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SOLAR PV COUPLED WITH PASSIVE AND ACTIVE EFFICIENT COOLING SYSTEMS FOR A SMART AFRICAN SOLAR HOUSE

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Dedication

I dedicate this work to my family and friends. A special gratitude goes to my loving mother for always believing in me, for her continuous support and strong words of encouragement.

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Biographical Sketch

Francis Sadeu obtained a bachelor's in Petroleum Engineering from the Catholic University of Cameroon in 2015. Prior to joining PAUWES, he spent two years working in the Oil and Gas sector and also freelancing as bilingual translator. He is very passionate of energy efficiency in Buildings and Industries and the integration of renewable energy technologies. While at PAUWES, he attended several trainings abroad in the field of energy efficiency, energy system modelling, green energy management, cutting edge solar technologies. He also served in the leadership position of two main clubs at PAUWES, working to establish and build networks between students, professionals and young entrepreneurs. Besides that, he is currently volunteering as project manager in a team of more than 30 members from all over Africa, where he manages and coordinates the overall design, construction and operation of an energy efficient solar house in the Solar Decathlon Africa Competition.

See most recent CV in appendix

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Abbreviations and Acronyms

PV: photovoltaic
DC: Direct current
AC: Alternating current
A/C: Air conditioning
HVAC: Heating ventilation and Air conditioning
HFCs: Hydrofluorocarbons
SDGs: Sustainable Development Goals
SDA: Solar Decathlon Africa
IEA: International Energy Agency
OECD: The Organisation for Economic Co-operation and Development
IECC: International Energy Conservation Code
ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEES: Building energy efficiency standards
ECBC: Energy conservation building code
CDDs: cooling degree days
MEPS: minimum energy performance standards
PCMs: phase change materials
COP: coefficient of performance
ZT: Figure of merit
TE: Thermoelectric
TEC: Thermoelectric cooling
TEM: Thermoelectric materials
TEACs: Thermoelectric air conditioners
WWR: window-to-wall ratio
WFR: wall-to-floor ratio
CLTD: cooling load temperature difference
SCL: solar cooling load
CLF: cooling load factor
CFC: chlorofluorocarbons
HCFC: hydro chlorofluorocarbons)
GWP: global warming potential
ρ: electrical resistivity
α: Seebeck coefficient
k: thermal conductivity
Imax: Maximum current
Vmax: Maximum voltage
Voc: Open circuit voltage
Isc: Short circuit current
Eff_module: Efficiency of module
Vmaxmppinv: Maximum voltage of inverter
Vminmppinv: Minimum voltage of inverter
Imaxmppinv: Maximum current of inverter
Iminmppinv: Minimum current of inverter
Mppt: Maximum power point tracker
Ntot_mod: Total number of photovoltaic modules

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ABSTRACT

Africa is experiencing more and more serious challenges of energy crisis, ozone depletion and global warming. Space cooling is rapidly growing in both residential and commercial buildings accounting for about 18.5% of the total electricity used and the global energy consumption for cooling in buildings is expected to increase up to 35% in 2050, raising the CO_2 emissions due to the construction of new power plants. In Africa, more than 600 million people live without access to electricity and the poor economic development poses a serious hindrance to access to cooling. However, Africa is endowed with a huge potential for solar cooling due to the near coincidence of peak cooling loads with the available solar power. The design of a combined passive and active solar cooling solution was done in the context of Solar Decathlon Africa competition to provide a cost effective and energy efficient cooling solution for buildings in Africa. An of the energy analysis of the Jua house (solar house) was performed using DesignBuilder Software to evaluate the performance of proposed passive cooling techniques. The results revealed a 20% reduction from 2195kWh to 1758kWh in cooling energy per month. The optimal design of a compression cooling system with COP of 3.88 and electrical power requirement of 3.14kW and that of a Peltier cooling system with COP of 0.36 and electrical power consumption of 33.61kW, shows that compression system is the most energy efficient option for electrical cooling in buildings. The results of Solar PV sizing shows that a total of 272 modules of 250W PV panels are required for Peltier system compared to 30 modules of 250W PV panels for vapor compression system. Finally, A cost comparative study proves that air conditioning systems is cheaper option with total system cost of $13330 compared to $67120 for Peltier cooling system. However, rigorous actions from public authority need to be taken to curb the potentially huge growth in cooling demand and promote energy efficiency in buildings in Africa

Keywords: Solar Decathlon Africa, Energy Efficiency, Passive Cooling, compression cooling, Peltier cooling

CHAPTER 1. INTRODUCTION

The world is experiencing more and more serious challenges of energy crisis, ozone depletion and global warming. Space cooling is rapidly growing in both residential and commercial buildings. The energy consumption in buildings for space cooling worldwide has more than tripled between 1990 and 2016, accounting for about 18.5% of the total electricity used in buildings[1]. Heating ventilation and air conditioning (HVAC) contribute to 50 – 70% of energy consumed in buildings[2]. The global energy consumption for cooling in buildings is expected to increase up to 35% in 2050 and 61% in 2100, of the total heating and cooling needs in buildings[3]. Higher cooling demand in buildings is associated with significant increase in electricity production which may oblige construction of new power plants, thereby increasing the dependence on fossil fuels and climate change effects.

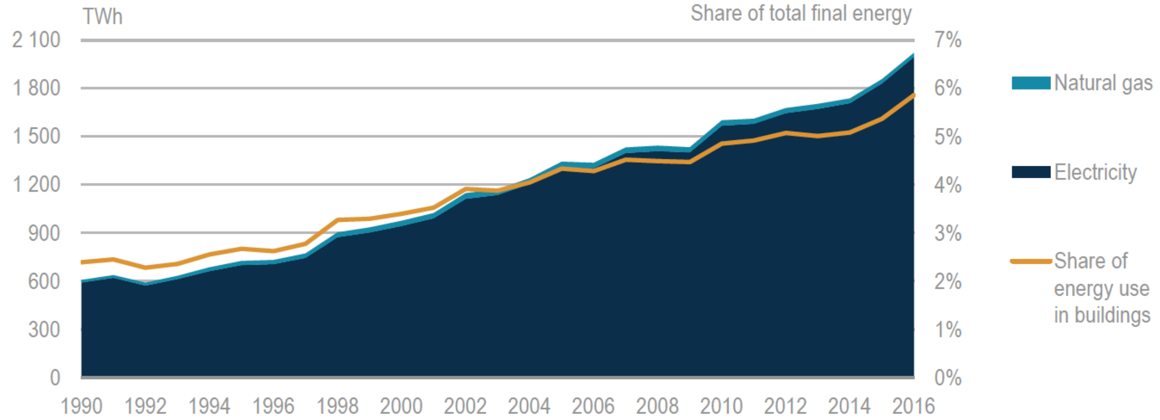


Figure 1: World energy consumption for space cooling in buildings (source: IEA 2016)

Space cooling technologies such as the conventional air conditioners which are largely used in residential and commercial applications, use refrigerants which can have impact on climate change. Also, Hydrofluorocarbons (HFCs) refrigerants currently used in air conditioning can contribute to global warming if leaked into the atmosphere. Therefore, the Kigali Amendment was introduced in 2016 to gradually phase out the production and use of HFCs in the world[4]. Moreover, CO_2 emissions produced from space cooling in buildings has doubled between 1990 and 2016 mainly due to burning of fossil fuel in power plants for which USA and China contribute about 55% of global cooling-related CO_2 emissions[5].

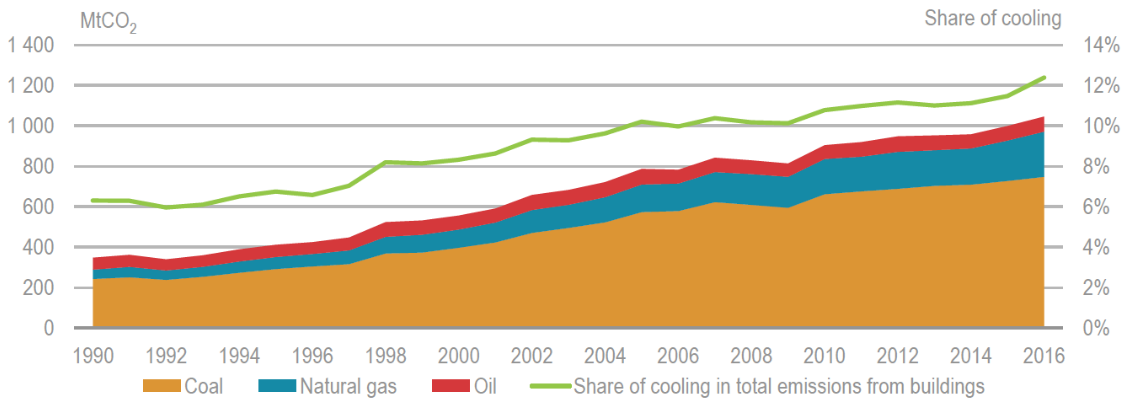


Figure 2: World CO2 emissions related with space cooling energy use by source (Source: WEO-2015 Special Report)

It is estimated that over 1.1 billion people globally face immediate risks from lack of access to cooling as global temperatures continue to rise. This includes 470 million people living in rural areas where grid electricity is largely unavailable, and 630 million people living in crowded cities where electricity is unavailable, unreliable or unaffordable [6]. Heatwaves already kill an estimated 12,000 people every year and the World Health Organization forecasts that deaths from more extreme heatwaves could grow to 255,000 annually by 2050 if no adaptation measures are taken [7].

Access to electricity in Africa is relatively low 44.6% in 2017 [8] which represents more than 600 million people without access to electricity and there are several areas where grid electricity is not available at the moment and is unlikely to be available in the next few decades due to the huge financial costs involved. These areas mainly include villages, rural areas and remote locations. Similarly, cooling demand is rapidly emerging in Africa and other developing countries, which signifies that building design and energy efficiency measures need to be carefully considered to meet the increasing cooling loads at minimum cost and reduced environmental effects.

The increasing effect of energy crisis and global warming have become a more and more serious hindrance to the social development in the Africa. Since buildings contribute to a significant share of the world energy consumption and carbon emissions, it is important and urgent to decrease energy consumption in buildings. This can be done by implementing energy efficiency measures and by integrating the use of renewable energy technologies into buildings. Increasing the efficiency of cooling equipment will also help reduce the impact of cooling on the energy use in buildings by more than 45%[9]. The combination of other measures such as building envelop improvements can lead to much greater energy savings.

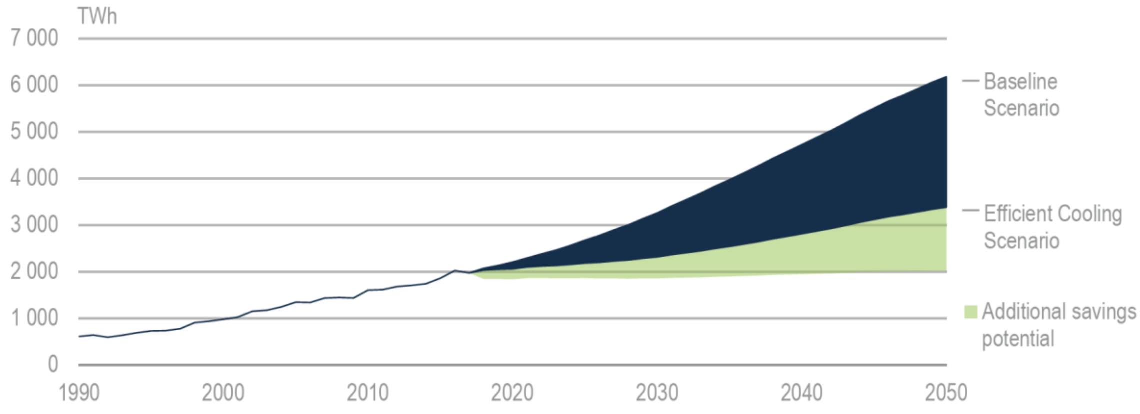


Figure 3: Contribution of energy-efficient Air conditioners to world energy savings (source: IEA report on cooling, 2017)

Solar energy is a particularly interesting source of energy for space cooling applications due to the near coincidence of peak cooling loads with the available solar power. This represents a good alternative to remove stress on grid electricity and also contribute to improve access to cooling in off grid areas. Africa is endowed with a huge potential for solar cooling, which provides an economically attractive source of cooling with zero or very low emissions and help to alleviate peak power load associated with cooling (see figure 4).

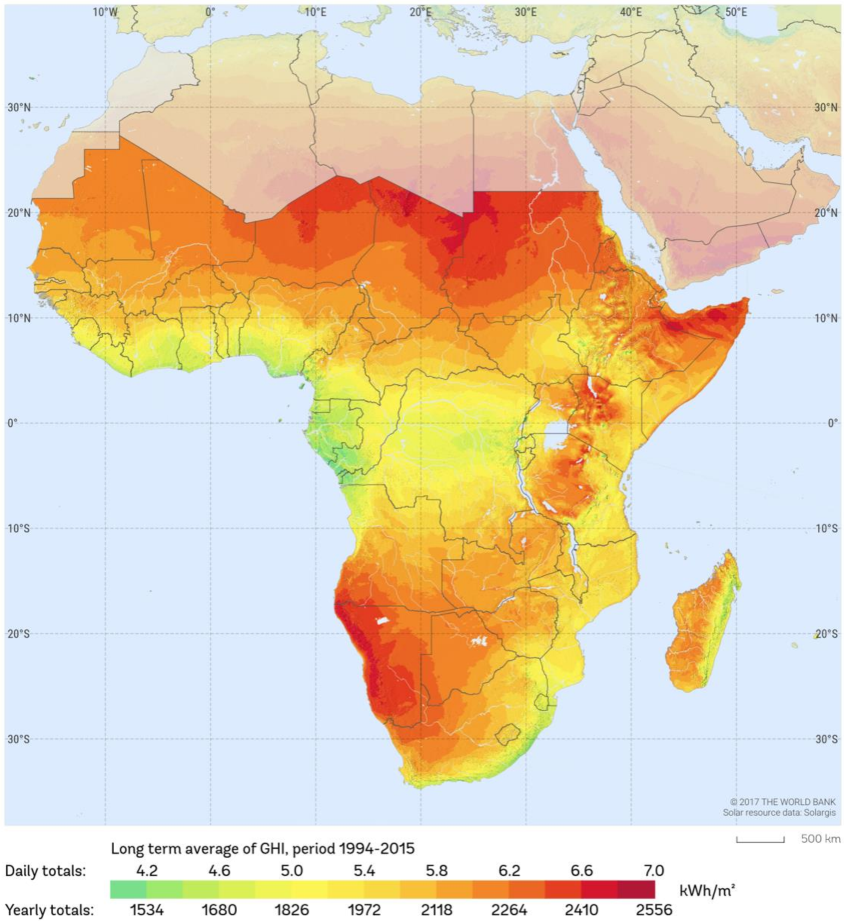
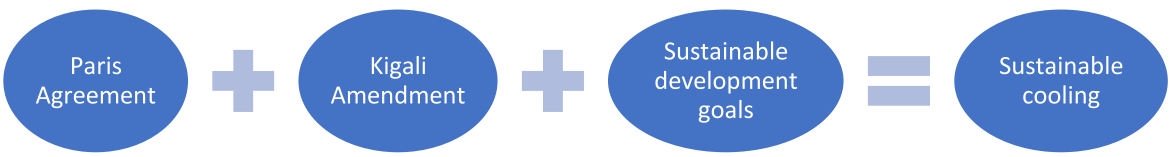


Figure 4: Map of global horizontal irradiation of sub Saharan Africa[10]

With this, it is necessary and urgent to develop sustainable cooling solutions which can be considered as the intersection of three historic international agreements reached in the past two years: Sustainable Development Goals (SDGs) agenda, international Paris Agreement and Montreal Protocol's Kigali Amendment, of which are the following objectives: -

- Sustainable Development Goals (SDGs) agenda: provide a pathway for achieving established targets on health, sustainable energy, among others, by 2030[11].
- International Paris Agreement: call for building resilience and decarbonizing our economy to stabilize global warming well below 2°C[12].
- Montreal Protocol's Kigali Amendment: phase down high global warming refrigerants, known as hydrofluorocarbons (HFCs), by 80 percent in the next 30 years[13].



This research work is carried out in the contest of the Solar Decathlon Africa competition (SDA) which is an international competition which challenges collegiate teams to design, build and operate grid-connected, attractive and net-zero-energy houses during an eighteen-month period. Solar Decathlon AFRICA is organized by the Moroccan Research Institute for Solar Energy and New Energies (IRESEN) and MOHAMMED VI POLYTECHNIC UNIVERSITY (UM6P), and under the aegis of the Moroccan Ministry of Energy, Mines, and Sustainable Development and the support of U.S. Department of Energy[14]. The purpose of this competition is to allow the understanding and raising the awareness of sustainable construction, and to shed the light on the importance of passive and Active solar design strategies combined to put the world in a sustained pathway for decarbonized energy systems and clean environment without compromising the high-standard of living for households.

Inspired by the concept of recycling, the JUA JAMII team is proposing an energy efficient and self-sustainable African solar house called Jua house, which integrate different technologies rekindling its unique feature of smart and traditional house.

In this competition, each house will be tested under 10 different contests: Architecture, Engineering and construction, Market appeal, communication and social awareness, sustainability, innovation, appliances, home life and entertainment, health and comfort, electrical energy balance.

However, this work is aimed at designing and implementing a cost effective and energy efficient cooling system combining both passive and active techniques and which will be entirely powered by a building integrated solar PV system. This will provide affordable and comfortable housing indoor conditions adapted to the needs of African Community.

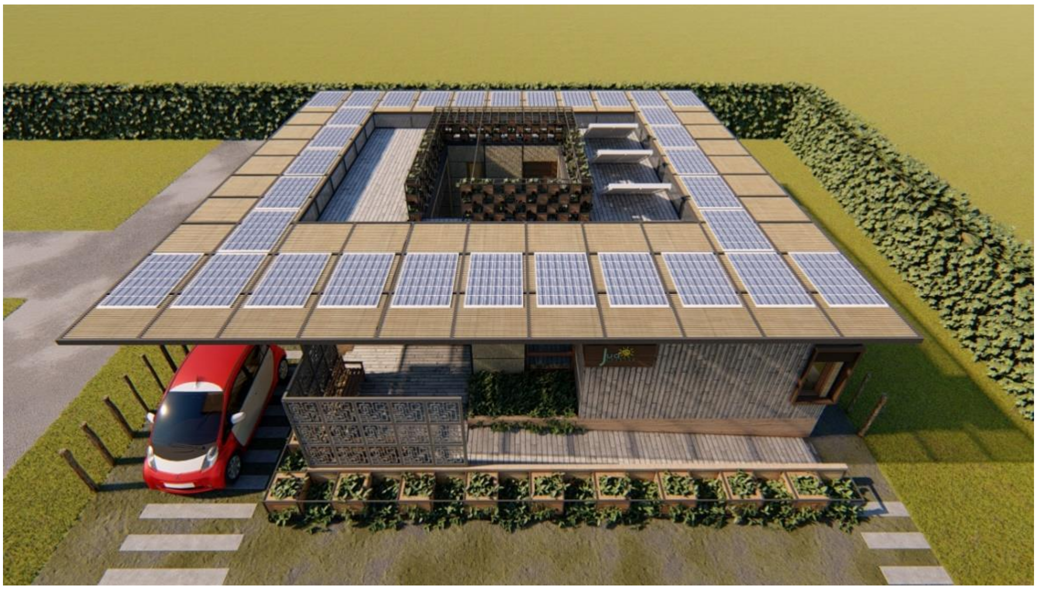


Figure 5: Picture of the Jua house

In addition, this research work addresses some of the main contests in the competition: Architecture, Engineering and Construction, Market Appeal, sustainability, Health and Comfort, Electrical energy balance and innovation.

- Architecture:

The house is inspired by the northern African Architecture which reflects the architecture of the host region of the competition. The objective is to use energy efficient building envelop solutions and local materials that will integrate and improves on the architecture of the house

- Engineering and Construction:

The building envelope of the house improves the energy performance of the house and integrates an energy efficient cooling system powered by a building integrated solar PV system.

- Market Appeal:

The use of energy efficient active and passive cooling technologies provides safe, functional, convenient, comfortable and affordable place to live in.

- Sustainability:

The use of passive technologies, recycle materials and the modularity of the house help reduce the energy consumption and provide optimal performance. This promotes sustainable construction and scaling up of the jua house.

- Innovation:

The jua house is a smart traditional and energy efficient house that integrates different systems adapted to the needs of African community and contributes in providing solutions to three thematic areas of development in Africa: Water, Energy and Food nexus.

- Electrical energy balance:

The house is powered by 9kWp integrated PV system and the implementation of cost effective and energy efficient cooling system improves the energy performance of the house and helps achieve self- sufficiency in terms of energy consumption.

- Health and Comfort

The integration of passive and active cooling solutions in the house helps control the temperature and humidity level in the house and ensure best indoor comfort.

According to the International Energy Agency (IEA), the two key cooling opportunities mainly relies on energy efficiency in building envelopes and in cooling technologies[15]. This involves two principal technologies: active and passive cooling.
Passive cooling mainly involves the use of natural processes for heating or cooling to achieve balance interior condition such the use of shading, solar orientation, insulation and other building designs [16]. While active technologies mainly involve use of energy to provide cooling effect of which the most advanced is air conditioning systems to provide indoor thermal comfort, and improve air quality [17].

CHAPTER 2: LITERATURE REVIEW

This chapter presents an overview of energy efficiency in buildings, the global approach and some actions taken in Africa. Then we will look at the main forms of cooling in buildings and the energy saving opportunities and the integration of solar PV technology in buildings for cooling applications.

2.1. Energy Efficiency in Buildings

Energy is used in buildings for various needs: heating and cooling, lighting, ventilation, cooking, hot water supply etc. Subdividing the energy consumption can be particularly difficult due to the use of different fuel types and same metering system which is common in most buildings. However, residential and commercial buildings contributed to around 49% of world electricity consumption in 2016 (see Figure 1) [18]. On the other hand, fossil fuels contributed to up to 65% of the world electricity production in 2016 (see figure 2)[18]. This clearly shows that reducing energy consumption in buildings can greatly reduce dependency on grid electricity, which is mainly driven by fossil fuels.

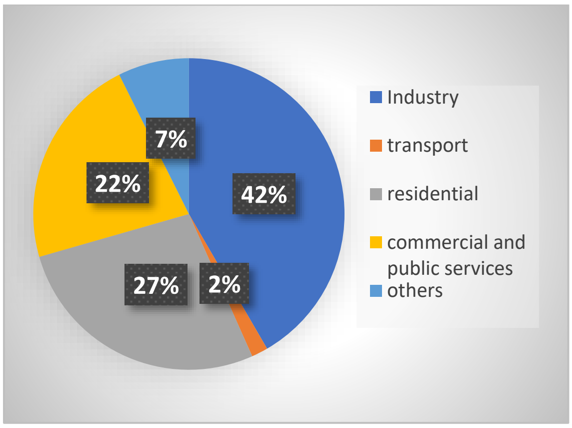


Figure 6: World Electricity Final consumption in 2016 (Source: IEA Electricity Statistics of 2016)

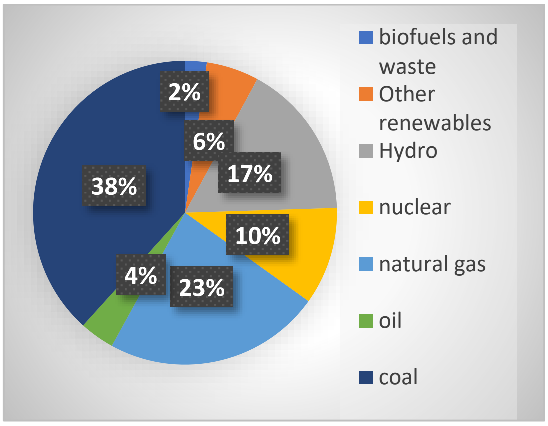


Figure 7: World Electricity generation by source in 2016 (Source: IEA Electricity Statistics of 2016)

For most countries across the world, energy efficiency requirements in buildings are usually addressed in building codes and standards, especially in OECD countries. There are many building codes in the world and different standards cover different regions and different types of buildings. This mainly include residential or simple buildings and commercial buildings. For the past decades, some collaborative efforts have been made to develop international energy efficiency standards. Examples include: IECC 2004 and ASHRAE 2014 US based standards and the European Energy Performance in Building Directive (EPBD)[19].
A study done by Wang et al. [20] shows that building energy efficiency standards (BEES) is one of the most effective policies to reduce energy consumption in buildings in China. It shows that the adoption of these standards could reduce the heating and cooling electricity use by 41% and 38% for low level and high-level standards respectively. Yu et al. [21] also studied the effect of energy codes for both residential and commercial buildings in India and using a global

change assessment model, it shows that the implementation of the Energy conservation building code (ECBC) could improve energy efficiency measures and results to additional 10% savings in electricity use. The introduction of energy efficiency measures in Europe such the Green Building Program proves that the use of main technological measures related to the building envelop, appliances and systems can play a major role in exploiting the massive energy savings benefits in reducing the energy consumption of non-residential buildings[22].

Iwaro and Mwasha [23] analyzed the status of building energy regulations in 60 developing countries and 25 countries were identified without any energy standards. Despite, the study revealed an increasing government involvement in the development and implementation of energy standards. Also, some barriers such as lack of adequate finances, information, production techniques were identified and solutions were proposed to promote the use of building energy regulations for energy efficiency in developing countries.

Moreover, a study done to evaluate the energy efficiency performance of 22 African countries revealed that South Africa, Zimbabwe and Zambia are the best performing economies (with mean energy efficiency scores of 88%, 73%, and 66%, respectively) followed by Algeria and Botswana. The rest of the countries had low performance scores, proving that there is significant need for improving energy efficiency in Africa [24].

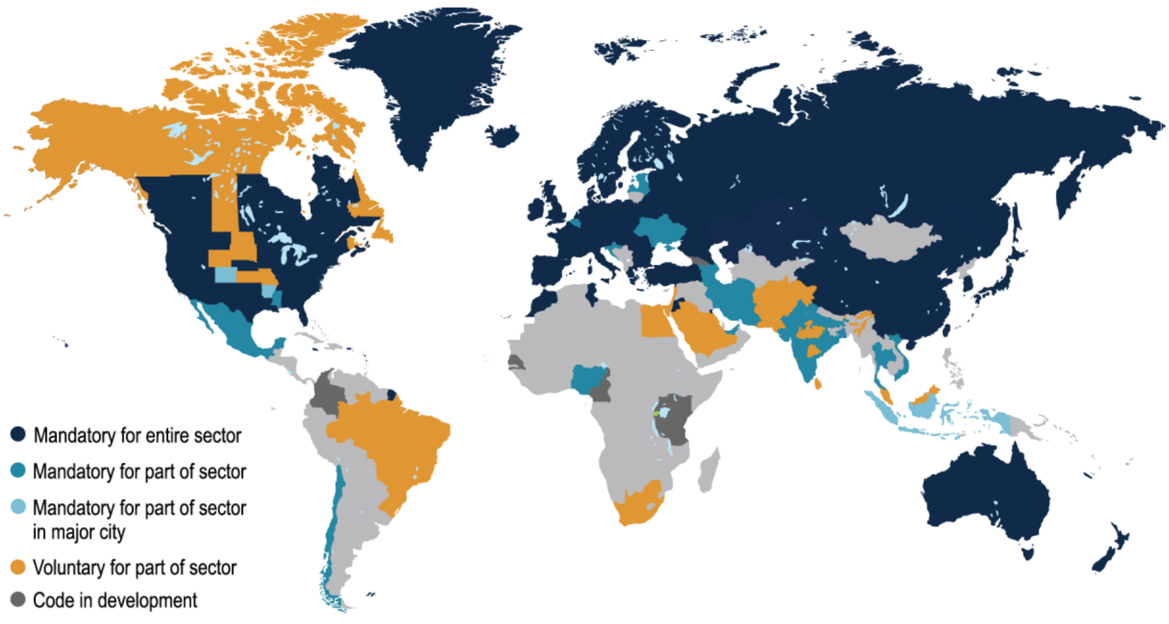


Figure 8: Map of building energy codes by country, state and province, 2017 (source: IEA report on cooling, 2017)

2.2. Overview of cooling in buildings

There are many factors that can contribute to rise in the energy consumption for space cooling. Some of these include: climate, economic growth and affordability, population growth and rapid urbanization, energy efficient technologies etc. Santamouris [3] also examined the different factors affecting the demand for cooling and air conditioning which he categorized into the followings: economic, climatic and technological factors. Economic factors illustrated that increase in family income is associated with higher capacity for energy consumption and particularly an increase in demand for cooling. Climatic factors are mainly associated with ambient air temperature, humidity and solar irradiation. Technological factors are specifically related to thermal quality of buildings and efficiency of air conditioning systems.

The influence of climate on cooling demand is much higher in tropical and sub-tropical regions due to the relatively high humidity levels and low building performance. Figure 9 shows the distribution of the mean annual average cooling degree days (CDDs) across the world during period from 2007 to 2017. This represents a measure of the positive deviation of temperatures from a reference point in a given location over a specified period[25]. The higher the CDDs, the higher the demand for cooling.

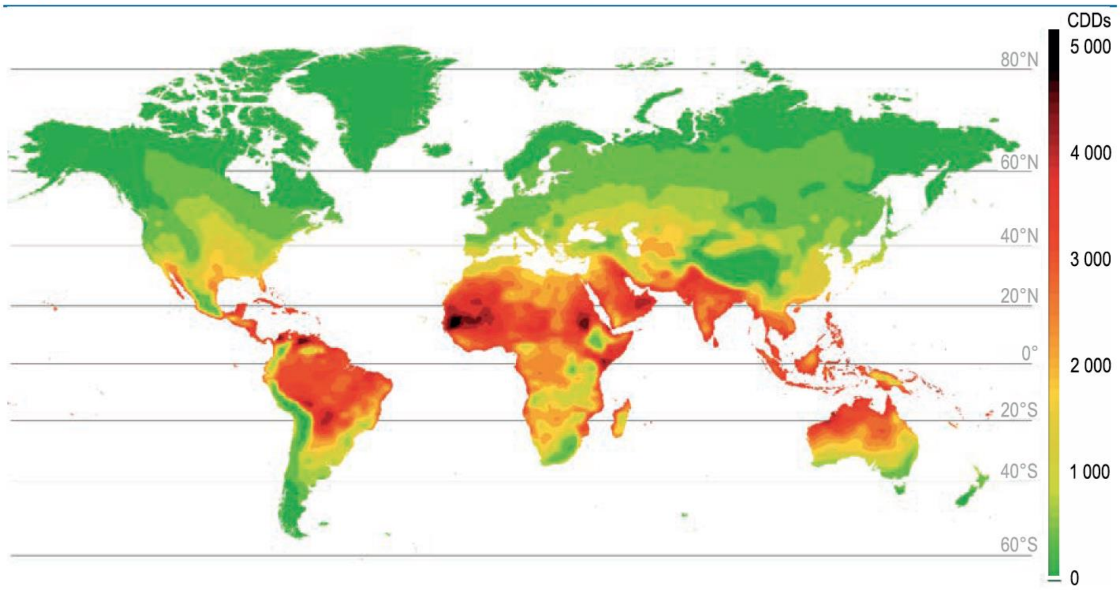


Figure 9: Mean annual average CDDs across the world (Source: IEA report on cooling, 2017)

The increased population and economic growth lead to the increasing demand for cooling especially in urban areas where income is higher. The rising phenomenon of rural to urban migrated has led to increasing density of urban population which can be a major contributor to the heat island effect leading to higher outdoor temperatures and reducing the efficiency of cooling equipment[26].

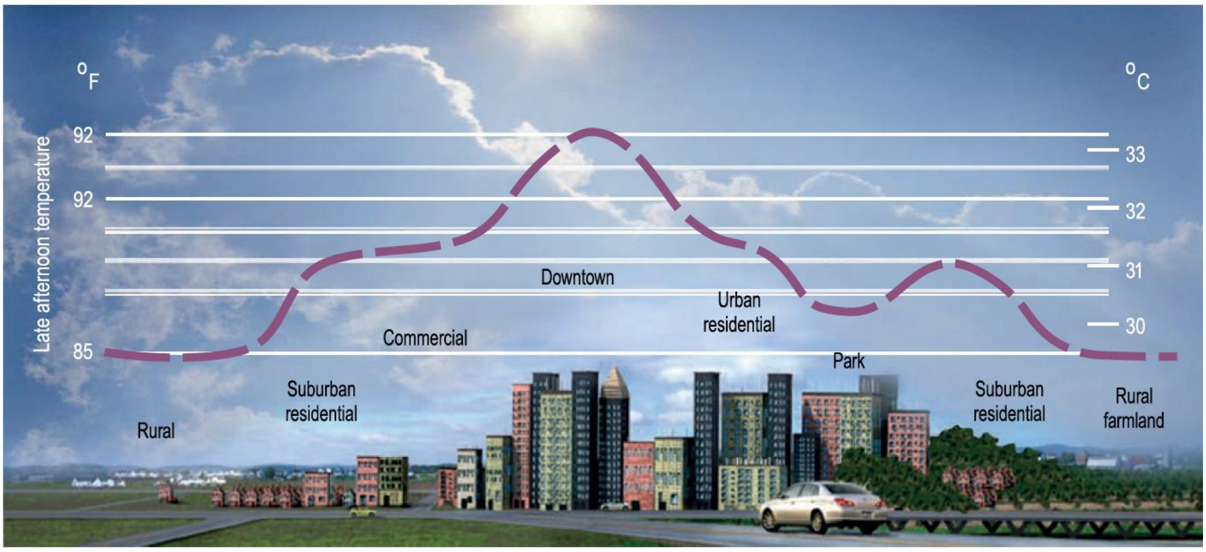


Figure 10: Illustration of island effect

Overheating of the indoor environment cause serious thermal discomfort and health problems which significantly affects the productivity and wellbeing of the occupants. Passive cooling techniques, usually based on the use of solar energy and other heat control systems may be used to prevent indoor overheating. Though the cooling potential of such natural techniques is proving to be very significant, the overall performance depends heavily on the climate and may not satisfy the requirements of indoor comfort under all climate conditions [3]. Therefore, the use of mechanical cooling systems is necessary to achieve the comfort levels needed in buildings.

The implementation of minimum energy performance standards (MEPS) and energy labelling for air conditioning systems is driving out the least-efficient cooling systems and encouraging manufacturers to develop more efficient ones. This has also helped reduce the price of efficient units due to increased production and thereby creating economies of scale[27].

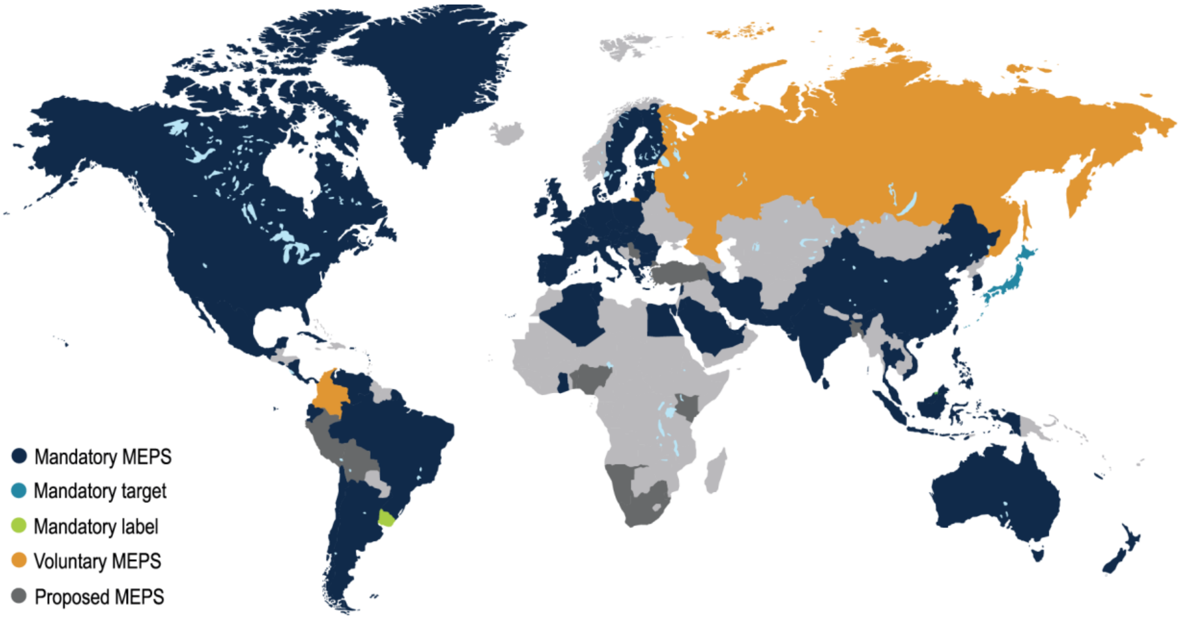


Figure 11: Map of MEPS and energy labelling for air conditioners

Cooling is an important aspect of energy use in buildings that requires integrated policy measures to achieve sustainable, low-carbon energy use in buildings with the principal aim of meeting the needs of consumers for thermal comfort. The principal regulatory actions that can be implemented include minimum energy performance standards (MEPS) and building energy codes. Also, incentives such as taxes and subsidies and information measures including equipment energy labels and capacity-building programs needs to be expanded and strengthen to promote energy efficient and sustainable cooling in Africa. This requires the support of the national governments especially where investment decisions are taken and implemented to encourage wholesalers to purchase the most energy-efficient cooling equipment and also builders and architects to develop more thermally efficient structures designed to minimize cooling requirements.

2.3. Cooling technologies in buildings

In this section, we will discuss the two main types of cooling techniques in buildings: Passive and Active cooling.

2.3.1. Passive cooling in buildings

Passive cooling techniques involve the use of natural cooling sinks such as building material, water, air to reduce the rise in temperature in a building due to heat sources such as ambient air, solar heat gain and internal heat gain. This helps to achieve the required comfort conditions in the buildings with minimum energy consumption. Therefore, passive cooling techniques can be classified into 3 main types: heat protection, heat modulation and heat dissipation technique [28].

Selecting the suitable passive cooling technique is an important task as it depends on climatic conditions, the building parameter and performance of the passive technique. Thus, it is necessary to do a review of the different passive cooling techniques along with an understanding of their applicability in order to adopt a suitable passive cooling technique for a given building. Moreover, a combination of two or more techniques may considerably reduce the energy consumption while satisfying the comfort requirements of the building. Thus, a detailed understanding of each technique is required to establish the importance of passive cooling techniques in building applications.

2.3.1.1. Heat protection technique:

This involves the use of landscaping, water surface, active vegetation, shading of the building surfaces to protect the building from direct solar heat gains or control the building microclimate.

Microclimate control:

A microclimate refers to the immediate atmospheric conditions of a building. The use of trees and green vegetation around the building is considered as a very old, convenient and cheap solution for blocking solar heat gains from reaching the building. Through the process of evapotranspiration, trees and green vegetation absorb heat from the microclimate and therefore helps in achieving the cooling effect [29]. There are two ways of using vegetation: in-house vegetation or outside vegetation. In-house vegetation includes vegetation inside the building like green roof, green terrace, indoor plants in atria, etc. Whereas, vegetation around the building helps reduce the temperature in the building and also acts as an obstacle to heat flow [30].

The roof is exposed to solar radiation from the sun for the longest time and receive highest solar heat gains as compared to other elements of the building. Water surface which includes Water ponds, sprays, pools or water fountain can help reduce heat flux in the house [31]. The roof pond is a cheap and environmentally friendly passive cooling technique use to protect solar heat gains on the roof as water is an ideal thermal mass having high volumetric heat capacity. Sharifi and Yamagata [32] reviewed the different roof pond technologies and it was concluded that the roof pond technique is an efficient passive cooling solution to reduce the energy demand for cooling and heating in buildings and in achieving the required thermal comfort conditions.

Figure 12: Example of trees and green Vegetation around house

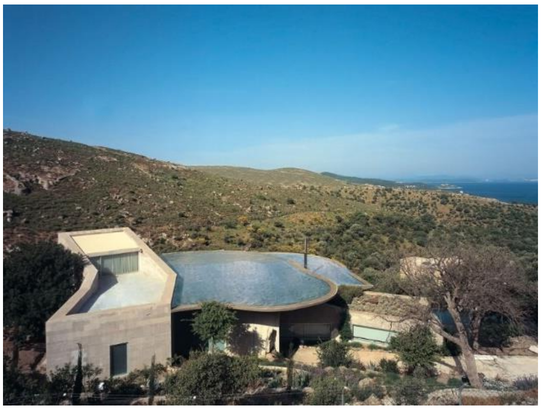


Figure 13: Example of roof pond

Solar Control:

It refers to the reduction of the intensity of transmitted solar radiation through building component like windows and openings by the use of some techniques such as glazing, shading and aperture control.

The energy performance of an opening such as windows depends on its optical and thermal properties such as the U-value, solar heat gain coefficient and transmittance of the glazing type. There exist two main types of glazing: static and dynamic. Dynamic glazing allows flexibility in the change of some parameters such as size and orientation of windows to accommodate for seasonal climatic conditions [33]. However, optimization is important for both glazing types to ensure maximum daylighting and minimum heat gain.

Shading helps protect the building from solar heat gains by the use of building elements such as overhangs, louvers, light shelf, blind system, trees etc. Shading can be active or passive depending on the source of energy used to provide the shading effect. However, window shading alone is insufficient to achieve satisfying thermal comfort conditions in buildings and may influence the visual comfort of occupants. Meanwhile, shading opaque façades of buildings offers more design flexibility and greater energy saving potential [34].

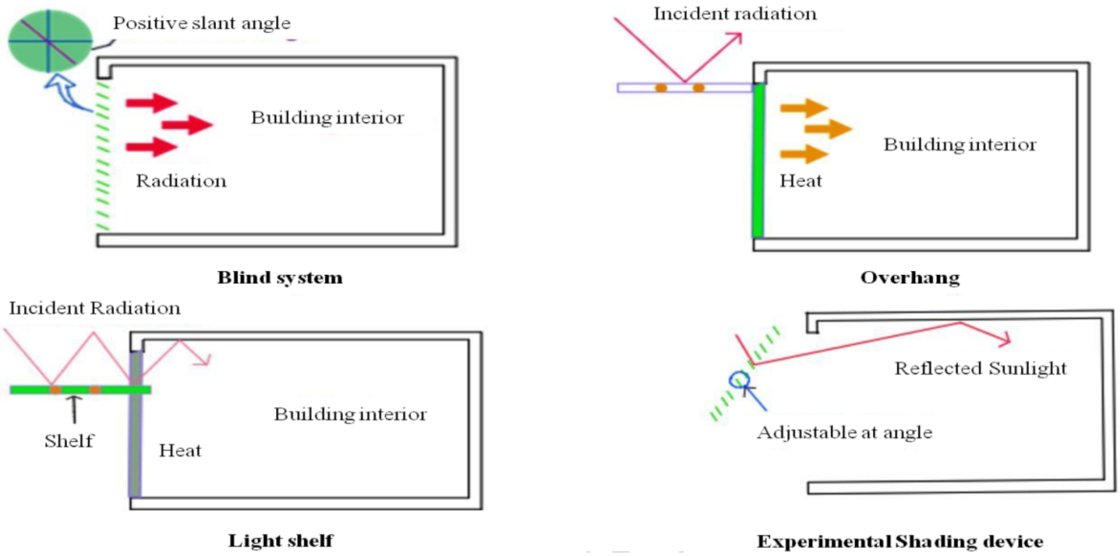


Figure 14: Types of window shading techniques

2.3.1.2. Heat modulation technique:

This refers to the reduction or storing of heat gain in the building by improving on the properties of the building materials. It can be broadly classified into two main categories: thermal mass and free cooling.

The higher the thermal mass of a building, the higher its capability of storing heat. The thermal mass potential depends on many parameters such as climatic conditions, building material properties, building orientation etc. Materials with high thermal mass offers energy saving solutions in hot climates; however, in cold climates this can cause an increase in energy use [35].

There are also latent heat storage materials which are capable of storing and releasing heat during phase change process at nearly constant temperature. These materials are referred as phase change materials (PCMs). During the day, the PCM absorbs heat (in the form of latent heat) and convert into a liquid at constant temperature, thereby reduce the temperature in the building [36]. When this absorbed heat is naturally released by night, it is termed passive cooling. There exist different techniques of introducing PCMs in the building structure, some of which include immersion, direct incorporation, vacuum impregnation, encapsulation etc. Marani and Nehdi [37] reviewed the incorporation of PCMs into building components like, wallboards, ceiling, roof and windows and it concluded that PCMs have a great potential for reducing the cooling loads and improving thermal comfort in buildings especially in urban heat island location.

Usually by night, the ambient air temperature is lower which makes the air colder, recirculating this air into the building through natural ventilation will help reduce the heat gain and cool the indoor air. The phenomenon of storing this cold energy of the night and using it during the day is referred to as free cooling [38]. This can be achieved by using the thermal mass of the building or PCMs. However, free cooling is limited to the size and material properties and also climate dependent. PCMs have proved to be more efficient for passive cooling applications in buildings for all climates except humid and temperature climate [39].

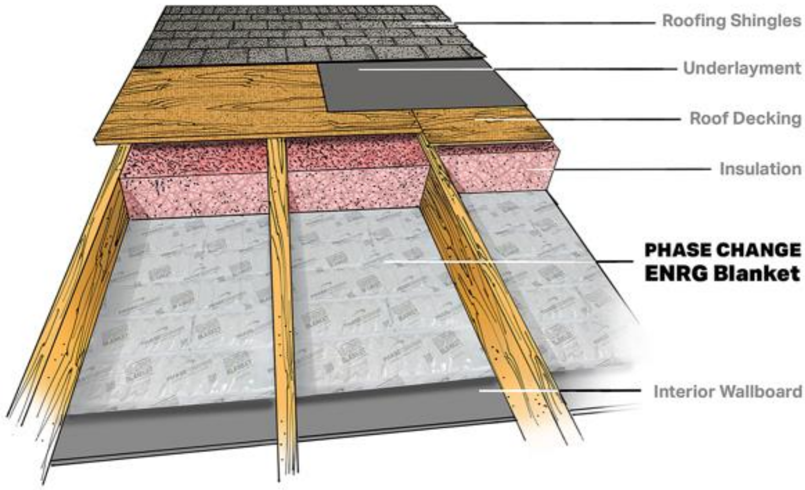


Figure 15: Example of PCMs integrated into ceiling

2.3.1.3. Heat dissipation technique:

This refers to the removal of excess heat gain from the building and rejecting into a suitable environment. Here, the environment is a considered as a heat sink which include the ambient air, water and atmosphere. This technique can be classified into 3 main categories: evaporative cooling, convective cooling and radiative cooling.

Convective cooling:

In convective cooling, air is used as the heat sink and the excess heat of the building is dissipated to the atmospheric air through various forms of natural ventilation. Natural ventilation can be driven by wind speed or due to the air temperature difference between indoor and outdoor conditions of the building [40]. Depending on the form of ventilation, convective cooling can be further classified as buoyancy-driven ventilation, Trombe wall, wind driven ventilation and solar chimney.

Wind-driven ventilation is initiated when there is pressure difference created around the building. When wind hits a building, it produces a high pressure on the windward side and a low pressure on the leeward side and this pressure difference drives air to flow from high pressure to low pressure openings [41]. The intensity of the driving force depends on the climate conditions such as wind speed, wind angle and direction, and also on building parameters such as the position of facades. Techniques such as wing walls, wind tower, wind catcher have been used to improve the performance of wind driven ventilation [42].

Buoyancy-driven ventilation is caused by vertical movement of air in the building arising due to density differences between warm air and cool air in the building [43]. This is influenced by factors such as temperature and height difference between the indoor and outdoor conditions of the building, building orientation, the shape of building etc. The use of Trombe walls can help in providing heating, cooling and ventilation in buildings. Trombe walls are usually used for the passive heating applications for cold climates. However, cooling based Trombe walls such as evaporative cooling wall or hybrid wall, photovoltaic Trombe wall etc can also be used for cooling applications [44]. Moreover, the performance of cooling based Trombe walls depends on many factors such as glazing type, construction materials, type of shading device etc. [45].

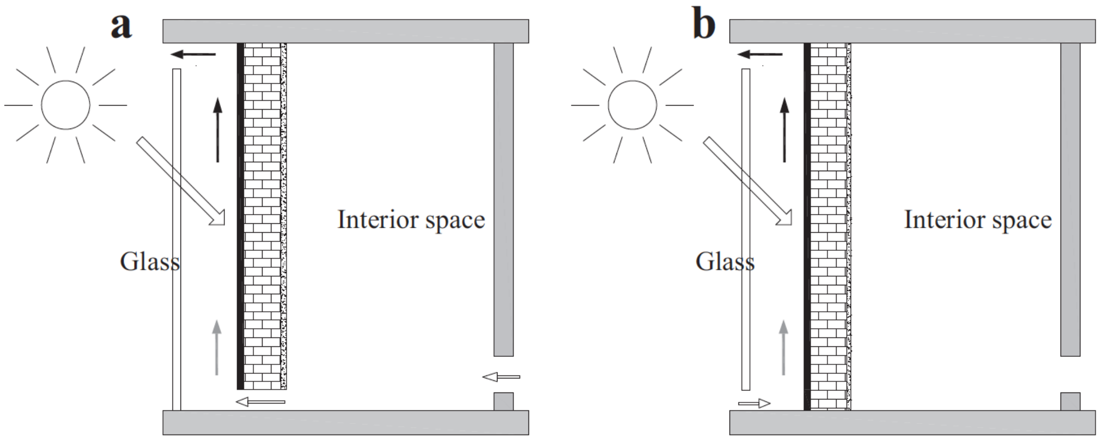


Figure 16: Trombe wall on cooling operation mode (a) natural ventilation mode (b) thermal insulation model[45]

The solar chimney is usually employed for improving daytime ventilation by passively heating or cooling the building. It is often installed at the level of rooftop or on walls. Air is circulated inside the solar chimney by buoyancy effect which moves the cooler air inside the building and draws the hot air towards top of the chimney cavity [46]. Depending on the temperature difference between indoor and outdoor conditions of the building, Solar chimney can operate in three different modes: passive heating, natural ventilation and thermal insulation mode. However, the performance of solar chimney depends on many factors such as chimney configuration, installation conditions, environment, material usage etc. [47].

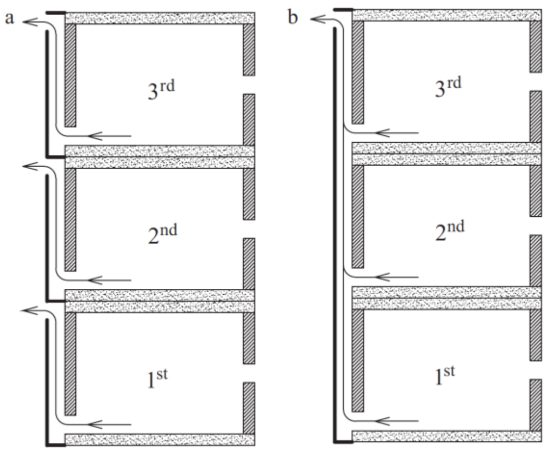


Figure 17: Multi-solar chimney configurations. (a) Separated solar chimney. (b) Combined solar chimney

Figure 18: Solar chimneys on West facade of the building

Evaporative cooling:

Evaporative cooling can be considered as a highly efficient and low-cost passive cooling solution in buildings for both hot and dry climates. When hot and dry air comes in contact with water, a large amount of the heat from the air is absorbed due to the high enthalpy of evaporation of water. This process results in reducing the temperature and increasing the humidity of the air, hence the providing a cooling effect which is referred to as evaporative cooling[48]. Evaporation of water can be through direct or indirect contact with air and thus can be classified as: direct and indirect evaporative cooling.

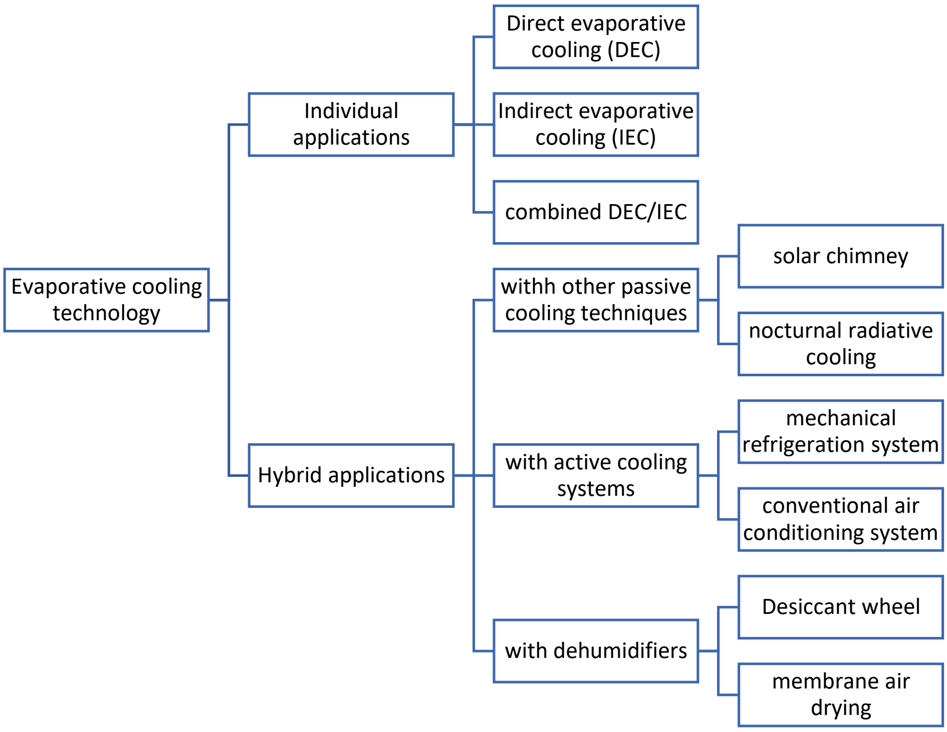


Figure 19: Classification of evaporative cooling techniques[49]

Direct evaporative cooling:

When surrounding air is in direct contact with water, the sensible heat from air is absorbed by water resulting to the evaporation of water due to gain in latent heat of evaporation. This process leads to reducing the temperature and increasing the humidity of air. Maximum temperature reduction depends on the dry bulb and wet bulb temperature of the intake air[50]. Also, for the case of saturated air, evaporation is more effective as the air will be cooled to its wet bulb temperature[51]. Thus, the cooling performance of direct evaporative cooling technique also depends on the moisture content of the air.

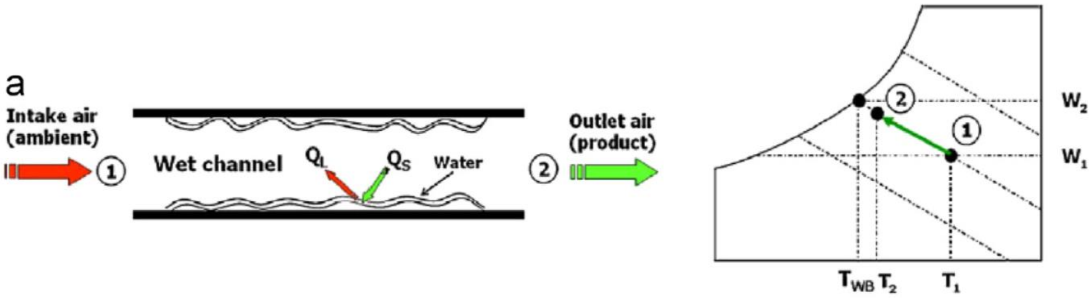


Figure 20: Direct evaporative cooling[48]

Indirect evaporative cooling:
In this case, the air stream is separated from the water stream by means of a heat exchanger. The working fluid is air which is passed through the wet channel to absorbed the sensible heat from the air in the dry channel, resulting in reducing the temperature of the product air[52]. Liberati et al. [53] reviewed the use of indirect evaporative cooling techniques in building and it was recommended to combine indirect evaporative cooling with other cooling system such as desiccant cooling, chilled water etc. for maximum performance.

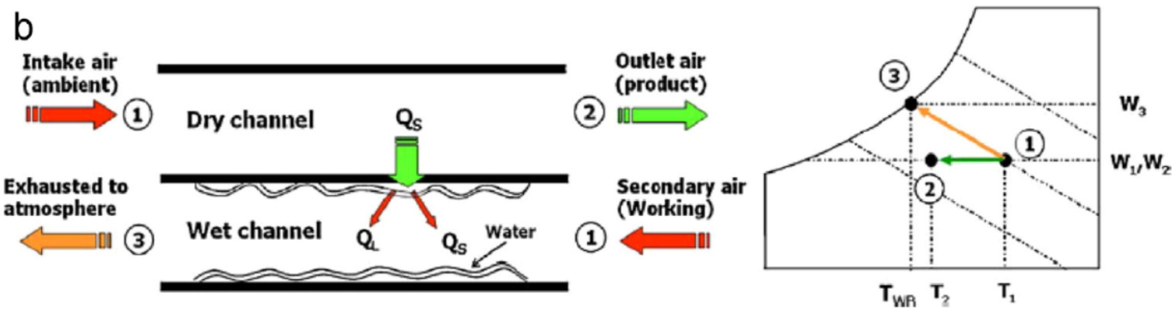


Figure 21: Indirect evaporative cooling[48]

Radiative cooling:
Our surrounding atmosphere is a medium through which radiation can be absorbed, emitted or reflected. Thus, a building with the appropriate thermal properties can dissipate its heat to the surrounding atmosphere. This can occur during the day or in the night and in this process, the surrounding is considered as heat sink[54]. Hence radiative cooling can be classified as: Nocturnal radiative cooling and radiant cooling system. Naturally occurring phenomenon such as frost and dew water formation on leaves can also be used to illustrate radiative cooling (Figure 23)
The energy balance of radiative cooling process is illustrated in Figure 22, where q_{rad} represents the energy radiated, q_{sun} is the solar energy absorbed, q_{sky} is the atmospheric radiative energy absorbed, and q_{loss} represents the intrinsic cooling loss[55].

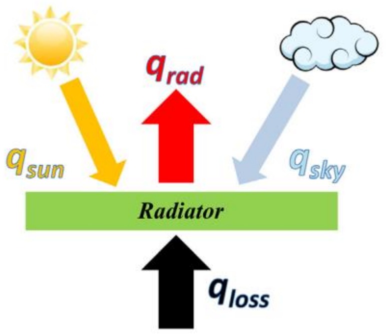


Figure 22:representation of heat fluxes for a radiative cooling structure[55]

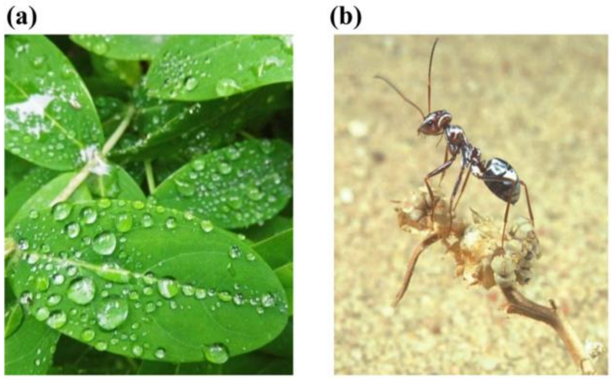


Figure 23: Nature radiative cooling. (a) Dew water formation on leaves and (b) silvery appearances of Saharan ants

The net radiative cooling power, $q_{\text{net-cooling}}$ can be calculated in equation, where T_r represents the absolute temperature of the radiator[56]:

$$q_{\text{net-cooling}} = q_{rad}(T_r) - q_{sky} - q_{sun} - q_{loss} \quad 1.1$$

In nocturnal radiative cooling, heat is lost from the building by directly exposing the heated surface to the surrounding (heat sink) during a clear cool night. The performance of this technique depends on many factors such as the thermal properties of the radiating panel (solar flat plate collectors), the humidity levels of the sky etc. [57].

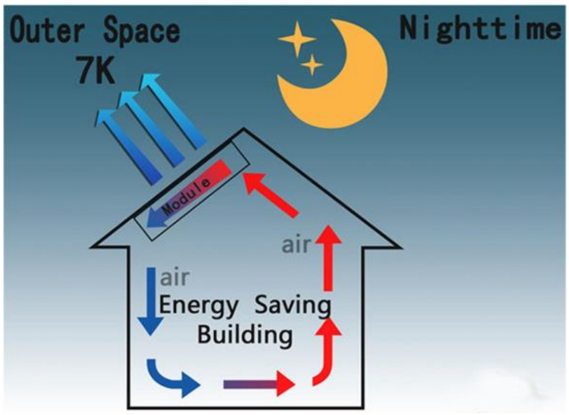


Figure 24: Schematic of air-based radiative cooling system.[55]

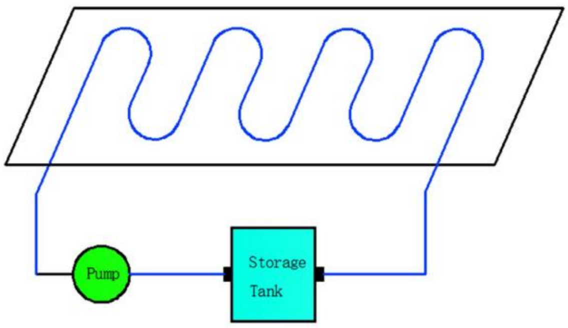


Figure 25: Schematic of water-based radiative cooling system: typical flat-plate radiator system[56]

For radiant cooling, the heat surface is indirectly exposed to the heat sink of the cool night by means of cold-water medium. Heat is removed from the building by the cold water circulating inside the pipes embedded into the walls of the building[58].
The heat transfer process between the indoor space and the radiant floor surface depends on the convection heat exchange (q_c), longwave radiation (q_{lr}), and absorption of shortwave radiation (q_{sr}) as shown in figure 27b

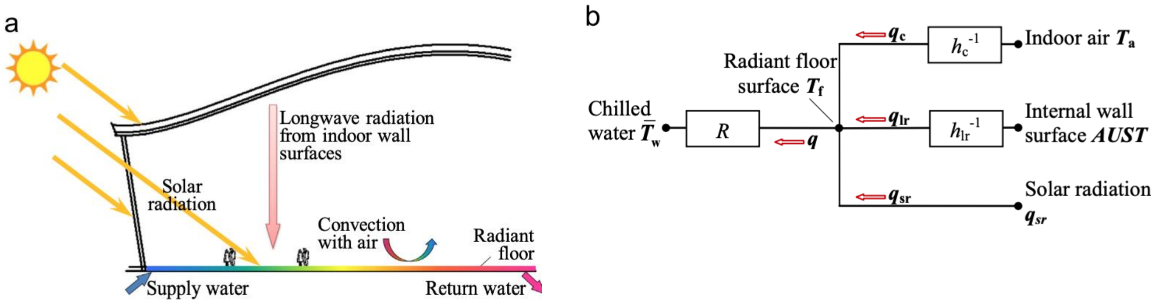


Figure 26: Heat transfer between radiant floor and its surroundings: (a) simple graph; and (b) schematic of the heat transfer process[58]

Summary of Passive cooling techniques:

It can be established from the literature that passive cooling techniques have a great impact in reducing the cooling load and improving indoor conditions in buildings. However, the performance of these techniques depends on local climate conditions.

Roof pond technique is more popular in hot and dry climates. The performance of solar control technique is dependent on the glazing types, shading devices etc. while taking into consideration both lighting and thermal comfort requirements.

An attempt was made to summarize the most common PCM modulation technique used in passive cooling. It is observed that PCM based passive cooling technique is mainly employed in hot and dry climates and hot and humid climates. In both cases, PCM integration is preferred in roof, ceiling, walls, windows assisted with night ventilation and free cooling. This is suitable for single or multi-storey buildings.

Whereas Convective cooling techniques such as wind-driven ventilation, buoyancy-driven ventilation are mostly employed in both hot and humid as well as temperate climates. While other technique like the Trombe wall are common in hot and dry, hot and humid climates. Other heat dissipation techniques like evaporative and radiative cooling are limited to hot and dry climates.

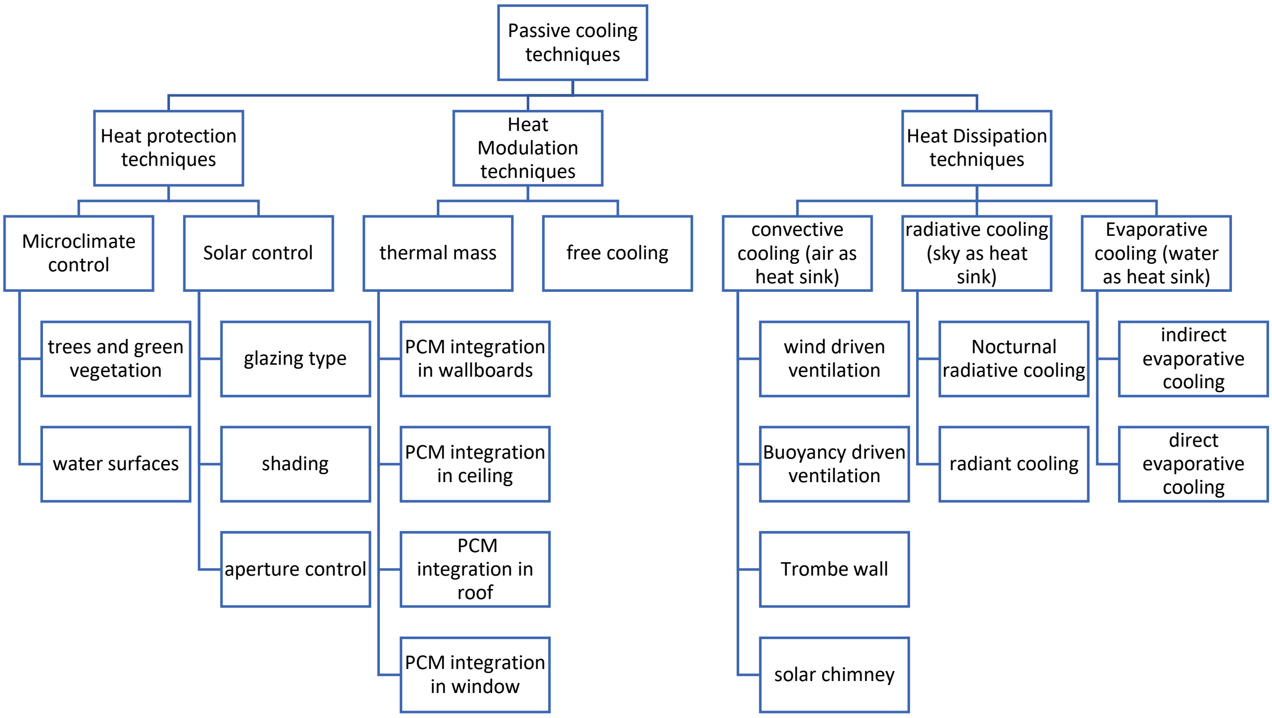


Figure 27: Summary of passive cooling techniques

2.3.2. Active Solar cooling in buildings

We have seen that passive building techniques are very important and dominate new building design. However, research, development, and deployment of active building techniques are rapidly growing and present new solutions to address energy efficiency in buildings.

The need for Solar cooling has been rising due to the increasing demand for cooling usually corresponding to the availability of solar resource. However, the investment cost for solar cooling is generally higher than conventional cooling technologies due to the lower price of grid energy. This cost depends on the type of cooling system, the availability of the solar resource, the length of the cooling season. There exist many solar cooling technologies both at the experimental and commercial scale, which can be classified into three categories: solar electrical cooling, solar thermal cooling, and solar combined power/cooling [59] as shown in figure 29 below. A market survey of solar cooling systems has shown that 82% of the installations are absorption chillers, 11% adsorption units and 7% desiccant systems but most of the installations are mainly used in medium-large scale applications in both commercial and industrial sector[60].

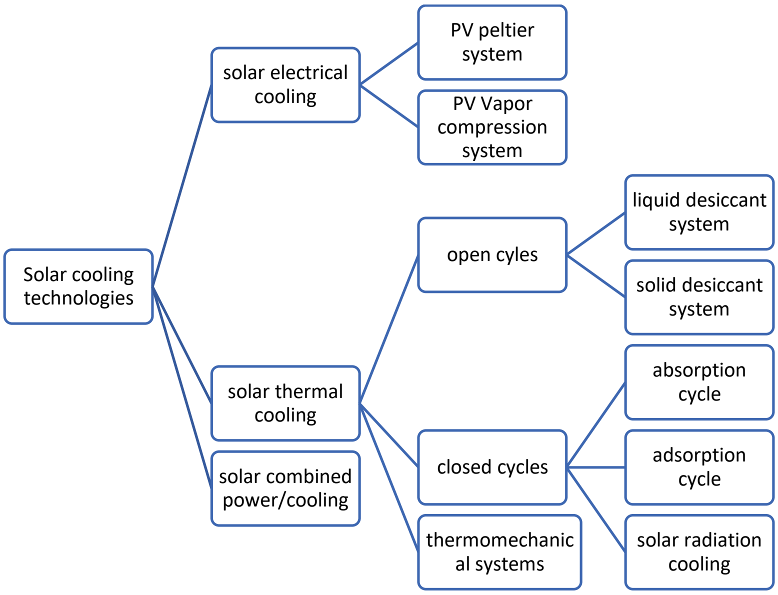


Figure 28: Classification of Solar cooling technologies

In the last five years, we have observed a dramatic decrease in the cost of PV modules, with prices that are now in the range of 0.45–0.60€/kWp for crystalline Silicon modules[61]. The cost is expected is continuously fall due to increasing manufacturing capacity and new developments in research. This makes Solar PV cooling technology more and more attracting and competitive compared to other solar cooling technologies. In Solar Electric cooling also referred to as Solar PV cooling, the electricity produced by the PV system is used to drive the cooling system. Based on type of PV connection with the grid or power consumption mode, we can have a standalone and grid-connected solar PV cooling system or a direct current (DC) and an alternating current (AC) solar PV cooling system. There are two main systems usually combined with solar PV installation to provide cooling in buildings: compression cooling and Peltier cooling system.

2.3.2.1. Vapor compression cooling system

Compression cooling system is generally referred to as air conditioning system. Air-conditioning systems are the biggest energy consumers in both public and commercial buildings in hot humid climatic regions in Africa, with consumption ranging between 50–80% of total electricity consumption[62]. Therefore, the implementation of Energy efficiency standards for air conditioners is crucial for reducing electricity consumption and cost in both the residential and commercial sector.

Modern compressor using variable speed compressor technologies (DC inverter technologies) have been designed for refrigeration and air-conditioning. This have proved to be more energy efficient compared to single speed compressors, with reduction in the energy consumption of up to 30–40%, making them possible to be powered by solar energy[63].

Solar compression cooling system consist of PV panels, inverter and air conditioning system. Such system can be DC or AC connected and can be used in grid-connected or off-grid areas. PV vapor compression cooling is considered to have more potential for cost and energy savings in buildings compared to other solar cooling technologies. It offers higher cooling efficiency and convenient integration with conventional buildings, making the system commercially availability and easily adapted to different climate conditions[64]. Figure describes the energy interactions in a grid-connected PV air conditioning system. The PV panels converts the energy from the sun into electricity, which is used to power the air conditioner to provide cooling for the house.

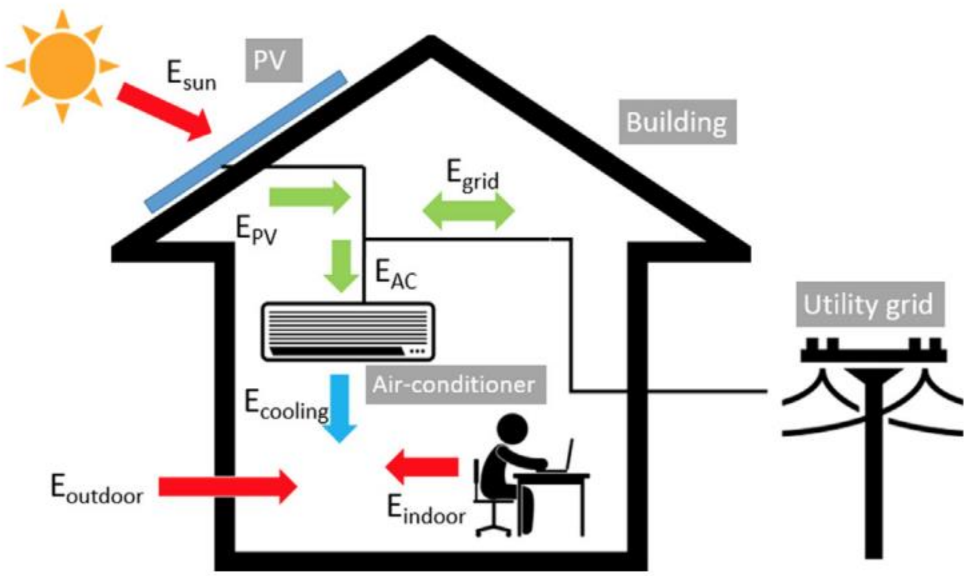


Figure 29: Schematic diagram of PV compression cooling system in a building[64].

The energy flows in the system are represented as follows:

$$E_{PV} = E_{sun}\eta \quad 1.2$$

$$E_{grid} = E_{PV} - E_{AC} \quad 1.3$$

$$E_{cooling} = E_{AC} COP \quad 1.4$$
$$E_{cooling} = E_{outdoor} + E_{indoor} \quad 1.5$$

where:
E_{sun} is the solar radiation absorbed by PV panel,
E_{PV} is the electricity produced by the PV,
η is the efficiency of the PV modules
E_{AC} is the electricity consumed by the air-conditioner
E_{grid} is the electricity from the grid. This can be either positive or negative depending on the difference between E_{PV} and E_{AC}.
COP represents the coefficient of performance of the air-conditioner,
$E_{cooling}$ is the cooling effect produced by the air-conditioner.
$E_{outdoor}$ is the heat transfer from the outdoor environment by heat convection and solar irradiation.
E_{indoor} is the heat generated by indoor factors such as human bodies, lightings, and equipment.

The vapor compression system consists of five principal components: compressor, evaporator, condenser, expansion valve and refrigerant. These components can be described as follows[65]:

- compressor is driven by electrical power and can be considered as the heart of air conditioning system as it pumps the refrigerant throughout the system. Its main function is to compress refrigerant low-pressure vapor refrigerant from the evaporator to a high pressure making it hot for the circulation process of the refrigerant.
- Refrigerant is a material that performs as cooling agent by absorbing heat from the surrounding as it is circulating through the air conditioning system.
- expansion device is located in between of the condenser and evaporator. It allows a controlled amount of the liquid refrigerant from the condenser to flow into the low-pressure evaporator section.
- Evaporator functions as a heat exchanger by using the liquid state refrigerant to absorbs the heat from the cooling space into the system. It is part of the indoor unit installed in the cooling area.
- The condenser also functions as a heat exchanger, where the heat absorbed by the evaporator is being removed. The condenser is located in the outdoor unit with the compressor.

2.3.2.2. Thermoelectric cooling system

Thermoelectric effect refers to the direct conversion of temperature difference into electrical voltage and vice versa and this involves three separate type of effects: the Seebeck, Peltier, and Joule Thomson effect. These effects can be produced using a thermoelectric module which is a solid-state device made of a set of thermocouples electrically connected in series and thermally in parallel [66]. A thermocouple is made of two different semiconducting P-Type and N-Type thermoelements. When direct current is sent through one or more pairs of P-type and N-type semiconductors, cooling is produced through a phenomenon called the Peltier effect (see Figure 32). By varying the direction of current, both cooling and heating can be achieved. TE module generally operates with two heat sinks connected to its hot and cold ends in order to improve the heat transfer and system performance.

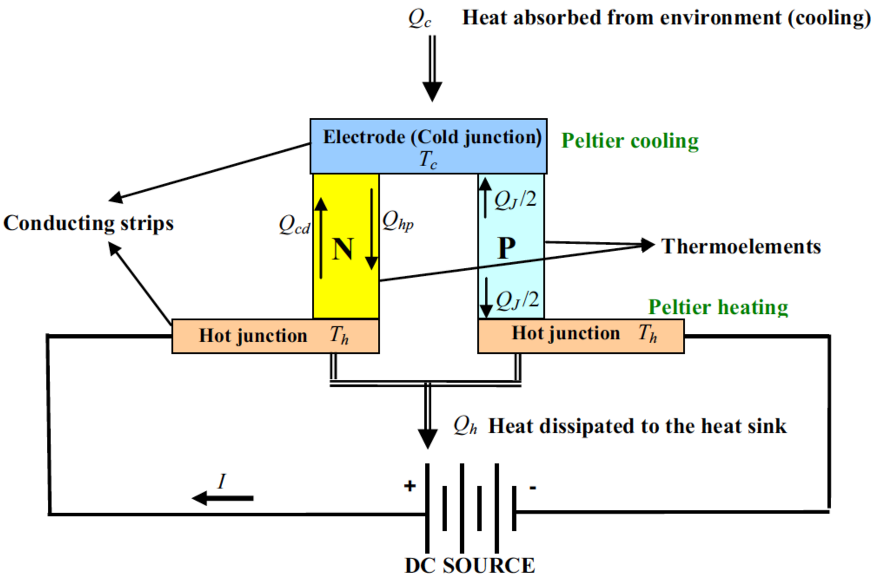


Figure 30: Schematic design of Thermoelectric refrigerator

Enescu and Virjoghe [67] defined some basic terms used in thermoelectric applications:

- Figure of merit, ZT: indicator for the performance of thermoelectric cooler. It depends on three main parameters: electrical resistivity ρ, Seebeck coefficient α and thermal conductivity k between the cold and hot sides. It is represented by equation…. below. The product ZT where, T represents the absolute mean temperature between the cold side and hot side of the thermoelectric module.

$$Z = \frac{\alpha^2}{\rho k} = \frac{\alpha^2 \sigma}{k} \quad 1.6$$

Research have proved that thermoelectric devices are considered to be:

- inefficient when ZT= 1;
- able to recover waste heat when ZT= 2;

- able to match a refrigerator when ZT = 4 to 5

- Cooling capacity, Qc: results from the energy balance at the cold side of the thermoelectric cooler.

$$Q_c = \alpha I T_C - K\Delta T - \frac{1}{2} R_e I^2 \qquad 1.7$$

where
$Q_g = \alpha I T_C$ is the thermoelectric heat pumping at the cold junction, I the input current, Tc the temperature of the cold junction and
$Q_d = K\Delta T$ is the heat flow conducted from the hot junction to the cold junction
$Q_j = R_e I^2$ is the Joule heat,

- The coefficient of performance, COP: the ratio between the cooling capacity Qc and the electrical power consumption Pe

$$COP = \frac{Q_C}{P_e} \qquad 1.8$$

However, there are two major conflicting parameters that describe the performance of Thermoelectric materials: figure of merit (ZT) and the power factor, these factors determines the thermal conductivity and electrical conductivity of TE material respectively and therefore represents essential criteria for the thermoelectric material selection[68]. Higher ZT factor is important to improve cooling performance of TE devices.
For a specific type of TE module, there exist a maximum COP at an optimum current and fixed hot/cold side temperatures as showed in equation 1.9. Figure below shows the variation of cooling COP of a TE module under optimum current with fixed hot side temperature of 300K [3]. This graph shows that increasing the figure of merit (ZT factor) of thermoelectric material could greatly improve the COP of thermoelectric cooling system. Tremendous improvement on the ZT of thermoelectric devices have been reported recently with ZT of more than 7[68], which justifies increasing application of TE devices for cooling and heating.

$$COP_{max} = \frac{T_c}{T_h - T_c} \frac{\sqrt{1+ZT_m} - \frac{T_h}{T_c}}{\sqrt{1+ZT_m}+1} \qquad 1.9$$

Where, ZT_m is figure-of-merit of the thermoelectric material at average hot and cold side temperature Tm.

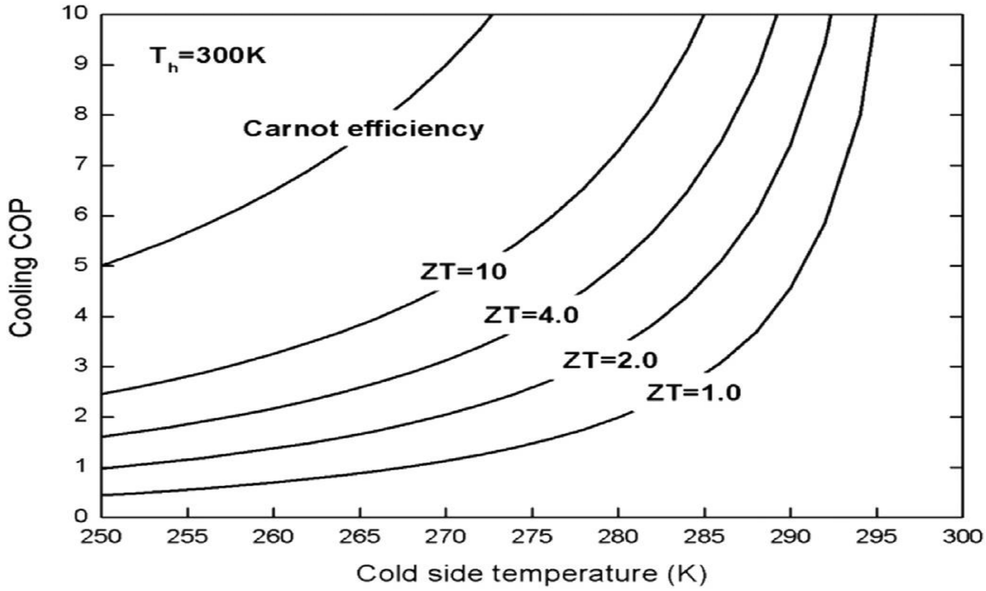


Figure 31: Cooling COP of a thermoelectric module under optimum electrical current with fixed hot side temperature of 300 K.

Zhao and Tan [66] analyzed different methods of Thermoelectric cooling (TEC) modeling: simplified energy equilibrium model and numerical compact modeling used in determining the cooling power output and the COP of the TEM. This research led to development of three methods that can be used in improving the TEC system performance: TE module design and optimization (such as the thermoelement length, number of thermocouples), cooling system thermal design and optimization (including heat sink geometry and heat transfer coefficient of hot and cold side) and the TEM working condition (i.e. electrical current input).

Thermoelectric cooling systems are commonly known as Peltier coolers, they have no mechanical moving parts and do not involve the use of any working fluid. This make the whole system less heavy, easily packable and reliable and in addition, free from Freon and therefore environmentally friendly. Due to these numerous advantages, thermoelectric cooling systems have been widely used in military, instrumentation, industrial and medical applications. Also, Thermoelectric cooling systems can be powered directly by solar PV without the need of any DC/AC converter. commercially available thermoelectric modules consist of P-type and N-type blocks of semiconductor materials.

Thermoelectric devices are used in varying range of cooling applications including cooling electronic devices, refrigerators, thermoelectric air conditioners (TEACs), hybrid systems for cogeneration applications. Sajid et al.[70] investigated the different cooling techniques used in thermoelectric system which can be divided into two main types: air cooled and water-cooled systems (see figure5). This study was aimed at improving the energy performance of the whole system. The results showed that evaporative cooling has the lowest cooling potential while forced convection of water can be used for large cooling applications with high thermal needs[70]. Riffat and Ma [71] also explored the possibility of improving COP of TEC by enhancing the efficiency of heat exchangers of TEC systems and discovered that water cooled forced convention have excellent performance. However, air cooled heat exchangers are more convenient to use and there have been recent development of air-cooled systems with higher performance.

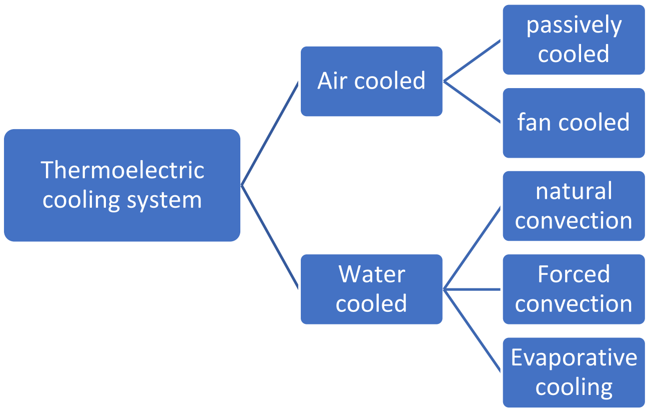


Figure 32: Thermoelectric cooling system

Liu et al.[72] explored the use of thermoelectric devices in active building envelops, thermoelectric energy recovery systems and solar thermoelectric air conditioners. So far, passive solar building envelops have been used to increase the heat gains during heating seasons, contributing to overall reduction in energy consumption for heating needs. However, this system cannot be employed during cooling season whereas building envelops integrated with thermoelectric devices offer new solutions for heating and cooling which can offset thermal loses or gains. Liu et al.[72] observed that the coefficient of performance (COP) of solar thermoelectric air conditioner with hot water supply could reach up to 4.51 when water temperature was 20°C and 2.74 when water temperature was 42°C. While the performance of the solar thermoelectric radiant air conditioning system and solar thermoelectric energy storage air conditioning system could reach 1.9 and 1.22 respectively. These different applications of solar thermoelectric cooling can be summarized in the following diagram (see Figure 33).

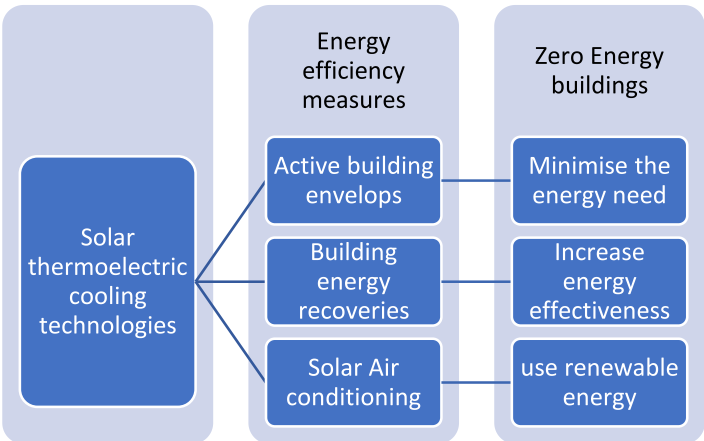


Figure 33: Solar thermoelectric cooling technologies in zero energy buildings

It is also reported that increasing the number of stages (Multistage thermoelectric modules) improves the cooling capacity and COP of about 35% and 25% respectively, compared to single stage modules[67].
Enescu and Spertino [73] also analyzed the application of thermoelectric material for cooling of solar PV modules called hybrid PV-TEC systems. The results of the simulation reported a temperature drop of 10°C in the PV cells and led to an increase in the efficiency and power capacity of the PV system. Many research works are being oriented to the development of TEC for air conditioning application with the hope of making them competitive with vapor compression systems. Results have showed that the actual COP of TEAC is in the range of 0.38 – 0.45, still low compared to 2.6 -3.0 for vapor compression systems.

2.4. Assessing the cooling energy demand in buildings

Estimating the heating and cooling energy demand in buildings have become a key approach to achieve the goals on reducing energy consumption and emissions in buildings as it allows to improve on the sizing of HVAC systems. However, determining energy needs of a building depends on multiple variables including the building geometry and characteristics, weather, occupants, equipment and systems in the house. There exist different approaches used in estimating the energy demand in buildings. However, this section will focus on four main modeling approaches: physical, statistical, regression and artificial intelligence methods.

Geekiyanage and Ramachandra [2] analyzed the factors that influenced cooling energy demand of buildings termed "building design variables" and developed a model based on regression analysis to estimate the annual cooling demand of condominium buildings in Sri Lanka. The design variables used include: building shape, building orientation, window-to-wall ratio (WWR), wall-to-floor ratio (WFR), type and area of roof. The results of the model showed that 91% of the variation in cooling load of a condominium building depends on the number of floors and WWR. Vallejo-Coral et al.[74] explored the use of cooling load temperature difference/solar cooling load/cooling load factor (CLTD/SCL/CLF) method to estimate the cooling demand for buildings in warm climates in Mexico. In this study, cooling loads were calculated through the walls and roofs as an estimate of the heat gains through the building envelop.

Fumo [75] reviewed the different existing models used in entire building energy simulation and classified them in three main categories: statistical, gray box and engineering models, including calibration, verification and weather files. The results of this research showed that calibrated engineering models (i.e. software such as EnergyPlus, ESP-r, TRNSYS, e-QUEST) have gained particular interest since they allow for reliable simulations to determine energy savings and potential emission reductions in buildings. Bruno et al.[76] carried out the assessment of the cooling needs of building in a Mediterranean climate based on the "black box" approach (EN ISO 52016-1 quasi-steady model), a concept of utilization of energy gains and heat transfer. Simulation results obtained indicated deviances lower than 5% in calculating the monthly cooling energy demand compared with TRNSYS software.

Koo et al.[77] developed a model based on building envelop design using Microsoft Excel based VBA to estimate the cooling and heating demand in a building. This research was based on architectural design elements and window design elements and it revealed that this model can be used to analyze the alternatives and cost effectiveness of building envelop design in the early design phase

Jihad and Tahiri [78] developed an algorithm based on artificial intelligence (Artificial Neuron Network) using six inputs variables (wall area, relative compactness, glazing rate, orientation, height and building area) to predict the heating and cooling demand in residential buildings in Morocco. The results of this method were compared with "Designer builder" tool of EnergyPlus software and an average accuracy of 94.8% and 98.5% was achieved. Therefore, this tool can be used to predict energy consumption of a new or existing building.

CHAPTER 3: METHODS

This chapter describes the steps used in designing a cost effective and energy efficient cooling solution to ensure the best comfort in the house to be built up. In order to effectively carry out this work, an energy analysis of the house was done to propose some passive cooling techniques in order to reduce the overall cooling load of the house. Then the design of a separate Solar PV Peltier and Compression cooling system was performed to select the most efficient and cost-effective system for the house.

3.1. The Jua house Project

The jua house (solar house in Kishawili language) is developed by the JUA JAMII team, which is a collaboration between the Pan African University Institute of Water and Energy Science, the University of Tlemcen and the National University of Lesotho. The team is made up of more than 30 students with various disciplines and background from all over the African Continent. Our uniqueness is inspired from the concept of recycling to produce a house that a traditional and smart meeting the needs of African community and culture.

3.1.1. The Jua House Architecture

The architecture of the house is inspired from the Northern African architecture of Patio and separate day and night spaces. The house is made from reused shipping metallic containers and assembled in a special configuration that reflects an African footprint design. All this makes the house modular and flexible.

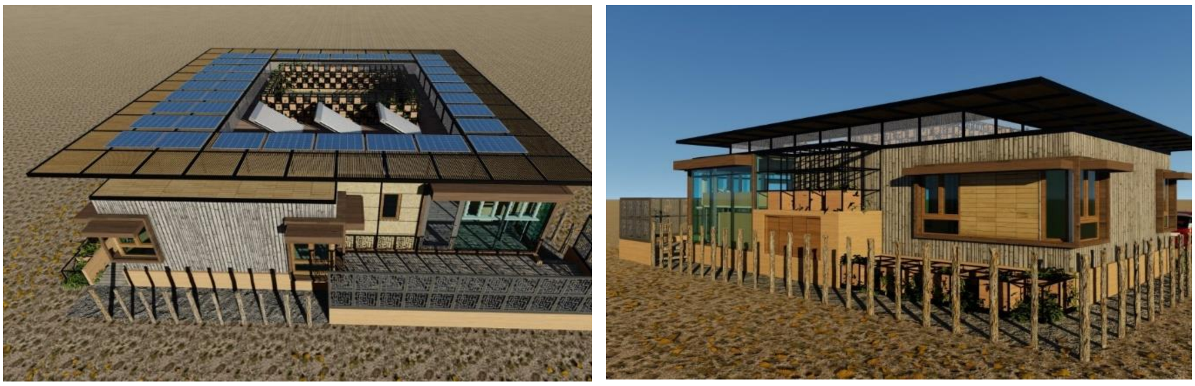


Figure 34: Renderings of the Jua house

3.1.2. Construction materials in the house

The materials used in the house are local materials that are hugely available in Africa and the choice of these materials was based on the designed energy performance of the house. Also, the impact of house on the occupants and on the environment was keenly taken into consideration in the selection of materials. The main insulation materials used in the house are: cork, light weight wood, bit felt and placo BA13, which are used for the insulation of external and internal walls, roof and floor. For the openings, wooden doors and double-glazing windows are used. These materials were carefully chosen to reduce the heat gains in the house and ensure comfortable indoor conditions. The thermal properties of the materials are shown in the table

Figure 35: Insulation materials used in the house

Table 1: Thermal properties of materials

Materials	Thermal conductivity (W/m.K)	Density (Kg/m3)	Specific heat capacity (J/kg.K)	References
Shipping containers	46	7500 - 8200	500	[79]
Cork	0.041	240	1670	[80]
Light weight wood	0.14	550	1200	[81]
Bit felt	0.024	26.02	940-960	
Placo-BA13/14	0.25	825	1425	[82]
Air gap	0.027	1.204	1005	[83]

3.2. Thermal analysis of Jua house

The weather data of the competition site together with the building envelop was studied to develop a thermal model for the energy simulations. This thermal model was created with the help of Designbuilder interface of EnergyPlus software[84] to validate and evaluate the thermal performance of the house before performing energy simulations. The following depicts the steps carried out for the thermal analysis.

3.2.1. Climate conditions of Ben guerir

The competition will take place in Ben Guerir during the month of September which is summer period, as indicated in the weather data collected from the IRESEN High Precision Meteorological Station in Ben Guerir, Morocco.

Ben guerir has a semi-arid climate which is characterized by warm to hot summer period and cool to warm winters, occasionally falling below freezing point[85]. July is considered the hottest month of the year with an average temperature of 28.8°C and February the coldest with an average temperature of 13.0°C. The average humidity over the year 2016 was 59% and wind speed of 3m/s in the North direction.

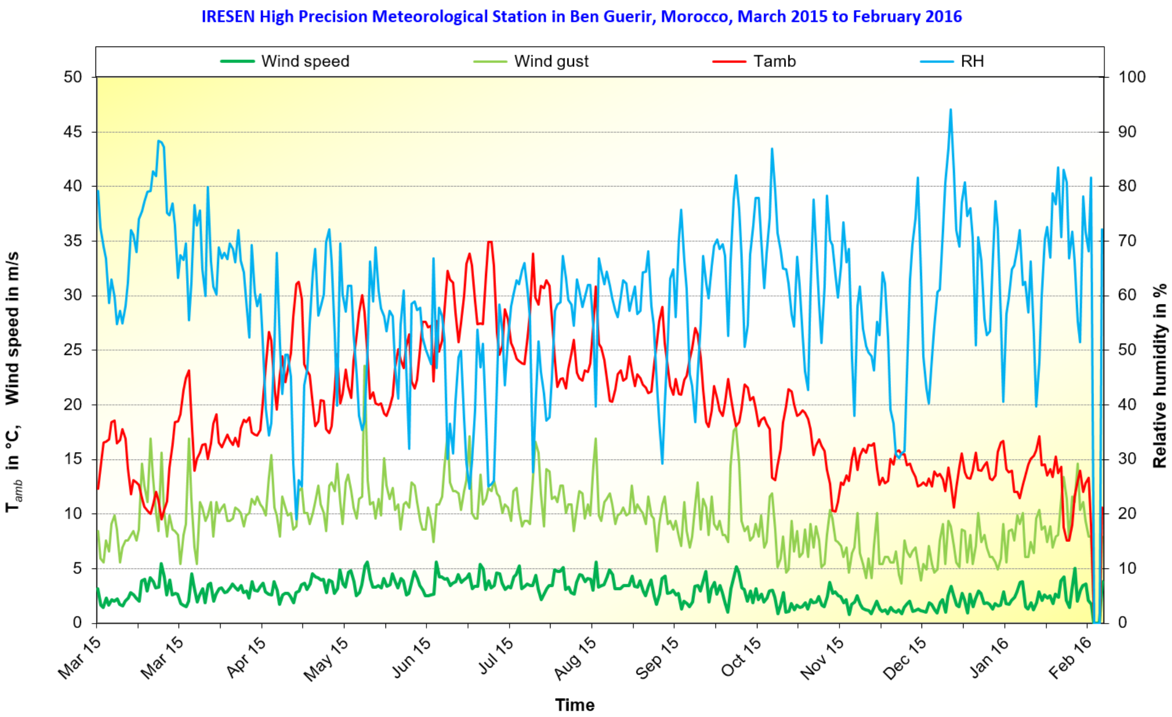


Figure 36: Yearly variation of ambient Temperature, humidity and wind speed in Ben Guerir

3.2.2. Indoor comfort Conditions

The competition prescribes comfort temperature and relative humidity zones of 22°C – 25°C and 45% - 55% respectively as shown in the psychometric chart below.

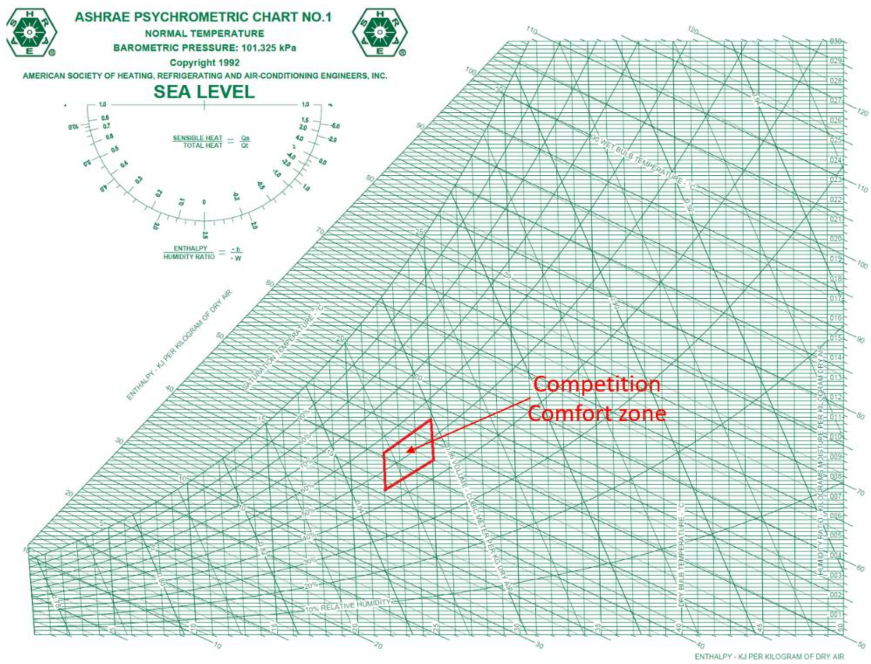


Figure 37: comfort zone per the requirements of the competition

3.2.3. Building envelops

After the choice of the insulating materials to be used in the house, it is important to use the right thickness of each material that will provide the optimal thermal performance without comprising the living space of the house and modularity of the house. Figure 39 below represents the thickness of the different materials used.

Roof	
U-value: 0.425 W/m²K	
Outer surface	
20 mm	Container
10 mm	Bit felt
20 mm	Air gap
40 mm	cork
20 mm	BA 13
Inner surface	

Internal wall	
U-value: 1.998 W/m²K	
Outer surface	
30 mm	BA 13
20 mm	Container
30 mm	BA 13
Inner surface	

Double glazing window	U-value of 2.665 W/m²K

Wooden door,	U-value of 2.823 W/m^2K

Floor	
U-value: 0.425 W/m^2K	
Outer surface	
30 mm	Light weigh wood
40 mm	cork
10 mm	Air gap
10 mm	Bit felt
20 mm	container
Inner surface	

External wall	
U-value: 0.271 W/m^2K	
Outer surface	
20 mm	Light weigh wood
40 mm	cork
20 mm	Air gap
10 mm	Bit felt
20 mm	container
10 mm	Bit felt
20 mm	Air gap
20 mm	BA13
Inner surface	

Figure 38: Building envelop of the house

3.2.4. Thermal zoning of the house

The 2D drawing of the building was imported from AutoCAD Software into DesignBuilder to accurately perform the modeling. Due to the complex geometry of the house, the building envelop was divided into 8 thermal zones for detailed analysis. These zones include: 3 bedrooms, gallery, bathroom, aquaponics and the living/kitchen room (see Figure 40).

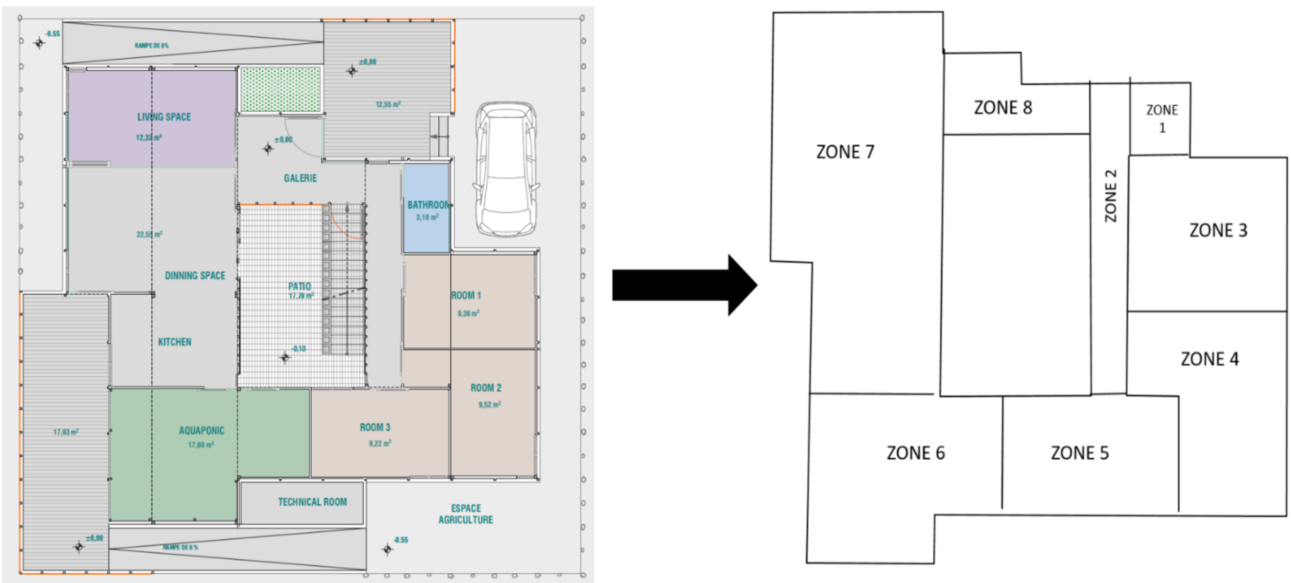


Figure 39: Thermal zones of the house

3.3. Energy simulation of the house

Energy simulations were performed under some set model parameters (see Table 2) using the DesignBuilder software, a user-friendly interface of EnergyPlus commonly used for cooling and heating simulations in buildings[86]. There are generally two major types of heat gains considered in energy simulations in buildings: internal heat gains and external heat gains[87]. Internal heat gains represent the sensible and latent heat generated inside the house due to equipment, lighting, occupants[88]. While external heat gains are the sensible and latent heat penetrating the house by solar irradiation through the walls, roofs, windows, infiltrations of solar rays, heat conduction and convection through facades of the house[89].

However, the main objective of this energy simulation is to reduce and/or remove heat gains in the house by:

- Determining the optimal orientation of the house
- Using passive cooling techniques

Table 2: model set parameters

Type	Data
Infiltration	0.2 ac/h
Natural ventilation	1ac/h
Cooling zones (04)	3 bedrooms, living/kitchen room
Lighting	1W/m^2
Equipment	25 W/m^2
Mechanical ventilation	Off

3.3.1. Selection of the orientation

Each house on the site of the competition has a defined solar envelop so as not to be shaded or shade the neighboring house. Hence, all the facades of the house are exposed to the solar irradiation. A well orientated building can contribute to a significant amount of energy savings throughout the lifecycle of a building [7]. In order, to minimize the heat gains in the building, the orientation of the building was varied for 8 possible orientations (North, South, West, East, North west, North East, South West and South East) and simulations were performed to determine the optimal orientation during the month of September, the competition period. The best orientation chosen is the orientation with the minimum cooling load.

3.3.2. Passive cooling techniques

Passive cooling is used for prevention; modulation and dissipation of heat gains in buildings. Modulation involves the use of thermal storage capacity of the building envelop while heat dissipation refers to techniques such natural ventilation used to dispose of excess heat in the building to the external environment[90]. Protection of heat gains may involve the use of thermal insulation, building form, solar control and shading of external surfaces, control of internal heat gain etc.[91].

There exist many passive cooling solutions used to reduce or remove heat gains in buildings. However, in the course of this research, four (04) passive technologies were explored to analyze their effects in reducing the cooling energy requirements of the house:

- **Use of window blinds and overhangs:** Window blinds are usually used in buildings to shade the windows from the sun and thereby reducing the amount of solar irradiation received by windows. Interior window blinds with high reflective slates and overhangs of 0.5m length were added to all the windows.
- **Use of triple glazed windows**: All the windows were replaced with triple glazed windows (U-value of 0.687W/m^{2}K)
- **Improving on the thermal insulation of roof**. The thermal performance of the roof was improved by adding new materials and increasing the number of layers of the roofing structure from the inside and outside (see Figure 41).

Improved Roof
U-value: 0.425 W/m^{2}K

Figure 40: cross section of improved roof

- **Natural ventilation:** The effect of Night Natural ventilation was also evaluated using the following parameters to control natural ventilation.

Table 3:Natural ventilation set parameters

Indoor max temperature	Outdoor max temperature	Outdoor min temperature	Delta T limit
25°C	25°C	20°C	0°C

The outdoor maximum temperature control is set to avoid overheating the house, which could result in increasing the cooling load. The Delta T limit is the temperature difference between the indoor and the outdoor dry-bulb temperature below which ventilation is shut-off.

The energy simulation was performed for each scenario (see Table 4) and the effect of each solution was analyzed and compared.

Table 4 : Summary of passive cooling techniques used

	Base case scenario	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
Double glazing window	X	X	X	X		
Natural ventilation		X				X
Triple glazing window					X	X
window blind and overhangs			X			X
Improved roof				X		X

3.4. Design of Solar PV cooling system

After the implementation of the different passive cooling techniques, the reduced cooling demand of the house was obtained and a solar PV cooling system was designed to meet this demand. The cooling system will be entirely powered by solar energy as per the requirement of the competition. Hence the use of solar electric cooling system was explored to design an energy efficient and cost-effective active cooling solution to complement the above passive techniques.

Solar electric cooling systems mainly involve two types of technology: solar PV vapor compression system and Solar PV Peltier system. Both systems use electrical energy generated by Solar Photovoltaic to produce cooling effect. The design of these two systems was proposed and comparative cost analysis was later performed to determine the best system for the house.

3.4.1. Design of the vapor compression cooling system

The compression system includes the compressor, condenser, evaporator, expansion valve and refrigerant. A study of each component was done to select the appropriate component type for the cooling system.

- **Selection of Compressor:**

The vapor compression refrigeration represents the most commonly used source of space cooling in buildings. There are 5 major types of compressors used in Air conditioning: reciprocating, screw, rotary, scroll, and centrifugal. Reciprocating (piston), rotary or scroll compressors are usually used in residential and small commercial air conditioning. For medium size and large size cooling capacities, screw compressors and centrifugal compressors are frequently used respectively (see Figure 42)[92]. However, compressor efficiency or compressor power loss are important parameters in compression type selection. In practice, isentropic efficiency above 70% (in the order of 10% motor losses, 10% friction losses and 10% heat transfer losses) are good compressor efficiencies[93] .

$$\text{Where, Isentropic efficiency} = \frac{Isentropic\ power\ output}{Actual\ power\ output}$$

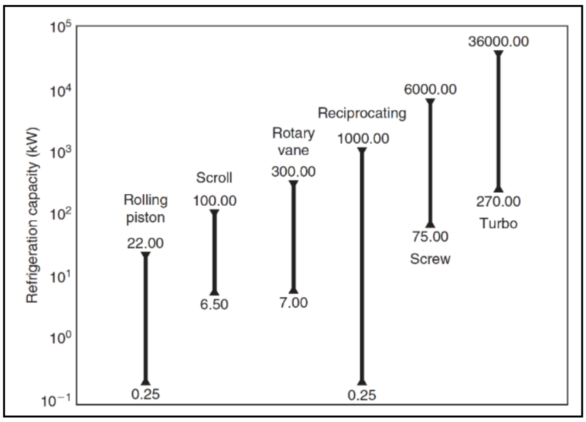


Figure 41: Approximate range of cooling capacities covered by various types of compressors

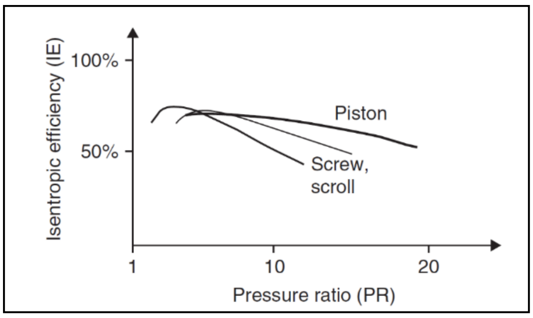


Figure 42: Typical Isentropic efficiencies for various compressor types

• Selection of Condenser:

In cooling applications, the condenser is generally used to reject the heat gains during the evaporation process and compression process of the refrigerant to the environment. There are 3 major types of condensers: water cooled, air cooled and evaporative cooled condenser. Air cooled condensers are most commonly used in small and medium size cooling systems especially in residential areas. Air cooled condensers are simple, does not need a water system, have low capital and running cost compared to water cooled and evaporative cooled[94]. However, air cooled condensers are noisier and consume more power than other condenser types.

Table 5: Typical condensing temperatures for air-cooled and evaporative condensers in various locations[95]

Climate	Air-cooled		Evaporative	
	Dry bulb (°C)	Condenser (°C)	Wet bulb (°C)	Condenser (°C)
South United Kingdom	27	42	21	33
Scotland	24	39	18	30
Mediterranean	32	47	24	36
Desert	47	62	24	36
Tropical humid	33	48	28	40

• Selection of Evaporator:

Evaporator are used to cool the air or liquid which then cools the load. Hence there exist two main types of evaporators: Air cooled evaporators and water-cooled evaporators. Air cooled evaporators are commonly used for small scale applications such as offices, residential buildings[96]. Fan system is generally used to blow the air over the coil by forced convection. All Air-cooled evaporators are direct expansion type. However, maintaining the evaporator at optimum temperature will greatly help reduce the energy consumption[97].

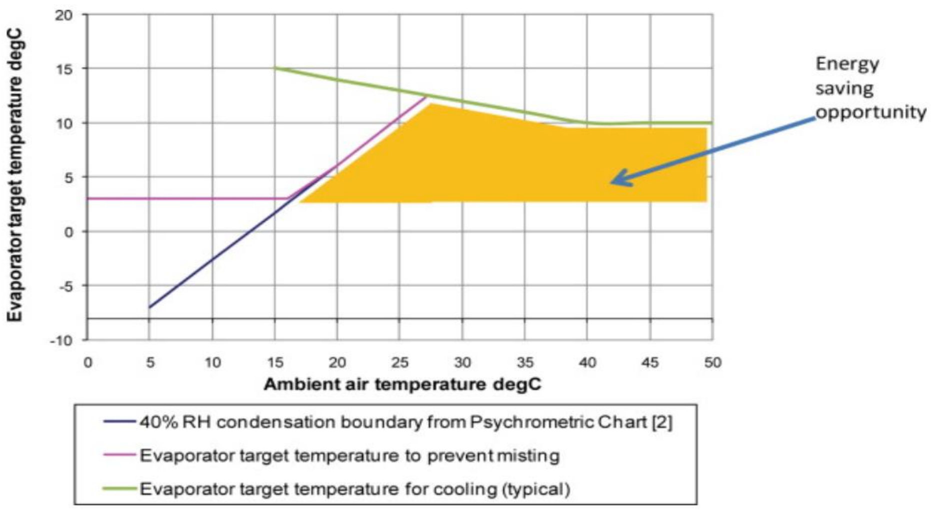


Figure 43: Determination of evaporator target temperature

- **Selection of Expansion valve:**

The expansion valve controls the flow of refrigerant from the high-pressure condenser end to the low-pressure evaporator end. There exist different types of expansion valve based on the control method: thermostatic expansion valve, electronic expansion valves, low pressure float valves, high pressure float valves etc.[92].

The design and installation of direct expansion valve should ensure no liquid refrigerant returns back to the compressor. This is done by allowing a super heat value of about 5K to get the dry saturated gas into the superheat region.

- **Selection of Refrigerant:**

For the past 25 years, there have been great evolution in the use of refrigerant for thermodynamic processes such as CFC (chlorofluorocarbons), HCFC (hydro chlorofluorocarbons) etc. Resulting from Kyoto protocol, hydrofluorocarbons (HFC) have been developed to reduce the greenhouse effect of chlorine based refrigerants[98]. R717 (Ammonia) is a natural refrigerant with zero global warming potential (GWP) and lower cost than HFCs and mainly used for industrial applications[99]. However, HC-1270 (propene) has low GWP and has been used for small split air-conditioning units in Europe for several years since it offers great performance for lower temperature applications and low discharge temperature at compressor, which makes it suitable for single stage compressor[100].

REFRIGERANT OPTIONS for AIR CONDITIONING SYSTEMS (Small and Large)

Type	Refrigerant	GWP	ODP	Flammability	SYSTEM TYPE S	SPL	L	CH	Note #
CFC	CFC-11	4660	1						
	CFC-12	10200	1						
	CFC-13	5820	0.8						
HCFC	HCFC-22	1810	0.055						
	HCFC-141b	782	0.11						
	HCFC-142b	1980	0.065						
Blend	R-404A	3922	0						
	R-410A	2088	0						
	R-407C	1774	0						
HFC	**HFC-134a**	1430	0						
	HFC-32	675	0	2L					1
HC	R-441A (HCR188C)	6	0	3					2
	Propane (HC-290) (R-290)	3	0	3					3
	HC-1270	1-5	0	3					4
Blend	R-432A, B, C	1-5	0	3					5
	R-436A, B	1-5	0	3					5
	R-447A	582	0	2L					6
	R-446A	460	0	2L					6
	R-454B	460	0	2L					6
	Blends awaiting ASHRAE number	250 to 700	0	2L					7
	R-450A	601	0	1					8
	R-513A	631	0	1					8
	R-513B*	596	0	2L					8
	R-451A	140	0	2L					8
	R-451B	150	0	2L					8
	Blends awaiting ASHRAE number	150 to 700	0	2L					9
CO2	CO2 (Carbon Dioxide) (R-744)	1	0	1					10
HFO	HFO-1234yf	4	0	2L					11
	HFO-1234ze	7	0	2L					11
	HFO-1233zd	5	0	1					12
	HFO-1336mzz	9	0	1					12
Water	R-718 (Water)	0	0	1					13
NH3	R-717 (Ammonia)	0	0	2L					14

LEGEND 1:
- High GWP
- Med GWP
- Low GWP

LEGEND 2:
- **S** Small Self-contained
- **SPL** Small Split
- **L** Large Air-to-Air
- **CH** Water Chillers

Not In Kind Solutions
- Improved Building Shell
- Evaporative Coolers
- Desiccant Drying
- Absorption Chillers

Figure 44: Refrigerant alternatives for air-conditioning systems (small and large)

- **Summary design of standard vapor compression refrigeration system:**

The standard vapor compression refrigeration cycle is made up of 4 principle processes (see Figure 47):

- Process 1-2: Isentropic compression of saturated vapor in compressor
- Process 2-3: Isobaric heat rejection in condenser
- Process 3-4: Isenthalpic expansion of saturated liquid in expansion device
- Process 4-1: Isobaric heat extraction in the evaporator

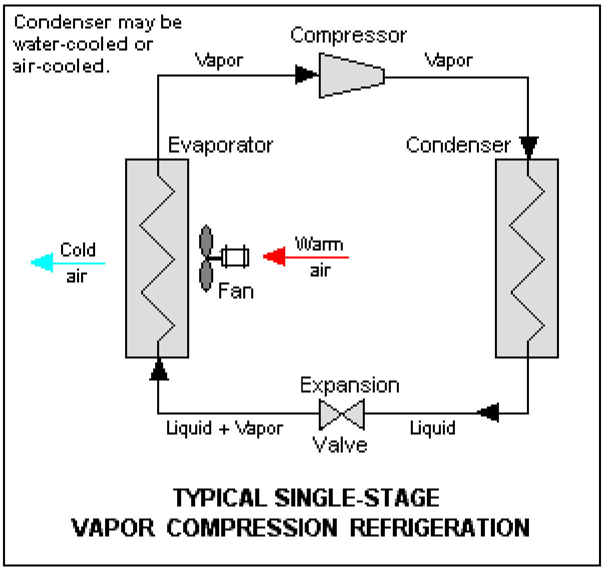


Figure 45: Single stage vapor compression cooling system

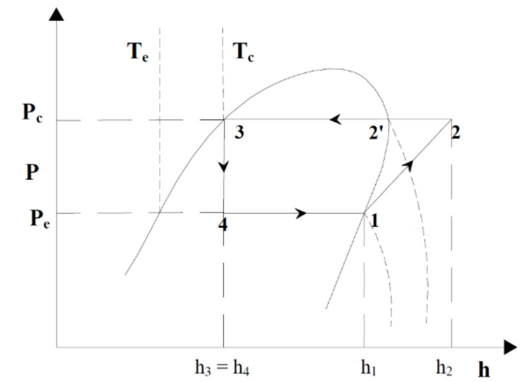


Figure 46: Standard vapor compression refrigeration cycle on a P-h graph

The following table describes the design analysis of each component of the compression system under the assumptions of steady flow, no heat loss through pipes and negligible kinetic and potential changes across each component:

Component	**Definition**	**Description**	**Equation**
Evaporator	heat extracted at the evaporator, Q_e	Also called the refrigeration capacity	$Q_e = m_r(h_1 - h_4)$
	evaporator pressure, P_e	saturation pressure at evaporation temperature, T_e	$P_e = P_{sat}(T_e)$
Compressor	power input to compressor, W_c	Electric power consumption of compressor	$W_C = m_r(h_2 - h_1)$
Condenser	heat rejected at the condenser Q_c		$Q_c = m_r(h_2 - h_3)$
	condenser pressure P_c	saturation pressure at condenser temperature, T_c	$P_c = P_{sat}(T_c)$
Refrigerant mass flow rate, m_r		Ratio of volumetric flow rate V, to specific volume v, at a point	$m_r = \frac{V}{v}$

Expansion device	Enthalpy change	Enthalpy at inlet and outlet of expansion device is constant	$h_3 = h_4$
	quality of the refrigerant at inlet of evaporator, X_4	expansion device exits the refrigerant into the two-phase region	$h_4 = (1 - x_4)h_{f,e} + x_4 h_{g,e} = h_f + x_4 h_{fg}$
Coefficient of performance, COP		ratio of refrigeration effect to the input power of the compressor	$COP = \frac{Q_e}{W_c}$
Where: m_r is the refrigerant mass flow rate h_1 and h_4 are the specific enthalpies at exit and inlet of evaporator respectively h_1 and h_2 are the specific enthalpies at exit and inlet of compressor respectively h_3 and h_4 are the specific enthalpies at inlet and exit of expansion device respectively $h_{f,e}$, $h_{g,e}$, h_{fg} are enthalpy of saturated liquid, saturated vapor and the latent heat of vaporization at evaporator pressure respectively.			

3.4.2. Design of the Peltier cooling system

In this case, the cooling demand of the house is entirely provided by the cooling capacity of the Peltier cooling system, which is electrically powered by the solar PV system.

- **Selection of Peltier module:**

There exist different types of thermoelectric modules based on the different applications. These include: Annular style, Ceramic plate (CP), HiTemp ET, Powercycling (PC), porch-style, miniature (OptoTEC), high heat flux density (UltraTEC), high performance (ZT), Multistage (MS) series thermoelectric modules[101]. Standard Ceramic plate (CP) series of thermoelectric modules are assembled with Bismuth Telluride semiconductor material and thermally conductive Aluminum Oxide ceramics[102]. This series type can be designed for higher current and large heat-pumping applications and was chosen for the design of the Peltier cooling system for this study[103]. Commercially available thermoelectric module (type 9500/127/060B) with its parameters (see table) were used for the design[104].

- **Design of the Peltier cooling system:**

The design of the Peltier cooling system was done as shown in the table below [105]

	Definition	Equation
Q_C	heat absorbed at cold site	$Q_C = N \times \left[\alpha \times I \times T_C - \frac{I^2 \times R}{2} - K \times (T_H - T_C)\right]$

Q_H	heat rejected from the hot side	$Q_H = N \times \left[\alpha \times I \times T_C + \frac{I^2 \times R}{2} - K \times (T_H - T_C)\right]$
P_E	electrical power consumed by the system	$P_E = N \times [\alpha \times I \times (T_H - T_C) + I^2 \times R]$
COP	coefficient of performance	$COP = \frac{Q_C}{P_E}$
Where: N is the number of thermoelectric devices, T_C and T_H, the temperature at cold side and hot side respectively α, K and R are the Seebeck coefficient, thermal conductivity and electrical resistance of the of TEM respectively I, the current		

3.4.3. Design of the Solar PV system:

The purpose of the design is to determine the size and quantity of the main components of the solar PV system that will provide the required electrical energy to run the cooling system. The schematic diagram below illustrates the configuration of the Solar PV cooling system. No battery storage is considered in the design calculations.

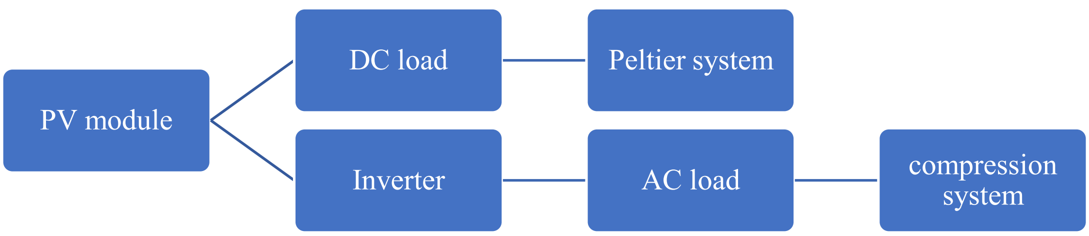


Figure 47: Schematic of Solar PV cooling system

- **Solar irradiation potential**

The daily average irradiation of 5.64KW/m^2/day from the Site's Meteorological station was used in the analysis.

IRESEN High Precision Meteorological Station in Ben Guerir, Morocco, March 2015 to February 2016

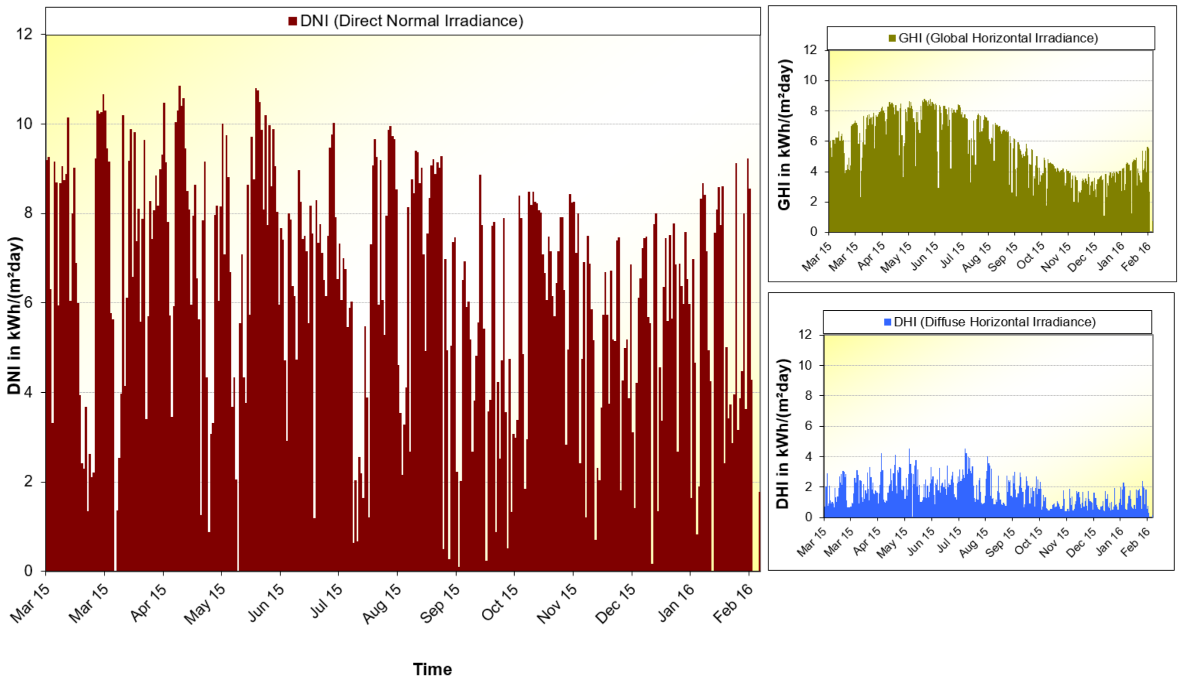


Figure: Daily global, Direct and Diffuse irradiance in Ben guerir

- **Load analysis:**

The Peltier module and compressor are the two main component loads considered in the sizing and both systems are operating for 8 hours per day. The electrical specifications of the compressor (Table 8) was used for the selection of the appropriate inverter.

Table 6: specifications of the Peltier module

Length	39.70 mm
Width	39.70 mm
Thickness	4.16 mm
Number of thermocouples	127
Q_{max} (W)	57
DT_{max} (K)	72
I_{max} (A)	6
V_{max}	17.5
T_{ho} (K)	323
α (V/K)	0.0542
K (W/K)	0.5666
R (Ohm)	2.2665
ZT_{ho}	0.7389

Table 7: compressor specifications

Technology	Reciprocating
Configuration	Single
Refrigerant	HC-1270
Capacity control	Variable speed
Speed [rpm]	3217
Power [W]	3507
Current [A]	7.535
Frequency [Hz]	50
Power supply	380 - 400 V (415 V) 3 ph*
Mass flow [kg/s]	0.1202

- **Selection of main components:**

High performance PV module HIT technology was selected for the sizing of both systems. Also, a hybrid off-grid inverter was chosen to satisfy the electrical requirements of the compressor.

Table 8: PV module specifications

Module Specification	
Component	**Capacity**
Manufacturer	Panasonic
Technology	Hit
Model	slim VBHN250SJ25
Price ($)	200
Max Power (W)	250
Imax (A)	5.65
Vmax (V)	44.3
Voc (V)	53.2
Isc (A)	6.03
Eff_module (%)	19.8

Table 9: Inverter specifications

Component	**Capacity**
Manufacturer	SMA
Technology	SUNNY BOY
Model	7.7-US
Price ($)	1100
Max AC power (W)	7680W
Efficiency (%)	0.975
Vmaxmppinv (V)	550
Vminmppinv (V)	100
Max DC voltage (V)	600
Imaxmppinv (A)	10
Iminmppinv (A)	1
Operating voltage, DC (V)	100 – 550
Phase	3phase
Frequency (Hz)	50/60
Power Ratio	1
Max recommended DC power (W)	7950

The above data were used and computed on EXCEL to determine the size of each component for both cooling systems

CHAPTER 4: RESULTS AND DISCUSSION

This chapter deals with the results obtained from our simulations. These results are thereafter discussed.

4.1. Energy analysis and simulation

The results of the energy simulation are presented as follows:

4.1.2. Optimal orientation of the building

The building orientation at 315° was chosen as the optimal orientation since it shows minimum cooling load (see Figure 49). Adopting this orientation contributes to energy savings and help reduce the size of active cooling system.

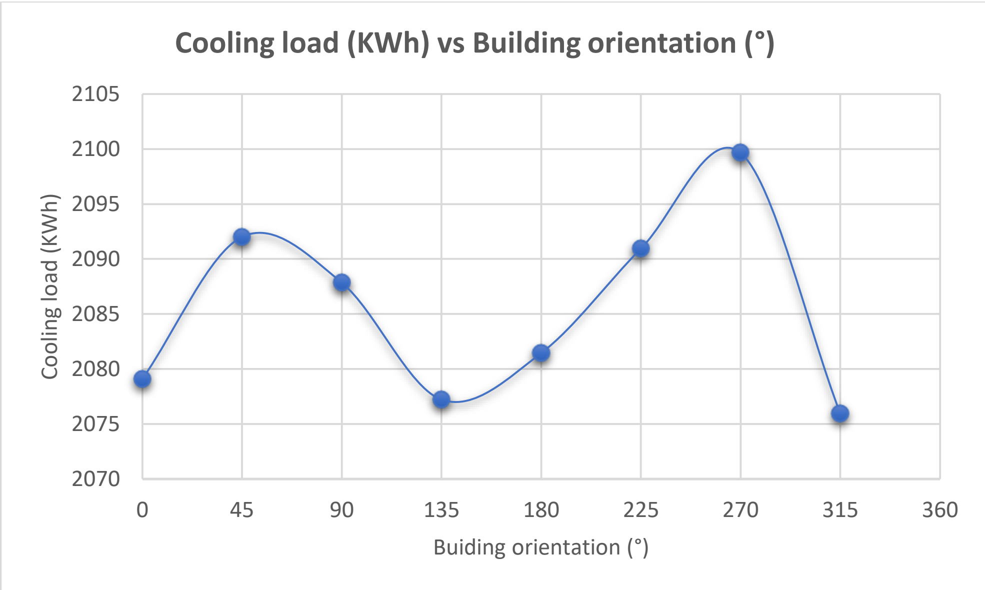
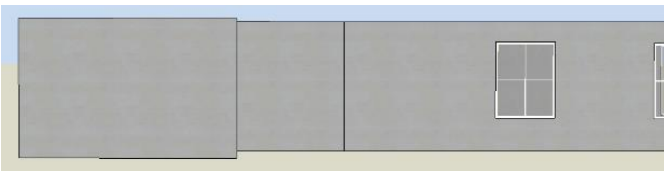


Figure 48: Building orientation vs cooling load

The figure below shows the orientation of the different facades at optimal building orientation. This represents the orientation of the house with facades exposed to minimum heat gains.

East facade



North facade

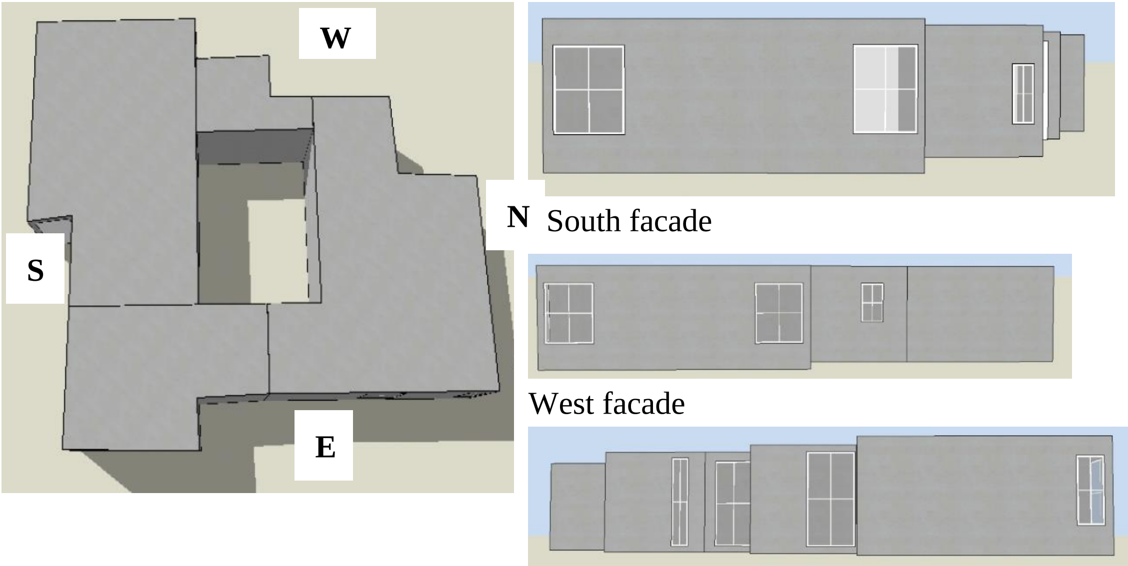


Figure 49: Optimal orientation of the house

4.1.3. Passive cooling solutions

The energy analysis of the building at optimal orientation (base case scenario) shows that solar heat gains through the windows, heat gains through roofs and walls greatly contribute to the overall external heat gains in the house during the period of the competition (see Figure 51). This is summarized in Figure 52.

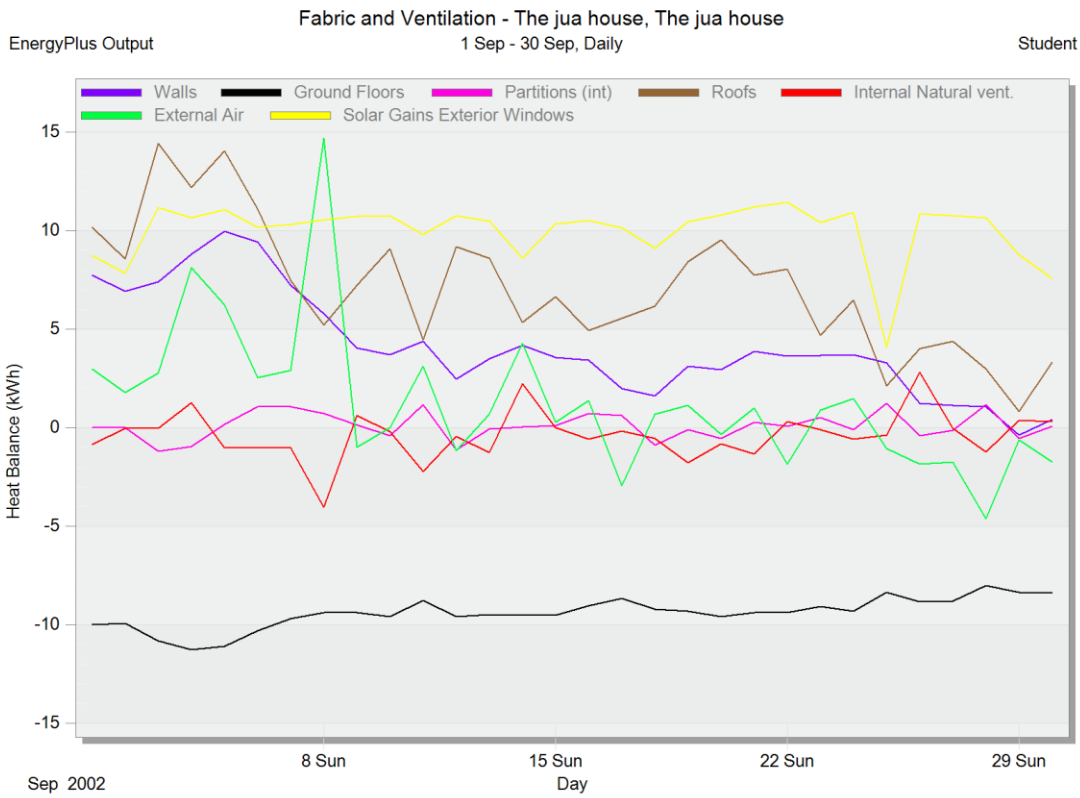


Figure 50: External heat gains in the house during month of competition

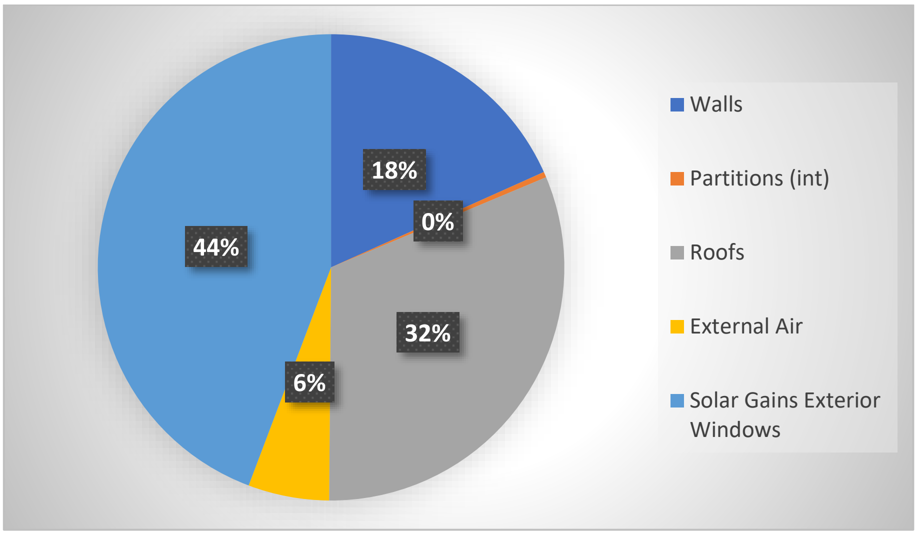


Figure 51: Summary of monthly external heat gain in the house

The following shows the effects of each passive solution on the overall cooling load of the house compared to base case scenario. This includes the use of natural ventilation, triple glazed windows, window blinds and overhangs and improved roof.

- Effect of Natural ventilation:

Figure 52 shows the contribution of natural ventilation in reducing the cooling load in the house. This represents the cooling energy savings from natural ventilation during the competition period. This variation is affected by the outdoor temperature, the direction and wind speed and the orientation of windows.

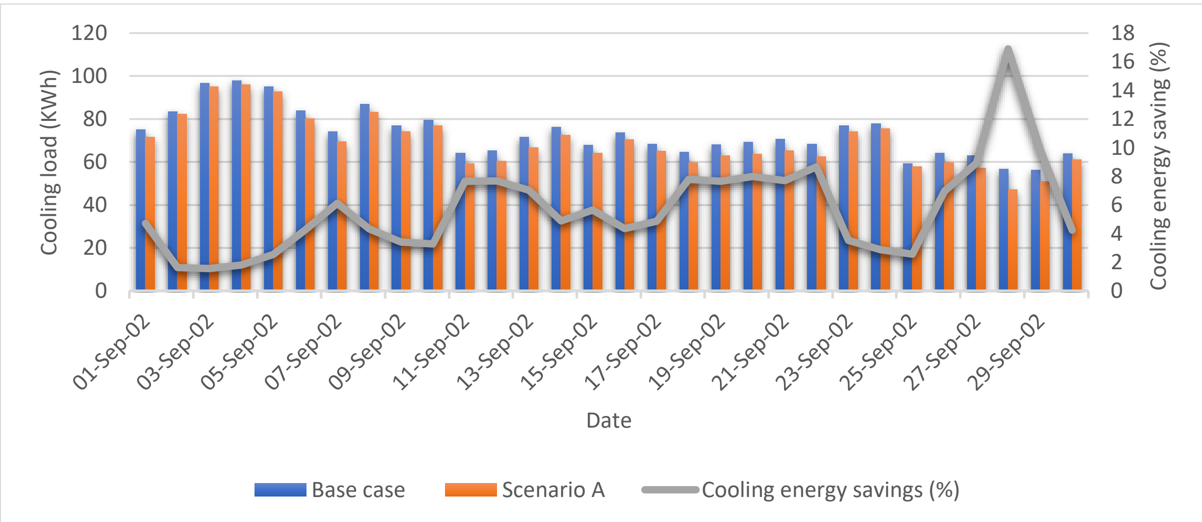


Figure 52: Effect of Natural ventilation on daily cooling load

- Effect of window blinds and overhangs:

This shows that the use of window blinds and overhangs reduces the amount of solar heat gains through the windows and thereby reducing the cooling load in the house.

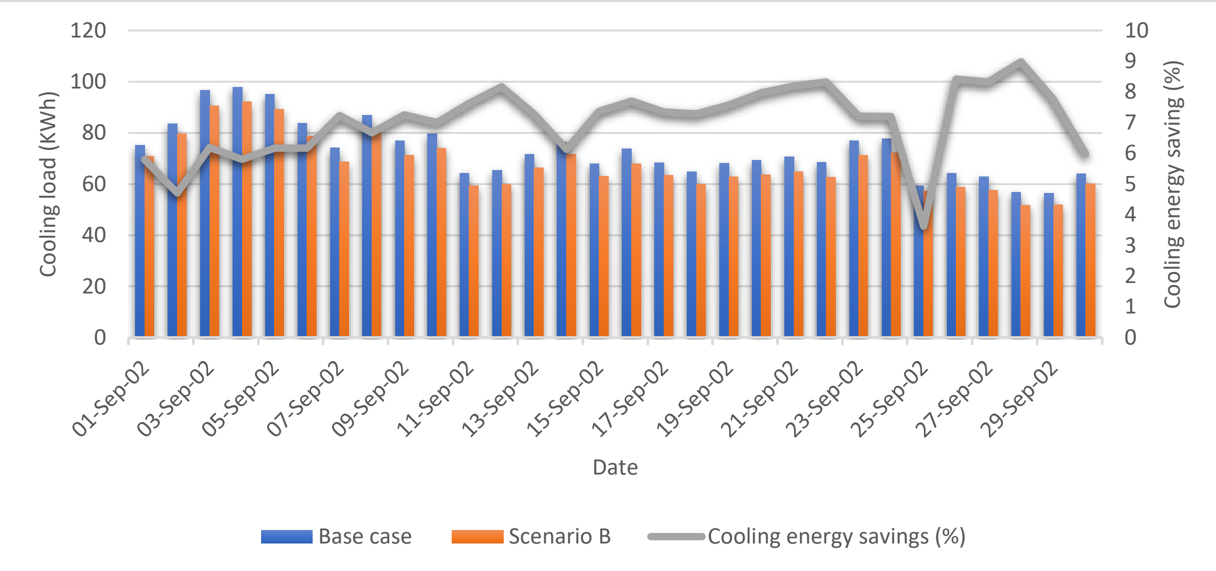


Figure 53: Effect of window blinds and overhangs on daily cooling load

- Effect of improved roof:

Improving the thermal performance of the roof helps reducing the heat gains in the house through the roof and therefore decreasing the amount of energy need to cool the house.

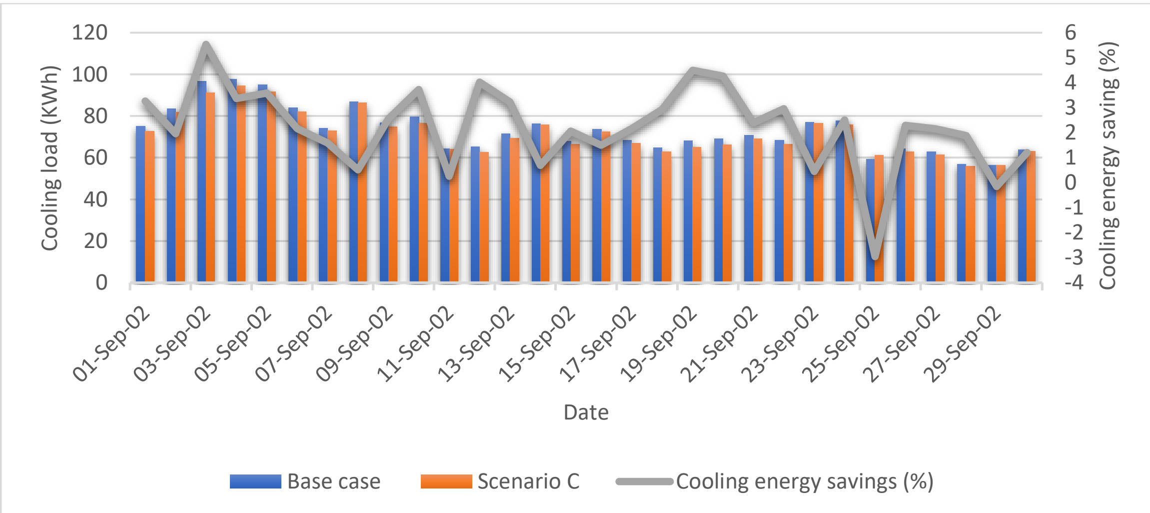


Figure 54: Effect of improved roof on daily cooling load

- Effect of triple glazing windows:

Replacing the windows in the house with high performance triple glaze windows helps in reducing the heat gains through the windows and thereby decreasing the cooling load.

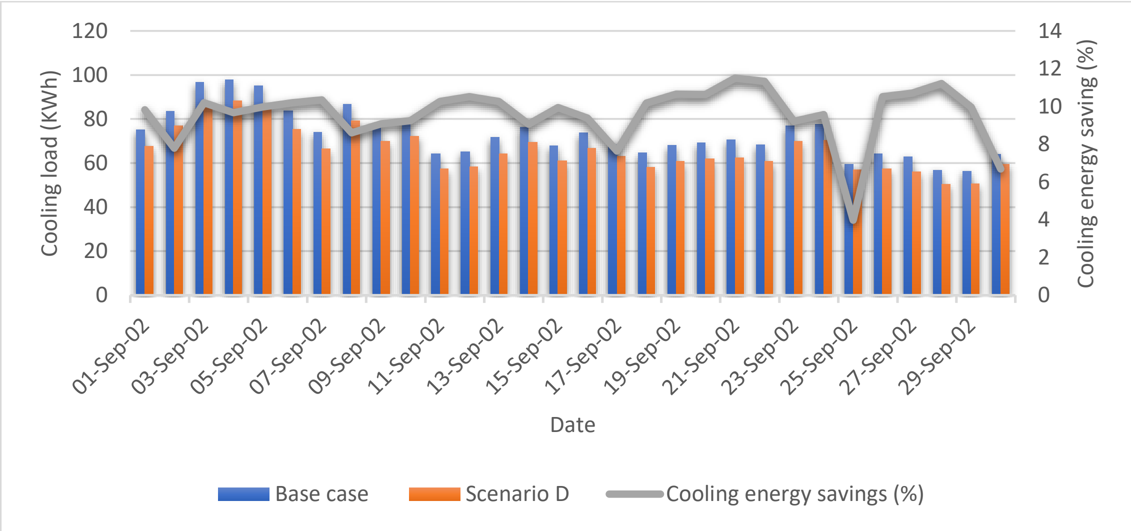


Figure 55: Effect of tripled glazed windows on daily cooling load

- Effect of combine passive solutions:

Figure 57 shows that applying the different passive solutions in the house greatly helps in the reducing the cooling load in the house.

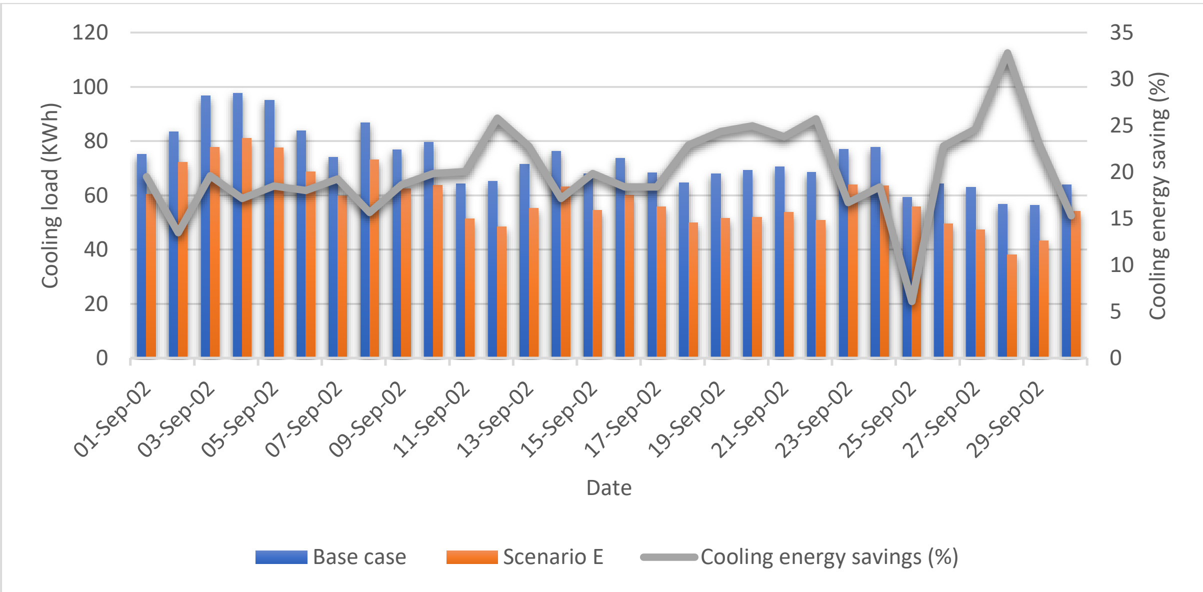


Figure 56: Effects of the combined passive solutions on the daily cooling load

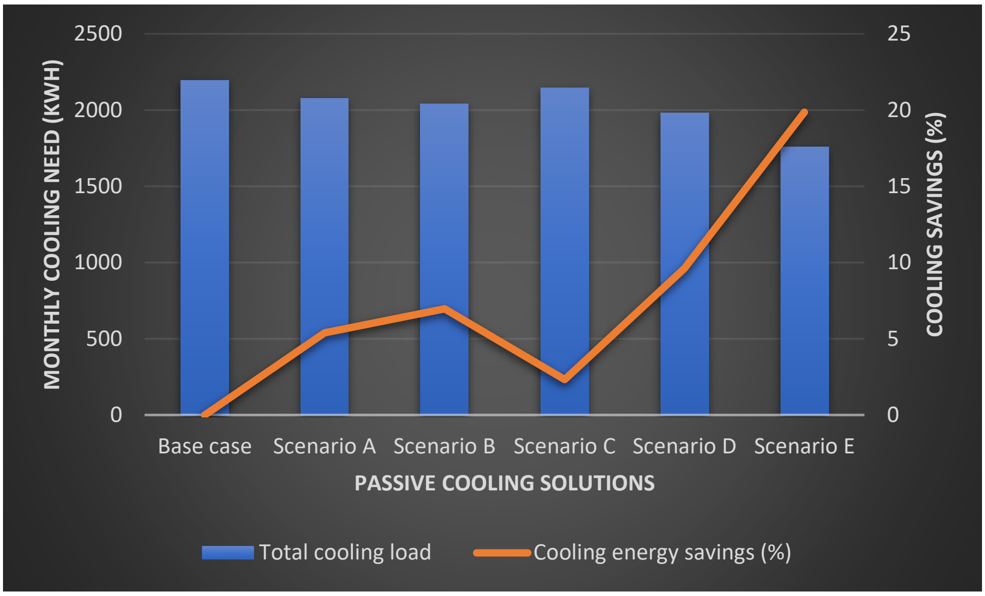


Figure 57: Effects of passive cooling techniques on monthly cooling demand of the house

The above results show that the addition of window blinds and overhangs, triple glazing windows and improvement of roof thermal insulation all contribute to the reduction in cooling load of the house. The combined effect of these solutions contributes in reducing the cooling demand of the house by 20% averagely during the period of the competition.

4.2. Solar electrical cooling system

4.2.1. Compression cooling system

After the evaluation of the cooling load of the house, a vapor compression cooling system was designed with the aid of CoolPack and EES software[106] to fulfil this cooling requirement and provide the adequate comfort conditions in the house. Table 10 shows the cooling design for the four conditioned zones considered.

Table 10: Total cooling load for the building conditioned zones

	ROOM1	ROOM2	ROOM3	LIVING ROOM & KITCHEN	Total
Total Cooling Load (kW)	1.99	2.08	2.27	4.23	10.57
Design Capacity (kW)	2.29	2.39	2.62	4.87	12.16

The design of the system was done based on the optimal conditions of the system components chosen.

Table 11: vapor compression cooling system design parameters

Parameter	Value
Refrigerant	HC- 1270
Evaporator temperature	8°C
Condenser temperature	47°C
Compressor isentropic efficiency	70%
Compressor heat loss	10%
ΔT superheat	5K
ΔT cooling	2K

Figure 59 below defines the characteristics of the cooling system at its different state points

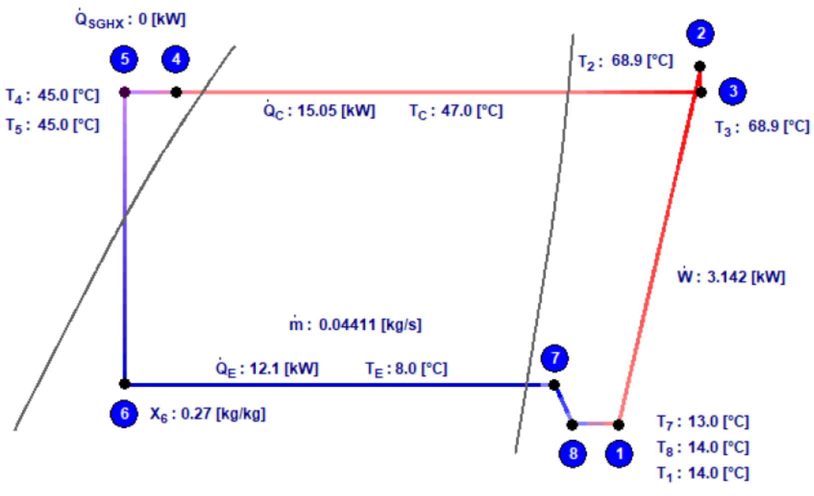


Figure 58: p-h diagram of compression cooling system and characteristics of its different state points.

Table 12 and 13 below summaries the characteristics of the vapor compression cooling system that has been designed.

Table 12: Summary of component system design

Evaporator capacity	12.1 kW
Condenser output	15.05 kW
Compressor power	3.14 kW
Refrigerant volume flow rate	10.78 m^3/h
Coefficient of performance (COP)	3.88

Table 13: Pipe dimensions at different sections of the compression cooling system.

Pipe section	Refrigerant velocity	Internal pipe diameter (mm)	Condition correspond to
Suction line	10	19.5	State point 1
Discharge line	12	11.3	State point 2
Liquid line	0.6	14.2	State point 5

4.2.2. Peltier cooling system

The design of the Peltier cooling system was performed on Excel spreadsheet under assumed operating temperature conditions of hot and cold side as shown below:

Design Parameters						
Parameters	Designation	Units	Value		Design units	
Cooling capacity	Qc	W	12000		12	KW
Temperature different between hot and cold side	dT= (Th-Tc)	K	30			
Temperature at cold side	Tc	K	278		5	°C
Temperature at hot side	Th	K	308		35	°C
Calculated parameters						
Parameters	Designation	Values		Design units		
Number of thermoelectric modules	N	368				
Electrical consumption	Pe (W)	33614.84		33.61	KW	
Coefficient of performance	COP	0.36				

4.2.3. Solar PV sizing for the Peltier system and compression system

Both the compression and Peltier cooling system are operating individually for 8 hours per day to provide required indoor comfort conditions in the house.

Two separate solar PV systems are designed to meet the electrical power consumption of compressor and the Peltier system.

Table 14: sizing of Solar PV for the Peltier system

	units	**Value**
Electrical consumption	kW	33.6
Hours of use	hours	8
Daily Energy consumption	kWh	268.8
Performance Ratio		0.7
Daily average irradiation	kWh/m2/day	5.64
PV field size	kW	68.09
Number of panels		**272**

Table 15: Sizing of the Solar PV for compression system

	Units	**Value**
Electrical consumption	kW	3.507
Hours of use	hours	8
Daily energy consumption	kWh	**28.056**
Performance Ratio		0.7
Daily irradiation	kWh/m2/day	5.64
Min Energy Supplied by PV	kW	7.3
Number of panels		29.2
Number of panels in parallel	Np. Max	1.8
	Np. Min	0.2
Number of panels in series	Ns. Max	11.3
	Ns. Min	2.3
Total Panels Max	Mppt 1	**11.0**
	Mppt 2	**11.0**
	Mppt 3	**8**
	Ntot_mod	**30**

No inverter is used for the PV sizing of the Peltier cooling system since it uses direct current from the PV modules. A total of 272 modules of 250W are required to meet the electrical consumption of the Peltier cooling system. On the other hand, in the case of compression system, an inverter is necessary to convert the direct current from PV modules to AC current for compressor. A total number of 30 PV panels are required to meet with the electrical consumption of the compressor.

4.3. Comparative cost analysis of compression cooling system vs Peltier cooling system.

This section presents a comparative cost estimate analysis of both systems based on a market survey. 2.5kW and 5kW split air conditioning system (compression system) was chosen for the rooms and living room respectively (see Appendix for technical specifications). The prices of different components of the system were consulted from different manufacturers and to the total cost estimate of each system was performed as shown in table 16 and 17 below.

Table 16: Total cost estimate of Vapor compression cooling system

Compression cooling system					
Item	Item specifications	quantity	Unit price ($)	Cost ($)	Manufacturer
Split A/C Inverter system	2.5 kW	3	900	2700	Dimplex
Split A/C Inverter system	5 kW	1	1360	1360	Dimplex
PV module	250W HIT	30	200	6000	Panasonic
Inverter	Sunny Boy 7.7 US	1	1725	1725	SMA
Wires and Accessories		Lumpsum (20%)		1545	
Total system Cost ($)	**13330**				

Table 17: Total cost estimate of Peltier cooling system

Peltier cooling system					
Item	Item specifications	quantity	Unit price ($)	Cost ($)	Manufacturer
Peltier modules (type 9500/127/060B)	57 W	368	5	1840	Digi Key
PV module	250W HIT	272	200	54400	Panasonic
Wires and Accessories		Lumpsum (20%)		10880	
Total system Cost ($)	**67120**				

We can see from table 16 and 17 that the cost of Peltier system is about five (05) times higher than the compression system. This is mainly due to the higher electrical consumption of Peltier modules (The COP of Peltier system is less than that of compression system) which greatly increases the amount of PV modules needed for the system.

Conclusion and Recommendations

The energy consumption in the building sector is quite high and is expected to further increase due to factors such as climate, economic growth, population growth and rapid urbanization. The use of air conditioning has increasingly penetrated the market during the last decades and considerably contributes in the upsurge of energy consumption in buildings due to lack of minimum energy performance standards (MEPS) and energy labelling for air conditioning systems. The use of Hydrofluorocarbons (HFCs) refrigerants in air conditioners have greatly contributes to increasing global warming. In addition, the increasing demand for space cooling has led to significant increase in electricity production and hence raising the CO_2 emissions as a result of construction of new power plants. Africa is greatly affected by effects of climate change and global rising temperatures which raises the need for space cooling. However, poor access to electricity coupled with low income earnings makes access to cooling a challenging issue. However, Africa is endowed with a huge potential for solar cooling due to the near coincidence of peak cooling loads with the available solar power. All these show that the implementation of energy efficiency measures and the use of solar energy technologies into buildings will greatly help reduce the energy demand for cooling. Hence, the need to develop cost effective and energy efficient cooling solutions to provide sustainable access to cooling in Africa. The review of passive cooling technologies in buildings has proved that the use of simple passive cooling techniques can greatly help in reducing the cooling load in buildings at affordable cost. Also, the use of energy efficient active cooling technologies such conventional air conditioning systems greatly contributes in reducing the energy consumption for space cooling.

The design of a combined passive and active solar cooling solution was done in the context of Solar Decathlon Africa competition as a way to promote energy efficiency and to shed the light on the importance of passive and Active solar design strategies in buildings in Africa.
Energy need analysis for a smart African solar house called Jua house designed for the Solar Decathlon Africa, was performed using DesignBuilder Software to better understand the findings from previous works and propose a sustainable cooling solution that can be implemented in new and existing buildings across Africa. The results of this analysis show that the use of simple cooling techniques such as building orientation, use of window blinds and overhangs, natural ventilation, triple glazing windows and high thermal performance roof can contribute for up to 20% reduction in cooling load from 2195kWh to 1758kWh cooling energy per month. The optimal design indicates that compression system is the best energy efficient solution for active electrical cooling in buildings. In fact for the same cooling needs, a compression cooling system with COP of 3.88 and electrical power of 3.14kW has been designed, and a Peltier cooling system with COP of 0.36 and electrical power consumption of 33.61kW was obtained as an equivalent cooling system. The results of Solar PV sizing shows that a total of 272 modules of 250W PV panels are required for Peltier system compared to 30 modules of 250W PV panels for vapor compression system. A cost comparative analysis

proves that air conditioning systems is a cheaper option with total system cost of $13330 compared to $67120 for Peltier cooling system

However, this research was done on a building with some already implemented energy efficiency measures but with the goal of reducing cooling demand and cost of cooling the house by improving on the energy performance of the house. Further work can be done in comparing this building with a typical house in Africa and also evaluating the overall lifecycle cost for implementing both active and passive solar cooling solutions.

Rigorous actions need to be taken to curb the potentially huge growth in cooling demand and promote energy efficiency in buildings in Africa. It is clear that without government intervention, sensitizing and education of public authorities, building professionals and the communities, access to energy-efficient cooling equipment will remain an expensive option and neither will builders and architects develop energy performance buildings to minimize cooling requirements. Public authorities at national, regional and local levels should take the responsibility to promote investments and mandate standards in the energy performance of buildings and cooling equipment that are needed to provide sustainable solution to reduce demand for cooling. Policy action such as efficiency standards for air conditioning systems and building codes have been in place for many years in many countries and have rendered large and cost-effective energy savings. Strengthening and broadening the use of such measures is the key to meeting the needs for space cooling in Africa in a truly sustainable way.

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Appendix

Appendix A: Technical Specifications of Air conditioning system

2.5kW DC Inverter Split System Air Conditioner

Dimplex

eliteSeries

- Accurate thermostat +/- 0.5°C
- Slim body
- Powerful cooling & heating
- DRED function
- 5-speed fan
- DC inverter motor
- 3 way air flow
- Child lock
- Display shutdown
- Titan Gold Compressor
- Outdoor unit wall brackets included with DCES09, DCES12 & DCES18

Model No.		DCES09
Cooling Capacity	kW	2.5
Heating Capacity	kW	2.5
EER / COP	W/W	4.43 / 4.33
Energy Star for Cooling	-	4
Energy Star for Heating	-	4
Moisture removal	L/h	0.8
Noise Level	dB(A) Indoor	24-42
	dB(A) Outdoor	52
Electrical Data		
Power Supply	V -/HZ	220-240V -50Hz
Running Current	Cooling (A)	3.6 (1.3-6.5)
	Heating (A)	3.6 (1.3-7.0)
Power Input	Cooling (W)	590 (290-1300)
	Heating (W)	590 (290-1500)
Refrigerating System		
Refrigerant	R410A Volume (kg)	1
Compressor	Type	Rotary
Connections		
Connecting Pipe	Gas (inches)	3/8"
	Liquid (inches)	1/4"
Dimensions		
Net Dimensions (W x H x D)	Indoor (mm)	814 x 306 x 210
	Outdoor (mm)	760 x 551 x 256
Net Weight	Indoor (kg)	9
	Outdoor (kg)	28
Operating Range Limitations	°C	-15°C - 52°C
Warranty	Domestic Use	5 years
	Commercial Use	1 year

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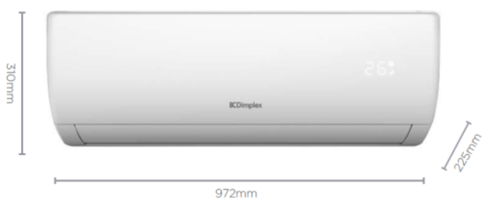
Figure 59: Technical specifications of 2.5Kw Split Air conditioning system

5kW DC Inverter Split System Air Conditioner

Dimplex

eliteSeries



- Accurate thermostat +/- 0.5°C
- Slim body
- Powerful cooling & heating
- DRED function
- 5-speed fan
- DC inverter motor
- 3 way air flow
- Child lock
- Display shutdown
- Titan Gold Compressor
- Outdoor unit wall brackets included with DCES09, DCES12 & DCES18

Model No.		DCES18
Cooling Capacity	kW	5
Heating Capacity	kW	5
EER / COP	W/W	3.28 / 3.54
Energy Star for Cooling	-	2
Energy Star for Heating	-	2.5
Moisture removal	L/h	2
Noise Level	dB(A) Indoor	28-46
	dB(A) Outdoor	56
Electrical Data		
Power Supply	V -/HZ	220-240V -50Hz
Running Current	Cooling (A)	6.6 (1.4-10.3)
	Heating (A)	6.2 (1.4-10.9)
Power Input	Cooling (W)	1510 (300-2300)
	Heating (W)	1420 (300-2450)
Refrigerating System		
Refrigerant	R410A Volume (kg)	1.2
Compressor	Type	Rotary
Connections		
Connecting Pipe	Gas (inches)	1/2"
	Liquid (inches)	1/4"
Dimensions		
Net Dimensions (W x H x D)	Indoor (mm)	972 x 310 x 225
	Outdoor (mm)	780 x 605 x 290
Net Weight	Indoor (kg)	12
	Outdoor (kg)	36
Operating Range Limitations	°C	-15°C - 52°C
Warranty	Domestic Use	5 years
	Commercial Use	1 year

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Figure 60: Technical specifications of 2.5Kw Split Air conditioning system

Appendix B: Data sheet of Sunny boy inveter

Technical data	Sunny Boy 6.0-US		Sunny Boy 7.0-US		Sunny Boy 7.7-US	
	208 V	240 V	208 V	240 V	208 V	240 V
Input (DC)						
Max usable DC power	5400 W	6200 W	6900 W	7200 W	6900 W	7950 W
Max. DC Voltage	600 V					
Rated MPP Voltage range	220 - 480 V		245 - 480 V		270 - 480 V	
MPPT operating voltage range	100 - 550 V					
Min. DC voltage / start voltage	100 V / 125 V					
Max. operating input current per MPPT	10 A					
Max. short circuit current per MPPT	18 A					
Number of MPPT tracker / string per MPPT tracker	3 / 1					
Output (AC)						
AC nominal power	5200 W	6000 W	6660 W	7000 W	6660 W	7680 W
Max. AC apparent power	5200 VA	6000 VA	6660 VA	7000 VA	6660 VA	7680 VA
Nominal voltage / adjustable	208 V / ●	240 V / ●	208 V / ●	240 V / ●	208 V / ●	240 V / ●
AC voltage range	183 - 229 V	211 - 264 V	183 - 229 V	211 - 264 V	183 - 229 V	211 - 264 V
AC grid frequency	60 Hz / 50 Hz					
Max. output current	25.0 A	25.0 A	32.0 A	29.2 A	32.0 A	32.0 A
Power factor (cos φ)	1					
Output phases / line connections	1 / 2					
Harmonics	< 4 %					
Efficiency						
Max. efficiency	97.2 %	97.6 %	97.1 %	97.5 %	97.1 %	97.5 %
CEC efficiency	96.5 %	97 %	96.5 %	97 %	96.5 %	97 %
Protection devices						
DC disconnect device	●					
DC reverse polarity protection	●					
Ground fault monitoring / Grid monitoring	●					
AC short circuit protection	●					
All-pole sensitive residual current monitoring unit (RCMU)	●					
Arc fault circuit interrupter (AFCI)	●					
Protection class / overvoltage category	I / IV					
General data						
Dimensions (W / H / D) in mm (in)	535 x 730 x 198 (21.1 x 28.5 x 7.8)					
Packaging Dimensions (W / H / D) in mm (in)	600 x 800 x 300 (23.6 x 31.5 x 11.8)					
Weight / packaging weight	26 kg (57 lb) / 30 kg (66 lb)					
Operating temperature range	- 25°C ...+60°C					
Noise emission (typical)	39 dB(A)		45 dB(A)			
Internal power consumption at night	< 5 W					
Topology	Transformerless					
Cooling concept	Convection		Fan			
Features						
Ethernet ports	2					
Secure Power Supply	●*					
Display (2 x 16 characters)	●					
WLAN	●					
Sensor module / External WLAN antenna	○ / ○					
Warranty: 10 / 15 / 20 years	●/○/○					
Certificates and approvals	UL 1741, UL 1998, UL 1699B, IEEE1547, FCC Part 15 (Class A & B), CAN/CSA V22.2 107.1-1					
● Standard features ○ Optional features – Not available	Data at nominal conditions NOTE: US inverters ship with gray lids. * Not functional with Power+ Solution					
Type designation	SB6.0-1SP-US-40		SB7.0-1SP-US-40		SB7.7-1SP-US-40	

Figure 61: Technical sheet of inverter

Appendix C: Research grant expenses

Monthly Breakdown	Item	Description	Price (local)		Price (USD)	Quantity	Amount, $
March	Flight ticket	Return flight for research	DZD	129,500.00	$ 1,146.02	1	$ 1,146.02
	Visa Togo	30 days validity	CFA	25,000.00	$ 45.45	1	$ 45.45
	Travel Insurance to Togo	3 months coverage	DZD	5,500.00	$ 48.67	1	$ 48.67
	Internet	10.8gb/15 days	CFA	15,500.00	$ 28.18	1	$ 28.18
	TOTAL						$ 1,268.33
April	Internet	10.8gb/15 days	CFA	15,000.00	$ 27.27	1	$ 27.27
	Software	1 year student license			$ 480.00	1	$ 480.00
	Visa Togo	30 days validity	CFA	25,000.00	$ 45.45	1	$ 45.45
	TOTAL						$ 552.73
May	Internet	7.2gb/15 days	CFA	10,000.00	$ 18.18	1	$ 18.18
	Internet	3.6gb/15 days	CFA	5,000.00	$ 9.09	1	$ 9.09
	Admin fee	change of flight date	DZD	25,800.00	$ 228.32	1	$ 228.32
	Visa Togo	30 days	CFA	25,000.00	$ 45.45	1	$ 45.45
	TOTAL						$ 301.05
June	Insurance Morocco	3 months coverage	DZD	8,052.00	$ 71.26	1	$ 71.26
	Visa Morocco	90 days validity	MAD	330.00	$ 34.74	1	$ 34.74
	field transportation	Marrakech to benguerir	MAD	40.00	$ 4.21	3	$ 12.63
	Flight ticket	Return flight for internship	DZD	45,045.00	$ 398.63	1	$ 398.63
	Internet	10gb	MAD	100.00	$ 10.53	1	$ 10.53
	TOTAL						$ 456.52
July	internet	5gb	MAD	50.00	$ 5.26	4	$ 21.05
	TOTAL						$ 21.05
August	internet	5gb	MAD	50.00	$ 5.26	5	$ 26.32
	TOTAL						$ 26.32
	SUM TOTAL						$ 2,625.99