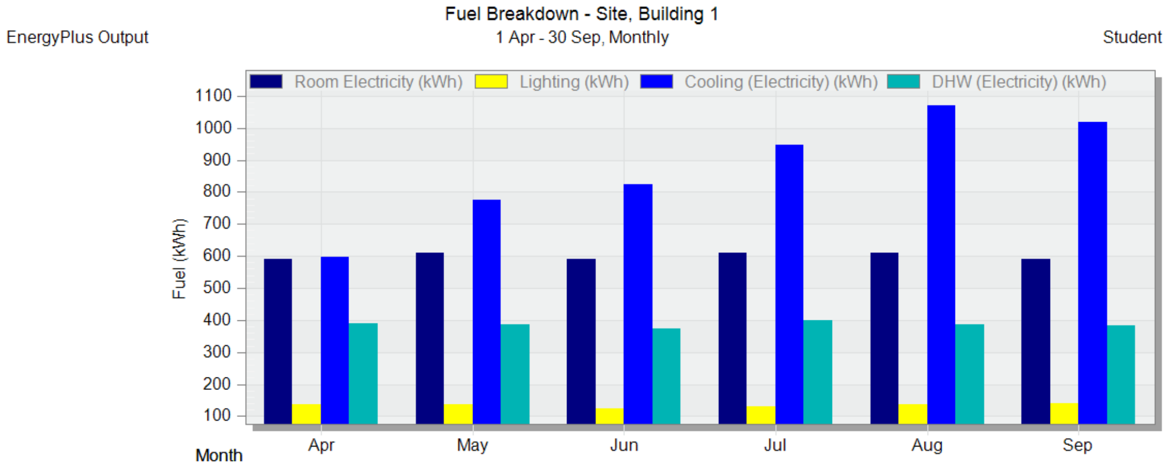


Figure 4.32. Annual energy consumption in kWh



Month	Apr	May	Jun	Jul	Aug	Sep
Room Electricity (kWh)	722.92	745.36	721.50	746.78	745.36	722.21
Lighting (kWh)	671.75	689.67	667.92	693.50	689.67	669.83
Cooling (Electricity) (kWh)	2617.72	3670.82	3888.97	4637.96	4978.15	4543.38
DHW (Electricity) (kWh)	456.90	452.52	440.09	469.33	452.52	448.50

Figure 4.33. Base-Case energy consumption breakdown in summer



Month	Apr	May	Jun	Jul	Aug	Sep
Room Electricity (kWh)	591.99	610.26	590.73	611.51	610.26	591.36
Lighting (kWh)	137.94	136.02	124.45	129.93	137.39	139.44
Cooling (Electricity) (kWh)	595.82	776.36	823.58	948.45	1069.95	1019.11
DHW (Electricity) (kWh)	389.31	384.99	374.48	399.81	384.99	381.89

Figure 4.34. Passive House Case energy consumption breakdown in summer.

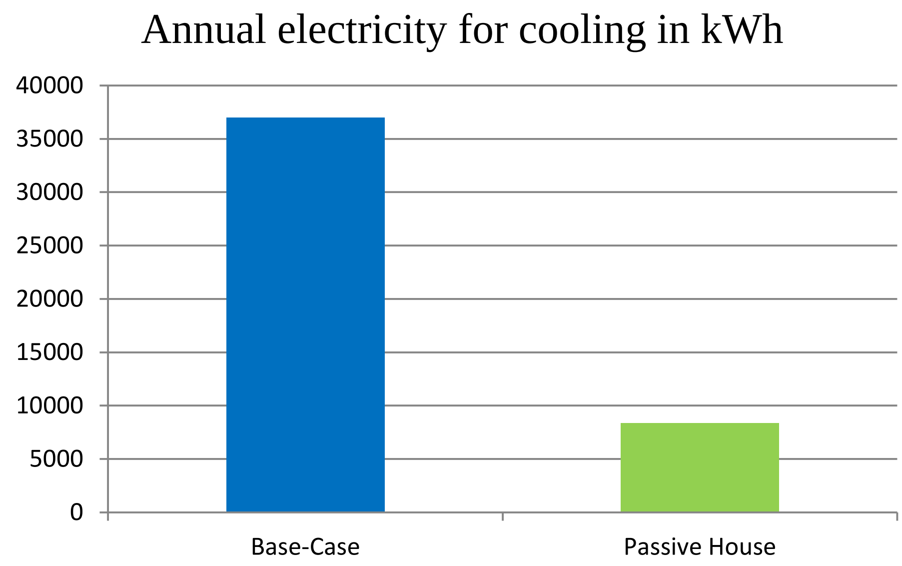


Figure 4.35. Annual electricity for cooling consumption in KWh.

According to (Passive House Institute, 2015) for a building to be considered a Passive House, it must meet the following criteria:

The building's annual space cooling/heating demand should not exceed 15 kWh per square meter or 10 W (peak demand) per square meter of usable living space. This represents more than 90% reduction in space heating and cooling energy use when compared to the consumption of a typical building.

The annual primary energy demand should not exceed 120 kWh per square meter of living space for all domestic applications (heating, cooling, hot water, domestic electricity).

When comparing the house's rsults after applying the Passive House principles, the annual cooling load reached 28.29 kWh/m2/yr which is still bigger than the criteria. However; the house's annual energy consumption achieved 74.33 kWh per squar meter based on DesignBuilder simulation, which means it has reached the passive house's criteria of not exceeding 120 kWh/m2/yr. Unfortunattly the house is still far behind reaching the net-zero energy through applying only the Passive House principles. While the Passive House standard has achieved net-zero energy in cold climates, it fails to reach net-zero energy in hot climates and even failed to reduce cooling loads by 90%.

4.4. Proposing Vernacular Solutions for Passive Cooling

As the main problem in hot climates is the cooling load, some other techniques for passive cooling were tested in order to try to minimize the cooling energy as much as possible, in order to try to come closer to the net-zero energy.

Natural ventilation is one of the major techniques known in vernacular architecture in hot climates, and since Jeddah has a mild winter it has the privilege to benefit most of natural ventilation in winter. Natural ventilation does not contradicts with the airtightness principle of the Passive House as airtightness prevents uncontrolled air leakage but a Passive House in general can still enjoys natural ventilation through controlled window opening.

The Air-shaft is one of the elements found in the vernacular architecture of Jeddah. An air-shaft was introduced into the house's design (Figure 4.37, 4.38) as well as an interpretation of *Mashrabiyya* to allow natural ventilation while reducing the solar gain and at the same time revive the identity of the local architecture. Results in terms of cooling electricity were investigated after applying the vernacular techniques. A section through the house (Figure. 4.38) shows how air is moving through the building by raising the circulation part in the middle of the house to be a ventilation corridor.

Figure 4.36. Ground floor + First floor plans after adding the Air Shaft (by author).

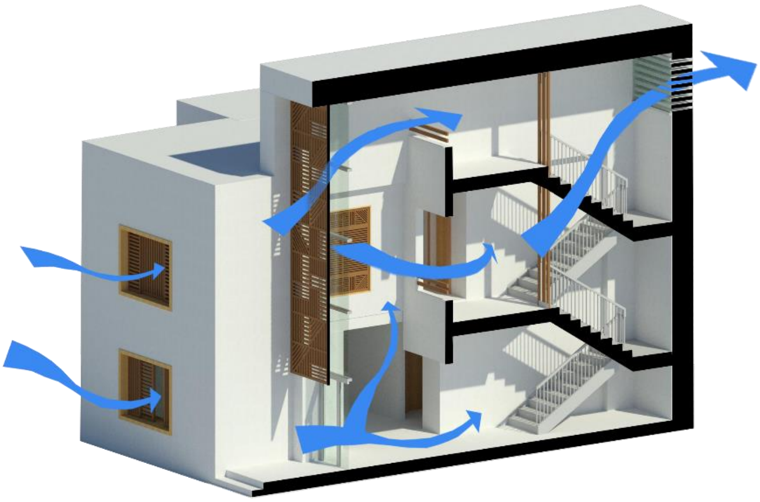


Figure 4.37. House section with Natural ventilation (by author).

Natural Ventilation option on DesignBuilder was turned on with mixed mode which is a hybrid approach that combines the use of natural ventilation through operable windows (either manually or automatically controlled), and mechanical systems for air conditioning. Mixed mode allows the use of natural ventilation whenever it's desirable, to minimize air conditioning load all year-round. Minimum outdoor dew point was set to 15°C and the maximum outdoor dew point was set to 30°C (DesignBuilder, 2009).

By doing the CFD analysis for the house (Figure 4.39) based on the wind data of Jeddah taken from Climate Consultant program, wind Direction all year round is found to be mainly from North and north-west with an average of 4 velocity and temperature between 24-38C (Figure 4.40). In winter (Dec, Jan, Feb) wind becomes more desirable with average temperature between 20-24C (Figure 4.41) which means that natural ventilation is more convenient in winter in Jeddah. That was proven by the simulation analysis in winter after engaging natural ventilation, where cooling loads have dropped from 285.54 kWh to 27.46 kWh in January (Figure 4.42). Summer simulation as well recorded reduction in cooling load changing from 1069.95 kWh to 845.34 kWh in August (Figure 4.43). This means that the annual electricity consumption was reduced from 21927.95 kWh to 19697.67 kWh which means it achieved 10.17% reduction (Figure 4.44). This reduction comes from reducting cooling loads as the total cooling load of the passive house was 8346.07 kWh and after applying vernacular techniqes for integerating natural ventelation the annual cooling loads reached 5139.32 kWh which means it was reduced by 38.42% which makes the total reduction in cooling loads compared to the Base-Case is 86.11% (Figure 4.45), as the annual cooling load of the Base-case was 36989.98 kWh. Annual CO2 emission has decreased form 35956.13 kg/yr from the base case to 11936.8 kg/yr, which means it was reduced by 66.80% (Figure 4.46).

Table 4.4 represents how much reduction in cooling loads and energy consumption occur when applying Passive House principles and vernacular techniques separately to the Base-Case.

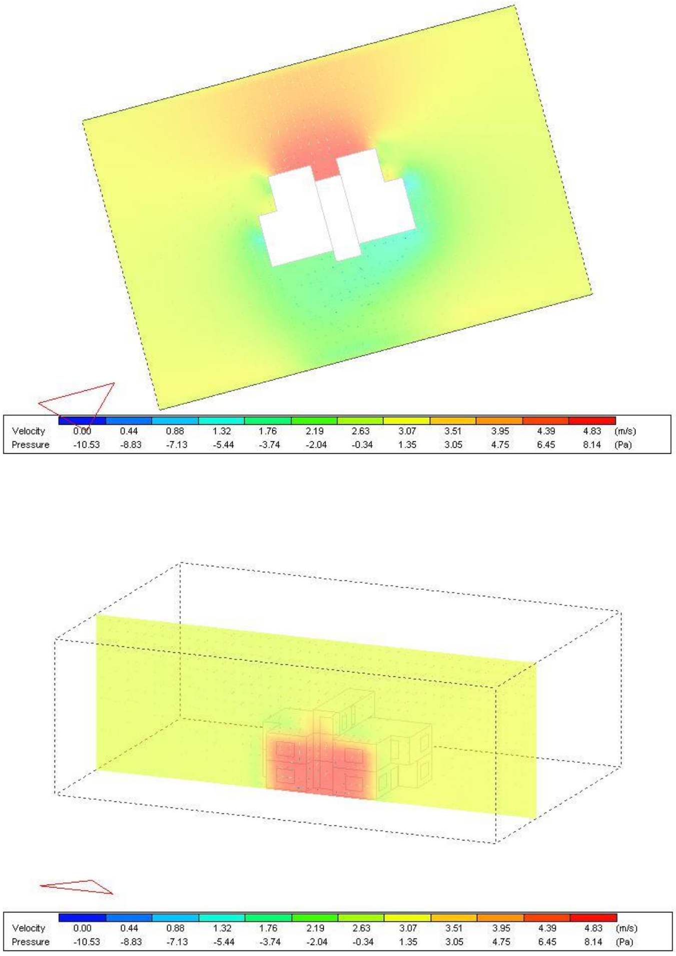


Figure 4.38. CFD analysis from Design Builder, Red represents the maximum velocity of wind.

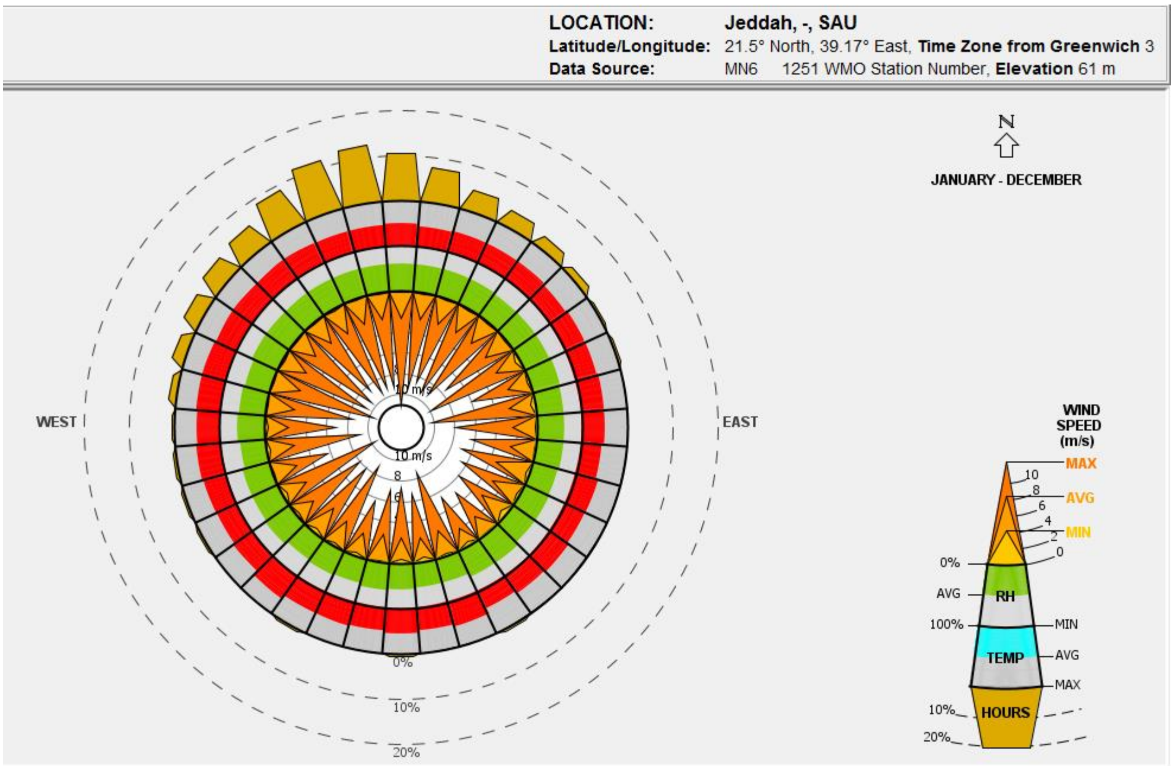


Figure 4.39. Wind Data for Jeddah all year (Climate Consultant)

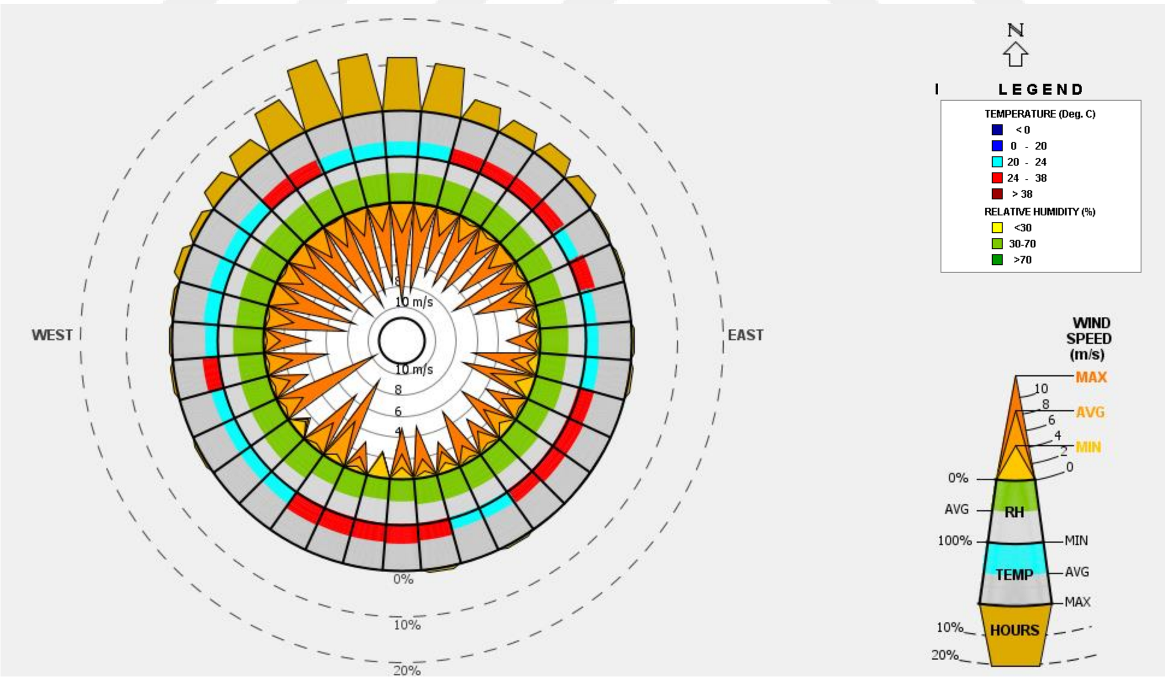


Figure 4.40. Wind Data for Jeddah in (Dec, Jan, Feb) (Climate Consultant)

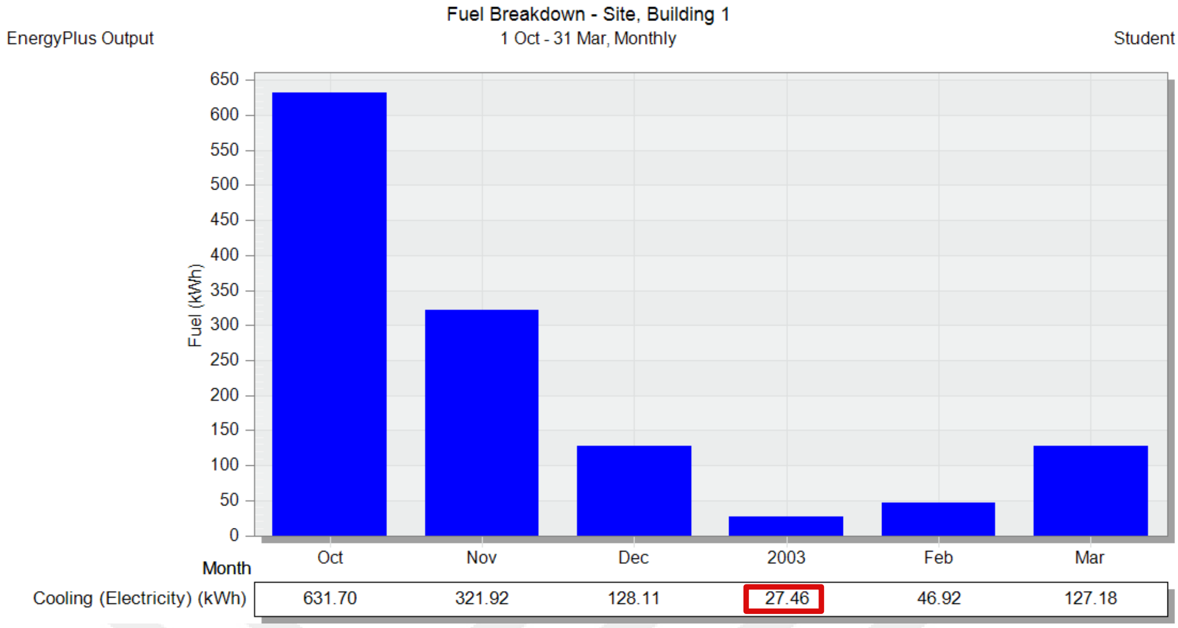


Figure 4.41. Cooling loads all winter after applying vernacular techniques for natural ventilation

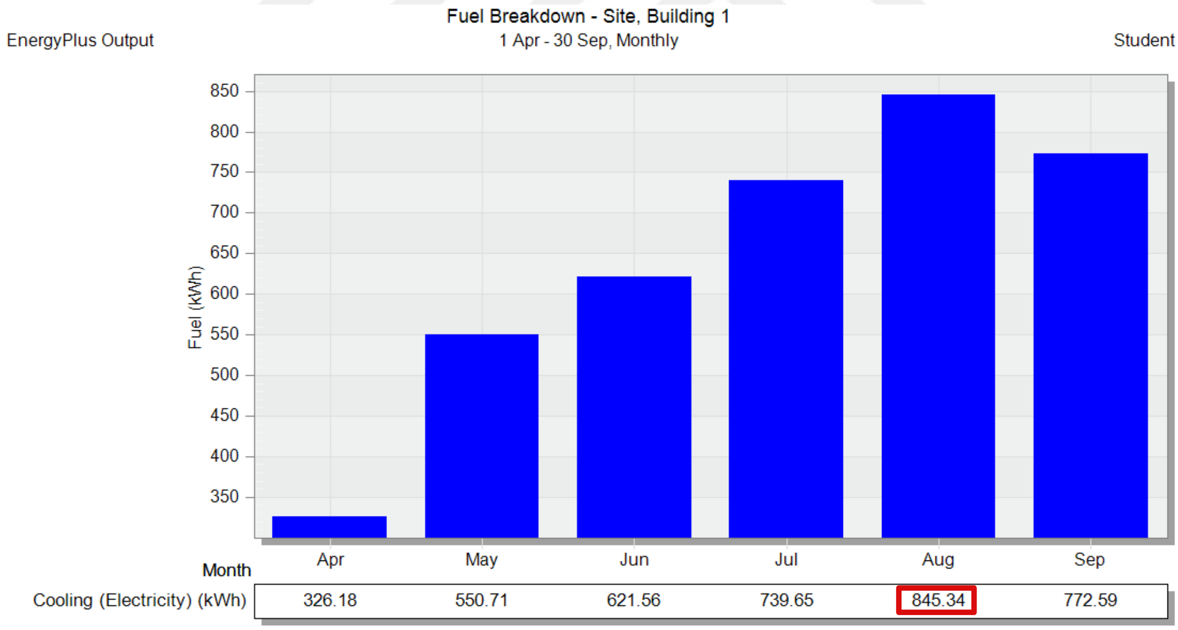


Figure 4.42. Cooling loads all summer after applying vernacular techniques for natural ventilation.

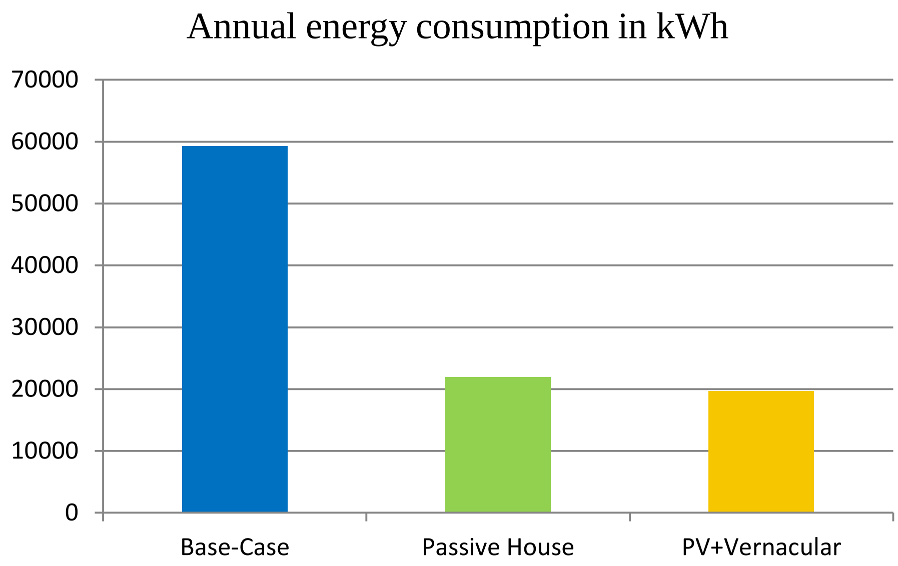


Figure 4.43. Comparison of annual energy consumption in kWh

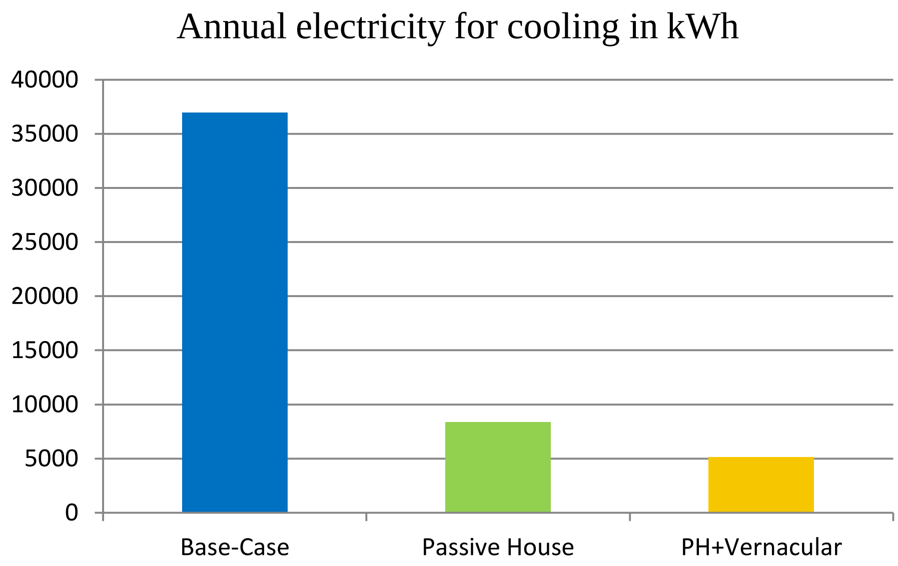


Figure 4.44. Comparison of annual Cooling consumption in kWh

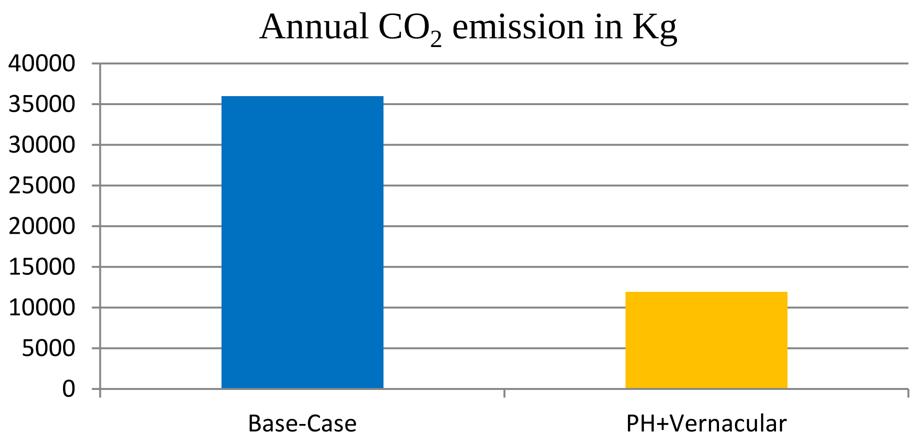


Figure 4.45. Comparison of annual CO_2 emission in kg

Table 4.4. Comparing energy reduction and cooling load after applying passive house principles and vernacular techniques to the Base-Case.

	Annual cooling load in kWh	Cooling reduction in %	Annual energy consumption in kWh	Annual energy reduction in %
Base-Case	36989.98	-	59333.63	-
Base Case+Passive House Principles	8346.07	77.44%	21927.95	63.04%
Base Case+Vernacular techniques: Natural ventilation	22802.08	38.35%	44671.45	24.71%
Combination of both[1]	5139.32	86.11%	19697.67	66.80%

[1] * The percentages are not the sum of both techniques as some elements are found in both such as window shading.

4.5. Solar Panels to Provide Renewable Energy

To calculate how many panels the house needs to cover its electricity consumption, average monthly consumption was determined as 1641.47 kWh per month, this value was divided by 30 days to get the electricity consumption in one day: 1641.47/30= 54.716 kWh per day.

The electricity consumption of one day must be divided by the number of sunshine hours in the area. The daily sunshine duration in Saudi Arabia differs between 9.4 and 7.4 h/day with an average of approximately 8.89 h/day (Rehman, 1998).

54.72/8.89= 6.155 kWh, this means to provide 1641.47 kWh per month in an area that gets 8.89 hours of direct sunlight per day it require a 6.155 kW solar energy system.

6.155 *1000= 6155 Watts (to convert the result to watts it was multiplied by 1000). Then it should be divided by the wattages of the solar panel.

Solar panels can produce from 45 Watts to 315 Watts. If a 300 watts solar panel was chosen then the 6150/300 = 20.527 so the house needs almost 21solar panels to cover its electricity consumption, this number may vary according to summer and winter; it can provide excess energy that can be stored in solar battery storage.

To check the calculation: a 300-watt (0.3kW) solar panel in full sunshine generates 300 watt of electricity in one hour. So if 300 watt was multiplied by the number of panels and by the hours of sunshine (300*20.527*8.89) = 54745.5 watts per day (54.75 kWh per day), multiplied by 30 days (54.75*30)= 1642.5 we got the average monthly consumption.

Solar panels average dimensions are approximately (165cm*99cm) =1.63 m for each panel which mean (21*1.63=34.23) the solar system will need 34.23 m2 area in the roof to cover almost 100% of the house's electricity consumption, as a result the house can be cut off-grid and can achieve the Zero-energy target.

Solar panels can be placed on a canopy over the roof (Figure 4.47) to reduce heat gain, as well as to provide shading area that can be used by the occupants for outdoor activities.

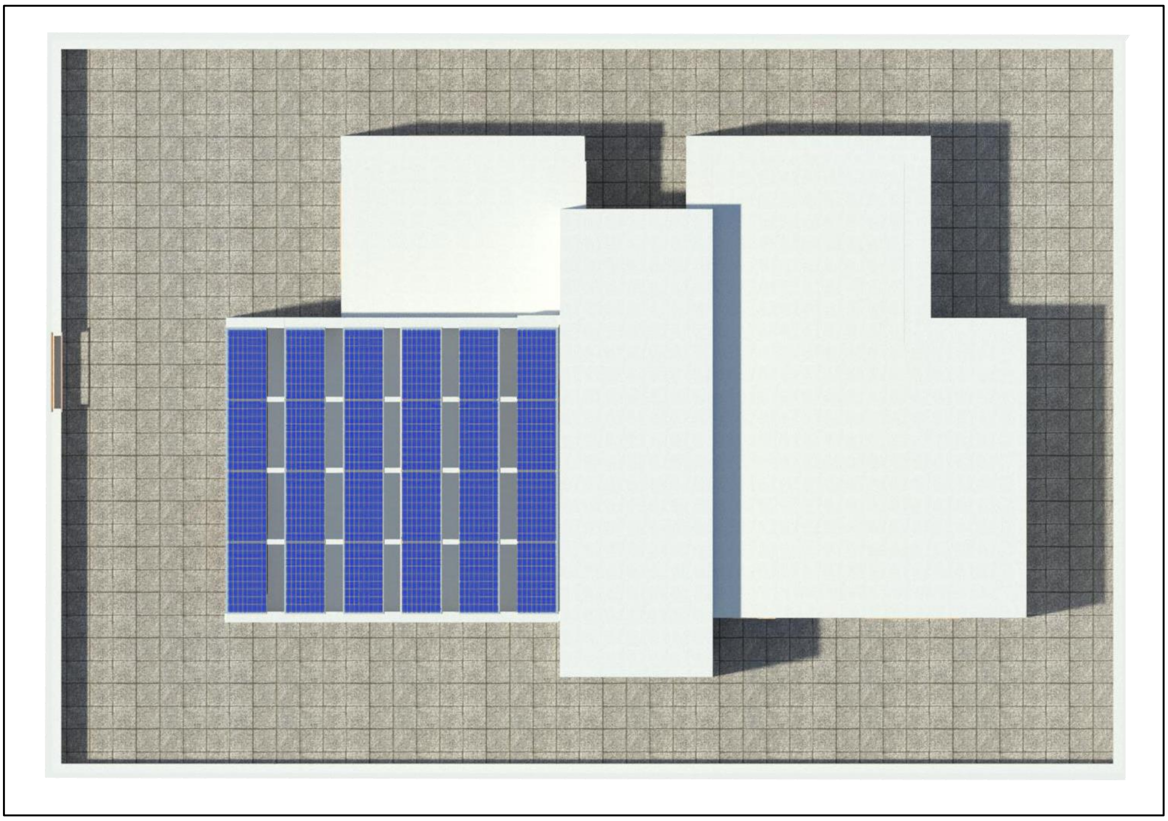


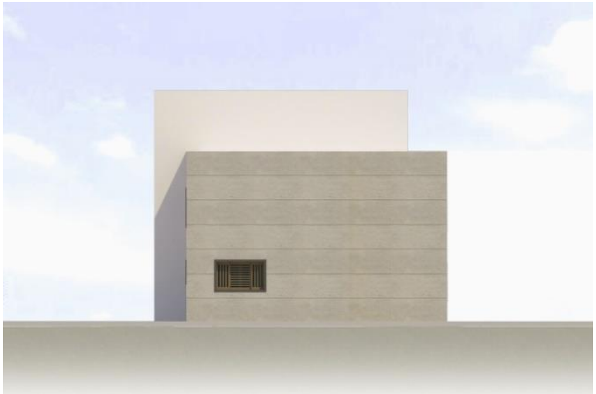
Figure 4.46. Net-Zero Energy House Site Plan (by author).

The net-zero energy house (Figure 4.48, 4.49) in Jeddah was achieved by merging the basic principles of the Passive house with passive solutions learned from the vernacular architecture for natural ventilation. This method achieved great cooling reduction yet the cooling load cannot be met by passive means only in this hot weather. Therefore, renewable energy was utilized through the use of on roof photovoltaic to supply the house with the needed energy. (Table 4.5) summarizes the construction and systems used in the conventional houses in Saudi Arabia (Base-Case) and the proposed net-zero energy house.

Table 4.5. Comparison between construction and systems of Base-Case and proposed Net-zero energy house

		Base-Case	Proposed Net-zero energy
Construction	Exterior Wall	200 mm concrete block	200 mm concrete block 380 mm extruded polystyrene layer
		U- Value (W/m2-K) = 2.817	U-Value = 0.085
	Roof	250 mm reinforced concrete 20 mm humidity insulation 15 mm polystyrene layer	200 mm cast concrete 20 mm humidity insulation 380 mm polystyrene layer
		U- Value = 0.453	U- Value = 0.087
	Glazing	Single glazed 6 mm clear glass	Triple glazed windows 6mm clear glass with double 12mm cavity filled with Krypton gas
		U- Value = 5.778	U- Value = 0.793
	Windows frame	Aluminium	UPVC
		U-Value= 5.881	U-Value= 3.476
	Shading	None	Mashrabiyya
	Infiltration	0.7 ac/h	0.5 ac/h
HVAC		Split system no fresh air	Variable refrigerant flow (VRF) with humidifier
Lighting		Low efficiency lighting bulbs	LED with lighting control
Natural ventilation		None	integrated
Solar Panels		None	22 panels

West Elevation



East Elevation

North Elevation

South Elevation

Figure 4.47. Net-Zero energy House elevations

Figure 4.48. Net-Zero energy House rendered 3D view

5. CONCLUSION AND FUTURE REMARKS

This study aims to reduce the massive energy consumption of the residential building sector in Saudi Arabia, which is responsible for environmental and economic complications due to the dependence on oil as the sole source of energy. As cooling loads are the main contributors to the high energy consumptions, the first step was to develop passive ways to reduce the extreme dependence on air-conditioning. Passive House standard is found to be the most modern effective standard applied worldwide today regarding energy efficiency in architecture. Therefore, this study has examined the applicability of this standard under the harsh hot climate of Saudi Arabia particularly in Jeddah city where the cooling load is all year round. In fact, by applying the Passive House standard on a contemporary single family house in Jeddah modelled using DesignBuilder, the house annual cooling demand was reduced by 77.44%. Yet in hot climates the Passive House standards alone failed to approach the net-zero energy as was the case in cold climates. Furthermore, other solutions that can help reduce the cooling demand were investigated. The concept of the Air-shaft in the vernacular architecture was introduced to the house’s design in order to take advantage of natural ventilation. Therefore, energy simulation results have recorded cooling loads reduction mainly in winter months, and the annual reduction in cooling load achieved 86.11% compared to the conventional house. After applying passive techniques to reduce the energy consumption as much as possible, from 201.12 kWh/m2/yr to 66.77 kWh/m2/yr which meant 66.80% of the annual electricity consumption was reduced, the second step was to cover up the remaining 33.2% of the energy demand by a renewable source of energy. Solar energy is the most beneficial in such a climate. As a result, 21 (300 watts) solar panels on the roof could achieve the average monthly energy consumption (1641.47 kWh) if it was backed up by using battery storage.

As a result this study’s hypothesis was proven, that the net-zero energy house is possible to be achieved by the integration of passive methods (PH standards and vernacular techniques) if supported by renewable energy. This study has answered the following research questions:

- How can the net-zero energy residential buildings in Jeddah city be achieved?

The net-zero energy houses in Jeddah city can be achieved by lowering the energy consumption passively through adapting the PH standard with techniques learnt from the vernacular architecture regarding natural ventilation.

- Will the Passive House standards prove its efficiency under Jeddah's climate?

It is seen that the PH standards can work under Jeddah's climate; however the results are lower than what the standards can achieve in colder climates in terms of lowering the heating demand. Techniques regarding natural ventilation or passive cooling must be considered in hot climates in order to reduce the cooling demand.

- How can we learn from the vernacular housing in the region? What kind of vernacular passive cooling techniques can be applied to modern houses together with passive house standards?

Building's orientation, placement of functions and openings, Mashrabiyya and air-shaft, are all aspects learnt from the vernacular house which contributes to ensuring the maximum benefit of natural ventilation. These features proved their impact on lowering the cooling loads when integrated in the modern house and even along with the Passive House.

Although this study has proposed the possibility of achieving a net-zero energy house, that does not mean that all houses can be changed at one time or that all residents can afford the cost of constructing a net-zero energy house even if the payback is much more in long term regarding electricity bells. However, Saudi Arabia's 2030 Vision is targeting the improvement and expansion of the renewable energy industry by initiating power plants that can be connected to the residential electricity grid. This can save the solar panel expenses for the occupants; therefore, the house's design and construction must reduce heat gains and encourage natural ventilation in order to reduce the electricity consumption. This can be accomplished by setting strict building regulations by the government, and by raising the awareness regarding the potential long-term benefits in the society which is now going to be more open to solutions that will lower their electricity bells since electricity prices are not as low as before in Saudi Arabia.

Among Passive House basic principles, thermal insulation for walls and roof was found to be the most effective principle on reducing heat gains which are responsible for the high cooling loads. And so, insulation can be applied even to existing buildings and work effectively in reducing their electricity consumption.

This study for sure has its limitations; the results cannot be generalized to all cities in Saudi Arabia as there're climate variations between the different regions of the kingdom especially that Jeddah has no cold winter and no heating demand. Also it should be noted that the exact design cannot be replicated everywhere because building layout and openings must be adjusted according to each site.

Recommendations for future studies:

- A detailed analysis of natural ventilation circulation inside the building can be studied using another software tool in conjunction with design builder.

- Technologies can be introduced along with the vernacular passive techniques such as the use of mechanical fans in the Air-shaft, humidity and dust control, automatic control for openings and for *mashrabiyya.*

- This study has examined only the detached villa type of residential buildings, other types can be investigated such as apartments or residential complexes.

- Net-zero energy buildings in Saudi Arabia can be studied from the economical point of view which was not included in this study, to define how much the construction and material will cost, and how it's going to be beneficial in the long term.

- Other measures of sustainability could be studied, such as reducing water consumptions in residential buildings via using gray water systems.

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