The Performance Investigation of a Grid Connected Solar Photovoltaic System in a Passive Energy Designed Dwelling at the Foothills of the Western Himalayas

A Thesis Submitted for the Degree of Doctor of Philosophy

By:

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Abstract

The unpredictability of the fossil fuel energy market and the noticeable growing understanding of its impact on the environment, research in reducing energy consumption in buildings, has gained significant traction. The UNEP (United Nation Environment Program) in its 2020 Buildings Global Status Report, suggests the level of CO_2 emissions from the building sector is 38% of the total CO_2 energy related emission worldwide. This is important in the subtropical regions where the CO_2 emission percentage is likely to be higher due to the pattern and nature of energy consumption. The energy portion consumed in the residential sector on comfort cooling is the highest, and the main contributor of other than CO_2 GHG (Greenhouse Gases), due to the use of refrigerants, while electricity needed to drive the power-hungry compressor motors is mostly generated from burning fossil fuels. In Southwest Asia, including the Gulf Region, which is the area chosen in this research, up to 70% of the electricity consumption during the long summer months, and approximately 50% annual average, is attributed to air conditioning. This energy consumption will continue to rise due to the unabating population growth, persistent demand for houses, and the growing impoverished neighbourhoods in many metropolises. Energy saving guidelines have become mandatory, particularly, for commercial, institutional, governmental and industrial sectors. However, this is to a lesser extent in the private residential sector. This is further compounded by the inability to enforce these guidelines. In addition, the heavily subsidized electricity tariff in comparison with other sectors. In some of the GCC (Gulf Cooperation Council) countries, the residential tariffs can be up to 13 times lower than other sectors and 20 to 25 times lower than the cost of electricity production. In Kuwait, which holds 7% of the global oil reserves, experiences electricity blackout during the long summer months due to the difficulty of keeping up with the growing demand for electricity.

In this research a number of measures to reduce electricity consumption has been reviewed.

- The house performance throughout the various stages of construction and occupancy has been examined using the wealth of data available, which extends over a period of 12 years - during construction (2012 to 2015), before the installation of a grid connected 12.18 KWp Solar PV (2016 to 2020), and after the installation of the Solar PV system (2021 to 2023).

TRNSYS used to simulate the Solar PV installed system, with a cross reference using PVGIS. 12 simulation cases at different tilt and azimuth angles and tracking on one, and two axes were conducted. This including the actual case of exported monthly electricity units. TRNSYS and PVGIS results exhibited acceptable margin of error in the annual total for each case when comparing with actual, from -2% to +7%. Accounting for the number of electricity blackout hours was quite challenging, otherwise

the difference between actual and simulated would have been even less. The analysis proved that up to 50% more KWH can be generated by the same system when tracking on 2 axes, and approximately 40% when tracking on the Azimuth only. Tracking on two axes is commercially prohibitive, but on one axis only is feasible.

Declaration

No section of this PhD thesis has been submitted in any other application for a degree or qualification at Brunel University or any other university or Institute of learning. I confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Impact Statement

The research results will help trigger further interest and support the current effort being made in the field of energy conservatism and thermal performance improvement in the housing sector, particularly, in already constructed buildings. Evidence of this the interest shown in the published papers in “The International Journal of Thermofluids and “Energy”, and the multitude of invitations received from sustainable energy conference organizers to attend as well as present my ideas. The extensive literature review and simulation work using TRNSYS, compared with actual field data collected over a two-year period, highlighted the importance of designing for the local environment, in the case of new buildings, while in existing buildings, even simple retrofit solutions, such as roof thermal insulation, utilizing night time ventilation, either naturally or mechanically, at times when the outside air temperature is favourable (below 27^{o}C), , optimize the azimuth and tilt angles of already installed solar photovoltaic panels, modifying the panels’ support structure to allow for tracking the sun on at least single axis, incentivise the installation of solar photovoltaic system, as well as promote the understanding of the local climatic conditions, would help a great deal in pragmatically reduce energy consumption.

The novelty in this research is the geographical location, which is Pakistan, a subtropical region in Southwest Asia and the fifth most populated country in the world (230 million inhabitants). A locality near the capital city of Pakistan Islamabad has been considered for its representative subtropic climatic conditions, which is common with many other regions in the world. The availability of an already well constructed house with many energy conservation features, such as thermal insulation in walls and roof (75 mm EPS –Expanded Polystyrene Panels), double glazing throughout, help on focusing of the research gaps. The estimated U Value for walls is 0.277 W/m^{2} ^{o}K while in roof 0.255 W/m^{2} ^{o}K, This is a gigantic leap in a very poor construction quality housing market, where insulation is considered unnecessary expenses, and the majority of consumers are ignorant of its benefits. In addition, natural ventilation through vent openings in shafts one meter above the roof top of the building permits natural cool air during the summer nights to seep through the house when desired, shading, either by recessed windows throughout, or substantial shading elements, particularly on the south façade has been incorporated, while trees on the eastern and western facades and mostly green landscape all approximately the house has been implemented as part of the landscape. These features allowed the research work to focus on how to further enhance the energy performance with the use of a 12.18 KW$_{p}$ grid connected Solar PV.

Pakistan's mushrooming energy crisis due to inconsistent planning and the absence of workable implementation strategies, where more attention is given to improve power production, while matching transmission network tends to be dealt with as a second priority, resulted in persistent shortage in energy, continual electricity interruptions, lack of awareness of energy conservation, lack of implementation of energy conservation guidelines, as well as lack of clear directive on energy conservation by the municipal authority. In addition, misconceptions about the impact on construction cost from adopting such energy conservation measures, has often demotivated house owners from investing in better designed houses, and to the importance of the role of experienced architects and engineers in the design and construction of energy efficient buildings. Quantity over quality is the norm, and the construction market appears to be more suited to builders in the absence of rules that would protect owners against over commercialization and inferior construction quality or even abiding by the very basic municipal energy conservation guidelines. It was even noticeable that architects either misunderstood or were misled to believe that some of the modern materials such as waterproofing membrane can also act as an alternative to thermal insulation. The research also demonstrated that an integrated approach of applying a multitude of energy conservation strategies, such as thermal insulation in the building envelope, double glazing, night-time ventilation, building shading devices and planting trees on the sunny facades, coupled with renewables such as Solar PV, extended the benefits by reducing electricity consumption and in turn increasing the Solar PV production credit. It was also quite noticeable that the cooling demand per m^2 has almost reduced by approximately 25% on average when compared with the ASHREA (American Society for Heating, Refrigeration and Air Conditioning Engineers) guidelines. In addition, the availability of actual electricity consumption data over a period of 10 years (2012 to 2022) i.e. during construction (2012 to 2016), before Solar PV installation (2016 to 2021) and after Solar PV installation (2021 to 2023), helped in accurate assessment of the impact of Solar PV provided a greater insight into the understanding of the pattern of consumption with and without Solar PV coupled with the other energy conservations strategies. This would help the concerned authorities to use the findings to enhance the current local legislations and policies, as well as introduce new ones.

This research findings will help enhance existing energy conservation guidelines, bridge the efficiency gap between energy generation and consumption end, and equally important, the ease of implementing many of this passive energy saving measures, including Solar PV, in impoverished neighbourhoods, which is another research novelty. According to the United Nation, quarter of the world population live in impoverished neighbourhoods. Their carbon-footprint is large, trash production and use of plastic are the highest per capita. In my 3,000 housing units improvised neighbourhood charity project, at the outskirts of Islamabad, 230 houses inhabitants have adopted some of the green ideas highlighted in this research. The project captured the attention of the United Nation Global Compact Group. One of the bold steps to be taken is to equip each house with a 3 KWp Solar PV system with manually tracking on the azimuth.

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Publications

Published Journal paper

(1) The utilisation of useful ambient energy in residential dwellings to improve thermal comfort and reduce energy consumption.

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(2) Analysis of energy demand in a residential building using TRNSYS.

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Ref	Subject	Organizer	Date
1	PhD Induction	Brunel	23/1/20
2	Getting started workshop	Brunel	5/2/20
3	TRNSYS	Online	26/2-10/4//20
4	Writing skills	Brunel – Webinar	
5	Research integrity module	Brunel - Blackboard	
6	Creating better places for people through LEED	Kuwait Green Building Cll-Webinar	9/6/20
7	How to communicate better	Brunel - Webinar	22/6/20
8	How to think strategically	Brunel - Webinar	30/6/20
9	Publishing in academic journals	Brunel - Webinar	21/9/20
10	Scopus training	Brunel - Webinar	22/9/20
11	The Arab architecture week	ArchiNet - Webinar	3/11/20
12	General aviation prospects summary	Brunel - Webinar	3/11/20
13	The well building rating system	Kuwait Green Building Council -Web.	9/11/20
14	Design talk	ArchiNet - Webinar	8-11/11/20
15	MAE-BCAST PGR symposium	Brunel- Paper Presented	13/01/21
16	Design Optimisation	DesignBuilder - Webinar	23/2/21
17	Design talk (Riyadh)	ArchiNet - Webinar	7/4/21
18	How to communicate better	Brunel Inkpath - Webinar	23/7/21
19	Writing an effective literature review	Brunel Inkpath - Webinar	29/7/21
20	Radiative cooling workshop	KFAS Kuwait – Webinar	11/8/21
21	Solar PV projects workshop in the Arab world	Kuwait Engineering Society -Webinar	8/9/21
22	How local authorities can meet net-zero carbon targets by 2030	IES - Webinar	13/9/21
24	Carbon capture	Prof. H Jouhara - Webinar	21/1/22
25	Scientific writing lecture	Prof. D. Eskin - Webinar	25/1/22
26	CEE seminar ocean wave energy potential and its sustainability under a changing climate	Dr. Mei Yin - Webinar	28/1/22
27	How to plan, structure, write up, submit and revise your PhD Thesis	Dr. Giulio Alfano	11/2/22
28	Error analysis workshop	Prof. H. Nadendla	21/2/22
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34	8th International conference on energy Research and development	ASHRAE and Kuwait University	28/11/23
35	10th International conference on materials Science & smart materials (MSSM2024) - District cooling – an energy conservation technology (presentation)	National and Kapodistrian University of Athens Greece	15-17/5/24

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4. Nomenclature

Abbreviation	Definition
A	Azimuth angle of the Solar PV panels
AC	Alternating Current
BOE	Barrel of Oil Equivalent
CAD	Computer Aided Design
CAPEX	Capital Expenditure
CDA	Capital Development Authority
COP	Coefficient of Performance
CSP	Concentrated Solar Power
DB	Distribution Board
DC	Direct Current
E	East
EES	Engineering Equation Solver
EIPPCB	European Integrated Pollution Prevention & Control Bureau
EFLH	Effective Full Load Hour (annual total hours of full plant operation)
EGEC	European Geothermal Energy Council
ESTI	European Solar Test Installation
FIS	Fully Independent System
FIT	Feed-in Tariff
GCC	Gulf Cooperation Council
GFA	Gross Floor Area
GHG	Greenhouse Gas Emissions
GWP	Global Warming Potential
HP	Horsepower
HTF	Heat Thermal Fluid
HVAC	Heating Ventilation and Air Conditioning
IEC	Indirect Evaporative Cooling
I_{SC}	Short Circuit Current
IMP	Current at Maximum Power
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LED	Light Emitting Diode
LFR	Linear Fresnel Reflector
MEED	Middle East Economic Digest
N	North
NOC	Network Operations Centre
NOCT	Nominal Cell Operating Temperature
NZC	Net Zero Carbon
OPEX	Operating Expenditure
PCM	Phase Change Materials
P_{max}	Maximum Power
PV	Photo- Voltaic
PVGIS	Photovoltaic Geographical Information System
PT	Parabolic Trough
PV/T	Photovoltaic/Thermal
RH	Relative Humidity

RT	Refrigeration Ton
SAM	System Advisor Model
SDGS	Sustainable Development Goals
SEG	Smart Export Guarantee
STP	Solar Tower plant
STP	Standard Testing Conditions
T	Tilt angle of the Solar PV panel
TES	Thermal Energy Storage
TMY	Typical Meteorological Year
TRNSYS	Transient Systems Simulation
UPS	Uninterruptible Power Supply
VOC	Open Circuit Voltage
Symbol	
^oC	Degree Celsius
CO_2	Carbon Dioxide
gCO_2eq/KWH	Grams of carbon-dioxide equivalent per kilo-watt hour
^oK	Degree Kelvin
Kg	Kilogram
KW_c	Kilowatt Cooling
KW_e	Kilowatt Electric
KWH	Kilowatt Hour
KWp	Kilowatt power
GW	Giga Watt
MW_c	Megawatt Cooling
MW_e	Megawatt Electric
MWH	Megawatt Hour
WH	Watt Hour
m^2	Metre square
m^3	Metre cube
mm	Millimetre

5. Introduction

5.1 Background and Motivation

Buildings are essential to modern living, offering shelter, comfort, and functionality to billions of people worldwide. However, buildings' energy consumption, particularly in the residential sector is among the highest in the built environment, and is still dependent largely on fossil fuels, whether directly from burning gas and coal or indirectly from consuming electricity. A significant portion of this energy is attributed to maintaining indoor conditions within the comfort range 22ºC- 25ºC and 50% + or – 5% RH J. V. Hoof [1], [2], [3]. Therefore, improving the energy performance of buildings by adopting innovative solutions to make them more sustainable will help in the quest to overcome the climate change challenges and energy resources depletion.

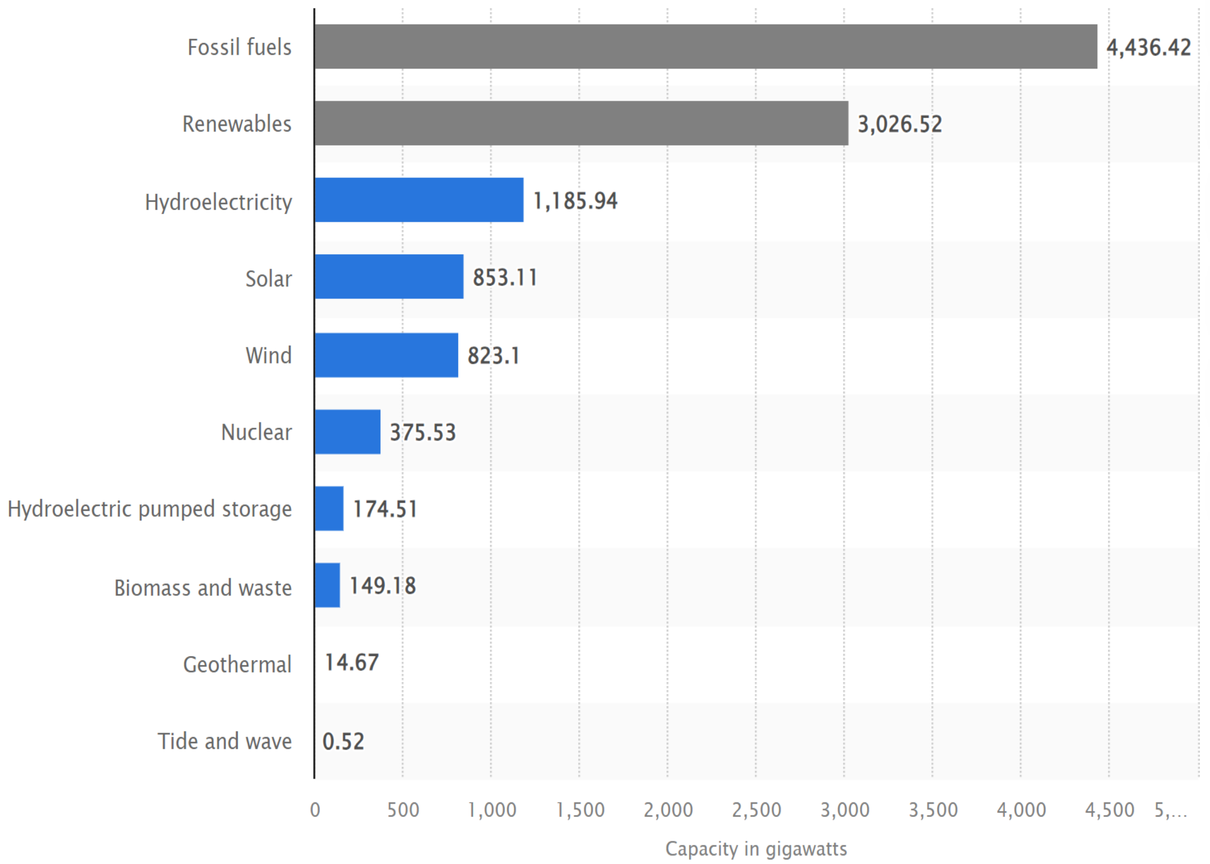


Figure 1: Installed Electricity Capacity Worldwide in 2021

The combined total global power capacity from renewables in 2021 was just over three terawatts (10^{12}). With coal and gas still are the prime source for electricity generation, the capacity of all fossil-based energy sources stood at 4.4 terawatts (Figure:1) EIA [4].

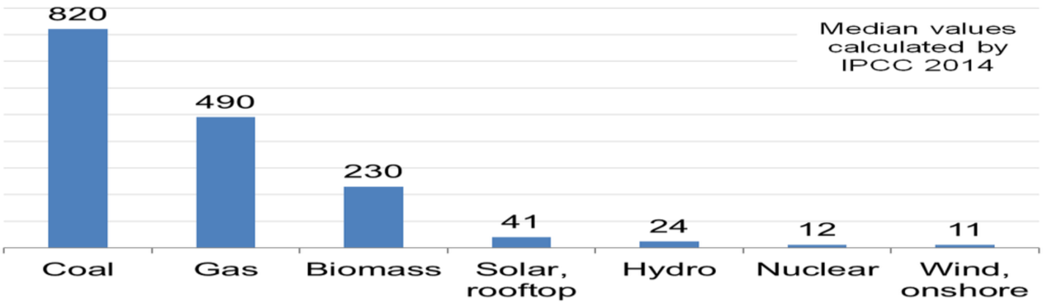


Figure 2: Lifecyle CO_2-equivalent emissions (g/KWH)

However, the intensive CO_2 emissions from fossil fuels, in contrast with the emissions from renewable technologies (Figure:2), has ignited the global push towards renewable technologies S. Shlomer et al. [5].

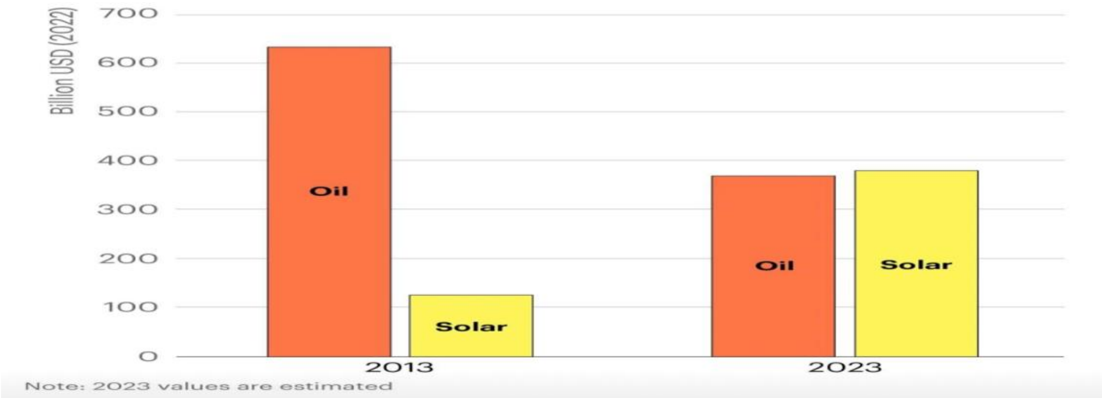


Figure 3:Investment in global oil production and solar -2013 vs 2023

Driven by some of the renewable technologies, particularly Solar PV, which is gradually becoming cost effective, and the determination to move away from fossil fuels, to mitigate the global warming, the installed capacity of renewables has more than doubled in the past decade, and is expected to overtake fossil-based fuel by 2035, reaching 15 thousand terawatt-hours, while capital investment in solar is on the path to surpass investment in oil production (Figure:3) Iea [6].

The estimated global urbanized area currently stands at approximately 240 billion m^2 and is expected to grow to six hundred billion m^2 by 2050. A considerable proportion of this built environment is in the shape of low-rise development, single and multi-story houses, educational, institutional, hospitals and government buildings. In addition, informal unsustainable impoverished neighborhoods within metropolises or entire towns and villages. It is estimated approximately 1.1 billion people (Figure: 4), a number likely to increase to two billion by 2030, live in these rapidly sprawling impoverished localities United Nations [7].

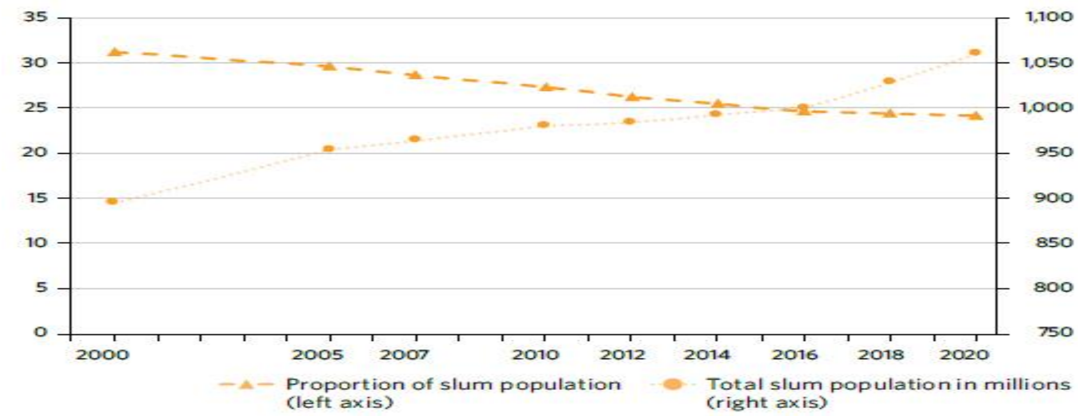


Figure 4:Proportion of global urban population living in slums (percentage) and total slum population (millions), 2000–2020

Low-rise developments can be thoughtfully designed or retrofitted to incorporate sustainable measures effectively. In stark contrast, impoverished areas often exemplify urban degradation, expanding over time due to the persistent growth of global population and poverty. Many of these areas have evolved into sprawling metropolises in their own right, such as Orangi Town in Karachi, Pakistan [8], with an estimated 2.4 million inhabitants, and Ciudad Nezahualcóyotl (Ciudad Neza) near Mexico City, home to approximately 1.2 million people.

While low rise development can be well planned and made to easily allow for the implementation of many sustainable measures, whether during design stage or to retrofit after construction, in total contrast impoverished localities are the epitome of urban degradation, mushrooming in time due to the persistent increase in world population and poverty, to the extent many have/and are gradually turning into metropolises in their own rights, such as Orang Town in Karachi Pakistan [8], approximately 2.4 million inhabitant and Ciudad Neza Mexico City, approximately 1.2 million inhabitants. A well-known and made famous by the movie “Slumdog Millionaire 2008” is Dharavi in Mumbai India, a 2.39 square kilometers town with over one million inhabitants. Dharavi has an occupancy density sixty-six times more than Gaza Strip, which is considered the most populated urban area in the world. Low rise developments, both planned and unplanned, share a few common features from a building energy perspective:

- wall to floor area ratio is higher than in the case of vertical rise buildings. This results in higher heat losses (or heat gains) of energy per m^2.
- the common use of individual standalone heating and cooling systems, which are less efficient than centralized or district scale systems,
- more difficult for municipal/local regulatory authorities to enforce energy conservation and sustainability guidelines,
- lack of access to professional architectural and engineering services by people of limited income.

This often means that low-income home builders must settle for an extremely uncomfortable, perhaps unhealthy, or even dangerous dwelling risk of buildings collapsing during adverse weather conditions and earthquakes. Unlike vertical rise developments, energy saving guidelines, in many countries mandatory, are much easier to enforce due to the involvement of experienced building professionals. On the positive side, low rise developments can be easily retrofitted to improve their energy efficiency, as well as make them more adaptable to renewable energy technologies such as Solar PV, which is more effective due to the lower (small) power needs of such buildings. While low rise development, particularly those in impoverished localities tend to endure the test of time and continue to thrive and expand, for example Dharavi Mumbai beginning can be traced back to the British Colonial era in the late 1800s [9]. This is attributed to a fundamental reason; they evolved out of desperation to meet the pressing needs of the underprivileged population, who have no choice but to continue to endure these exceedingly difficult living conditions. Ironically, unplanned developments tend to outlive many new modern sustainable developments. The former evolved out of the desperate need of limited income population while the latter mostly evolved to fulfil the needs of prosperous population, many can afford to own more than one home and/or move approximately easily to more comfortable or luxury homes as they become more prosperous.

Impoverished localities seldom get the attention needed to be redeveloped with an all-encompassing solution to improve, not only the living conditions of their inhabitants, but also to address their sociological and economic challenges. This is in total contrast with new well-planned prestigious suburbs with impressive developments and sustainable features. Impoverished localities will continue to expand with poorly constructed, haphazardly planned energy hungry dwellings, lacking in all but the extremely basic facilities, in the absence of any energy conservation measure or form of sustainability. The energy bills make up a significant share of their living cost. In many countries' electricity prices increased by almost 133% during the period 2020 to 2023, while income remained the same with crushing inflation hitting all basic commodities. To overcome this hike in energy cost, burning low grade fossil fuels, deforestation and burning trash and trash derivatives significantly increased. Islamabad, once among the most beautiful capital cities in the world, master planned on grid system in the late 1950s/early 1960s with many sustainable features by Doxiadis Associates from Greece, now this City is gradually moving up the list of the topmost polluted cities in the world e.g. Delhi, Dacca, Lahore and Bagdad Samnda Dorger [10].

In the persistent endeavour to shift towards renewable energy like solar, wind, sea wave power and geothermal, renewable energy is gaining traction . The main contributors to reach this remarkable renewable power capacity are solar and wind, and to a lesser extent hydropower and geothermal International Renewable Energy Agency [11]. However, overall energy demand is still significantly high in fossil fuels, such as coal, natural gas and oil due to transportation, particularly in countries with less motivation to switch to renewables due to cost or the absence of pragmatic government policies and or comprehensive building planning regulations to incentivise consumers. Also, when energy consumption comparison is drawn between fossil fuel and renewable energy, the tilt is more towards fossil fuels due to the intermittent nature of renewables and the still prohibitive cost of storing energy. In addition, sizeable proportion in the reduction in energy consumption over the last 3 years has been a consequential outcome of the global economic meltdown during the coronavirus pandemic years (2020-2022). On the other hand, innovations, modern technologies and digitization have the tendency to increase the need for more energy that can, for now, still easily met by fossil fuels, because they themselves are power hungry to operate and even more power dependent to manufacture their various components at the outset. The road to transitioning away from fossil fuels is still a long one. It is also imperative to address the use, distribution and production of energy simultaneously, and not individually to reap the maximum benefits of renewables. This can be achieved by upgrading distribution infrastructure, improving building energy efficiency and increasing consumers' awareness. Sustainability and energy conservation technologies, such as district energy (cooling and heating), where the energy is produced at central plant and then distributed to buildings via pre-insulated buried pipes, have shown some positive signs with significant improvement in lowering energy demand by taking advantage of demand diversity and off-peak thermal energy storage. However, it is quite common at building level, energy tends to be inefficiently distributed and consumption due to misalignment between building architecture and suitability to local climate, as well as consumers habits, particularly in energy tariff subsidized environment, in order . Full glazed building elevations are quite common in warm climates including the research study region. Burj Khalifa in Dubai, Etihad Towers in Abu Dhabi, Ufone Tower in Islamabad, are but a few examples, of alien architecture, which, replicated all over the world with no due regard to the climate variation. It is now quite apparent to witness iconic buildings with similar features approximately the world, in cold and warm climates. In addition, there is always a tendency to overestimate energy demand (heating or cooling), as well as underestimate the importance of BEMS (building energy management system) and controls, Silver Foundation [12]. Demand for energy is further increased with prosperity, changing social habits and misconceptions, a few examples:

- Over comfort commonly perceived as a target to rank the quality of a building, be it overheating during winter or over-cooling during summer.
- Hospitals consume much more energy per m^2 than residential or commercial buildings because of patients' more stringent and varying comfort needs and operating theatre, higher fresh air induction rates to prevent contamination.

All this leads to more energy demand in the building sector, making it more challenging to satisfy with renewables alone. Unless renewables are coupled with energy conservation design and developments of efficient means of using energy, as well as harnessing renewable energy sources, the dependence on fossil fuel will continue for years to come and the transition to renewables will always be an even bigger challenge, particularly with the climate change. which is now quite noticeable. In regions such as the Gulf, temperatures have already increased by 2°C since the 1980s, which is almost three times the global average, while peak summer months (June to August) temperatures rising even higher since the late 1970s by almost 2.5°C.

The adaption of renewables with good energy conservation design in new buildings, better understanding of the local climate and suitable retrofit solutions for existing inefficient buildings, particularly in the residential sector, will help support the transition towards cleaner sustainable energy future by reducing buildings' carbon footprint, lower energy costs and improve the overall environmental landscape, as well as promote healthier indoor and outdoor conditions.

Indoor thermal comfort in residential buildings is of paramount importance because we spend much of our time indoors. Uncomfortable indoor conditions lead to unhappiness, loss of productivity and detrimental impact on health and psychology of occupants F. Schaudienst et al, [13]. The problem is further compounded when houses are poorly designed and/or badly constructed. With the escalating cost of energy, many people will compromise further on comfort to cut down their energy bills to the extent that indoor conditions would be far from ideal and at times worse than outdoors. In addition, in their struggle to improve their indoor comfort with the least cost, many people end up investing in far from ideal inefficient commercially bias solutions. In countries where climatic conditions necessitate indoor temperature and humidity control, electricity and gas consumption in the residential & commercial sectors are among the highest. In the Gulf Region, for example, electricity consumption in air conditioning equipment could account for up to 70% of the total nationwide consumption during the peak summer months, and 50% annually average. In houses constructed with walls that do not meet any specific local or international energy efficiency standards building fabrics behave like a furnace wall during summer, absorbing and radiating heat inwards throughout the day and well after sunset, and as cold-store surfaces in winter even on sunny days. External concrete walls experience long hours of thermal lag. The issue is exacerbated by the lack of even basic passive energy design measures. These include proper building orientation, double or triple glazing, suitable external colours and facades with balanced wall-to-window ratios, and ventilated facades. Additionally, the use of energy-efficient building materials is often overlooked. The problem is further intensified by the absence of shading devices, especially adjustable ones that can be deployed in summer and retracted in winter. In addition, lack of proper temperature controls, inadequate fresh air, incorrect air and hot/chilled water distribution as well as overestimating or underestimating the cooling and/or heating demand, etc. are quite common occurrences which further compound the above problems. Yet the use of free ambient energy (e.g. diurnal temperature variation, solar thermal energy, direct/indirect evaporative coolers, etc.), are but a few of the strategies that can be applied along with some basic passive design measures which will significantly help in achieving much improved indoor comfort while minimizing dependence on electrically or gas operated equipment. Table 1 illustrates the average annual electricity consumption, estimated barrel of oil equivalent (BOE), D. J. Campbell Alison et al, [14] and CO_2 emissions in a few countries, where climatic conditions favour the utilization of free ambient energy during significant periods of the year.

Table 1: Population & average electricity consumption, BOE and CO_2 emission [14]

Country	*Population*	*Average Electricity Consumption (KWH/person/year)*	*Average Electricity Consumption (MWH/Year/Country)*	*Average BOE/Year*	*CO_2 Emission Ton/Year*
Egypt	*94,666,993*	*1,510*	*142,947,159*	*228,715,454*	*68,614,636*
Pakistan	*211,995,540*	*405*	*85,858,194*	*137,373,110*	*41,211,933*
Greece	*10,773,253*	*4,919*	*52,993,632*	*84,789,811*	*25,436,943*
Jordan	*8,185,384*	*1,954*	*15,994,240*	*25,590*	*7,677,235*
Lebanon	*6,237,738*	*2,565*	*15,999,798*	*25,599,676*	*7,679,903*

5.2 Research Study Region

Islamabad, capital city of Pakistan, has been chosen for this research study. It is the 17th most populated city in the world with a population close to 1.3 million. Pakistan is among the countries at the risk of the impact of climate change, where water resources are depleting, and the average temperature is noticeably increasing. In addition, it is one of many countries where building planning regulations are not yet upgraded to encourage sustainability. In the subtropical region, which is the chosen area for the research study, the climate is characterized by warm to hot/humid summers and mild to cold winters. In this region indoor climate control is a necessity and not a luxury. However, the metrological condition itself presents a potential source of free energy which if harnessed well can significantly reduce dependence on fossil fuels (electricity and gas). The CDA (Capital Development Authority) is responsible for the building control regulations. The latest amendments were introduced by Islamabad ICT Building Regulations in August 2023[15], but did not mandate, or promote or even address energy conservation in any specific way nor encouraged renewable, such as Solar PV in more effective ways. For example, the only reference to green technology in an 118 page document appeared in two paragraphs in Sheet-5 under Green Architecture “Suitable green architecture design features to be used with suitable details may be shown", no specific targets are mentioned, for example, the Overall Heat Transfer Coefficient of buildings' external envelope (U Value), recommended thermal insulation in walls, double glazing, external colours, orientation, architectural shading elements and natural ventilation. Also, indoor temperature set point in summer and winter, temperature controls, target heat-gains/loss per m^2, air conditioning equipment energy efficiency, permissible maximum $KW_{electric}$ per $KW_{cooling/heating}$ and floor area in m^2. The only specific requirement stipulated in section 9.9 Miscellaneous, Clause 2 Energy Saving "Installation of at least one solar geyser (boiler) in residential houses, whereas 10% electricity/energy consumption in all other buildings will be through solar system. This shall be ensured at the time of issuance of completion certificate." These are the only two references to energy conservation and sustainability in the Islamabad ICT Building Regulations document [16].

In contrast, the research rig (building) has been designed and constructed taking into consideration the most the missing energy conservation measures guidelines in the CDA Building Control Regulations. All external walls and roof have been constructed with 75 mm EPS (expanded polystyrene) panel insulation sandwiched between the external wall layer and internal wall, and within the roof construction slab and finishes. The 'U' value of all the building external fabrics (walls and roof) is approximately 0.304 $W/m^2\,^oK$. Also, double glazed windows throughout the house, expect for the main door and, front and back terrace doors. In addition, building orientation, external finishing colours, shading elements, manually controlled ventilation shafts, green surrounding landscape, in addition, to indigenous trees that would offer shade in summer, particularly on the west elevation to protect the house from the low sun during late afternoon hours, and allow for longer exposure to the sun in winter when trees shed their leaves, have been implemented. In section 7 "Experimental Rig," the full description is provided, as well as the construction details and U value calculation.

The solar energy market in Pakistan has the potential to grow from 1.3 GW, the current estimated market size (2023) to 10 GW in 2028 as suggested by the International Renewable Energy Agency (IRENA) [17]. In a country where power interruption is quite common, whether independent with storage or grid connected (Figurers 5 &6).

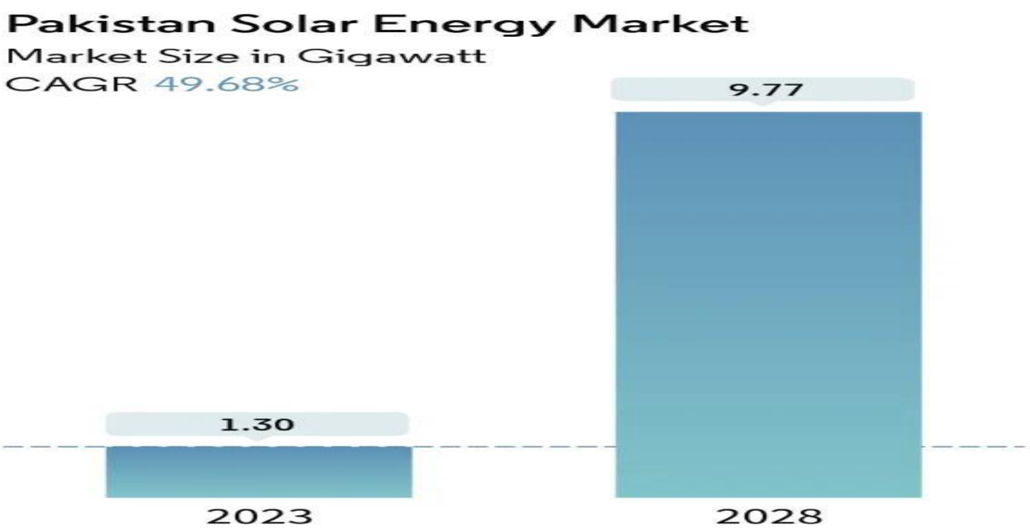


Figure 5: Pakistan Solar Energy Market-Gigawatt (IRENA)[17]

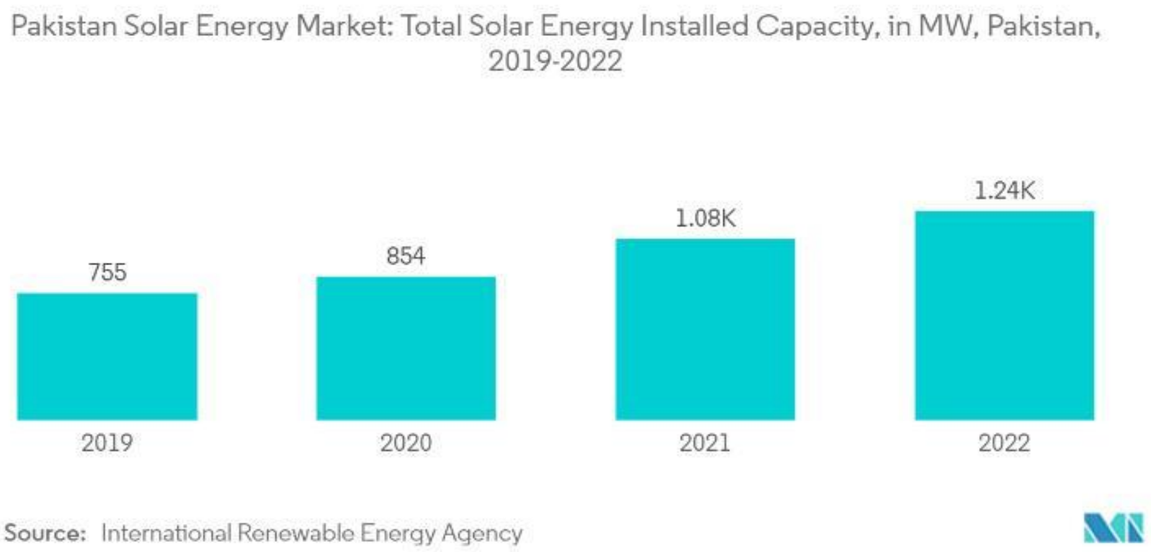


Figure 6: Pakistan Solar Energy Market: Total Solar Energy Installed Capacity in MW Between 2019 and 2022 (IRENA)[17]

In its endeavour to reduce the importation of costly diesel and furnace oil, Pakistan government approved the National Solar Energy Initiative to add 10 GW of solar generated electricity to the grid through the participation of the private and public sectors in utility-scale projects. With the vast potential of solar energy and available land for mega solar projects, taking into consideration the average solar global insolation is 5-7 KWH/m2/day, to tap into this renewal energy source, Pakistan government needs to be steadfast and continue to encourage the transition towards becoming energy independent F. Kamran [18], [19].

Figures 7 to 13 provide a snapshot of the energy landscape in Pakistan F. Kamran [18]. Energy supply, production, consumption nationwide, consumption per capita, energy emissions by sector for the period

2016 to 2021, it is clearly noticeable that buildings and transport are among the highest sectors producing greenhouse emissions. Additionally, policies, programs, and legislation can play a crucial role in reducing electricity consumption. There is also significant potential to transition to renewable energy sources, thereby decreasing reliance on fossil fuels. However, implementing these legislations is quite challenging, particularly in the current geopolitical environment and economic downturn, International Energy Agency, Renewable Readiness Assessment [20].

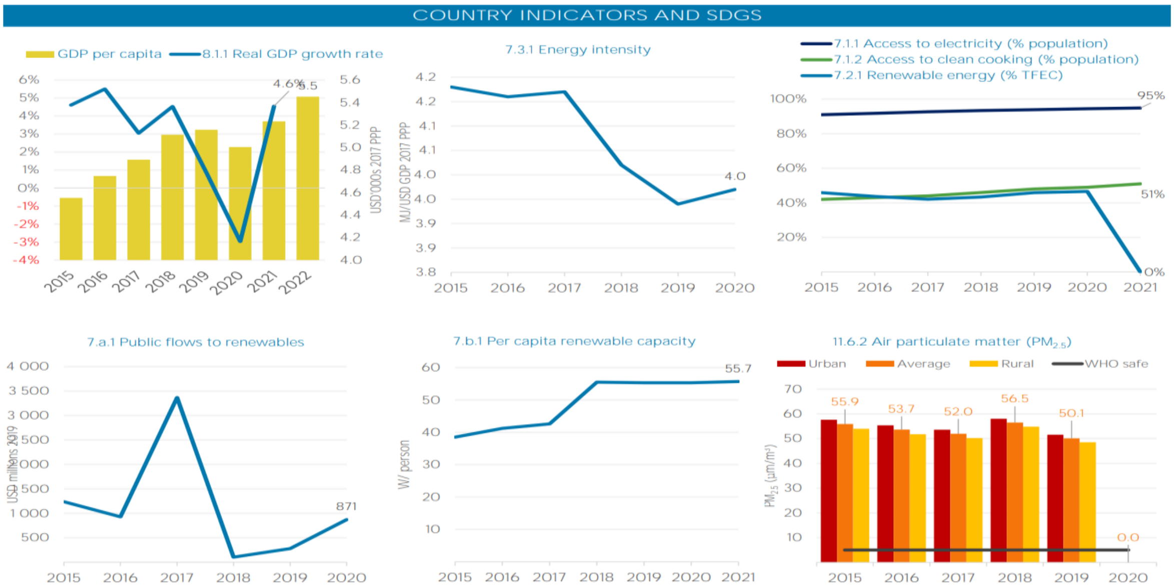


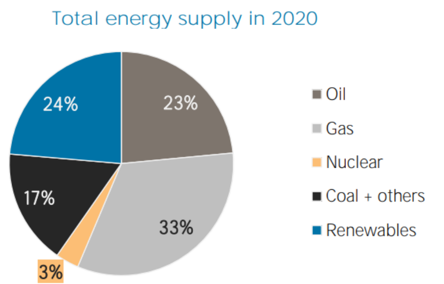
Figure 7: Country Indicators and SDGS[18]

TOTAL ENERGY SUPPLY (TES)

Total Energy Supply (TES)	2015	2020
Non-renewable (TJ)	2 485 002	2 826 476
Renewable (TJ)	835 997	874 721
Total (TJ)	3 320 999	3 701 197
Renewable share (%)	25	24

Growth in TES	2015-20	2019-20
Non-renewable (%)	+13.7	-5.8
Renewable (%)	+4.6	+0.7
Total (%)	+11.4	-4.4

Primary energy trade	2015	2020
Imports (TJ)	1 057 964	1 475 260
Exports (TJ)	17 742	30 760
Net trade (TJ)	-1 040 222	-1 444 500
Imports (% of supply)	32	40
Exports (% of production)	1	1
Energy self-sufficiency (%)	70	60



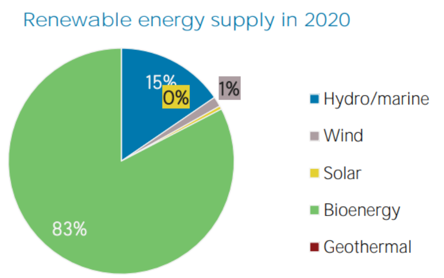


Figure 8: Total Energy Supply[18]

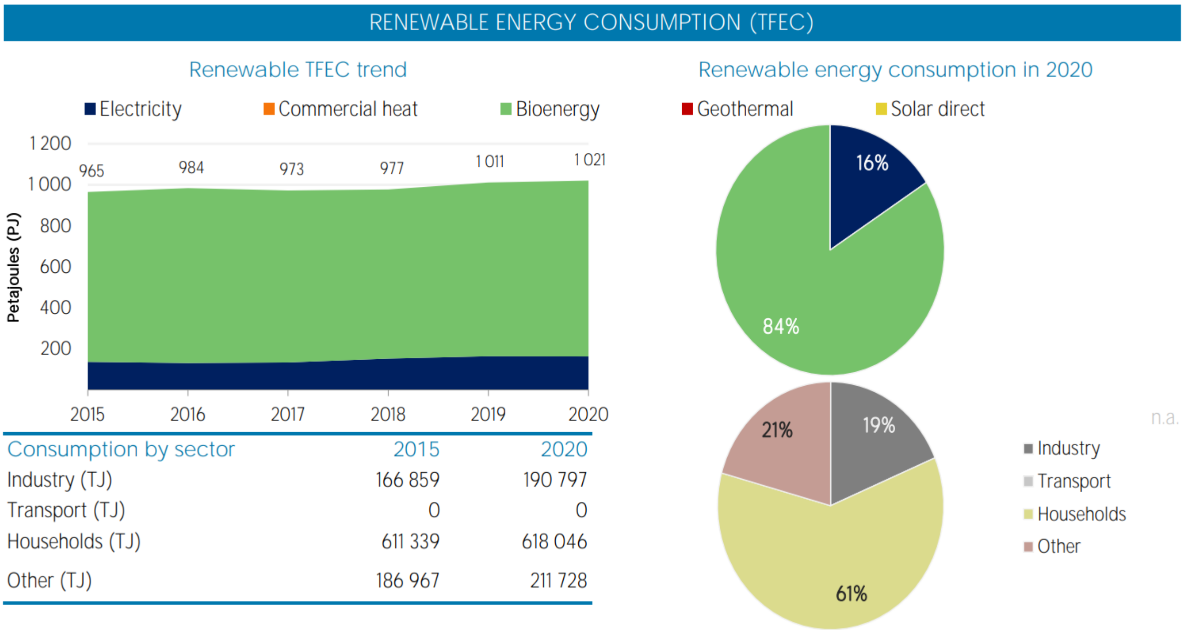


Figure 9:Renewable Energy Consumption (TFEC)[18]

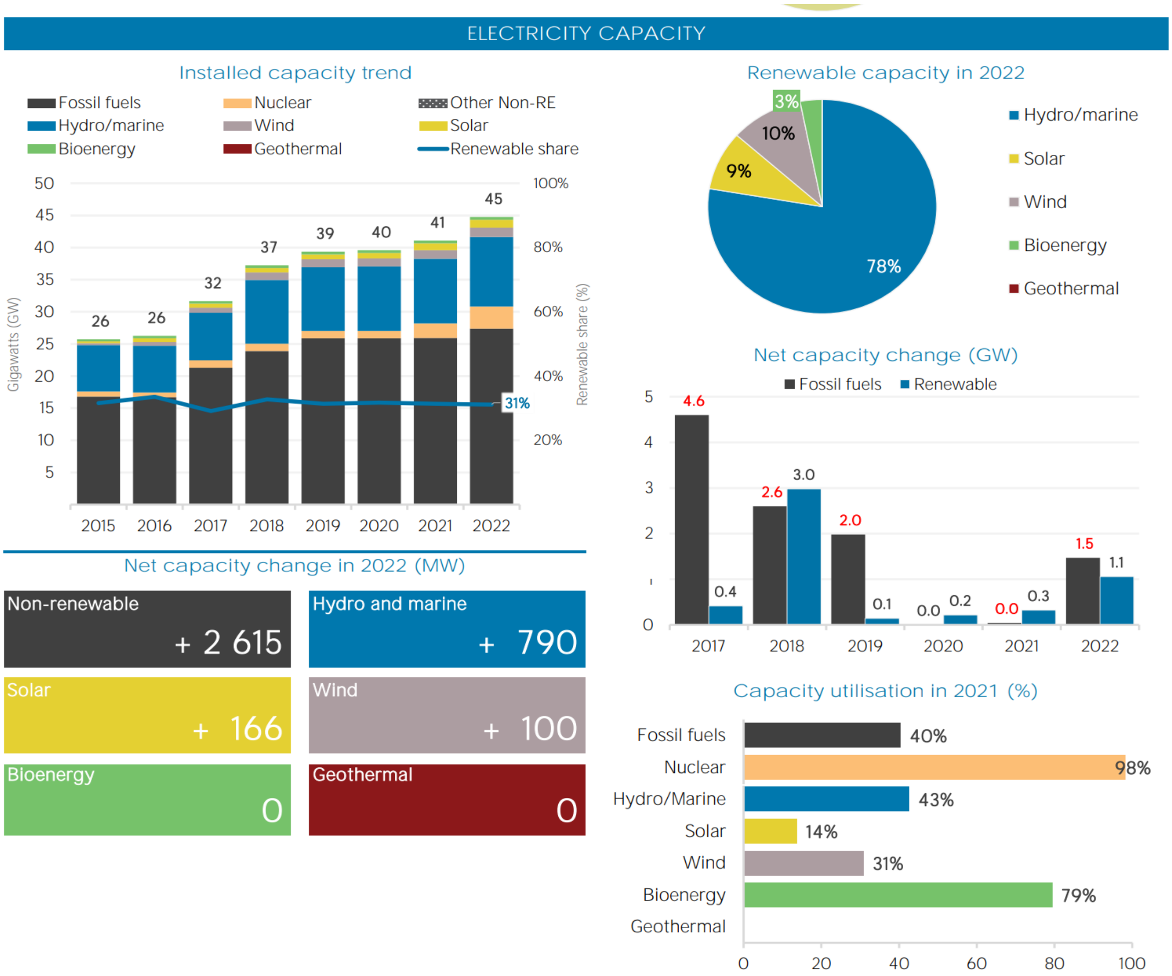


Figure 10:Electricity Capacity[18]

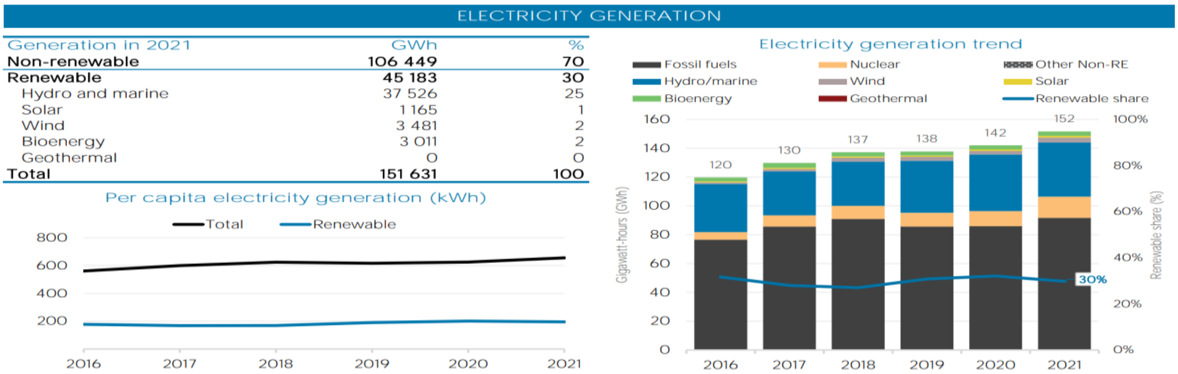


Figure 11: Electricity Generation[18]

LATEST POLICIES, PROGRAMMES AND LEGISLATION	
1 Pakistan MEPS and labelling for electric fans	2016
2 Pakistan net metering policy for solar PV and wind projects	2015
3 Minimum Energy Performance Standard (MEPS) For Window Type & Split Air Conditioners With Cooling Capacity under: 14000 W (12000 - 48000 BTU/hr)	2014
4 Pakistan feed-in tariff for solar power	2014
5 Upfront Generation Tariff for Solar PV Power Plants	2014

Figure 12:Latest Policies Programmes and Legislation[18]

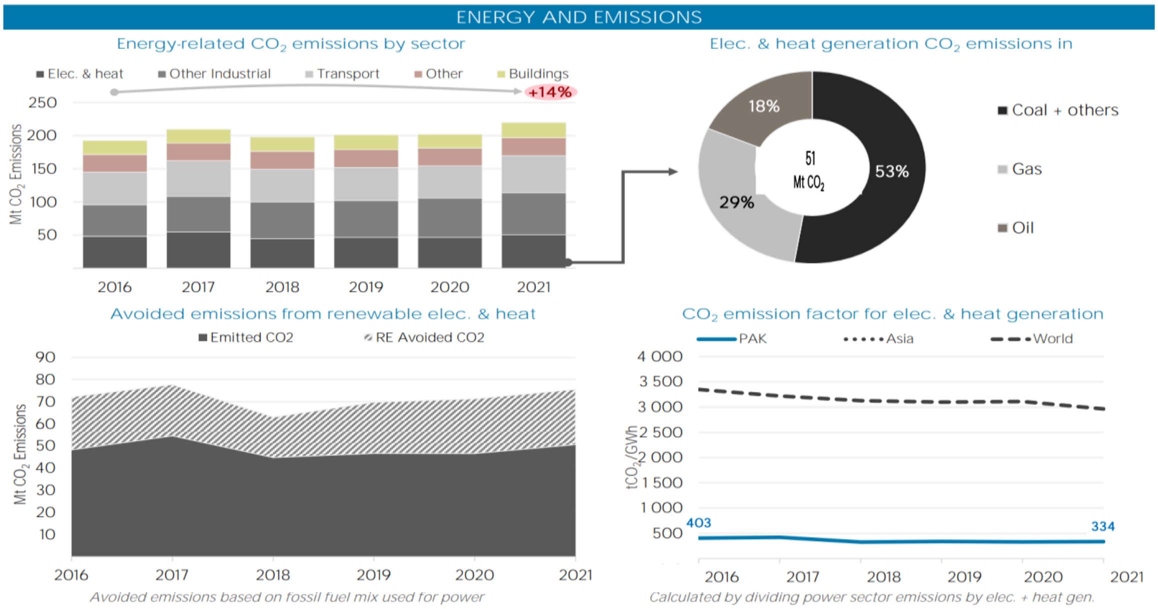


Figure 13:Energy and Emissions[18]

5.3 Aims and Objectives

In this research the focus is on low rise buildings since per m^2 of construction the heat-gains and heat-losses are higher than tall buildings due to the higher ratio of facades and roof to GFA (gross floor area). The aim is to advance the understanding of the factors that determine the level of energy consumption and how to reduce taking advantages of favorable ambient conditions during seasonal variations. Particular attention has been given to Solar PV and how to optimize its performance. The research investigation seeks to provide insight into how to further the benefits of renewable energy such as Solar PV in well design and constructed building with many passive energy measures such as thermal insulation in walls and roof, double glazing throughout, controlled natural ventilation, building orientation, architectural shading elements and a green surrounding landscape. The desire to construct tall buildings, not necessarily suitable for the local environment, often result in architects and engineers focusing more on corporate clients and serve neglect people who cannot afford to pay for professional services when constructing their homes. Limited resources, market conditions and lack of access to professional services often mean that low-income home builders must settle for extremely uncomfortable, perhaps unhealthy, or even dangerous dwellings.

Improving the power supply is naturally a more demanding task but it basically boils down to finding feasible financing options that will enable residents to pay for solar power systems out of savings in electricity bills. With the recent unprecedented hike in electricity rates and the expected drop in solar panels prices, a solution might be close at hand.

The following energy-saving strategies were reviewed closely in the context of well-designed building research rig, two floors house with a total constructed area of six hundred m^2:

1. **Night-time ventilation**

   Basically, permitting night-time air to be induced naturally into the house during the night, generally between 10 pm and 6 pm when the outside temperature is below 27°C. Noticeable improvement has been observed in the indoor conditions with prolonged periods of comfortable temperatures during the day without reliance on mechanical air conditioning.

2. **Nocturnal Radiation Exchange**

   Nocturnal radiation exchange, also known as nocturnal heat exchange or night-time cooling, refers to the process of heat transfer that occurs during the night between the Earth's surface and the surrounding atmosphere. As the Earth's surface cools down after sunset, it emits longwave radiation (infrared radiation) into the atmosphere. This radiative cooling can lead to the formation of dew, frost, or even a drop-in temperature, especially under clear and calm conditions when heat loss is most efficient. It plays a crucial role in the Earth's energy balance and has significant implications for various environmental processes, including weather, agriculture, and ecosystem dynamics.

3. **Indirect Evaporative Cooling**

   Indirect evaporative cooling is a cooling process that utilizes the principles of evaporation to lower the temperature of air without adding moisture to the conditioned space. Unlike direct evaporative cooling, which adds moisture to the air, indirect evaporative cooling uses a heat exchanger to transfer heat from the incoming hot and dry air to a separate stream of cool and moist air without mixing them. This allows the cooled air to be delivered to the space while maintaining a low humidity level. Indirect evaporative cooling is an energy-efficient and eco-friendly cooling technique often used in HVAC systems and air conditioning applications.

4. **Grid Connected Solar PV**

   The study of a grid connected Solar PV with no battery storage except for limited number of hours UPS (uninterruptible power supply) with smart metering. This type of Solar PV system has proved its worth ais commonly used worldwide. It lends success to its simplicity, ease of adaptability, minimal maintenance and cost effectiveness. It is important to conduct research to thoroughly investigate how to further enhance the performance as well adaptability, and how to mitigate the challenges of making this technology more affordable. Of particular interest is implementing this technology in impoverished localities approximately the world. TRNSYS has been used extensively to simulate the Solar PV system at various tilt and azimuth angles and tracking the sun on one and two axes. In addition, PVGIS was also used, particularly to deduce the optimum tilt and azimuth angles. All Solar PV simulation results were compared with the actual as installed Solar PV performance over one full year.

6. State of The Art

6.1 Introduction

In this chapter technologies which can help improve sustainable aspects of the built environment are reviewed. A popular definition of sustainable development is the one adopted by the UN Environment Commission and published in “Our Common Future” in 1987, a “Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” United Nation Environment Commission (Brundtland Commission) [21]. It is a simplistic definition yet one which offers a moral direction to highlight the importance of carefully managing the planet natural resources, without negatively impacting its delegate natural balance. The built environment consumes 40-50% of the world’s materials, uses approximately 25% of the global wood harvest, consumes about 20% of the world water and 30-40% of the world’s energy, and responsible for 25% of the CO_2 emissions, as reported by the World Green Building Council (WGBC 2010) [22]. These are rising trends due to the increase in population, which is likely to hit 9 billion inhabitants by 2050 (WGBC 2010) [22]. Leading to increase in the demand for new built environment along with the necessary infrastructure (roads and utilities). These problems will further be exacerbated with the voluminous stock of inefficient buildings, that occasionally outlive modern constructions due to the desperate need for shelter by their occupants and the absence of more efficient affordable alternatives, twinned with mushrooming impoverished neighbourhoods due to increasing worldwide poverty. In addition to international pledges to curb global warming, concerted effort is needed to look for pragmatic, not idealistic solutions, to rapidly reduce the carbon footprint of the built environment, whether new constructions or upgrading existing ones. Equally important to carefully consider solutions that eco the local environment and climate, not mere replication of trendy but alien architecture grossly suitable for the localities they intended for. For example, in the Gulf, an excessively warm climate region, curtain wall (glazed building facades) buildings are quite common. This unsuitable architectural has resulted in turning the Gulf Region into among the top in the world in terms of electricity consumption per capita. Much of electricity is needed for driving the power-hungry air-conditioning equipment for comfort cooling purposes.

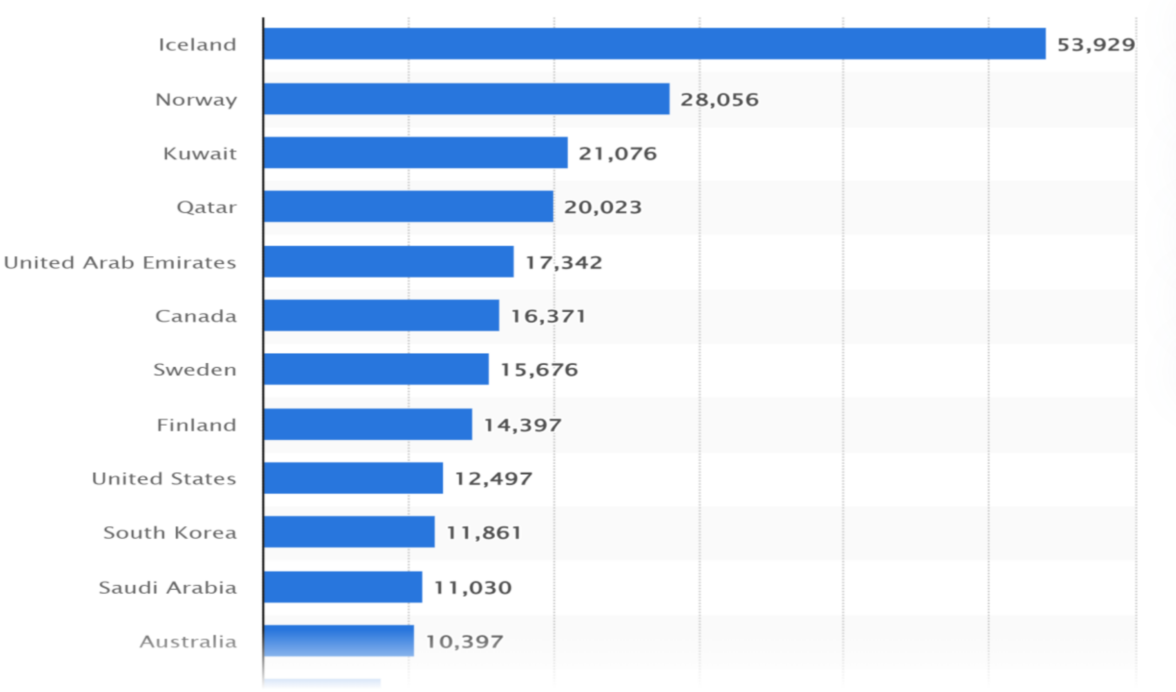


Figure 14: Electricity consumption per capita worldwide in 2022, by selected country(in kilowatt-hours) [23]

The uncertainty in the energy market over the last 30 years and the growing awareness of the impact fossils fuels have on the environment are the driving force behind the increasing research interest in finding ways to reduce residential buildings energy footprint. This drive is gaining traction in both developed and developing nations, including those who rely heavily on oil exports as the only or main source of revenue. Dermot Gately et al. reported that the domestic oil consumption in 2012 in the Kingdom of Saudi Arabia (KSA) reached 3 million barrels per day with an estimated annual growth rate of 5.7% D. Gateky et al, and A Al Saggaf et al [24], [25]. The Figure is approximately 4 million barrels today as reported by CEIC [26]. This number is likely to double over the next 10 years if the current rate of increase in electricity demand continues, the estimated annual increase being 5 % to 7% [27], with approximately 40% of this oil used to generate electricity M. Krarti et al, [27]. The estimated electricity consumption in the residential sector in Kuwait is 60% of the total national power generated, particularly during the peak summer months because of air conditioning B. Jaffar et all, [28]. Figure 14 shows electricity consumption in KWH per capita worldwide in 2022 (selected countries). In Kuwait, on 16th July 2016, a record peak daytime temperature of 53.9 °C was recorded Global Weather & Climate Extremes Maps [29], while temperatures of 50 °C plus are a common occurrence in other cities such as Riyadh and Baghdad. While the cost of building power plants and transmission lines is in the region of £1.5 million per Mwe I. Partridge [30], the cost of air conditioning is in the range of £50,000 to £100,000 per MWc Bazeeth Ahamed K M [31] depending on the type of system i.e., central or unitary. Mechanical cooling by refrigeration process is an expensive necessity in the Gulf Cooperation

Council (GCC). Figure.15 shows the demand for cooling in millions of Refrigeration Ton (1 RT = 3.515 KWc) in 2010 and how it is expected to be in 2030 G. Sarraf et al, [32]. It is estimated that one Megawatt Hour (MWH) of electricity requires 1.71 Barrel of Oil Equivalent (BOE) to burn [14] and each BOE results in the formation and emission of 390 kg of CO_2 approximately N. A. Azzolina et al, [33]. The GCC along with many other countries where air conditioning is a necessity are among the highest contributors of GHG (Greenhouse Gases). Figure 16 shows the average CO_2 emission in tonnes S. Soimakallio et al, [34]. Table 1 illustrates the average annual energy consumption, estimated BOE and CO_2 emissions in a few countries [14]. Most of these countries are in the 53% global emissions red zone according to Our World in Data [35]Temperatures are less extreme in tropical regions, but humidity tends to be higher, and the warm season is longer or all year round. High humidity requires dehumidification, this is typically done either by subcooling the room air to saturation conditions as it passes through the cooling coils in the air handling or fan coil units and then by re-heating back to required supply air temperature, or by desiccant dehumidification, which requires regeneration to remove excessive moisture. Both solutions lead to more energy expenditure. In winter, space heating is essential in many countries. In Kuwait and the northern parts of Pakistan, for example, the yearly range (the difference between the highest and lowest temperatures) is 35-45 degrees Celsius Global Weather & Climate Extremes Maps [29], also, it is quite common to see temperatures tumble down to near zero at night and during the early hours of the morning. The Northern Region of Saudi Arabia and parts of Jordan, Syria and Lebanon have frequently experienced heavy snowfall during winter in recent years.

Passive cooling building design is gaining momentum through the necessity of improving the thermal performance of buildings and reducing their carbon footprint by increasing reliance on renewable energies. However, commercial buildings (6 floors and above), shopping malls, institutional and government buildings have received more attention than low rise residential buildings with growing public and private sectors interest. Existing commercial buildings have benefited from the experience gained and accumulated knowledge in sustainability as well as the viability of conducting and implementing the findings of energy audits. While commercial buildings, which are normally equipped with relatively more efficient HVAC systems and benefit from a wider diversity of cooling and heating loads, which can be as high as 60% in the case of district cooling, due to size and occupancy patterns, receive more attention, residential buildings (below 6 floors) and housing units (detached, semidetached villas and town houses) do not receive enough attention or practical incentives to improve their energy ratings as commonly seen in the United Kingdom and Europe. In addition, most of these residential constructions are equipped with the least efficient cooling equipment such as window type air conditioners, mini-split, Variable Refrigerant Flow (VRF), package/split Direct Expansion (DX) and air-cooled chillers X. Chen, et al [36]. In contrast, commercial buildings are normally equipped with far more efficient cooling equipment such as water-cooled chillers or receive chilled water as a utility from town scale district cooling schemes. The problem is further compounded with the electricity consumption characteristic which tends to be more residential than commercial. In Kuwait, for example, up to 60% of the electricity consumption is in the residential sector Y. Song, et al [37], H. Ali, et al [38]. Similar electricity consumption characteristics can be found in the rest of the GCC and the Midde East North Africa (MENA) region. In Saudi Arabia, the existing low-rise building stock is approximately 1.5 million units with a shortage of 500 thousand; similar order of magnitude numbers can be found in other countries such as Pakistan and Egypt. Considerable research work has been conducted using a variety of passive energy saving strategies, either individually or in a hybrid configuration of more than one strategy. This research review looks at the state of the art of some of these strategies which have exhibited some degree of success with the intention of finding research gaps for further work. The aim is to evaluate how to implement them better in a cost-effective way in existing and new buildings.

Passive energy strategies considered:

- Passive building design.
- Night ventilation: the use of night-time ambient air when its temperature drops below a certain threshold by inducing it into buildings.
- Nocturnal cooling: night sky radiation exchange with building surfaces as well as cooling media such as water.
- Phase Change Material (PCM) and Indirect Evaporative Cooling (IEC): use of phase change material to increase the sensible cooling efficiency of evaporative coolers and use of water as a cooling medium whereby air is induced into the evaporative cooler through a controlled spray of water to lower its Dry Bulb Temperature (DBT) when ambient air conditions permit.
- Solar thermal energy.
- Solar Photovoltaic

Figure: 15 shows the GCC (Gulf Cooperation Council) peak cooling demand in millions of RT (Refrigeration Ton) in 2010 and how it is expected to be in 2030 (RT = 3.515 KWc) [32]. Figure: 16 shows the average yearly carbon dioxide (CO_2) emissions in tonnes [36].

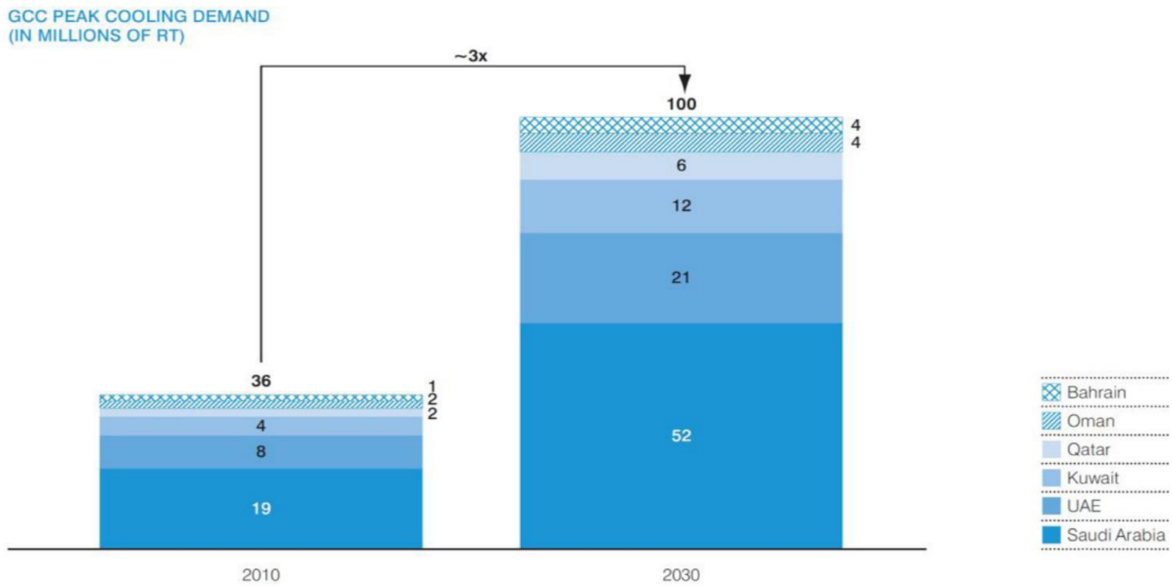


Figure 15: GCC peak cooling demand in millions of refrigeration ton [32]

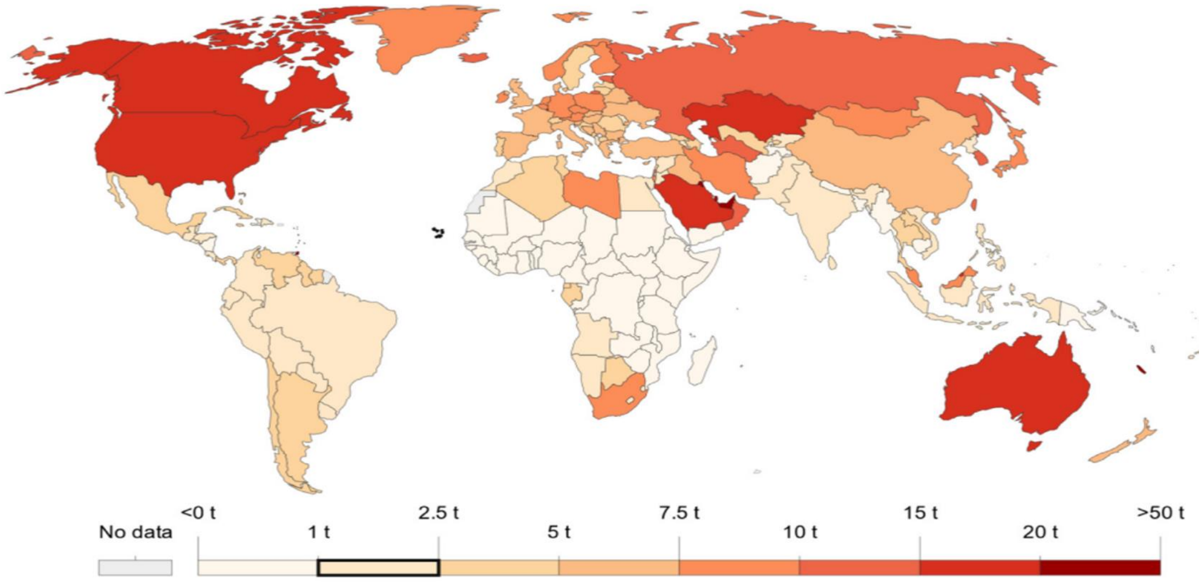
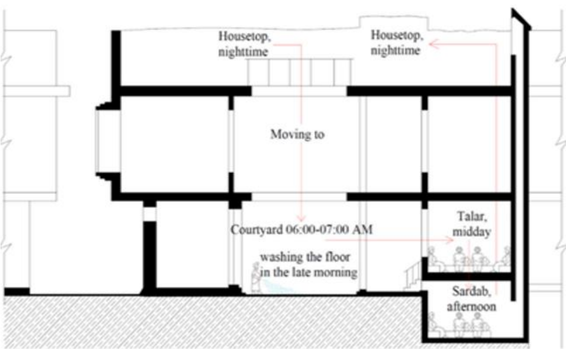


Figure 16: Average yearly carbon dioxide (CO_2) emissions in tonnes [36]

6.2 Passive building design

The concept of a "house" evolved in the history of humankind through a process of trial and error motivated by having to shelter from the climate adversity and for safety and security. From the humble beginnings of a temporary or permanent shelter (tree, cave, overhang, etc.) houses evolved to today's complex mechanized buildings, not only protecting from the weather but also creating specific indoor conditions to meet specific needs all year round. Even the concept of indoor comfort itself changed with time from the basic need to keep dry, warm or cold to being accustomed to precise temperature, humidity and air quality conditions. People have become sensitive to the slightest variation in temperature and humidity, while the natural ability to climatize between the different weather patterns diminished, i.e., at the beginning of summer there is a tendency to feel warmer at lower temperatures while at the beginning of winter the tendency is to feel colder at higher temperatures. Also, social as well as clothing habits have added to the higher demand for better controlled indoor thermal conditions. All this led to the relentless rise in domestic energy demand compounded further with population increase and the need to house more people. The growing awareness of the energy efficiency features of the historical vernacular architecture led to many researchers look closely how they work and how they can adopt them to help improve the prospective energy requirements of contemporary architecture with the use of modern construction materials. H. A. Abdulkareem [39] correctly stated that "Dwellings are built to serve a variety of functions, but one of the most important is to create living conditions that are acceptable to their occupiers particularly in relation to the prevailing climates". One of the outstanding examples of a successful historical traditional built form is the courtyard house. Many examples can be seen across the globe from China to the Indian Subcontinent, the Middle East, North Africa, Southern Europe and Latin America. This was a successful example of how man learned to couple his complex needs for a shelter by building for and in harmony with the environment. As referred to by the same author in his paper H. A. Abdulkareem [39], "The creation of shelter is our response to the environment and the context of our existence, which consists of a complex set of components." This form of house topography can be seen in its basic form as a simple house with a few rooms surrounding an open space (courtyard) as well as in much more complex and sophisticated forms of palaces, forts, temples, churches and mosques. While the best way to save energy is not to use it at all, which obviously is an impractical proposition, the courtyard house tends to score high on the scale of free ambient energy utilisation. It has many built-in passive energy measures, one of which is its fundamental principle of the open space right in the core of the house (the courtyard) and its ability to efficiently exchange energy with the night sky in what is known as nocturnal radiation exchange. The night sky absorbs the radiant energy emitted from the house walls, roof and courtyard surfaces, which was received the previous day. This results in these construction surfaces cooling down, the air in the courtyard also, and in addition some of the cooler denser air from the roof of the house sinks and collects in the courtyard. In the early hours of the morning, relatively cooler air flows into the living spaces surrounding the courtyard, keeping them cooler than the outside for a bit longer during the day before the cycle repeats. Figure. 18 shows the actual temperature measurements taken in a courtyard house in Baghdad in the early 1970‘s. Other fundamental principles of the courtyard house are the minimal fenestrations on external walls, which reduce solar gains as well as the infiltration of warm ambient air, the high thermal mass of external walls, which increases the lag time between the maximum external and internal dry bulb temperatures, controlled ventilation openings at roof level, known as Badgeer, which allow the cooler night air to be transported directly into the living accommodation through masonry channels in the thick walls. Further enhancement to the indoor thermal comfort of the house was achieved by installing a fountain or ornamental water pools in the courtyard as well as vegetation. Obviously, the social movements shown in Figure:17 and dress habits helped, for example, the clothes thermal insulation factor (Clo) of the traditional Arab garment known as dishdahasha or Jalabiya is less than half as much as for a typical light suit or shirt and trousers. Also, what helped was the tendency of occupants to accept indoor thermal conditions which may be perceived in our time as outside the typical comfort range of 16°C to 28°C D. G. Leo Samuel, et al [40]. Other examples of passive design elements of traditional vernacular architecture, which help reduce heat gains and/or losses can be seen below:



Figureure 17: Section of courtyard house, illustrating daily movement in the summer period H, A, Abdul Kareem [39]

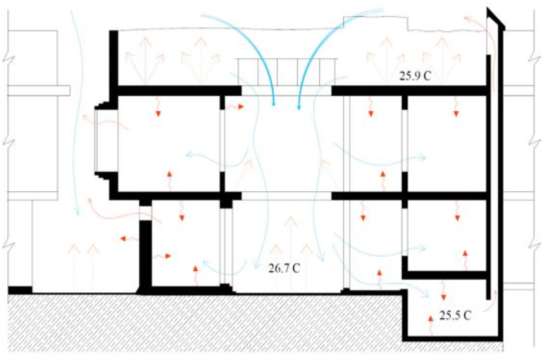


Figure 18: Thermal performance of courtyard house during the night in Baghdad H. A. Abdulkareem [39]

Construction materials: natural stone, mud bricks and wood. These basic natural materials, characterised by high thermal resistance, which delays heat transfer through the building envelope, were extensively used in the pre-cement era. Mashrabiya in the Middle East: allows day light to cascade through the living accommodation as well as natural ventilation air but prevents glare and excessive direct sunshine, see Figures 19 and 20. Sometimes porous clay pots filled with water are placed by the Mashrabiya to promote additional cooling through evaporation of the water that oozes out through the porous skin of the pot, keeping the outside surface wet and at the same time cooling down the rest of the water inside the pot for consumption A. A. Bagasi, et al [41]. Wind catchers (Badgir): induce ambient air naturally into the living space. This is done through a masonry shaft constructed from high thermal mass materials. The shaft traverses the full height of the building and rises above the roof level by several metres. As the cooler air is induced into the building the warmer is purged out. It used to be quite popular in warm climates, particularly the Middle East A. Zaki, et al [42].

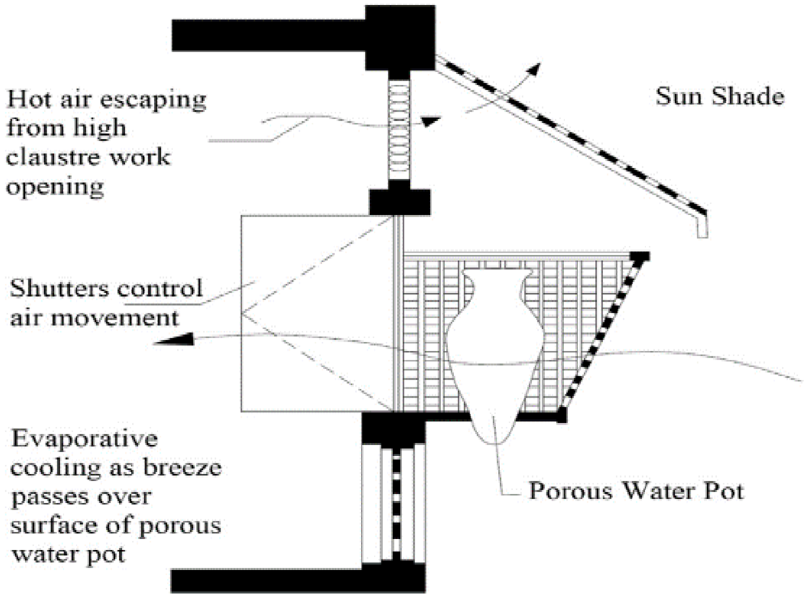


Figure 19 Section illustrates integrating window with porous water Haval H. A. Abdulkareem [39]

Figureure 20: Mashrabyia facade as seen from inside the living space
H. A. Abdulkareem [39]

Z. Zamani, et al. [43] highlighted the sustainability aspects of the courtyard and how it can passively improve the thermal and microclimatic conditions, particularly in hot arid climates, and the need to accurately identify the influential factors which determine its thermal performance. The researchers looked at how the courtyard configure ration and components in terms of geometry, construction material, proportion, orientation, shading elements, vegetation and water features can be utilized to improve the thermal performance of the courtyard in the context of solar gain, humidity and natural air movement. However, it is important to point out that, with the climate changes experienced in our time and the commonly unclear night skies due to pollution, the very fundamental principles by which the courtyard as well as exposed surfaces such as roofs cool down at night, through the exchange of longwave radiation with the night sky, has been inhibited (the night sky acts as a black body). The research highlights the importance of shading elements to reduce solar gains, a valid argument but only during daytime as the same elements will inhibit the ability of the courtyard to effectively exchange radiation with the night sky. Therefore, it is important to study the use of shading elements that can be deployed during the day and retracted during the night. The researchers highlighted the importance of natural ventilation and how it can be affected by the geometrical configure ration of the courtyard, i.e., ratio of height to floor area and shape, and how it affects the thermal performance of the courtyard. While natural air movement may be desirable during mild/cool seasons, during the warmer season, it is best if it is encouraged at night, when the air temperature is lower, as the daytime air temperature in hot arid climates can be excessively high. Y, Song et al. [37] X. Chen et al. [44] and X. Gong et al. [45] highlight that typical passive design features, which would significantly impact building energy consumption, include layout, building fabric thermo-physics and the extent to which buildings are airtight to minimise infiltration and/or exfiltration. In addition, building geometry plays an especially key role in reducing envelope gains; for example, a circular building will have the least envelope area when compared with other building shapes with the same floor area, but circular buildings are not usually functionally practical. Also, the following are important: the ratio of window areas to wall areas, external wall and roof colours (lighter colours reduce thermal heat absorption), architectural shading elements, particularly on the south elevation in the northern hemi sphere, as well as vegetation approximately buildings. Chen et al. [46]conclude that considering as many passive design measures as possible early in the design stage will help in energy Optimisation. D. Dan et al. [46] stated that a passively designed house can generate improved indoor comfort with low energy consumption. A study was conducted on an energy efficient house in which passive energy measures were applied, such as extensive thermal insulation (polystyrene panel thermal insulation of thickness 300 mm in walls and 425 mm in the roof were used), advantageous orientation, heat recovery, and an air-tight envelope. The house was monitored for an extended period (2 years) and its design parameters and the results from monitoring were compared with those of a conventional house designed in accordance with the

Romanian energy efficiency requirements. The measures applied to the passively designed house have resulted in a significant reduction in the energy consumption. It achieved a target of 15 KWH/m^2 year cooling/heating demand and a total primary energy requirement of less than 120 KWH/m^2 year. M. Zune et al. [47] highlighted in a study of vernacular architectural houses in Myanmar from a thermal performance perspective, that traditional passive design is not enough to achieve indoor thermal comfort due to the noticeable changes in the climate as a result of global warming. Further studies needed to focus on exploring innovative ideas which will help mitigate the additional challenges brought about by climate change. W. R, M, Zaki et al. [48] simulated two hypothetical terraced houses, a conventional traditional Malaysian terraced house and another in which passive architectural strategies were implemented. The aim was to explore ways of improving the thermal performance by adapting passive measures such as more appropriate orientation, thermal insulation, particularly in the roof, larger windows and adequate shading devices. The simulation work revealed that significant improvements in the indoor thermal comfort can be achieved. I. Sartori et al. [49] conducted a literature study on the life cycle energy use of 60 buildings from 9 different countries. Two interesting findings emerged: a passively designed house outperformed an equivalent self-sufficient solar house in terms of energy efficiency and reduced the life cycle energy demand by a factor of 3 as well. The study also highlighted that operation represents the greater proportion of the total life-cycle energy consumption in conventional buildings, up to 90% to 95%, while the remainder represents the energy expended (embodied energy) in the manufacturing of construction materials Figure. 21. Y. Wang et al. [50] in their simulation of a number of passive heating and cooling strategies, such as energy recovery ventilation (heating and cooling), pre-heating/cooling fresh air, pre-ventilation and night ventilation, in different weather conditions in passive buildings, found that it is quite possible to combine energy efficiency and acceptable indoor conditions. Q. Roslan et al. [51] suggested that it is possible to maintain indoor thermal comfort all day long by minimizing the heat transfer through the building envelope, particularly the roof, as well as by removing internal warm air in hot humid regions. Taking into consideration the building orientation and local weather conditions, a reflective cool roof with an optimised pitch along with the ventilated roof can be introduced as design guidelines to help in improving the thermal performance of passively designed modern houses.

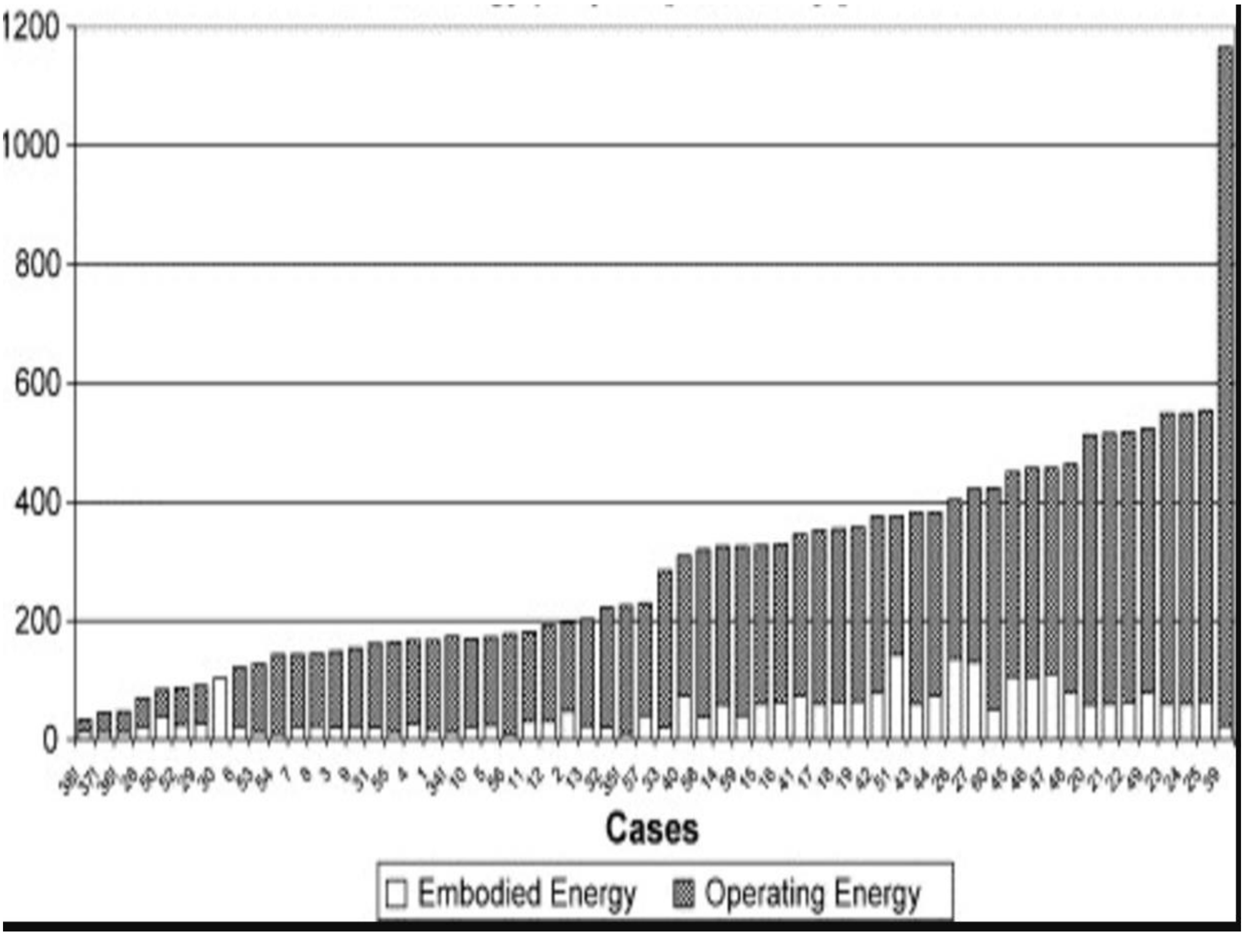


Figure 21 Normalized total energy for the 60 cases I. Sartori et al. [49]

6.3 Night ventilation (NV)

Night ventilation is the utilization of the nocturnal cooler air to drive down the temperatures of the building's internal air and surfaces (walls, floor, ceiling) to aid in cooling indoor spaces during the day in summer. E. Solgi et al. [52] defines night ventilation as ".an effective passive cooling technique whereby the daytime heat gain of a building is released during the night through the intake of the cooler outdoor air." Air is induced into the building either naturally or mechanically through apertures in the building envelope, windows and/or dedicated ventilation openings. Depending on the thermal mass of the building, orientation, facade design, shading elements, particularly on the south elevation in the northern hemisphere and the adjacent external landscape, the effect of the nocturnal cooling will help increase the time lag between maximum external and indoor temperatures. According to the same source the longer the time lag, the lesser the number of hours needed to run the air conditioning, or to have to run the air conditioning at full load, particularly during peak summer hours, to maintain indoor comfort. Also, it is concluded that there is enough evidence to suggest that night ventilation strategies can be applied to most climate types but there is a need for Optimisation as well as integrating this passive energy solution with other passive strategies for more effective results, for example, indirect evaporative cooling and nocturnal radiation exchange. With climate change and the apparent evidence of globe warming S Peng et al [53], the fundamental parameters which govern the effectiveness of night ventilation, that is the diurnal range (maximum difference between the peak day time and minimum night-time temperatures) and the duration of the lower night-time temperatures, are not as common as before. Narrower diurnal ranges and shorter durations of lower night-time temperatures are more frequently experienced in regions expected to make full use of night-time ventilation. It is quite evident that night ventilation on its own as a passive strategy may not necessarily yield the expected results and further research work needs to be conducted to optimise the use of this especially important passive energy strategy. As reported by M. P. Aimilios Michael et al. [54] in a study on natural ventilation for cooling in a vernacular architectural building with high thermal mass in Cyprus, the maximum benefit can be achieved from cross ventilation at night. However, as the duration of the field measurement was limited to 27 days (7th July to 2nd August 2105), field measurements spanning a longer period, particularly during peak months, are recommended for more substantiated findings. This would allow more accurate measurements as well, by giving more time for the building to stabilise thermally between the various ventilation regimes adopted in the study i.e. (1) No Ventilation, (2) 24-hour ventilation, (3) Night-time Ventilation (21:00 to 07:00) and (4) Day Time Ventilation (07:00 to 21:00). According to Giovani B. [55], indoor thermal conditions can improve in an external temperature range of 28 °C to 32 °C with an indoor air movement of 1.5 m/s to 2 m/s. According to the same source, maximum benefits can be realised from night-time ventilation when the nocturnal air temperature is approximately 20 °C and the diurnal day fluctuation is more than 10 °C. More studies are needed particularly on contemporary passively designed buildings with common construction materials, which would make up for the desired high thermal mass found in vernacular buildings, e.g., composite external wall and roof structures with thermal insulation, high emissivity light colours to reflect solar heat and double glazing. N. Aste et al. [56] studied how well thermally insulated buildings will perform under the influence of the thermal inertia of external walls. The U value (overall heat transfer Coefficient) should be in accordance with the international and local recognized energy conservation codes T. A. H. Loveday [57], M. A. E. Siviour [58], T. Kubpta et al. [59] and A. A. Jamaludin et al.[60] investigated different ventilation strategies and their impact on indoor conditions in residential buildings. Both concluded that night-time ventilation performed better than daytime or full day ventilation. M, Kololotrone et al. [61] concludes that night ventilation would be considered successful if the peak and average indoor temperatures are reduced the following day. H, M, Taleb [62] refers to the wind catchers in Dubai encouraging natural cross ventilation, particularly at night, a common vernacular architecture in many areas in the Gulf Region and Iran long before mechanical cooling had become readily available. Wind Catchers may have offered some thermal relief to occupants at a time when the perception about indoor comfort was different to that today. Careful consideration must be given particularly with the noticeable changes in the climate where higher day time temperatures and a narrower diurnal range are quite common. In addition, the increased dust storms, which demand effective filtration of external air prior to induction into the living spaces, would significantly inhibit natural ventilation. There is not enough evidence in the article to support the benefits of wind catchers. The researcher describes the UAE climate, particularly in Dubai, as predominantly arid with sufficiently low night-time air temperatures to make night-time ventilation effective with the help of Wind Catchers. Dubai is a coastal city at the northern part of the UAE with a seafront to the West/Northwest of the City. The prevailing wind direction in the Gulf Region is mostly North-Westerly coming from the Saudi Arabian/Iraq desert. During the warm season, the wind heats as it passes over the desert, increasing the capacity of the air to pick up moisture from the Gulf as it traverses the coastal cities on the eastern part of the Arabian Peninsula. This is one of the main reasons why most of the Western Gulf Coast Cities south of Kuwait i.e., Jubail, Dharan / Khobar, Doha, Manama, Abu Dhabi and Dubai, tend be hotter and more humid than arid. Dubai itself receives the lion's share of this humid air as it faces the Gulf from the North and Northwest as well as the Arabian Sea from East and Southeast, making it even more prone to humidity when the wind changes direction at the end of the warm season. The researcher suggests a 23.6% saving in energy if the passive strategies considered in the research are applied. The basis on which this saving was calculated is not clear. Also, there is no evidence that the thermal performance of the experimental house was recorded before any of the various passive strategies discussed in the article were applied, including the Wind Catcher. P. Blondeau et al. [63] conclude that night ventilation has significant potential on its own to improve indoor thermal conditions and not necessarily the same potential can be realised by coupling night ventilation with other ventilation modes i.e., all day and daytime. They also highlighted that further research work needs to be conducted to understand how night ventilation would affect the whole building and not just the restricted experimental space within the building which was under investigation. While night ventilation as a passive strategy has great potential, it may on its own improve indoor thermal conditions only under certain meteorological conditions B, Givoni [64] concludes in his experiment to study the effect of ventilation on buildings with different thermal masses that night ventilation out-performed other modes of ventilation by lowering the indoor maximum temperature in high mass buildings in comparison with low mass buildings. D. H. C. Toe [65] demonstrate that high thermal mass houses with roof insulation and small internal courtyards would maximise the benefit of night ventilation in the Malaysian tropical climate, while E. Shaviv et al. [66] studied the influence of thermal mass when using night ventilation on the maximum indoor temperature in various locations in Israel. The results were turned into a design tool to help predict at the initial stages of the design process the conditions most favourable for maximum benefit from night ventilation and thermal mass.

J. Landsman et al. [67] suggested that the most influential parameters that affect the thermal performance of night ventilation is the ventilation system set point; the higher the set point the higher the efficiency, as well as the number of hours of operation of the ventilation system; the longer the hours the more benefits can be achieved. Equally important is the outdoor night-time temperature, the lower the temperature, the greater the potential of night ventilation. The results of the study also showed that night ventilation in mild climates can maintain the indoor temperature within 80% of the acceptable comfort limit (indoor comfort range 17 C to 27 C and 50% + or 10% Relative Humidity). B. Chenari et al. [68] highlighted the importance of improving the efficiency of ventilation systems to reduce the impact of local and international guidelines pertaining to the requirements of outdoor air to maintain indoor air quality. They also highlighted the significant importance of hybrid mechanical and natural ventilation systems with control strategies to enable switching between the active and passive systems (that is, mechanical and natural), which will lead to accumulating savings in energy while maintaining indoor air quality. S. Omrani et al. [69] highlighted the importance of natural ventilation as a passive cooling strategy to reduce energy demand in regions where cooling is necessary. They proposed a process model that would help in evaluating as well as adopting the design of natural ventilation in multi-story buildings. Various evaluation methods were considered with the aim of developing a more cost-effective inexpensive method of evaluating the potential natural ventilation during the design stages of the building projects with more accurate methods to be used as the design develops further and during construction. TAS (an industry-leading building modelling and simulation tool) simulations were conducted during a number of thermal discomfort hours in a typical year. It was concluded that full day natural ventilation can improve the thermal comfort in the hot-humid climate of Singapore. This, coupled with a number of passive design measures, such as horizontal shading devices, increased window to wall ratios (0.24) and, surprisingly, no insultation in walls, can lead to better results (this requires further investigation). In addition, careful design of facades would help in gaining more benefits from natural ventilation, M, Santamouris et al [70] analysed the energy data from 214 airconditioned residential buildings using night ventilation to help reduce demand for energy. They reported that the potential contribution of night ventilation increased within buildings with higher cooling demands under specific boundary conditions and that an increased air flow rate is another potential contributing factor. Taking advantage of night-time ventilation requires a comprehensive understanding of following parameters to ensure maximum effectiveness:

- Building Layout and Usage.
- Floor plans including room sizes and functions.
- Occupancy patterns to determine cooling needs based on when spaces are in use.
- Internal heat gains from occupants, equipment, and lighting.
- Weather data: Temperature profiles and humidity for both day and night hours, daily range (lowest and highest daily temperature),
- Sudden daily temperature changes, a common phenomenon in monsoon regions where temperatures tumble down to below 20^{o}C during the warm season [monsoon weather].

- Wind patterns to leverage natural ventilation if applicable.
- Building envelope characteristics including insulation levels, thermal mass, and glazing types.
- Material properties such as specific heat capacity, density, and thermal conductivity.
- Air change rates appropriate to achieve desired cooling and air quality.

6.4 Nocturnal radiation exchange (NRE)

Nocturnal radiation exchange (NRE), also, known as nocturnal sky radiation cooling (NSRC), passive radiative cooling (PRC) and night sky cooling (NSC) is the cooling of building by rejecting heat to the night sky. Flat surfaces such as building roofs absorb most of the solar radiation during the day. The surface temperature of sun-exposed surfaces in warm climatic regions can reach well above 70 °C and a record high black bulb temperature of 85°C has been reached. Provided the right meteorological conditions exist, i.e., a clear sky, a low moisture content in the air, the absence of dust or low dust levels, minimal pollution and a reasonable diurnal nocturnal temperature range, the night sky acts as a heat sink which absorbs longwave radiation from building surfaces, particularly those exposed to the sky, i.e., roofs of buildings, walls not obstructed by nearby buildings, hills, trees, etc. It is an old technique which human beings gradually, through a process of trial-and-error spanning centuries, learned how to adopt and make use of in their localities to reduce the impact of the adversity of the climate throughout the seasons. Being a passive strategy, it has gained a lot of interest by researchers over the last past 40 years and more so recently with the perceived changes in the climate due to pollution and the uncertainty of the energy market. The night sky plays the role of a heat sink exchanging radiation with hot surfaces on earth. This results in heat losses from building surfaces exposed to the night sky. The greater the exposure is, the higher the rate of heat rejection and the lower the surface temperature will drop. This phenomenon, if deployed on its own or in a hybrid HVAC system as a passive strategy, can help cool down buildings at night to near comfort range in some regions. The main challenge with nocturnal cooling is how to store the coolness at night for utilization as long as possible during the day and not just when the conditions are favourable for nocturnal radiation exchange at night. A hybrid NSRC system, which included a number of active components such as a heat pump and several pumps to move the cooling medium (water) across the various components of the system were used in a research study by A. Amir et al [71] in which it was concluded that a hybrid system employing more than one strategy (passive and active) will offer the maximum benefits and performance. Y. Man et al [72] used nocturnal cooling radiation in a novel nocturnal cooling radiator to aid the heat rejector of a conventional active cooling system, when meteorological conditions permitted, to improve its energy performance. The simulation results in a humid tropical climate proved that it is feasible to use nocturnal cooling to supplement as a heat sink the heat rejection capability of an active cooling system. B. Zhao et al. [73]

experimented with a conventional PV panel modified to be operated as diurnal PV panel and a Nocturnal Panel. The PV-RC system schematic and the actual modified PV Panel can be seen in Figures in 12a and 12b in Appendix 11.1. The PV panel face was covered by a transparent low-density polyethylene sheet while all other 4 sides and the bottom were well insulated with polystyrene thermal insulation to ensure no heat transfer or gain which might reduce the performance of the panel. The panel was installed on the roof a building and was only protected with the low-density polyethylene cover during the nocturnal cycle. He concluded that the PV panel thermal emission within the infrared wavelength band makes it a potential candidate for doubling up as nocturnal radiative cooling panel during the night hours. An average of 12.4% PV conversion and an average equilibrium temperature difference (Delta Tap) of 12.7°C for nocturnal RC process were achieved, which supported the idea of PV panel dual function (PV conversion during daytime and nocturnal cooling during night-time). He also demonstrated that the performance is significantly affected by water moisture in the air, which proved that low humidity regions allow for better performance. Also, a clear night sky is equally important to release the full potential of the nocturnal cooling strategy. With polluted skies due to burning of fossil fuels, nocturnal cooling on its own may not be the most rewarding solution. A hybrid system along with the deployment of other passive strategies would offer the best chance to achieve better results. S, Zhang et al. [74] demonstrated the potential of using a hybrid system combining Microencapsulated Phase Change Material (MPCM slurry storage) with nocturnal radiative cooling. Encouraging though limited results were produced showing a potential annual energy saving when this strategy is applied in low rise buildings. The savings ranged from 12% to 77% across five cities in China (Figure 22). Shuo et al recommended the use of this strategy in northern and central China where the metrological conditions are more favourable for nocturnal radiative cooling, being dry with low ambient temperatures at night. B. Bokor et al. [75] used a corrugated perforated metal plate as a radiant surface, to study the potential of nocturnal cooling in four European Cities. He concluded that nocturnal cooling performs

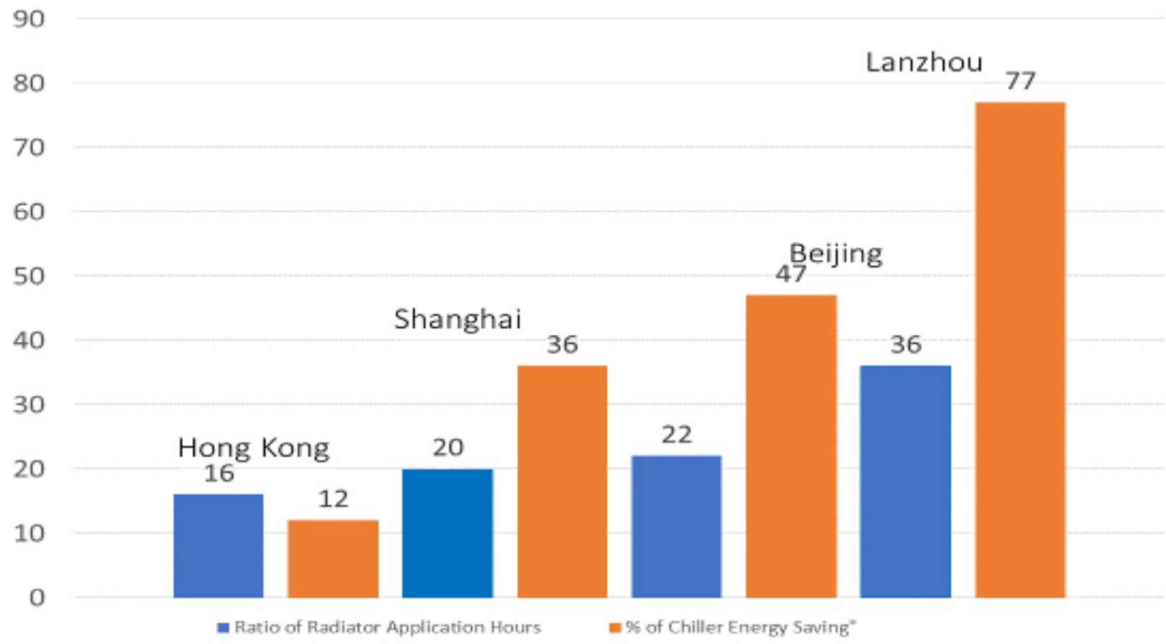


Figure 22: % of chiller energy saving and the utilization ratio of nocturnal radiator [74]

better in locations with drier climates due to the absence of water moisture in the air, which impedes the radiation exchange with the night sky. In this paper the use of TSC (Transpired Solar Collector) is being suggested as means of doubling the benefit of a solar collector by using it for cooling the air through longwave radiation exchange with the night sky (i.e., Nocturnal Cooling) in the warmer months as well as a solar heater in winter. Encouraging results were produced but further research work needs to be conducted to evaluate this approach and determine its feasibility as a strategy to aid active HVAC systems and in turn reduce their energy footprint. It may be worth investigating applying the same strategy with the use of purpose-built solar air heaters which permit the living space air to circulate through them (for winter heating), a technology evolved out of the Antarctic expeditions to heat tents in the harsh frozen conditions of the south pole. The same device can be used in reverse in summer to cool down the air at night and allow air circulation in the living space. G. Nwaji et al. [76] investigated a hybrid flat plate water heating solar collector that can double up as a nocturnal radiator to demonstrate the worth of investigating this passive strategy further. The finite element analysis of the dynamic performance of the solar collector in five Nigerian city temperatures produced impressive results. The difference between the maximum achieved during the diurnal period and that achieved during the nocturnal period was 73.55 °C, i.e., 93.67 °C in the case of diurnal heating and 20.12 °C in the case of nocturnal cooling. Further investigation is required. Z, Wang et al. [77] developed a new numerical algorithm based on a solution of the energy balance equations in an attempt to characterize the complex thermodynamics of nocturnal cooling when applied to intensively urbanized cities. The complex urban development landscape surface and surrounding atmosphere with its multitude of interwoven parameters such as tall buildings, short buildings, masonry and glazed facades, flat and sloping roofs, asphalted streets, parks, etc., which lead to what is known as Urban Heat Islands (UHI), are but a few of the challenges met. Further work needs to be conducted to understand nocturnal cooling better and to attempt to quantify its benefits in the context of UHI. X, Lu et al. [78] reviewed the potential of different PRC (Passive Radiative Cooling) systems to assess their performance by simulations. It was concluded that the diurnal performance is limited when compared to nocturnal performance even under the most suitable meteorological conditions. It was also concluded that the commercialization of this passive strategy is heavily dependent on the discovery, reliability and availability of the coating materials, which themselves are subject to extensive research and development work. M. Hu et al. [79] looked at diurnal solar heating and nocturnal radiative cooling using a Solar Heating/Radiative Cooling Collector. A mathematical model to establish the performance of the collector in both modes was established. The thermal performance of the collector was investigated using parameters with different specifications and conditions, e.g., insulation thicknesses, wind velocities, ambient and inlet temperatures, water flow rates, precipitable water vapor amounts and solar irradiance. It was concluded that the multi functionality of the solar collector through its increased utilization was one of the main advantages when compared to traditional single mode solar thermal collectors. The heating and cooling gains varied across the four Chinese cities in which the collector was investigated. Parameters such thermal insulation, ambient temperature and wind speed impacted directly on the performance of the collector in both modes. Further research work is required to establish the practicality and cost effectiveness of such multifunction collectors under various meteorological conditions.

6.5 Feasibility of Solar PV simulations

The 2020 Buildings Global Status Report published by the United Nation Environment Program, have predicted the CO_2 emissions from the buildings sector may be approximately 38% of total global energy-related CO_2 emission Solar Photovoltaic (PV) has proved its worth as a supplementary as well as a prime renewable source of electricity, particularly in new and existing residential buildings. In countries where electricity is unreliable, costly or not available, the adaptability of this technology, the continuous improvement, both in performance and cost effectiveness, as well as the ease of connecting to existing gird, made it gain traction, immensely popular and the preferred choice by consumers.

Three common methods in adopting Solar PV:

1. FIS (Fully Independent System)**:** Solar PV panels plus batteries for storage installed on roof areas of the building. Both CAPEX and OPEX expensive.

2. FIT (Feed-in Tariff) **:** Simple system, less costly and can be integrated with the grid via smart electricity meters. It is designed for homeowners to sell back to the grid any excess produced electricity. It requires IPP license and the appropriate legislation including billing to function properly.

3. SEG (Smart Export Guarantee) **:** It is a scheme designed to help homeowners and small renewable power producer to be compensated for any electricity produced and exported to the grid. Compensation can be in many different ways (direct refund or net billing). Under this scheme, all licenced energy companies with 150,000 or more customers must provide at least one SEG tariff. Smaller suppliers can offer a tariff if they want to on a voluntary basis. All suppliers can also choose to offer other means of making payments for exported electricity, separate to the SEG arrangements.

Computer simulation is the most economical method to transform ideas into reality. Optimisation, running the system being simulated under different climatic or process conditions to study its behaviour and suitability, stretch its boundary limits in a safe non-destructive environment, explore the different "what if" scenarios, results can be easily animated for better understanding and visualisation of the problem areas, increase accuracy, handles uncertainties, demonstration purposes, education and training but a few of what computer simulation can do. All this can be easily, and cost effectively accomplished in a desktop environment. System components can be rearranged, altered or redefined, individually or in groups to enable observing the impact of these changes on system behaviour. Analysis carried out can be easily verified and shared with others. It is a far more elaborate way to conduct model analysis than other methods such as Excel or linear programming or physical modelling which relied on mathematical models to work out analytical solutions to design problems by predicting the behaviour of the system/building. It enables examining and monitoring processes while interacting with the simulation model.

Simulation tools enable building designers to evaluate not just the active systems such heating, cooling and ventilation but also the passive building parameters such as site, orientation, building mass and structure, shape, envelope and façade, surroundings (external landscape and nearby buildings), daylight, glazing and occupancy pattern. The benefits help achieve building's sustainability targets, energy certifications, estimate future energy, demand and energy cost. More benefits can be achieved by energy modelling at the initial stages of building design. It helps in achieving energy-efficiency goals, design Optimisation through the implementation of alternative energy sources such as solar and wind and the avoidance of redesign by addressing at the outset design issues that can lead to delays and risks. In addition, to selection of the right simulation tools, the knowledge and experience of the user is vitally important to enable maximum usage of the modelling software Amol Patil [80].

While the use of building energy simulation is now common and significantly important in the R&D environment, it is still not as popular among building owners and designers due to the lack of understanding of the benefits, particularly in terms of construction and operating costs, and the absence of enough trained, experienced and skilled modellers. However, the use of simulation is gaining momentum with the increased awareness of the impact of fossil fuels on the environment and the tighter energy conservation legislation Anylogic Simulation Modelling [81] , M Fakoor "The Benefits of Building Energy Modelling - Simulation the future" [82].

Building Performance Simulation (BPS) developed as early as the late 1950s and early 1960s in the United States and Sweden. The beginning was a humble attempt to compute buildings parameters such as indoor and outdoor temperatures, heating and cooling loads to size and analyse individual air conditioning system components such as boilers, vapour compression (electric) chillers, absorption chillers, adsorption chillers, air handling/fan coil units, ventilation fans, direct/indirect evaporative coolers and solar water/air heaters, but a few of the examples of system components that can be modelled to study and predict their thermal behaviour in buildings for design Optimisation and their impact in reducing buildings' carbon footprint by minimising or eliminating the need to burn fossil fuels. In 1963 BRIS was developed by the Royal Institute of Technology in Sweden. It is one of the earliest examples of BPS which was based on a heat balance method where finite differences between internal and external surfaces were used G. Brown [83]. By the 1970s, the improvement in computer technology and hike in energy cost (1973 oil crises) increased awareness in energy saving and importance of energy efficient buildings to reduce energy bills. This intensified the effort of academic researchers, governmental institutions and specialised private companies to develop powerful simulation tools which lead to the emergence of many computer programmes such as BLAST, DOE-2, ESP-r, HVACSIM, Energy Plus, IES-VE, ICE and TRNSYS T. Kusuda, [84], Anon [85], S. Oh et al. [86]. In the 1980s building performance simulation turned into a specialized field with expertise offering their services while research work continues to improve the methodologies, versatilities, accommodate new applications J. Hensen [87], H. Wang et al. [88] and to develop more user-friendly tools as well as to accommodate new requests for improvements that may emerge in the future. In addition, the first equation-based simulation tool. The Neutral Model Format (NMF) for building simulation models which used at the present time was introduced in 1989 P. Sahlin et al. [89]. In 1993 the Engineering Equation Solver (EES) was introduced and in 1997 work on Modelica was reported S. A. Klein [90], S. Burhenne, et al. [91]. There are still many challenges that need to be addressed all those involved in the development and improvement of Building Performance Simulation tools such as better representation, performance appraisal support, operational application enabling, user education, user training and accreditation. Clarke et al summarize a few of these challenges J. Clarke [92]:

- Better concept promotion

- Standardization of input data and accessibility of model libraries
- Standard performance assessment procedures
- Better embedding of BPS in practice
- Operational support and fault diagnosis with BPS (Building Performance Simulation)
- Education, training, and user accreditation

Today, several accredited BPS tools are available, with excellent research application track records. These tools allow building energy researchers to perform simulations and optimize and evaluate research based on various performance indicators, covering indoor and outdoor parameters such as temperature, humidity, solar intensity, and wind direction/speed. Comparative studies of many popular simulation tools have been published, Q. T. Ahmad et al[93], R. Judkoff et al. [94], M. Nadarajan et al [95].

To simulate the Solar PV system for maximum benefits, several popular computer simulation tools were looked at to compare and identify the most suitable one to optimize Solar PV system for maximum benefits:

1. **TRNSYS** is an extremely flexible, graphically based software environment used to simulate the behaviour of transient systems. The vast majority of simulations are focused on assessing the performance of thermal and electrical energy systems Solar Energy Laboratory [96].
2. **PVGIS** is a freely available web application that provides data on solar radiation and photovoltaic (PV) system energy production for most parts of the world. This information ia easily accessible without any restrictions or registration requirements. PVGIS determines the off-grid PV energy production by considering hourly solar radiation data over several years. The calculation involves the following steps: For each hour, it calculates the solar radiation on the PV modules and the corresponding PV power output.
3. **ESP-r** building thermal, inter-zone air flow, intra-zone air movement, HVAC systems and electrical power flow simulation environment.
4. **EnergyPlus** Integrated energy simultaneous solution
5. **IES-VE (Integrated Environmental Solutions - Virtual Environment)** integrated analysis tools

6. **IDA Indoor Climate and Energy (IDA ICE)** is a Building performance simulation software.

TRNSYS is a highly adaptable, graphically-based software environment designed for simulating the behavior of transient systems. While most simulations focus on evaluating the performance of thermal and electrical energy systems, TRNSYS can also model other dynamic systems such as traffic flow or biological processes.

TRNSYS comprises two main parts. The first is the engine (or kernel), which reads and processes input files, iteratively solves the system, determines convergence, and plots system variables. The kernel also includes utilities for determining thermophysical properties, inverting matrices, performing linear regressions, and interpolating external data files. The second part is an extensive library of components, each modelling a specific part of the system. The standard library features approximately 150 models, including those for pumps, multizone buildings, wind turbines, electrolysis, weather data processors, economic routines, and both basic and innovative HVAC equipment. Users can modify existing components or create their own, enhancing the software's capabilities. With 35 years of commercial availability, TRNSYS remains a versatile, component-based software package that meets the evolving needs of researchers and practitioners in the energy simulation field.

TRNSYS was selected to conduct the simulation analysis of 12 cases, starting with Case 1 - actual and Case 12 – tracking on two axes, tilt and azimuth. Reasons for selected TRNSYS:

- A proven track record of research simulation tools that goes back to the early days of computer simulation tools development.
- Require detailed specific input parameters including manufacturers' data to build the model.
- Quite versatile and robust simulation tools.
- Built in plugins such as Tremble (Google Sketchup) which enables inputting building data easily and accurately.
- Able to read typical internationally recognized weather data reports such as TMY (Typical Meteorological Year) down to 15 minutes intervals.
- Dedicated technical back up support and availability of training material.

The same cases were also simulated using PVGIS for comparison and to build confidence in the simulation results. The results of both simulation tools compared favourably, however, confidence in TRNSYS proved to be higher because of detailed manufacture specific input parameters required.

However, there are several challenges which still makes Solar PV difficult to be a full right-full alternative to conventional fossil fuel-based energy power production technologies. Some of these challenges:

- Inherently intermittent because it is solar and sky condition dependent.
- Production efficiency drops noticeably in warm conditions.
- Requires regular cleaning particularly in dusty regions.
- Excessive heat shortens the life span of the PV panels.
- Spatial requirement may limit the installed capacity.
- Difficult to blend with architectural elevations which makes it undesirable at times.
- Complexity of the local legislation in case of the permit needed for net-metering installation.
- Cost is still comparatively high in the absence of government incentives and/or in low heavily subsidized electricity tariffs in countries such as Kuwait and Qatar for example.

7. Experimental Rig

7.1 Location

Country:	Pakistan
City:	Islamabad (north of the country, on the Potohar plateau)
Coordinates:	33^o 44’ 49” N and 73^o 14’ 13” E
Orientation:	-38^o (142^o from North) and 776 m Elevation
Climate:	Subtropical with mild, quite rainy winters and hot, very rainy summers due to the Indian monsoon World Climate Guide [97]

7.2 Building Description

Well-designed 6-bedroom house constructed in 2011 (Figure 23). A number of passive energy features have been incorporated such as substantial thermal insulation in walls and roof, double glazing, controlled natural ventilation and external light colour. The house design and construction information are available, and it is fully accessible all year round to enable conducting the research investigation without any interruptions. A substantial two-story house of approximately 600 m^2 GFA (Gross Floor Area - Build-up Area). The experience of a top-class architect was leveraged in the creation of a rural energy efficient dwelling. Incorporating passive energy strategies, like robust thermal insulation, double glazing, shading elements, purposely designed façade to reduce sun glare during summer and allow as much of it during winter. In addition, green landscape all approximately the house, appropriate orientation, and manually controlled natural ventilation throughout the house. These passive architectural features resulted in noticeable reduction in mechanical cooling and heating during the respective season, while making the most out of the milder season to promote and comfortable indoor conditions by reducing dependence on gas and electricity to the bare minimum.

Symmetrical house comprising two floors. On ground floor, a double height entrance lobby, main reception room, dining room, guest room, study, family room, kitchen, housekeeper quarter, 3 main bathrooms, two stores housing two electrical distribution boards and a foyer with staircase which leads to the first floor. On first floor, two ensue master bedrooms, two bedrooms and a foyer. Both ground floor and first floor foyers are served with two manually controlled natural ventilation shafts.

To further enhance the house’s energy profile, a 12.18 KW_p grid connected net-metering Solar PV system was installed. This addition feature has resulted in an impressive 65% average reduction in electricity consumption and the accumulation of substantial electricity credit. The house design is based achieving symmetry on both ground floor and first floor, as can be clearly seen from the AutoCAD as Built Drawings.

In pursuit of energy neutrality, upcoming plans involve implementing night-time ventilation, Indirect Evaporative Cooling (IDC), solar thermal water and air heating, and further landscape enhancement. This dwelling serves as a research platform, simulating and validating energy-saving measures, contributing to advancing energy-efficient solution that can be implemented in existing as well as new constructions.

7.2.1 Ground Floor

Comprises of double height entrance foyer, dining, bedroom and kitchen to the right. On the left, drawing room, bedroom, family room, a circulation vestibule, front and back patio areas (Figure 24).

7.2.2 First Floor

Comprises of two master bedrooms, two bedrooms, circulation vestibule, two front terraces and a single back terrace. Figure 25 is a photograph of the building front south elevation. The front patio with its overhanging beam overhang, together with the recessed doubled glazed windows provide optimized shading elements respecting the architectural design theme. Two penthouses accommodating 4 freshwater tanks of total capacity 4,000 litres.

Figure 23: House front elevation

7.3 Building Description

1. External walls: outer leaf cement plastered partially covered with stonework concrete blocks, 75 mm EPS (Expanded Polystyrene) and cement plastered brick wall.
2. Roof: Cementitious roof tiles, light cement screed, water proofing membrane, cementation screed, 75 mm EPS (Expanded Polystyrene), light concrete slab.
3. Windows: 95% of the windows are gas filled double glazing.

7.4 As Built Auto-Cad Drawings

Figure 24 is the “AS Built” architectural layout of the ground-floor, highlighting in different colours zones on this floor, 1 to 4. Zone 1 is the entrance lobby with double height, from ground floor to the first floor.

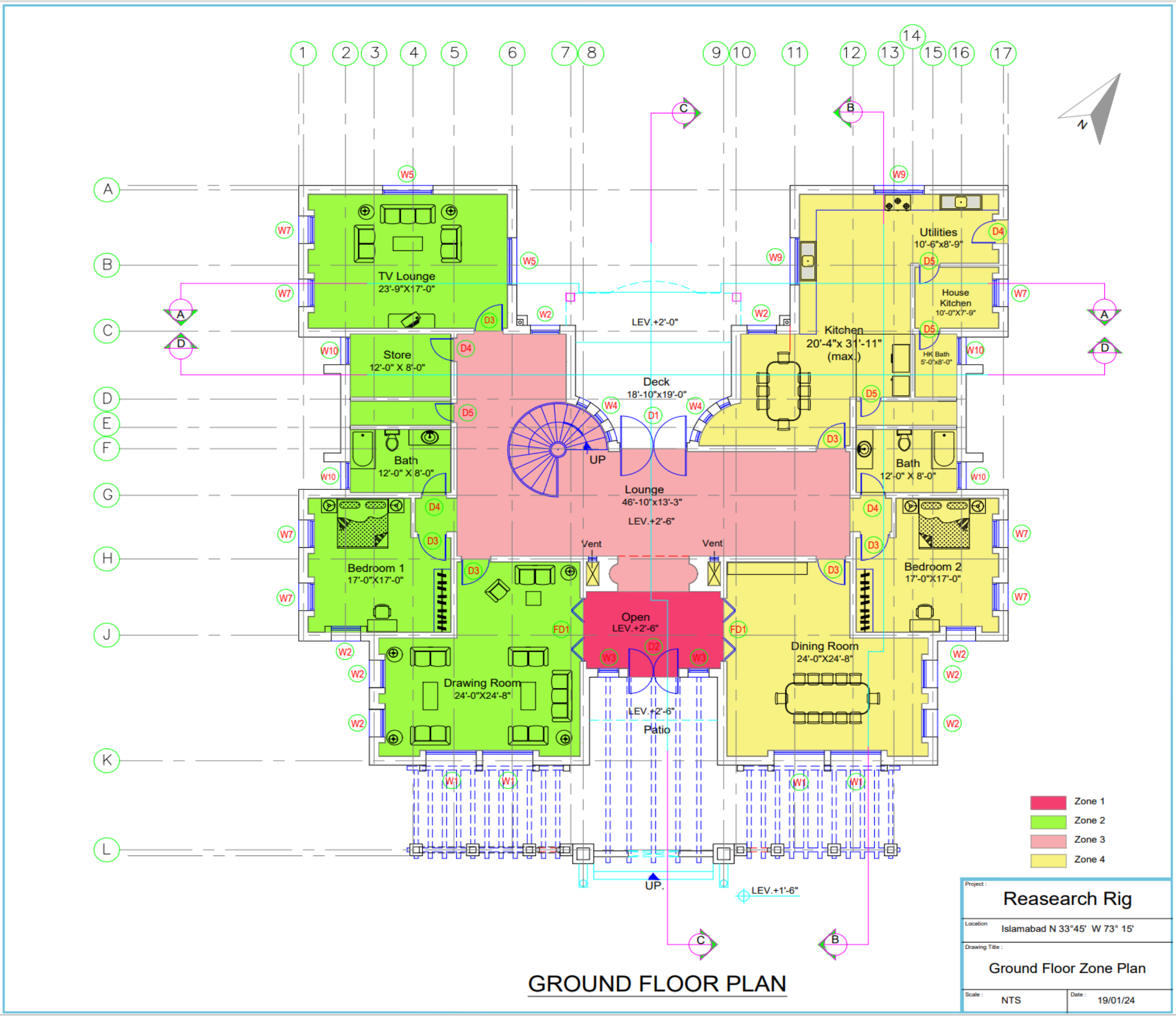


Figure 24: Ground Floor Zones 1 to 4

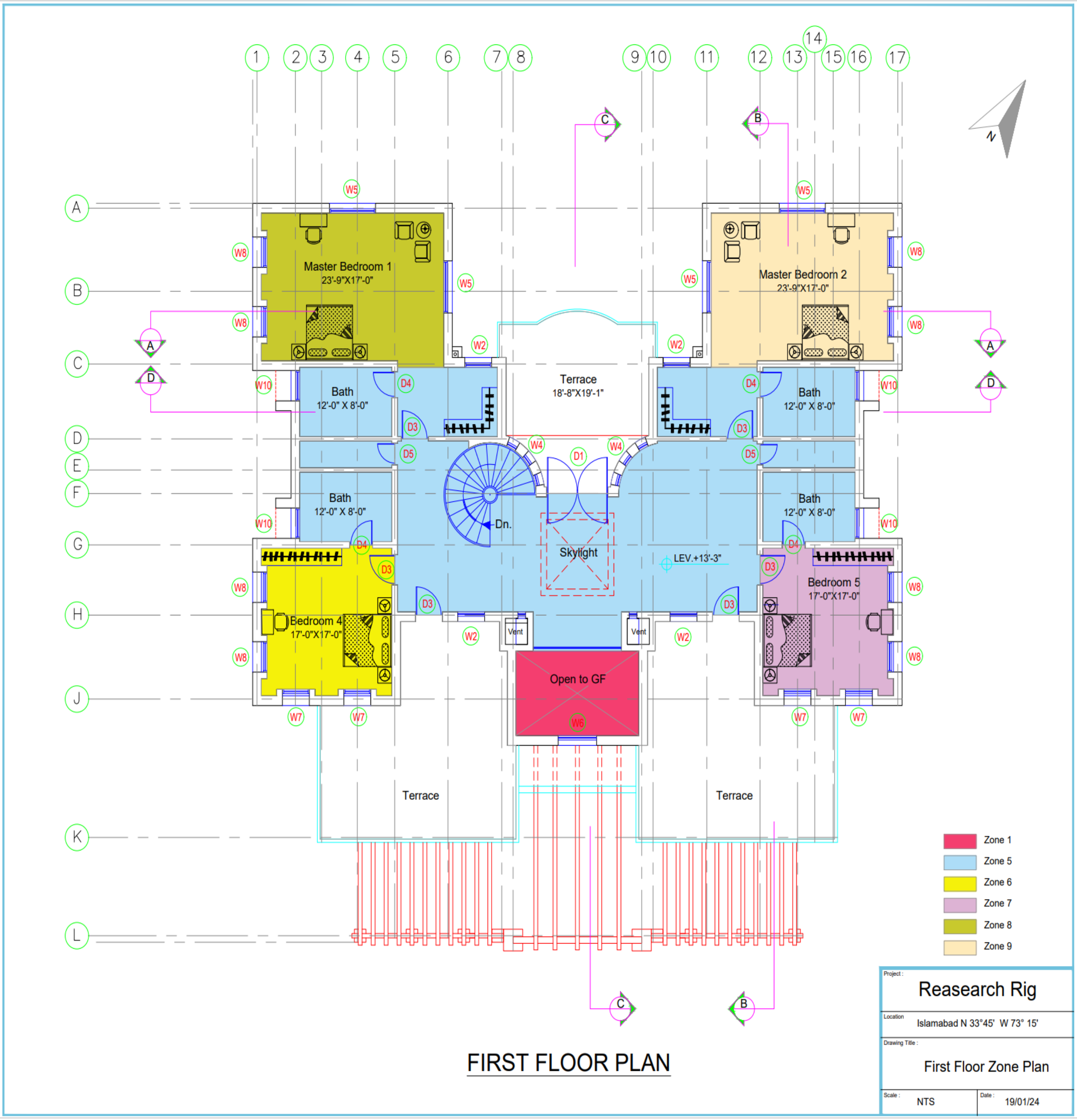


Figure 25: Zones 5 to 9 First Floor

Figure 25 is the "AS Built" architectural layout of the first floor, highlighting in assorted colours the various zones on this floor except for Zone 1, which is the entrance lobby with double height, from ground floor to the first floor. The front terraces are directly above the drawing room in Zone 2 and dining room in Zone 4. Both terraces are thermally insulated to the same standard as the main flat and slopping roofs using 75 mm ESP insulation panels. In addition, the waterproof membrane is made of thick bitumen hot applied sheets. The back-terrace flooring is not thermally insulated because it is an overhang (balcony) with open space below it.

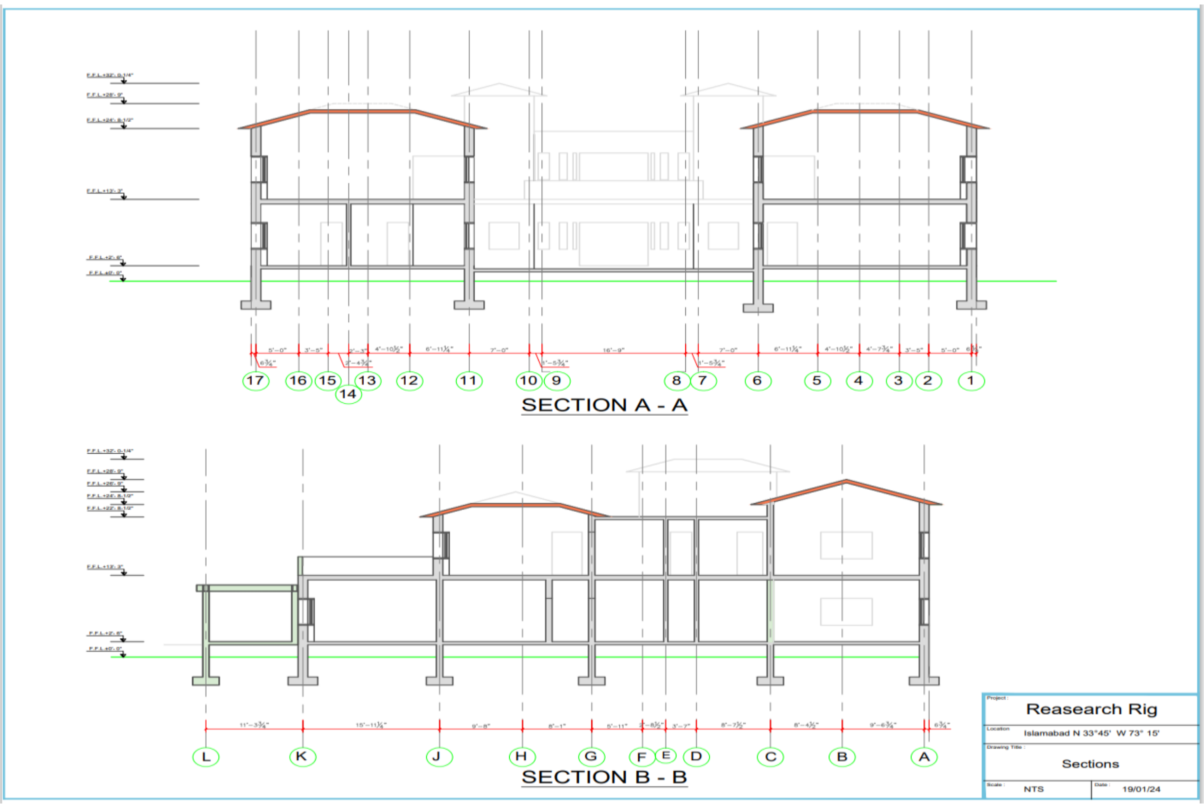


Figure 26: Building Sections A-A & B-B

Figure 26 illustrates the sectional details across the building to show the relation between floors and structural soffit heights.

In Table 2 the dimensional details of all types of windows and doors fixed in the building are shown along with the quantities (number off of each type).

Table 2: Schedule of Windows and Doors

***Windows Schedule**				**Doors Schedule**			
Ref	**Width mm**	**Height mm**	**Quantity no.**	**Ref**	**Width mm**	**Height mm**	**Quantity no.**
W1	1,829	2,134	4	D1	1,876	2,210	2
W2	1,067	2,134	6	D2	1,829	2,210	1
W3	762	2,134	2	D3	1,067	2,210	12
W4	381	2,134	12	D4	915	2,210	8
W5	1,219	1,829	8	D5	762	2,134	6
W6	610 Diameter		1	Vent Shaft	305	2,134	4
W7	1,067	1,524	11				
W8	1,067	1,524	8				
W10	1,067	1,219	8				
Sky Light	229	229	16				

'* All windows U Value 1.1 W/m^{2}K

7.5 Google SketchUp

SketchUp is a suite of subscription products that include SketchUp Pro Desktop, a 3D modelling Computer-Aided Design (CAD) program for a broad range of drawing and design applications — including architectural, interior design, industrial and product design, landscape architecture, civil and mechanical engineering, theatre, film and video game development.

The program includes drawing layout functionality, surface rendering in different "styles", and enables placement of its models within Google Earth. SketchUp is a program used for a wide range of 3D modelling projects like architectural, interior design, landscape architecture, and video game design, to name a few of its uses.

The program includes drawing layout functionality, surface rendering, and supports third-party plugins from the Extension Warehouse. The app has a wide range of applications, including in the worlds of architecture, interior design, landscaping, and video game design. Sketchup has also found success with people who want to create, share, or download 3D models for use with 3D printers.

Sketchup was created in 1999 by @Last Software. In 2006, Google acquired SketchUp after @Last Software created a plugin for Google Earth that caught the eye of the tech giant. In 2012, Trimble Navigation (now Trimble Inc.) acquired Sketchup from Google and expanded the app by launching a new website that hosts plugins and extensions.

The AutoCAD “As Built” drawings in Figures 24, 25 and 26 were used to meticulously digitize the whole building using Tremble (Google SketchUp), as clearly illustrated in Figures 27 to 32. This enabled creating the input parameters for each room/space and their layout relations i.e. external walls, partitions, roof, windows and orientation, for TRNSYS TRN-Build Module using Google SketchUp plugin. The house is divided into 9 zones as illustrated in Tables 3 to 11 below where indicate the constructional dimensions of the building fabrics (walls, floors, ceilings, roofs and windows) are indicated. Each fabric type i.e. boundary, external or adjacent, area in m^2 and orientation are shown. The orientation is key: the first letter identify the direction, and in case of a roof space letter H (Horizontal) is used, the first digit 0 to 180 indicates the angle of orientation. 0 for South, 90 for West, 180 for North and 270 for East. The second digit is the for the surface inclination angle: 0 to 90, a vertical surface and 25, for example, is for sloping roof where the angle it makes with a horizontal plain is 25.

Table 3: Zone 1 Walls, Floors, Ceilings, Roofs and Windows Detail

Volume (m^3)		81.016	**ZONE 1**	
Capacitance (KJ/K)		97.219		
Floor Area (m^2)		15.408		
Walls/Floors/Ceilings/Roofs/ Windows		Total Number: 9		
Surface ID	**Construction Type**		**Category**	**Orientation**
1	Ground Floor	**Area (m^2)**	Boundary	-
2	Wall	15.408	External	W-90-90
3	Wall	7.330	External	E-270-90
4	Wall	7.330	External	S-0-90
5	Wall	24.440	Adjacent	Zone 5
6	Wall	10.270	Adjacent	Zone 3
7	Roof	14.170	External	H-0-0
8	Wall	15.410	Adjacent	Zone 4
9	Wall	10.100	Adjacent	Zone 2
Window	W3	1.626	External	W-90-90
Window	W3	1.626	External	W-90-90
Window	W6	0.292	External	W-90-90

Table 4: Zone2 Walls, Floors, Ceilings, Roofs and Windows Detail

Volume (m^3)		485.915	**ZONE 2**	
Capacitance (KJ/K)		583.099		
Floor Area (m^2)		159.421		
Walls/Floors/Ceilings/Roofs/ Windows		Total Number: 24		
Surface ID	**Construction Type**	**Area (m^2)**	**Category**	**Orientation**
13	Ceiling	24.920	Adjacent	Zone 5
14	Wall	10.100	Adjacent	Zone 1
15	Ceiling	46.500	Adjacent	Zone 8
16	Wall	17.880	External	W-90-90
17	Wall	10.380	External	E-270-90
18	Wall	25.820	Adjacent	Zone 3
19	Wall	14.640	External	W-90-90
20	Wall	17.960	External	W-90-90
21	Wall	24.390	External	S-0-90
22	Wall	4.180	Adjacent	Zone 3
23	Wall	4.640	External	N-180-90
24	Wall	17.880	External	W-90-90
25	Ceiling	33.750	Adjacent	H-0-0
26	Wall	17.880	External	E-270-90
27	Roof	54.250	External	H-0-0
28	Wall	24.160	External	N-180-90
29	Ground Floor	159.420	Boundary	-
30	Wall	6.620	Adjacent	Zone 3
31	Wall	7.820	External	S-0-90
32	Wall	14.670	Adjacent	Zone 3
33	Wall	4.640	External	S-0-90
Window	W2x2+W7x3+W10x2	10.408	External	W-90-90
Window	W5	2.230	External	N-180-90
Window	W5	2.230	External	E-270-90

Table 5: Zone3 Walls, Floors, Ceilings, Roofs and Windows Detail

Volume (m^3)		267.94	**ZONE 3**	
Capacitance (KJ/K)		321.528		
Floor Area (m^2)		87.907		
Walls/Floors/Ceilings/Roofs/ Windows		Total Number: 18		
Surface ID	**Construction Type**	**Area (m^2)**	**Category**	**Orientation**
89	Wall	7.220	External	E-230-90
90	Wall	17.750	Adjacent	Zone 4
91	Wall	25.820	Adjacent	Zone 2
92	Wall	7.970	External	N-180-90
93	Wall	14.670	Adjacent	Zone 2
94	Wall	4.180	Adjacent	Zone 2
95	Wall	4.180	Adjacent	Zone 4
96	Ground Floor	87.910	Boundary	-
97	Wall	6.620	Adjacent	Zone 2
98	Wall	6.950	External	E-270-90
99	Wall	6.500	External	N-180-90
100	Wall	13.350	Adjacent	Zone 4
101	Ceiling	87.910	Adjacent	Zone 5
102	Wall	14.670	Adjacent	Zone 4
103	Wall	14.170	Adjacent	Zone 1
Window	W2	1.626	External	N-180-90
Window	W4	0.810	External	E-270-90
Window	W4	1.620	External	E-270-90

Table 6: Zone4 Walls, Floors, Ceilings, Roofs and Windows Detail

Volume (m^3)		544.314	**ZONE 4**	
Capacitance (KJ/K)		653.177		
Floor Area (m^2)		178.398		
Walls/Floors/Ceilings/Roofs/ Windows		Total Number: 30		
Surface ID	**Construction Type**	**Area (m^2)**	**Category**	**Orientation**
47	Wall	7.200	External	W-130-90
48	Wall	17.880	External	E-270-90
49	Wall	7.820	External	S-0-90
50	Wall	24.160	External	N-180-90
51	Wall	13.350	Adjacent	Zone 3
52	Wall	6.950	External	W-90-90
53	Wall	0.030	External	W-130-90
54	Ceiling	46.500	Adjacent	Zone 9
55	Ground Floor	178.398	Boundary	-
56	Wall	6.500	External	N-180-90
57	Wall	14.630	External	E-270-90
58	Wall	17.880	External	W-90-90
59	Wall	17.750	Adjacent	Zone 3
60	Wall	0.520	External	W-130-90
61	Wall	4.180	Adjacent	Zone 3
62	Ceiling	33.760	Adjacent	H-0-0
63	Wall	24.390	External	S-0-90
64	Wall	14.670	Adjacent	Zone 3
65	Wall	4.640	External	S-0-90
66	Wall	17.960	External	E-270-90
67	Roof	54.240	External	H-0-0
68	Ceiling	43.900	Adjacent	Zone 5
69	Wall	17.880	External	E-270-90
70	Wall	10.100	Adjacent	Zone 1
71	Wall	4.640	External	N-180-90
72	Wall	10.380	External	W-90-90
Window	W1x2 +W2	10.083	External	S-0-90
Window	W2x2+W7x3+W10x2	10.408	External	E-270-90
Window	W2+W4+W5	5.320	External	N-180-90
Window	W4x2+W5	3.043		W-90-90

Table 7: Zone5 Walls, Floors, Ceilings, Roofs and Windows Detail

Volume (m^3)		478.760	**ZONE 5**	
Capacitance (KJ/K)		574,512		
Floor Area (m^2)		156.730		
Walls/Floors/Ceilings/Roofs/ Windows		Total Number: 30		
Surface ID	**Construction Type**	**Area (m^2)**	**Category**	**Orientation**
136	Floor	24.920	Adjacent	Zone 2
137	Wall	13.960	External	S-0-90
138	Wall	6.610	External	W-90-90
139	Wall	7.580	External	N-180-90
140	Wall	2.610	External	W-90-90
141	Wall	6.850	External	W-130-90
142	Wall	6.190	External	N-180-90
143	Wall	7.470	Adjacent	Zone 7
144	Wall	3.980	External	E-270-90
145	Wall	2.610	External	E-270-90
146	Wall	17.09	External	W-90-90
147	Wall	13.960	External	S-0-90
148	Wall	3.210	External	S-0-90
149	Wall	6.190	External	N-180-90
150	Wall	7.480	External	Zone 6
151	Wall	3.980	External	W-90-90
152	Roof	8.410	External	H-0-0
153	Wall	2.610	External	S-0-90
154	Wall	18.560	Adjacent	Zone 9
155	Floor	43.900	Adjacent	Zone 4
156	Wall	18.560	Adjacent	Zone 8
157	Wall	2.610	External	N-180-90
158	Wall	17.090	External	E-270-90
159	Floor	87.910	Adjacent	Zone 3
160	Wall	10.270	Adjacent	Zone 1
161	Wall	6.870	External	E-230-90
162	Wall	6.610	External	E-270-90
163	Wall	12.260	Adjacent	Zone 6
164	Roof	156.730	External	H-0-0
165	Wall	12.260	Adjacent	Zone 7
Window	W2x2 +SKx4	4.762	External	S-0-90
Window	W10x2+SKx4	2.810	External	W-90-90
Window	W4X3	2.439	External	W-230-90
Window	SKx4	0.208	External	N-180-90
Window	W4x3	2.439	External	E-120-90
Window	W10x2+SKx4	2.810	External	E-270-90

Table 8: Zone 6 Walls, Floors, Ceilings, Roofs and Windows Detail

Volume (m^3)		111.966	**ZONE 6**	
Capacitance (KJ/K)		134.359		
Floor Area (m^2)		33.759		
Walls/Floors/Ceilings/Roofs/ Windows		Total Number:11		
Surface ID	**Construction Type**	**Area (m^2)**	**Category**	**Orientation**
194	Wall	16.680	External	S-0-90
195	Wall	4.420	External	N-180-90
196	Roof	9.170	External	N-180-25
197	Wall	7.480	Adjacent	Zone 5
198	Roof	9.170	External	S-0-25
199	Roof	9.200	External	W-90-25
200	Roof	9.200	External	E-270-25
201	Wall	9.540	External	E-270-25
202	Wall	17.020	External	S-0-90
203	Floor	33.760	External	H-0-180
204	Wall	12.260	Adjacent	Zone 5
Window	W7	1.626	External	S-0-90
Window	W8	1.626	External	W-90-90

Table 9: Zone 7 Walls, Floors, Ceilings, Roofs and Windows Detail

Volume (m^3)		111.947	**ZONE 7**	
Capacitance (KJ/K)		134.336		
Floor Area (m^2)		33.753		
Walls/Floors/Ceilings/Roofs/ Windows		Total Number: 11		
Surface ID	**Construction Type**	**Area (m^2)**	**Category**	**Orientation**
209	Roof	9.170	External	N-180-25-
210	Roof	9.200	External	W-90-25
211	Wall	7.470	Adjacent	Zone 5
212	Wall	9.540	External	W-90-90
213	Floor	33.750	External	H-0-180
214	Roof	9.170	External	S-0-25
215	Wall	16.680	External	S-0-90
216	Wall	4.420	External	N-180-90
217	Roof	9.200	External	Zone 2
218	Wall	17.010	External	E-270-25
219	Wall	12.260	Adjacent	E-270-90
Window	W7	1.626	External	S-0-90
Window	W8	1.626	External	E-270-90

Table 10: Zone 8 Walls, Floors, Ceilings, Roofs and Windows Detail

Volume (m^3)		184.603	**ZONE 8**	
Capacitance (KJ/K)		221.523		
Floor Area (m^2)		46.496		
Walls/Floors/Ceilings/Roofs/ Windows		Total Number: 10		
Surface ID	**Construction Type**	**Area (m^2)**	**Category**	**Orientation**
108	Roof	9.380	External	E-270-25
109	Roof	15.890	External	S-0-25
110	Wall	27.740	External	N-180-90
111	Roof	9.380	External	W-90-25
112	Wall	18.560	Adjacent	Zone 5
113	Wall	20.540	External	W-90-90
114	Wall	9.180	External	S-0-90
115	Wall	20.540	External	E-270-90
116	Floor	46.500	Adjacent	Zone 2
117	Roof	15.890	External	N-180-25
Window	W8x2	1.626	External	W-90-90
Window	W5	2.230	External	N-180-90
Window	W5	2.30	External	E-270-90

Table 11: Zone 9 Walls, Floors, Ceilings, Roofs and Windows Detail

Volume (m^3)		184.603	**ZONE 9**	
Capacitance (KJ/K)		221.523		
Floor Area (m^2)		46.496		
Walls/Floors/Ceilings/Roofs/ Windows		Total Number: 10		
Surface ID	**Construction Type**	**Area (m^2)**	**Category**	**Orientation**
122	Wall	27.740	External	N-180-90
123	Wall	9.180	External	S-0-90
124	Roof	15.890	External	N-180-25
125	Roof	9.380	External	E-270-25
126	Wall	20.540	External	E-270-90
127	Roof	15.890	External	S-0-25
128	Wall	18.560	Adjacent	Zone 5
129	Roof	9.380	External	W-90-25
130	Wall	20.540	External	W-90-90
131	Floor	46.500	Adjacent	Zone 4
Window	W8x2	1.626	External	E-270-90
Window	W5	2.230	External	W-90-90
Window	W5	2.30	External	N-180-90

The Auto-Cad "as built drawings" have been used to accurately digitize the building using Google SketchUp (Trimble) as illustrated in the images below. The same digital information has been uploaded into TRNSYS using Google SketchUp plugin to generate the zonal (zones 1 to 9) information in Tables 3 to 11 above.

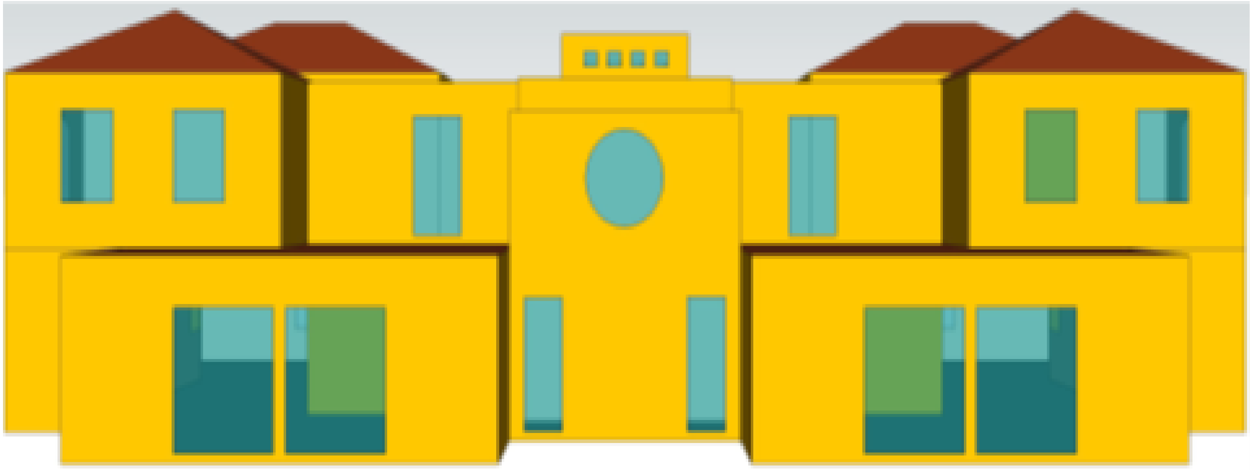


Figure 27: Front Elevation

Figure 27 illustrates the symmetry of the building. The vertical sixteen square skylight windows above the main flat roof areas are clearly visible.

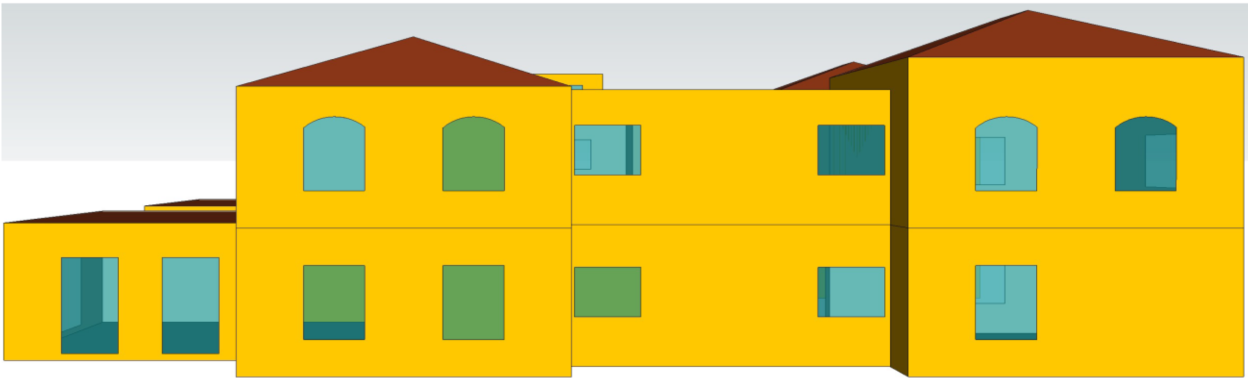


Figure 28: Right Hand Side Elevation

Figure 28 illustrates the right-hand side elevation showing the various building spaces on ground and first floor.

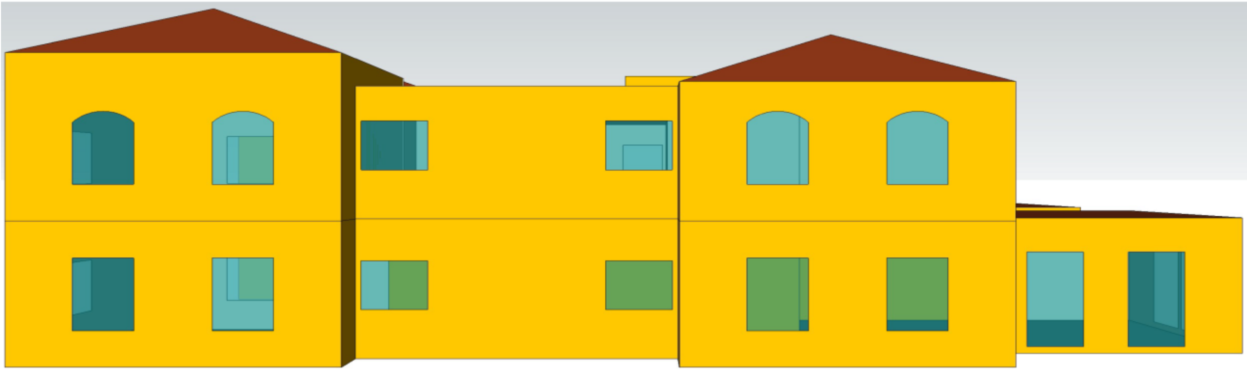


Figure 29: Left Hand Side Elevation

Figure 29 illustrates the left-hand side elevation showing the various building spaces on ground and first floor.

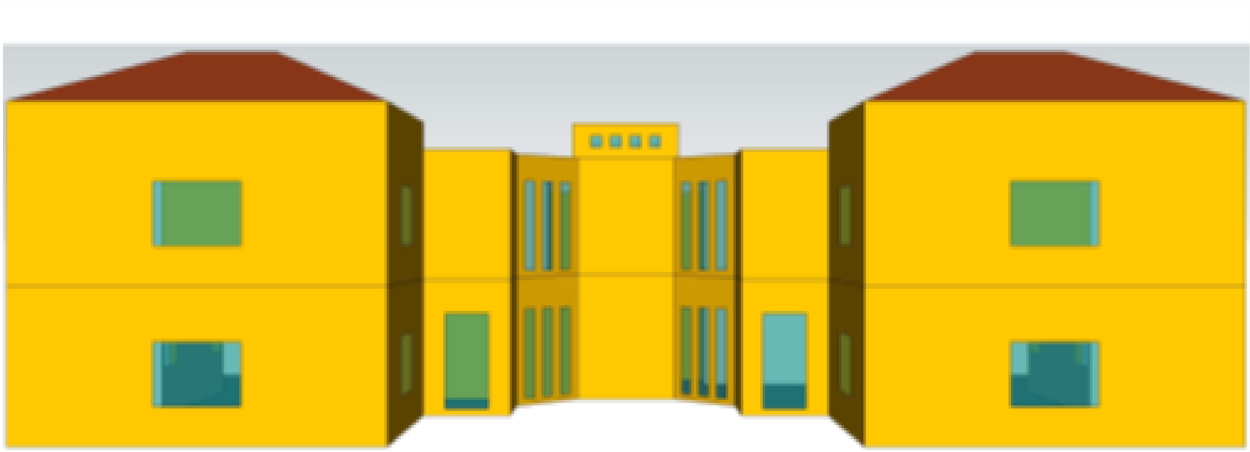


Figure 30: Back Side Elevation

Figure 30 illustrates the back elevation where the staircase slot windows are shown. The back trace is not shown for clarity, also it is does not affect in anyway simulation work carried by TNSYS since it is an outside architectural element, like a balcony, on the elevation facing north.

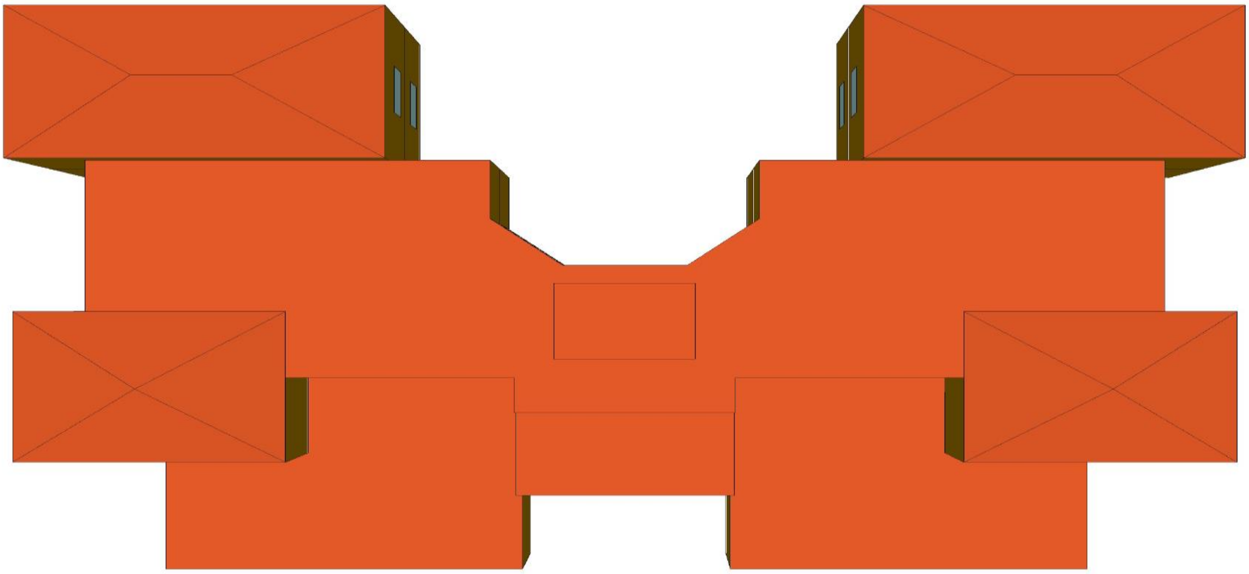


Figure 31: Roof Layout

Figure 31 illustrates the flat roof areas (main roof), skylight region, from terraces, roof of the entrance lobby and the sloping roofs above the first-floor bedrooms.

Figure 32: Building 3D View

Figure 32 is a 3-dimensional view which clearly demonstrates the geometry of the building and relationship between the various living spaces on both, the ground floor and first floor. Also, the terrace roofs above the drawing and dining rooms, flat roof areas, skylight and the sloping roof above the bedrooms.

7.6 Solar PV

7.6.1 General Description

The Solar PV installed system comprise 28 PV panels 435 W_p each. The panels are configured in two strings 14 PV panels to avoid complex extended steel structure between the roof areas need to accommodate them, as well as to reduce their visual impact. The total installed power 12.18 KW_p. One string is installed the roof of the carpark porch (Roof Area 1) and the second string in installed about the roof the outbuilding (Roof Area 2). The panels are installed over a sturdy steel structure at 8^o tilt angle and -38^o (142^o from North) azimuth angle. The inverter, DC (Direct Current) Panel, AC (Alternating Current) Panel and System Display Unit are installed inside a room directly below String 2 Panels for protection from the weather. Power connection to the grid, electrical connections between panels, earthing and connection to the smart meter are all laid through conduits and protected by sleeves wherever they cross structure elements. The smart meter is installed by the grid power connection structure on the other side of the road. The connection cable between the smart meter and Solar PV is laid under the road in a sleeve.

Roof Area 1: 3.3 x 8.5 + 5.8 x 2.4 = 42 m^2

Roof Area 2 : 4.7 x 10 = 47 m^2

Total Roof : 89 m^2 (approximately), the equivalent of 7.3 m^2 / KW_p

Figure 33: Solar PV 14 Panels Above Out-Building Roof

Figure 33 is a live picture of string two which is laid above the outbuilding roof. The panels are easily accessible for regular cleaning, maintenance, and repair.

Figure 34: Solar PV 28 Panels (Total System)

Figure 34 is a live picture of both strings, where string one can be seen above the roof of the carpark porch. The distance between the two strings is enough to prevent string 2 casting any shadow over string 1, in addition, both strings are slightly staggered for further spatial separation. There is enough space to expand the system by up to 8 PV panels, adding a potential of 3.48 KW_p, if similar panel specifications or up to 4 KW_p if higher power panels are used. This would increase the system overall capacity to 16.18 KW_p , however the current invertor will need to be upgraded to at least 15 KW_p from 10 $KW_{p.}$

7.6.2 Solar PV System Technical Specification

Table 12 shows the technical specifications of the Solar PV system (PV Panels, Inverter and accessories). The information is taken from the manufacturer's data sheets.

Table 12: Solar PV System and Components Technical Specification

<table>
<tr><th>Item Detail</th><th colspan="3">Specification</th><th>Quantity</th></tr>
<tr><td>Total System</td><td colspan="3">Rated power:12.18 KW_p</td><td>1</td></tr>
<tr><td rowspan="18">Solar PV Panel Grade-A, Tier 1 Poly Crystalline Model LR4-72HPH-435M</td><td colspan="3">Panel rated power: 435 W_p (each)</td><td rowspan="18">28</td></tr>
<tr><td colspan="3">Configure ration: two strings fourteen panels (each)</td></tr>
<tr><td colspan="3">Protective Glass: 3.2 coated tempered single glass</td></tr>
<tr><td colspan="3">Weight: 24 Kg</td></tr>
<tr><td colspan="3">Frame: Anodized aluminum alloy</td></tr>
<tr><td colspan="3">Dimensions:2115 x 1052 x 35</td></tr>
<tr><td rowspan="2">Electrical Characteristics</td><td colspan="2">Testing Conditions</td></tr>
<tr><td>STC*</td><td>NOCT**</td></tr>
<tr><td>Maximum Power (P_{max}/W)</td><td>435</td><td>322.2</td></tr>
<tr><td>Open Circuit Voltage (V_{OC}/V)</td><td>49.4</td><td>46.1</td></tr>
<tr><td>Short Circuit Current (I_{SC}/A)</td><td>11.26</td><td>9.08</td></tr>
<tr><td>Voltage at Maximum Power (V_{mp}/V)</td><td>40.8</td><td>37.7</td></tr>
<tr><td>Current at Maximum Power (I_{mp}/A)</td><td>10.67</td><td>8.56</td></tr>
<tr><td>Module Efficiency (%)</td><td colspan="2">19.6</td></tr>
<tr><td>Module Efficiency (%)</td><td colspan="2">19.6</td></tr>
<tr><td>Temperature Coefficient of I_{SC} (STC)</td><td colspan="2">+0.057/ºC</td></tr>
<tr><td>Temperature Coefficient of V_{OC} (STC)</td><td colspan="2">-0.286/ºC</td></tr>
<tr><td>Temperature Coefficient of P_{max} (STC)</td><td colspan="2">-0.370/ºC</td></tr>
<tr><td>Inverter</td><td colspan="3">10 KW Smart Energy Inverter</td><td>1</td></tr>
<tr><td>Smart Flow</td><td colspan="3">Intelligent energy management software</td><td>1</td></tr>
<tr><td>LCD Display</td><td colspan="3">9.7 Inch LCD display</td><td>1</td></tr>
<tr><td>Connectivity</td><td colspan="3">3G, Wi-Fi and cloud communication</td><td>1</td></tr>
<tr><td>System Monitoring</td><td colspan="3">24/7 Network Operations Centre (NOC) monitoring & support</td><td>Lot</td></tr>
<tr><td>Circuit Beakers</td><td colspan="3">Circuit breakers, changer over switches & DC/AC electrical DBs</td><td>Lot</td></tr>
<tr><td>Mobile Smart App</td><td colspan="3">Smart App system visibility on mobile</td><td>Lot</td></tr>
<tr><td>Raceways</td><td colspan="3">PVC conduits & wires</td><td>Lot</td></tr>
<tr><td>Earthing</td><td colspan="3">Independent earthing system</td><td>Lot</td></tr>
<tr><td colspan="4">Smart Application system visibility on mobile</td><td>Lot</td></tr>
<tr><td>Solar PV Structure</td><td colspan="3">Special Shed type Structure for PV modules 18/W</td><td>2</td></tr>
</table>

*STC (Standard Testing Conditions): Irradiance 1000 W/m^2, Cell Temperature 25ºC, Spectra at AM 1.5

**NOCT (Nominal Cell Operating Temperature): Irradiance 800 W/m^2, Ambient Temperature 20ºC, Spectra at AM 1.5, Wind at 1.5 m/s.

7.7 U Value

Since the 1970s oil crises, interest in using thermal insulation in building fabric grew exponentially due to the need to cut the cost of rising energy bills. In the present time many governments continue to mandate insulation in new construction and encourage retrofit solutions in old buildings, including offering grants. In addition, the building energy code continues to be updated with more stringent requirements for lower U-value insulation specifications. It is always desirable to incorporate an air gap in the building envelope to help achieve lower U value at almost no material cost. This is due to the insulative quality of stagnant air, in contrast with moving air. While moving air is a good heat transfer medium, stagnant air has a superior heat insulation property. Rigid type insulation is the most common. It is easy to manufacture, install, no risk of fibre becoming airborne and can help in achieve lower U values than fibrous insulation materials such as wool. This air thermal behaviour quality has been put into beneficial use by the manufacturer double glazing. When comparing the U value of single glazing and double glazing, the former is approximately 5.4 W/m^2K, while the latter is approximately 2.8 W/m^2K, more than 50% lower. All insulation materials (petroleum based, mineral based, organic based) have one thing in common, trapped air.

The U-value, which is known as the overall heat transfer coefficient, determines the overall resistance of building fabrics (floors, walls, roof and glazed areas) to heat losses or gains. HVAC (Heating Ventilation and Air Conditioning) engineers use the U value to calculated the steady-state heat loss (or gain) to determine the size and characteristics of the HVAC system that would maintain indoor conditions, in the case of buildings, comfort indoor temperature in the range of 22^{o}C to 25^{o}C and relative indoor humidity (RH) in the range of 50% +or- 5% RH, throughout the year under ambient design conditions specific to the geographical location. The U value is of paramount importance because it determines the degree the thermal insulative quality of buildings, and in turn how energy efficient they are. In many countries the U value is a target to be achieved and a perquisite by responsible municipal authorities for issuing building design approval, necessary construction permits and energy certificated. In addition, fully compliant new buildings and upgraded existing buildings i.e. cavity filling, retrofit walls and roof insulation cladding, replacing single glazing windows by double glazing would be far more thermally stable, comfortable, lead to significant savings in energy bills and achieve higher market value Harrow Council [98], Ministry of Energy Kuwait [99].

7.7.1 Building Envelope

The external fabrics (envelope) of the building under consideration are made up of various material layers, such as masonry/stonework, external weather-shield paint, cementitious plaster, cementitious block, layer of EPS (Expanded Polystyrene insulation, inner wall of backed mud bricks, internal cementitious plaster and internal decorative paint. No air gap is left between the insulation layer and the outer wall, though desirable to prevent moisture build-up and tow promote ventilation, the concern was that the air gap thickness would not have been consistent and the possibility of construction debris, such as sand and cement, would either partial block the gap or create thermal bridges. Furthermore, foil insulation was not used (EPS panels only). All windows throughout the house are double glazed except for the small vertical square 200 mm x 200 mm skylights (Skylight Table 2), a total of 16 pieces (0.64 m^2 total area), which are single glazed.

The thermal conductivity for each layer was deduced and the Overall Heat Transfer Coefficient, also known as the thermal transmittance or U-value has been calculated. The U-value is the total of the thermal resistance of each construction layer (inside to outside air). . Each material has a function; some structural (concrete, heavy blocks , steel), some cosmetic (stone cladding, brickwork, metallic panels) some added to provide thermal performance enhancement (insulation) and other layers to provide water/vapor resistance to eliminate or reduce the risk of condensation. Air gap/s incorporated, sometimes, to enhance the performance and or to act as break between outer and inner layers to eliminate rainwater migration. Each layer has a different thickness, density and thermal property, as well as acoustic performance and vapor permeability. Not forgetting thermal capacity (ability to store heat). Collectively such "constructions" has a unique thermal transmittance (U-value) that can be mathematically calculated and used for the sake of estimation of building need for heating and cooling energy (Eq.1).

$$U = 1/R_{tot} \tag{1}$$

where: U, R_{tot} is the thermal transmittance ($W/(m^2\ K)$) and the total thermal resistance ($m^2\ K/W$) respectively. The total thermal resistance of a flat building element for which the heat flow is perpendicular to the stacked, thermally homogeneous layers can be defined as:

$$R_{tot} = R_{si} + R_1 + R_2 + R_n + R_{se} \tag{2}$$

where R_{tot}, R_{si}, R_{se} is the total thermal resistance ($m^2\ K/W$), the internal surface resistance ($m^2\ K/W$) and the external surface resistance ($m^2\ K/W$) respectively. R_1; R_2,R_n are the design thermal resistances of each layer ($m^2\ K/W$); The thermal resistance of the layer can be described as a function of thermal conductivity (W/mK) and material layer thickness d (m):

$$R = d / \lambda \tag{3}$$

Table 13 illustrates the wall construction R Value and how the U Value has been calculated [102], [103], [104].

Table 13: Walls U Value Calculation

Ref	Walls Construction Layers Detail	Layer Thickness m	R Value $m^2\,^oK/W$
1	Outside air film	-	0.170
2	Protective coating	-	0.010
3	Cementation stonework	0.075	0.104
4	Plaster	0.030	0.042
5	Cementation block	0.200	0.532
6	Expanded Polystyrene Insulation	0.075	2.03
7	Red brick	0.100	0.161
8	Plaster	0.030	0.042
9	Paint	-	0.010
10	Inside air film	-	0.680
	R_{tot}	**0.510**	3.781

$\text{U (Wall)} = \frac{1}{\text{Rtot}} = \frac{1}{3.781} = 0.264\ \text{W/m}^2\,^o\text{K}$

Table 14 illustrates the wall construction R Value and how the U Value has been calculated[102], [103], [104].

Table 14: Roof U Value Calculation

Ref	Roof Construction Layers Detail	Layer Thickness m	R Value $m^2\,^oK/W$
1	Outside air film	-	0.170
2	Roof tiles protective coating	-	0.010
3	Roof tiles	0.030	0.042
4	Screed	0.100	0.532
5	Water proofing membrane	0.020	0.100
6	Screed	0.100	0.532
7	Expanded Polystyrene Insulation	0.075	2.030
8	Reinforced Concrete Slab	0.200	0.277
9	Plaster	0.030	0.042
10	Paint	-	0.010
11	Inside air film	-	0.680
	R_{tot}	**0.555**	**4.425**

$\text{U (Roof)} = \frac{1}{\text{Rtot}} = \frac{1}{4.425} = 0.226\ \text{W/m}^2\,^o\text{K}$

Both Walls and roof U Value are well below the current common local construction U Values, which are approximately 0,226 W/m^2K for roof and 1.46 W/m^2K, Ministry of Energy Kuwait [99], AHSRAE Fundamentals 2021 [100], Y. E. Bi-Chso et al [101], I. Asadi et al [102], G. L. Bai et al [103].

8. Simulation Work

TRNSYS and PVGIS simulation tools were used to simulate the performance of the installed Solar PV system. The total installed capacity is 12.18 KW_p generated by 28 Solar PV panes, each 435 $W_{p.}$

The Solar PV system was configured as FIT (Feed-in Tariff) **.** Simple system, less costly and can be easily integrated with the grid via smart electricity meters. It is designed for homeowners to sell back to the grid any excess produced electricity. It requires IPP license and the appropriate legislation including billing to function properly. The system has been in operation since September 2021.

8.1. Solar Net Metering System Modeling & Validation

Computer simulations have become a useful part of mathematical modelling of many natural systems in physics, chemistry and biology, human systems in economics, psychology, and social science and in the process of engineering new technology, to gain insight into the operation of those systems.

Before the advancement in the energy simulation, energy modelling used to be a cumbersome, complicated and time-consuming task and not necessarily yielded results that would help to achieve cost savings or lead to significant design Optimisation.

Nowadyas with the advancement of computers hardware and software simulating almost anything has become a lot easier and far more accurate and realistic. It has proved to be the most economical method to transform ideas into reality. In addition, to Optimisation, running the system being simulated under different climatic or process conditions, also comparison of different technologies, to study behavioure and suitability, allow to stretch boundary limits of research in laptops and desktop environment, remotely connected to servers, where powerfull simulation tools can be run, or in laborteries or on location. This approach provides a safe, non-destructive environment for conducting "what if" scenarios, leading to deeper understanding, comprehension, and visualisation of research fields and applications. It increases accuracy and the ability to handle uncertainties, enables the demonstration of research ideas and benefits, and is useful for education and training purposes. These are just a few of the benefits of computer simulation. It offers a cost-effective way to conduct research, allowing more researchers to push the limits even with limited budgets. System components can be rearranged, altered, or redefined individually or in groups to study the impact of these changes on system performance. Results and analyses can be easily verified, shared with others, and compared with results from other software for confidence building. It is a superior method for model analysis compared to using Excel, linear programming, or physical modelling, as it relies more on mathematical models to predict system behaviours. It enables examining and monitoring processes while interacting with the simulation model.

Simulation tools enable building designers to evaluate active systems such as heating, cooling, and ventilation, as well as passive building parameters like site, orientation, building mass and structure, shape, envelope and façade, surroundings (external landscape and nearby buildings), daylight, glazing, and occupancy patterns. These benefits help achieve building sustainability targets, energy certifications, and estimate future energy demand and costs. Energy modelling at the early stages of building design enhances energy-efficiency goals, design Optimisation through alternative energy sources like solar and wind, and avoids redesign by addressing potential issues early on. The selection of the right simulation tools, along with the knowledge and experience of the user, is crucial for maximizing the software's capabilities. While building energy simulation is now common and significantly important in R&D, it is still not as popular among building owners and designers due to a lack of understanding of its benefits, particularly in terms of construction and operating costs, and a shortage of trained, experienced, and skilled modelers. However, the use of simulation is gaining momentum with increased awareness of the impact of fossil fuels on the environment and tighter energy conservation legislation.

8.2 Multi Zone Building Type 56

The research rig is divided into nine zones as described in detail in Chapter 7 Research Rig. Tremble (Google SketchUp) was used to digitize the research Rig physical dimensions from the "As-built" Auto-Cad drawings. The TRNSYS Google SketchUp plugin was used to transfer the physical dimension in building type 56 module.

8.3 Simulation Input Data

Figure 35 shows TRNSYS Wizard simulation model with all input and output components which enabled the simulation of the of the actual 12.18 KW_p grid connected Solar PV system.

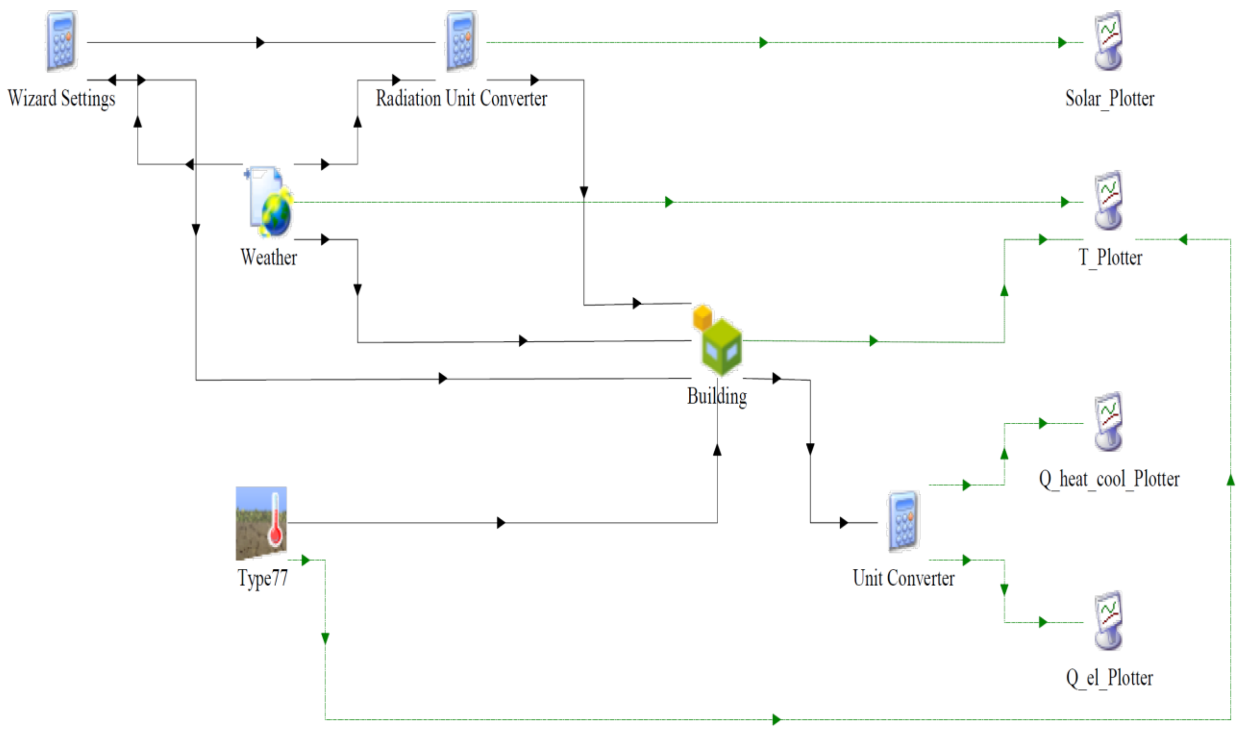


Figure 35: Solar PV 103a (No MPPT) and 103b (with MPPT) - Maximum Power Point Tracking TRNSYS Wizard

TRNSYS (Transient System Simulation Tool) is a widely used simulation software for transient energy system modelling. It is particularly valuable for renewable energy systems, building energy simulations, and HVAC analysis. One of its key applications is modelling grid-connected systems, such as photovoltaic (PV) and wind energy systems integrated with the electrical grid.

8.3.1 Grid-Connected Systems in TRNSYS

A grid-connected system refers to an energy system that is linked to the main electrical grid, allowing bidirectional energy flow. In TRNSYS, such systems typically involve renewable energy sources (e.g., PV panels, wind turbines) that generate electricity, which can either be used on-site or exported to the grid.

Key Components of a Grid-Connected System in TRNSYS:

1. Solar PV Panels

Converts solar energy into electrical power.

Modelled using Type 94 (for PV systems).

2. Inverter (Type 48)

Converts DC electricity from renewable sources into AC electricity for grid compatibility.

3. Load Profile (Type 14 or Custom Data Files)

Represents energy consumption patterns of a building or facility. Helps determine how much energy is used on-site versus exported to the grid.

4. Electrical Grid Connection (Type 47 or Customized Power Flow Models)

Models the interaction between the local energy system and the electrical grid. Can simulate energy export, import, and grid dependence.

5. Modelling a Grid-Connected PV System in TRNSYS

A typical grid-connected PV system in TRNSYS consists of the following steps:

Step 1: Weather Data (Type 15) to import meteorological data (solar radiation, wind speed, temperature) from a TMY file. This determines the solar energy available for PV generation.

Step 2: Model the PV System (Type 94) by configure parameters such as:

Number of PV panels and their arrangement.

Panel efficiency and temperature effects.

Maximum power point tracking (MPPT) settings.

Step 3: Integrate the Inverter (Type 48) to convert DC output from the PV system into AC power.

Step 4: Define Load Profile (Type 14)Use real-time or historical electricity consumption data.

Determines how much of the PV energy is self-consumed versus sent to the grid.

Step 5: Run Simulations and Analyse Results

TRNSYS is a powerful tool for modelling and simulating grid-connected energy systems, offering detailed insights into energy performance, economic feasibility, and grid interactions. By accurately modelling components such as PV panels, inverters, loads, and batteries, TRNSYS helps engineers, researchers, and policymakers design efficient and sustainable energy solutions.

8.3.2 Key Formulas for TRNSYS PV Grid-Connected Models

1. Photovoltaic Output Current:

$I = I_L - I_0 \left(e^{\{q(V + I\,Rs)/\{nkT\}} - 1\right) - ((V + I\,R_s)/R_{sh})$

Where:

I = Output current (A)

I_L = Light-generated current (A)

I_0 = Diode saturation current (A)

q = Charge of an electron (1.602×10^{-19} C)

V = Terminal voltage (V)

R_s = Series resistance (Ω)

R_{sh} = Shunt resistance (Ω)

n = Ideality factor of the diode

k = Boltzmann constant (1.381×10^{-23} J/K)

T = Temperature (K)

2. Maximum Power Output (Pmax):

$P_{max} = V_{mp} \text{ x } I_{mp}$

Where:

V_{mp} = Maximum power voltage (V)

I_{mp} = Maximum power current (A)

3. Solar Cell Efficiency:

Ŋ = P_{max}/GA

Where:

Ŋ = Efficiency (%)

G = Solar irradiance (W/m²)

A = Active PV area (m²)

4. Temperature Dependency of Voltage and Current:

$V_{oc}(T) = V_{oc,ref}$ + ꝏ(T - T_{ref})

$V_{oc}(T)$ = Open circuit voltage at temperature TÂ

$V_{oc,ref}$ = Reference open circuit voltage

ꝏ = Temperature coefficient of voltage (V/°C)

5. Grid-Connected Power Output:

Where:

$P_{grid} = P_{dc}$ x Ŋ$_{inv}$

P_{grid} = Power delivered to the grid (W)

P_{dc} = DC power from PV array (W)

Ŋ$_{inv}$= Inverter efficiency (%)

6. Inverter Efficiency Model (Typical Polynomial Form):

Where:

Ŋ$_{inv}$ = a + b (P_{dc}/P_{rated}) + c (P_{dc}/P_{rated})^{2}

a, b, c = Empirical coefficients from manufacturer data

P_{rated} = Rated inverter power

8.4 TRNSYS Input Data

Table 15 illustrates the input parameters inputted into TRNSYS simulation model based on the installed Solar PV Panels manufacturer's data

Table 15: TRNSYS Input Parameter Cards A & B

A. PARAMETER CARD			
This component is appropriate for modelling the electrical performance of mono and poly-crystalline photovoltaic panels. It is not appropriate for modelling the electrical performance of thin film PV arrays. It may be used in one of two modes depending upon how the first parameter is set. When the MPPT mode parameter is set to 0, the PV array is assumed to be directly connected to a load voltage and/or to a battery. The operating voltage of the PV/load is an input to the PV model. When the MPPT mode parameter is set to 1 then the array is assumed to be connected to its load through a maximum power point tracker. In this Case the load voltage is not needed as an input.			
1	Inverter mode	Mode 1: photovoltaic array only Mode 2: photovoltaic array and inverter	Mode 2
2	MPPT MODE	Mode 1: The PV is directly connected to a load voltage (taken as an input to this model). Mode 2: The PV is equipped with a maximum power point tracking (MPPT) device.	Mode 2
3	Modules short-circuit current at reference conditions.	The module's short circuit current reported on the manufacturer's spec sheet. Reference conditions are typically 1000 W/m^2 (incident solar radiation) and 25C (module temperature).	11.25 Amperes
4	Module open-circuit voltage at reference conditions	The module's open circuit voltage reported on the manufacturer's spec sheet. Reference conditions are typically 1000 W/m^2 (incident solar radiation) and 25C (module temperature).	45.4 V
5	Reference cell temperature	The module temperature at which the manufacturer reports open circuit voltage and short circuit current. According to the definition of standard test conditions, this value should be set to 25°C. The definition of STC is: 1000 W/m^2, module temperature 25°C, AM 1.5 after factory light soaking.	25°C
6	Reference insolation	The solar radiation level at which the manufacturer reports open circuit voltage and short circuit current. This value is typically 1000 W/m^2.	1000W/m^2
7	Module voltage at max power point and reference conditions	The module's maximum power point voltage reported on the manufacturer's spec sheet. Reference conditions are typically 1000 W/m^2 (incident solar radiation) and 25°C (module temperature).	40.8 V
8	Module current at max power point and reference conditions	The module's maximum power point current reported on the manufacturer's spec sheet. Reference conditions are typically 1000 W/m^2 (incident solar radiation) and 25°C (module temperature).	10.67 Amperes
9	Temperature coefficient of I_{sc} (ref. cond.)	This parameter describes the way in which temperature affects the module's short circuit current at reference conditions. Short circuit current typically increases with increasing ambient temperature. The parameter is expressed in units of A/K. Manufacturers express this	0.057 A/K

		value either in units of A/K or in %/K (percent of the short circuit current.	
10	Temperature coefficient of V_{oc} (ref. cond.)	This parameter describes the way in which temperature affects the module's open circuit voltage at reference conditions. Open circuit voltage typically decreases with increasing ambient temperature. The parameter is expressed in units of V/K. Manufacturers express this value either in units of V/K or in %/K (percent of the open circuit voltage).	-0.286 V/K
11	Number of cells wired in series	The number of individual cells wired together in series within a module. For monocrystalline silicon panels, each cell 1generates approximately 0.5V so an 18V panel would typically have 36 cells wired in series.	72
12	Number of modules in series	The number of modules wired in series within the PV array. Series wiring increases the array's total voltage.	14
13	Number of modules in parallel	The number of modules wired in parallel within the PV array. Parallel wiring increases the array's total current.	2
14	Module temperature at NOCT	The module's cell temperature at nominal operating cell temperature (NOCT) conditions. Typically obtained from the manufacturer's specification sheet.	40 ^{O}C
15	Ambient temperature at NOCT	The ambient temperature at NOCT conditions (expressed in K). This value is always 293^{o}K.	20 ^{O}C
16	Insolation at NOCT	The solar radiation at NOCT conditions (expressed in W/m^2). This value is always 800W/m^2.	800 W/m^2
17	Modula Area	The active area of the module.	2.07 m^2
18	tau-alpha product for normal incidence	The product of the module cover's transmittance and the substrate's absorptance for solar radiation normal to the plane of the module.	0.95
19	Semiconductor bandgap	For silicon panels, the material bandgap is 1.12 eV. For gallium arsenide, it is 1.35 eV. Units are "electron Volts". From Wikipedia: In graphs of the electronic band structure of solids, the band gap refers to the energy difference (in electron volts) between the top of the valence band and the bottom of the conduction band in insulators and semiconductors. This is equivalent to the energy required to free an outer shell electron from its orbit about the nucleus to become a mobile charge carrier, able to move freely within the solid material.	1.12 eV
20	Value of parameter "a" at reference conditions	This Type is based on an equivalent circuit model that requires five parameters. This parameter is typically generated using the PV_REF_PARAMS.EXE app located in the ...\TrnsysXX\Tools\ directory. Refer to the Mathematical Reference manual for a more complete definition of this parameter.	1.9
21	Value of parameter I_L at reference conditions	This Type is based on an equivalent circuit model that requires five parameters. This parameter is typically generated using the PV_REF_PARAMS.EXE app located in the ...\TrnsysXX\Tools\ directory. Refer to the Mathematical Reference manual for a more complete definition of this parameter.	5.4 amperes
22	Value of parameter I_0 at	This Type is based on an equivalent circuit model that requires five parameters. This parameter is typically	0.000000002053 amperes

	reference conditions	generated using the PV_REF_PARAMS.EXE app located in the ...\TrnsysXX\Tools\ directory. Refer to the Mathematical Reference manual for a more complete definition of this parameter.	
23	Module series resistance	This Type is based on an equivalent circuit model that requires five parameters. This parameter is typically generated using the PV_REF_PARAMS.EXE app located in the ...\TrnsysXX\Tools\ directory. Refer to the Mathematical Reference manual for a more complete definition of this parameter.	0.5 amperes
24	Shunt resistance and reference conditions	This Type is based on an equivalent circuit model that requires five parameters. This parameter is typically generated using the PV_REF_PARAMS.EXE app located in the ...\TrnsysXX\Tools\ directory. Refer to the Mathematical Reference manual for a more complete definition of this parameter.	16 ohms
25	Extinction coefficient-thickness product of cover	The extinction coefficient is a measure of how much solar spectrum radiation is absorbed as it passes through a transparent material. It has the units of 1/m. Typical values are between 4 and 32 [1/m]. This value is then multiplied by the thickness of the material in order to obtain the extinction coefficient-thickness product of the cover. The resulting value is dimensionless.	0.008
26	Maximum inverter power	The input power beyond which the inverter will be capacity limited.	10,000 W
27	Maximum inverter voltage	The maximum input voltage to the inverter. If the array voltage goes over this point, it will be internally limited, and the inverter efficiency will be determined for the maximum allowable input voltage.	100 V
28	Minimum inverter voltage	The minimum input voltage to the inverter. If the array max power voltage is below this minimum, the inverter will operate at reduced efficiency as long as the array's open circuit voltage is above the minimum. If the open circuit voltage and the maximum power point voltage are both below this minimum, the inverter will not produce any power.	0 V
29	Night tare	The inverter consumes power at this rate during the night (when there is no solar incident on the array).	0 W
30	Logical unit number for inverter data	The inverter data file is two dimensional. It provides values of inverter efficiency (0..1) for combinations of input power and input voltage.	76
		B. INPUT CARD	
1	Total incident radiation on tilted surface	Total incident radiation on tilted surface (beam, sky diffuse, and ground reflected).	
2	Ambient temperature	Ambient temperature, in degrees Celsius.	
3	Array slope	Array slope, measured from the horizontal.	
4	Beam radiation	Beam radiation on tilted surface.	
5	Sky diffuse radiation on tilted surface	The portion of total radiation on the module surface that is diffuse coming from the sky (i.e. not beam and not ground reflected).	

6	Ground diffuse radiation on tilted surface	The portion of total radiation on the module surface that is diffuse reflected off the ground (i.e. not beam and not sky diffuse).	
7	Incidence angle on tilted surface	The angle between the normal to the surface and the line made by beam solar radiation.	
8	Solar zenith angle	The angle between the line made by beam solar radiation and a vertical line.	
9	Wind speed	The speed of wind in the vicinity of the array. Note that the wind direction is not specified. As a result, this will provide a high estimate of the impact that wind has on the array power output.	

Table 16 illustrates TRNSYS simulation model output card data units

Table 16: TRNSYS Output Card Data

C. OUTPUT CARD			
1	Array voltage at maximum power point	The voltage at which the array operates. This value includes the impact of the inverter. This version of the model assumes that an MPPT is integrated with the array	
2	Array current at maximum power point	The current at which the array operates. This value includes the impact of the inverter. This version of the model assumes that an MPPT is integrated with the array.	
3	Array power at maximum power point	The power generated by the array. This value includes the impact of the inverter. This version of the model assumes that an MPPT is integrated with the array.	W
4	Array power at maximum power point	The power generated by the array. This value includes the impact of the inverter. This version of the model assumes that an MPPT is integrated with the array.	kJ/hr
5	Open circuit voltage	The x-intercept of the current-voltage characteristic of the array (as opposed to that of the module) at current operating conditions (as opposed to that at reference conditions).	
6	Short circuit current	The y-intercept of the current-voltage characteristic of the array (as opposed to that of the module) at current operating conditions (as opposed to that at reference conditions).	
7	Array fill factor	The ratio of the maximum power point power to the product of the product of the open circuit voltage and the short circuit current at current conditions. Expressed mathematically, the fill factor is: ff = (Vmp*Imp)/(Voc*Isc).	
8	Array temperature	The cell temperature at which the array is currently operating.	
9	Conversion efficiency	The ratio of the power delivered by the array to the quantity of solar radiation falling on it.	
10	Array voltage	The array voltage at the maximum power point (does NOT include inverter effects).	
11	Array current	The array current at the maximum power point (does NOT include inverter effects).	
12	Array power	The power produced by the array at the maximum power point (does NOT include inverter effects).	W

13	Inverter efficiency	The inverter's efficiency if the array is running at the user-specified load voltage.	Amperes

8.5 Output Data

Twelve cases have been investigated using TRNSYS and PVGIS (for comparison purposes). Case one is the actual generated data by the installed PV system being investigated collected over one complete year from 1st January to 31st December. The other eleven cases were simulated by TRNSYS and PVGIS.

8.5.1 Total Actual Yearly Electricity Consumption & Billing During the Various Stages of the building construction

Table 17 shows the actual annual consumption and electricity billing for the period 2012 to 2023. The bills have been converted from the local currency PKR (Pakistani Rupee) to £ (Pound Sterling) using an average annual conversion exchange rate for each year. The data has been complied in three distinctive periods - construction stage, before the installation of the Solar PV system and after the Solar PV installation. The average annual electricity consumption during the construction period 3,476 KWH, at an average annual cost of £ 443. The average annual electricity consumption after the house has been occupied, but prior to the Solar PV installation 9,437 KWH at an average annual cost of £964. The average annual electricity consumption (net) after the Solar PV installation – 576 KWH (net) at an average annual net saving of £233. The actual solar production(averaged for one typical year) 15,758 KWH. An estimate of the losses due to grid interruptions has been calculated from the Solar PV system production history and found to be 1,100 KWH approximately. Thus, the total production for one typical year can be safely considered as the sum of the recorded production plus the estimated losses i.e. 16,858 KWH. The house occupiers have enjoyed electricity zero billing since September 2021, while the electricity credit started to show up in January 2021 electricity bill and continued to build up from there on. The maximum recorded credit was £373 in December 2023 due to abnormal electricity consumption to facilitate 24/7 care for an elderly member of the household.

Table 17 shows the actual electricity consumption in KWH and cost in pounds sterling during three stages since the house was constructed and until the time when the solar PV system was installed. Stage 1 construction: from 2012 to 2015. Stage 2 pre-solar PV system installation: from 2016 to 2020 and stage 3 after solar PV system installation 2021 to 2023.

Table 17: actual annual consumption and electricity billing for the period 2012 to 2023

Year	Stage 1 Construction Stage		Stage 2 Before Solar PV Installation		Stage 3 After Solar PV Installation	
	KWH	£	KWH	£	KWH	£
2012	4,646	974				
2013	2,130	187				
2014	3,184	174				
2015	3,943	437				
2016			5,159	453		
2017			8,797	936		
2018			7,725	698		
2019			10,896	1,079		
2020			14,608	1,654		
2021					-4,639	139
2022					-6,090	-376
2023					9,000	936
Total	**13,903**	**1,772**	**47,185**	**4,819**	**-1,729**	**699**

8.5.2 Actual Average Monthly Electricity Consumption, Billing & Average Monthly Solar Production

In Table 18 the average monthly consumption in KWH with the corresponding billing cost have been compiled from the actual data collected for each of the three stages (1. 2. And 3). The Figures in blue are for the period 2012 to 2015 (construction stage), the Figures in yellow are for the period 2016 to 2020 (pre-Solar PV System) and the Figures in green for the period 2021 to 2022 (after the installation of the Solar PV System). These values have been collated from the monthly electricity bills for each period as defined above i.e., construction, before Solar PV installation and after Solar PV installation. This was done to be able to work out an average actual monthly consumption for each month of the year representative of each period. This is to enable a fair comparison with the actual average monthly solar production deduced from the period monthly production of 2021 starting from March, and the monthly production of 2023, which are shown in red.

Table 18: Average Monthly Electricity Consumption, Cost & Actual Solar Production

Average Monthly Consumption & Billing							Actual Average Monthly Solar Production		
Month	Stage 1 2012 To 2015		Stage 2 2016 To 2020		Stage 3 2021 To 2023		2021 To 2023		
	KWH	£	KWH	£	KWH	£	KWH	Losses *	Total
1	332	29	1,297	130	1,767	35	912	100	1,012
2	346	32	1,367	133	606	57	1,080	100	1,1180
3	331	43	689	62	-100	40	1,410	100	1,510
4	317	49	1,387	111	0	2	1,730	0	1,1730
5	480	97	891	141	0	0	2,010	0	2,010
6	222	78	384	36	-2,227	-67	1,820	0	1820
7	309	35	345	25	0	0	1,630	0	1,630
8	250	24	55	62	0	0	1,530	100	1,630
9	231	31	324	31	-5,060	-225	1,340	200	1,540
10	205	15	440	41	0	0	1,080	100	1,180
11	191	25	677	82	0	0	621	200	821
12	264	37	1,082	162	-350	7	595	200	795
Total	3,476	495	9,437	1,016	-5,365	-150	15,758	1,100	16,858

8.5.3 Annual Simulation Results vs. Total Solar Energy in KWH for Cases 1 to 12

Case 1: 8º Tilt and -38º Azimuth (Actual)

Case 2: 8º Tilt and -38º Azimuth (Simulated)

Case 3: 0º Tilt and -38º Azimuth

Case 4: 15º Tilt and -38º Azimuth

Case 5: 33º Tilt and -38º Azimuth

Case 6: 0º Tilt and 3º Azimuth

Case 7: 15º Tilt and 3º Azimuth

Case 8: 33º Tilt and 3º Azimuth*

Case 9: 0º Tilt and Tracking on Azimuth

Case 10: 15º Tilt and Tracking on Azimuth

Case 11: 33º Tilt and Tracking on Azimuth

Case 12: Tracking on 2 Axes (Tilt and Azimuth)

*Optimum Tilt & Azimuth as predicted by PVGIS

Table 19 represents the anticipated total annual solar energy in kilowatt-hours (KWH) projected to be reached by the 28 solar photovoltaic panels installed system, TRNSYS's estimated total energy production in KWH and the overall Solar PV system efficiency. This information is compiled for cases 1 to 12, along with a corresponding bar chart illustrating the data adjacent to the table.

Table 19: TRNSYS Annual Simulation Results vs Total Solar Energy (KWH) and System Efficiency

Case	Total Solar Energy (KWH)	TRNSYS	System Efficiency
1	114,686	16,858	14.7%
2	114,686	17,330	15.1%
3	113,005	17,487	15.5%
4	120,394	17,591	14.6%
5	120,715	17,344	14.4%
6	112,179	17,488	15.6%
7	122,451	20,100	16.4%
8	125,775	20,710	16.5%
9	113,005	18,389	16.3%
10	132,362	21,821	16.5%
11	146,606	24,276	16.6%
12	153,551	25,615	16.7%

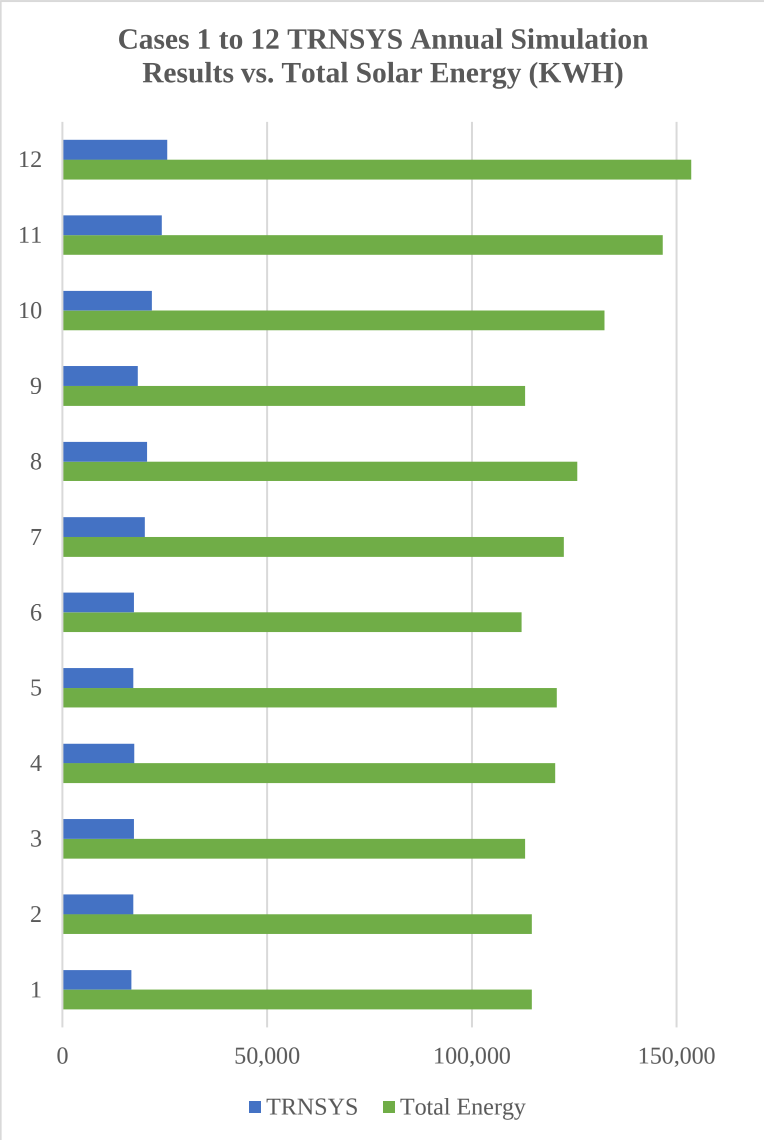
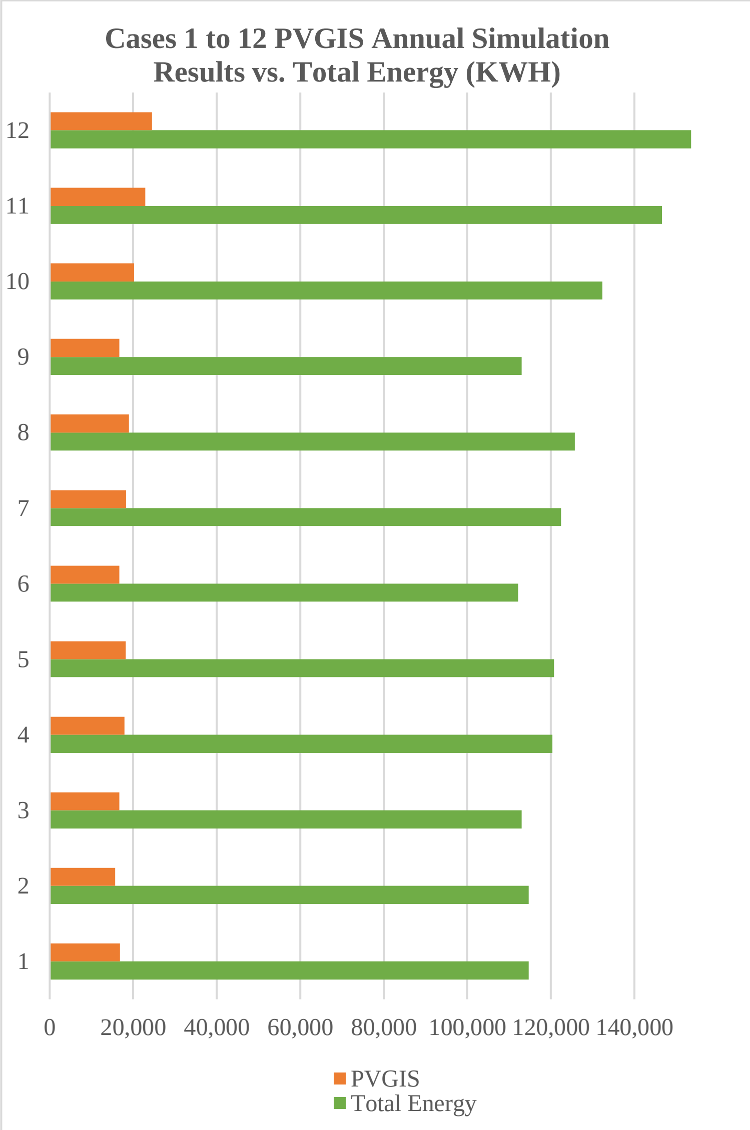


Table 20 represents the anticipated total annual solar energy in kilowatt-hours (KWH) projected to reach the 28 solar photovoltaic panels installed system, PVGIS's estimated total energy production in KWH and the overall Solar PV system efficiency. This information is compiled for cases 1 to 12, along with a corresponding bar chart illustrating the data adjacent to the table.

Table 20: PVGIS Annual Simulation Results vs Total Solar Energy (KWH) and System Efficiency

Case	Total Solar Energy (KWH)	Solar PV (KWH)	System Efficiency
1	114,686	16,858	14.7%
2	114,686	15,673	13.7%
3	113,005	16,675	14.8%
4	120,394	17,871	14.8%
5	120,715	18,188	15.1%
6	112,179	16,675	14.9%
7	122,451	18,269	14.9%
8	125,775	18,975	15.1%
9	113,005	16,644	14.7%
10	132,362	20,182	15.2%
11	146,606	22,867	15.6%
12	153,551	24,538	16.0%



System Efficiency % = S_m/S_e where: S_m - Simulated output (KWH) S_e – Total solar energy falling on the surface of the Solar PV panels (KWH)

Table 21 represents the actual monthly generated energy (KWH) by the Solar PV system as installed i.e. 8º Tilt and -38º (142⁰ from North) Azimuth (Case 1), the simulation results of PVGIS and TRNSYS, and the corresponding % variants using the actual "As Installed" as basis. Case 1 is the actual data and Case 2 is simulated data. . Figure 36 is a histogram of the same data.

Table 21: Actual Solar Energy Generated (Case 1) vs. Simulation Results (Case 2)

8T-38A (As Installed)					
	1	2			
Month	Actual	PVGIS		TRNSYS	
	Total KWH	KWH	Variant	KWH	Variant
Jan	1,012	754	-25%	1,151	14%
Feb	1,180	808	-32%	1,114	-6%
Mar	1,510	1,242	-18%	1,508	0%
Apr	1,730	1,561	-10%	1,477	-15%
May	2,010	1,879	-7%	1,535	-24%
Jun	1,820	1,889	4%	1,792	-2%
Jul	1,630	1,728	6%	1,754	8%
Aug	1,630	1,615	-1%	1,762	8%
Sep	1,540	1,428	-7%	1,672	9%
Oct	1,180	1,228	4%	1,278	8%
Nov	821	835	2%	1,230	50%
Dec	795	706	-11%	1,057	33%
Total	**16,858**	**15,673**	**-7%**	**17,330**	**3%**

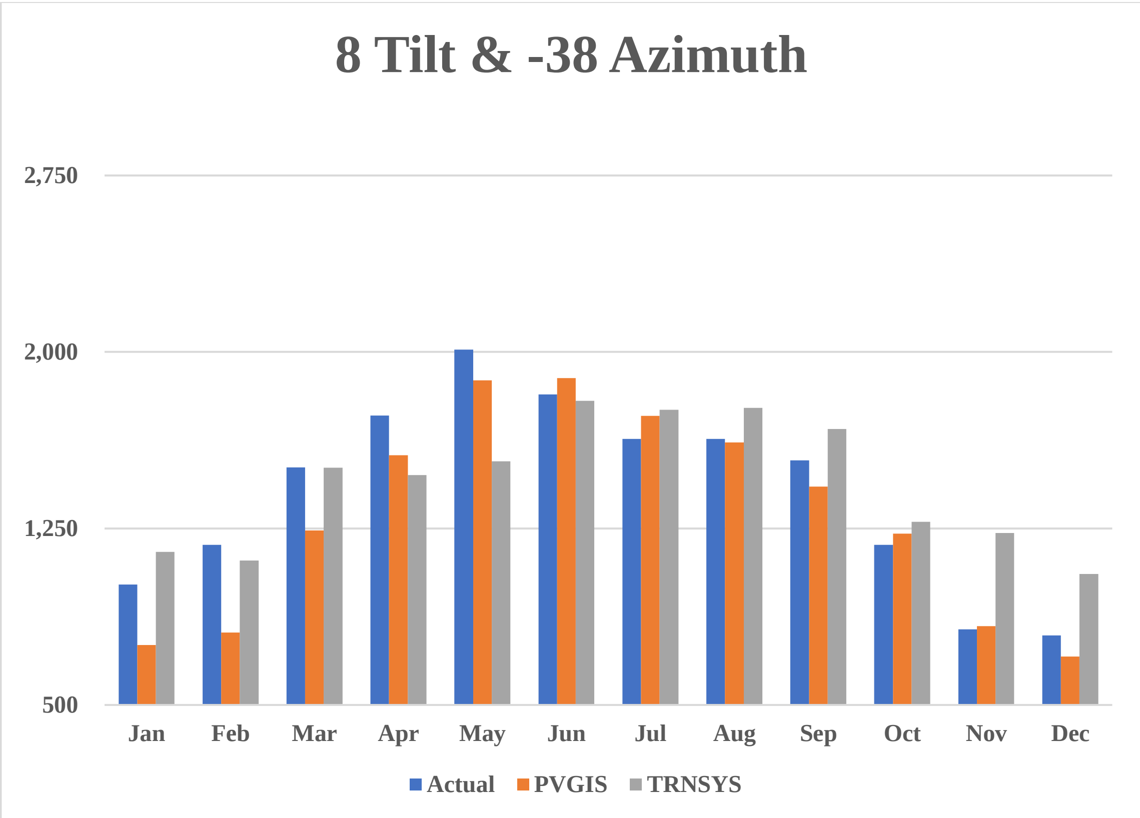


Figure 36:Actual Generated KWH (Case 1) vs. PVGIS & TRNSYS Simulated KWH(Case 2)

Figure 36 compares the actual monthly energy generation (KWH) of the installed Solar PV system (Case 1) with the simulation results from PVGIS and TRNSYS (Case 2).

Table 22 represents the actual monthly generated energy (KWH) by the Solar PV system as installed i.e. 8º Tilt and -38º (142^0 from North) Azimuth (Case 1), the simulation results of PVGIS and TRNSYS, and the % variants based on 0º Tilt and -38º Azimuth angles (Case 3), using the actual base case data as basis.

Table 22: Actual Solar Energy Generated (Case 1) vs. Simulation Results (Case 3)

0T-38A					
1		**3**			
Month	**Actual Total KWH**	**PVGIS KWH**	**Variant**	**TRNSYS KWH**	**Variant**
Jan	1,012	897	-11%	1,028	2%
Feb	1,180	906	-23%	1,027	-13%
Mar	1,510	1,332	-12%	1,524	1%
Apr	1,730	1,626	-6%	1,680	-3%
May	2,010	1,913	-5%	1,687	-16%
Jun	1,820	1,904	5%	1,849	2%
Jul	1,630	1,736	7%	1,821	12%
Aug	1,630	1,644	1%	1,764	8%
Sep	1,540	1,509	-2%	1,611	5%
Oct	1,180	1,365	16%	1,465	24%
Nov	821	981	19%	1,099	34%
Dec	795	863	9%	932	17%
Total	**16,858**	**16,675**	**-1%**	**17,487**	**4%**

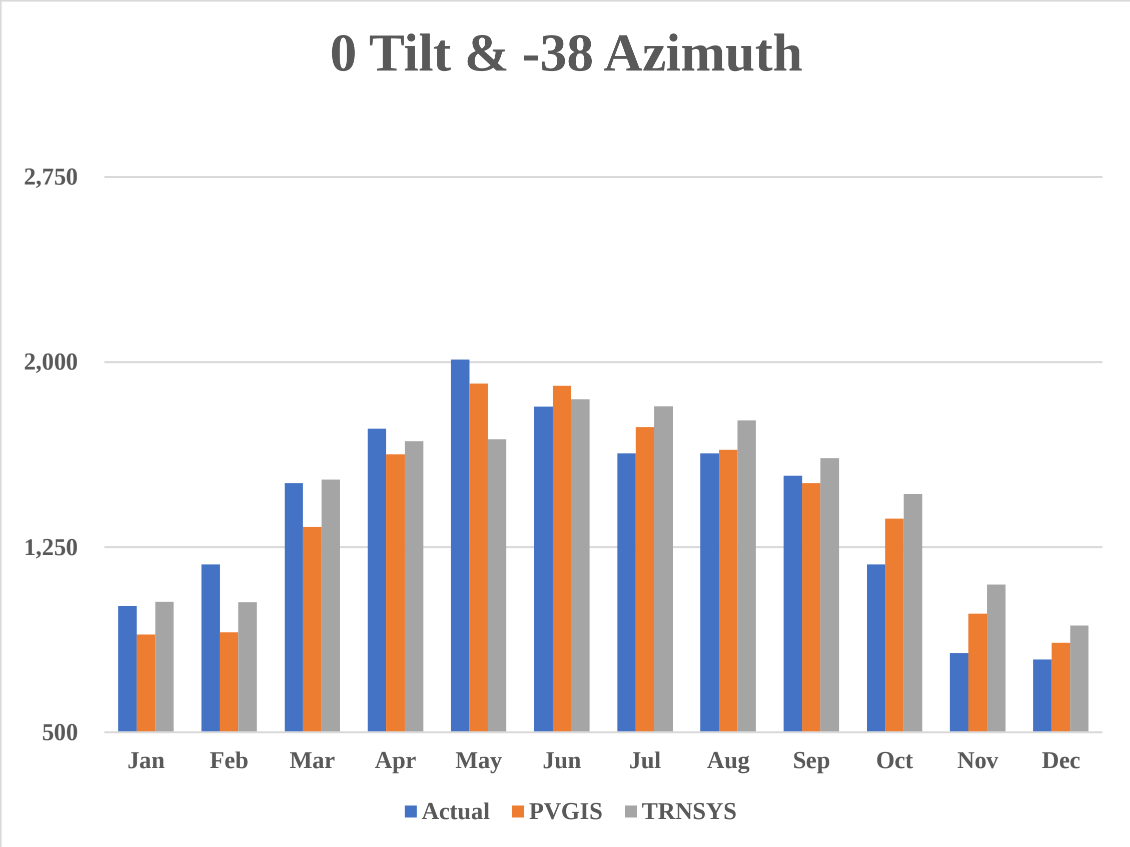


Figure 37:Actual Generated KWH (Case 1) vs. PVGIS & TRNSYS Simulated KWH(Case 3)

Figure 37 compares the actual monthly energy generation (KWH) of the installed Solar PV system (Case 1) with the simulation results from PVGIS and TRNSYS (Case 3).

Table 23 represents the actual monthly generated energy (KWH) by the Solar PV system as installed i.e. 8º Tilt and -38º (142^0 from North) Azimuth (Case 1), the simulation results of PVGIS and TRNSYS, and the % variants based on 15º Tilt and -38º Azimuth angles (Case 4), using the actual base case data as basis.

Table 23: Actual Solar Energy Generated (Case 1) vs. Simulation Results (Case 4)

15T-38A					
1		4			
Month	Actual Total KWH	PVGIS KWH	Variant	TRNSYS KWH	Variant
Jan	1,012	1,126	11%	1,241	23%
Feb	1,180	1,043	-12%	1,136	-4%
Mar	1,510	1,442	-5%	1,353	-10%
Apr	1,730	1,676	-3%	1,372	-21%
May	2,010	1,901	-5%	1,495	-26%
Jun	1,820	1,859	2%	1,677	-8%
Jul	1,630	1,694	4%	1,722	6%
Aug	1,630	1,656	2%	1,764	7%
Sep	1,540	1,599	4%	1,695	10%
Oct	1,180	1,561	32%	1,660	41%

Nov	821	1,201	46%	1,325	61%
Dec	795	1,115	40%	1,151	45%
Total	**16,858**	**17,871**	**6%**	**17,591**	**4%**

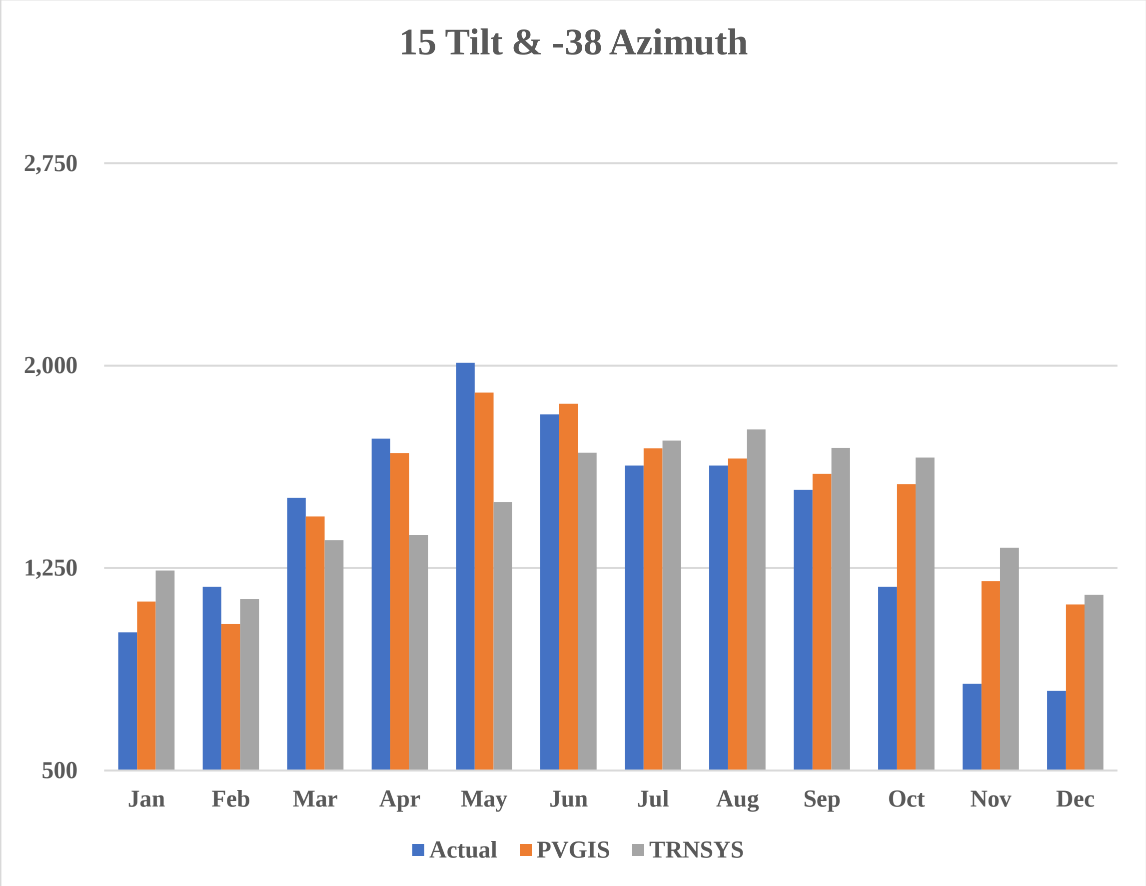


Figure 38:Actual Generated KWH (Case 1) vs. PVGIS & TRNSYS Simulated KWH(Case 4)

Figure 38 compares the actual monthly energy generation (KWH) of the installed Solar PV system (Case 1) with the simulation results from PVGIS and TRNSYS (Case 4).

Table 24 represents the actual monthly generated energy (KWH) by the Solar PV system as installed i.e. 8º Tilt and -38º (142^0 from North) Azimuth (Case 1), the simulation results of PVGIS and TRNSYS, and the % variants based on 33º Tilt and -38º Azimuth angles (Case 5), using the actual base case data as basis.

Table 24: Actual Solar Energy Generated (Case 1) vs. Simulation Results (Case 5)

33T-38A					
1		**5**			
Month	**Actual Total KWH**	**PVGIS KWH**	**Variant**	**TRNSYS KWH**	**Variant**
Jan	1,012	1,305	29%	1,367	35%
Feb	1,180	1,131	-4%	1,116	-5%
Mar	1,510	1,480	-2%	1,190	-21%
Apr	1,730	1,638	-5%	1,308	-24%

May	2,010	1,790	-11%	1,547	-23%
Jun	1,820	1,713	-6%	1,752	-4%
Jul	1,630	1,567	-4%	1,671	3%
Aug	1,630	1,586	-3%	1,669	2%
Sep	1,540	1,613	5%	1,505	-2%
Oct	1,180	1,683	43%	1,416	20%
Nov	821	1,365	66%	1,486	81%
Dec	795	1,317	66%	1,317	66%
Total	**16,858**	**18,188**	**8%**	**17,344**	**3%**

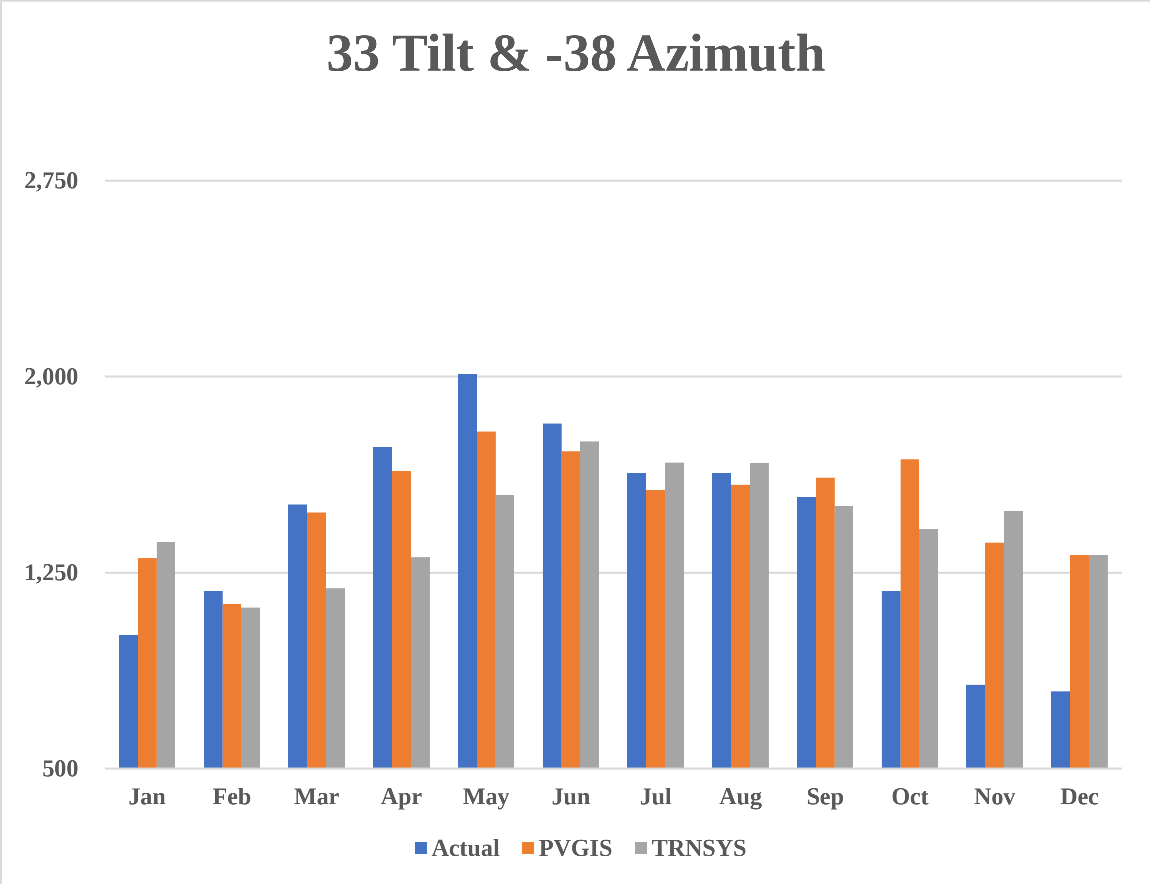


Figure 39:Actual Generated KWH (Case 1) vs. PVGIS & TRNSYS Simulated KWH(Case 5)

Figure 39 compares the actual monthly energy generation (KWH) of the installed Solar PV system (Case 1) with the simulation results from PVGIS and TRNSYS (Case 5).

Table 25 represents the actual monthly generated energy (KWH) by the Solar PV system as installed i.e. 8º Tilt and -38º (142º from North) Azimuth (Case 1), the simulation results of PVGIS and TRNSYS, and the % variants based on 0º Tilt and 3º Azimuth angles (Case 6), using the actual base case data as basis.

Table 25: Actual Solar Energy Generated (Case 1) vs. Simulation Results (Case 6)

0T3A					
1		6			
Month	**Actual Total KWH**	**PVGIS KWH**	**Variant**	**TRNSYS KWH**	**Variant**
Jan	1,012	897	-11%	1,028	2%
Feb	1,180	906	-23%	1,027	-13%
Mar	1,510	1,332	-12%	1,524	1%
Apr	1,730	1,626	-6%	1,680	-3%
May	2,010	1,913	-5%	1,688	-16%
Jun	1,820	1,904	5%	1,849	2%
Jul	1,630	1,736	7%	1,821	12%
Aug	1,630	1,644	1%	1,764	8%
Sep	1,540	1,509	-2%	1,611	5%
Oct	1,180	1,365	16%	1,465	24%
Nov	821	981	19%	1,099	34%
Dec	795	863	9%	932	17%
Total	**16,858**	**16,675**	**-1%**	**17,488**	**4%**

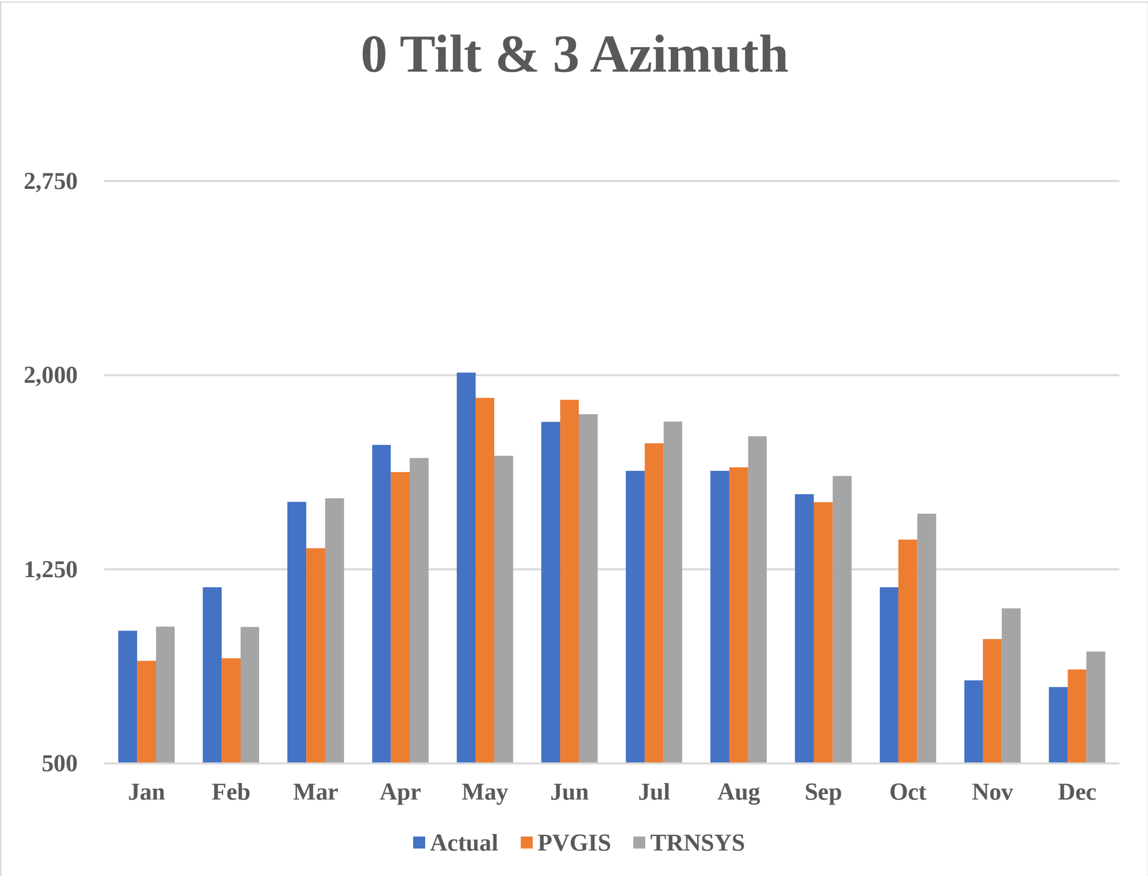


Figure 40: Actual Generated KWH (Case 1) vs. PVGIS & TRNSYS Simulated KWH(Case 6)

Figure 40 compares the actual monthly energy generation (KWH) of the installed Solar PV system (Case 1) with the simulation results from PVGIS and TRNSYS (Case 6).

Table 26 represents the actual monthly generated energy (KWH) by the Solar PV system as installed i.e. 8º Tilt and -38º (142⁰ from North) Azimuth (Case 1), the simulation results of PVGIS and TRNSYS, and the % variants based on 15º Tilt and 3º Azimuth angles (Case 7), using the actual base case data as basis.

Table 26: Actual Solar Energy Generated (Case 1) vs. Simulation Results (Case 7)

15T3A					
1		**7**			
Month	**Actual Total KWH**	**PVGIS KWH**	**Variant**	**TRNSYS KWH**	**Variant**
Jan	1,012	1,168	15%	1,317	30%
Feb	1,180	1,073	-9%	1,215	3%
Mar	1,510	1,469	-3%	1,688	12%
Apr	1,730	1,685	-3%	1,949	13%
May	2,010	1,907	-5%	2,185	9%
Jun	1,820	1,865	2%	2,028	11%
Jul	1,630	1,724	6%	1,823	12%
Aug	1,630	1,693	4%	1,825	12%
Sep	1,540	1,642	7%	1,748	14%
Oct	1,180	1,616	37%	1,721	46%
Nov	821	1,263	54%	1,384	69%
Dec	795	1,164	46%	1,217	53%
Total	**16,858**	**18,269**	**8%**	**20,100**	**19%**

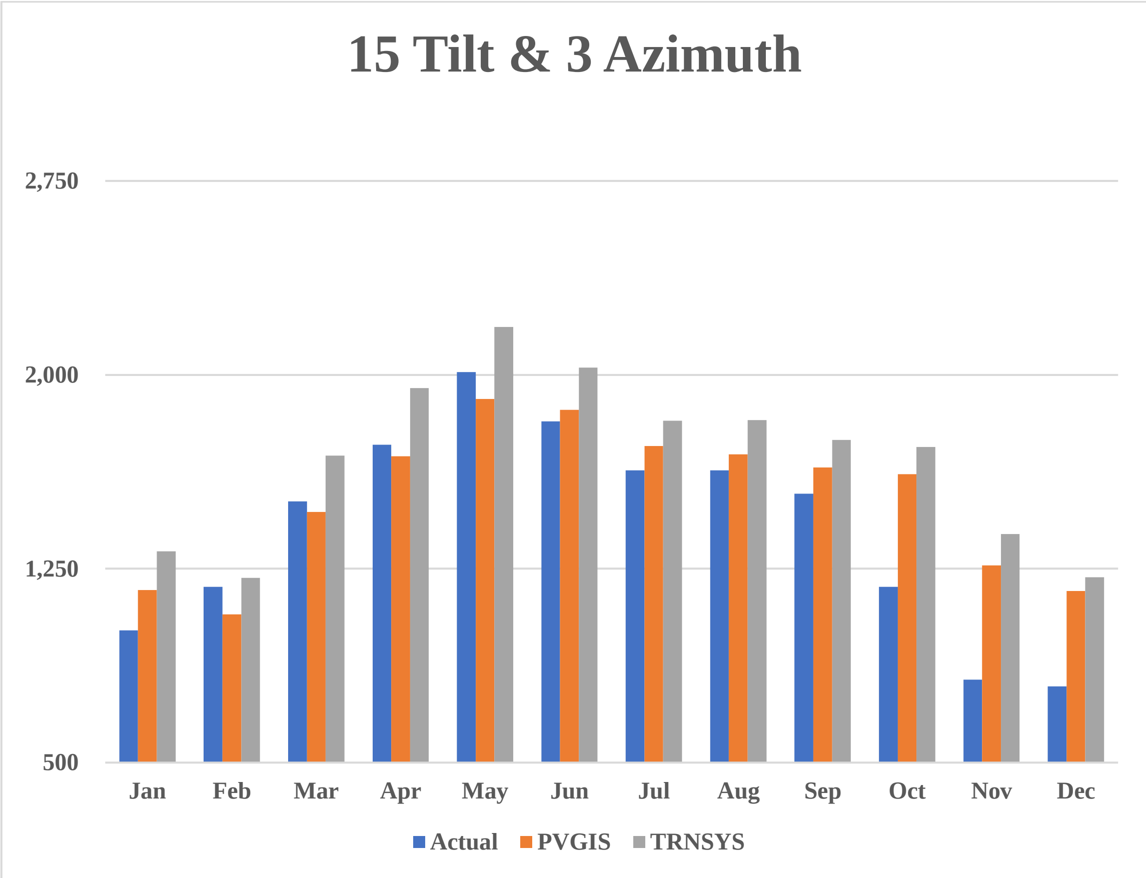


Figure 41: Actual Generated KWH (Case 1) vs. PVGIS & TRNSYS Simulated KWH(Case 7)

Figure 41 compares the actual monthly energy generation (KWH) of the installed Solar PV system (Case 1) with the simulation results from PVGIS and TRNSYS (Case 7).

Table 27 represents the actual monthly generated energy (KWH) by the Solar PV system as installed i.e. 8º Tilt and -38º (142^0 from North) Azimuth (Case 1), the simulation results of PVGIS and TRNSYS, and the % variants based on 33º Tilt and 3º Azimuth angles (Case 8), using the actual base case data as basis.

Table 27: Actual Solar Energy Generated (Case 1) vs. Simulation Results (Case 8)

33T3A					
1		8			
Month	Actual Total KWH	PVGIS KWH	Variant	TRNSYS KWH	Variant
Jan	1,012	1,393	38%	1,550	53%
Feb	1,180	1,200	2%	1,350	14%
Mar	1,510	1,543	2%	1,766	17%
Apr	1,730	1,663	-4%	1,924	11%
May	2,010	1,794	-11%	2,051	2%
Jun	1,820	1,717	-6%	1,863	2%
Jul	1,630	1,616	-1%	1,702	4%
Aug	1,630	1,645	1%	1,758	8%
Sep	1,540	1,695	10%	1,790	16%

Oct	1,180	1,798	52%	1,892	60%
Nov	821	1,492	82%	1,610	96%
Dec	795	1,419	78%	1,454	83%
Total	**16,858**	**18,975**	**13%**	**20,710**	**23%**

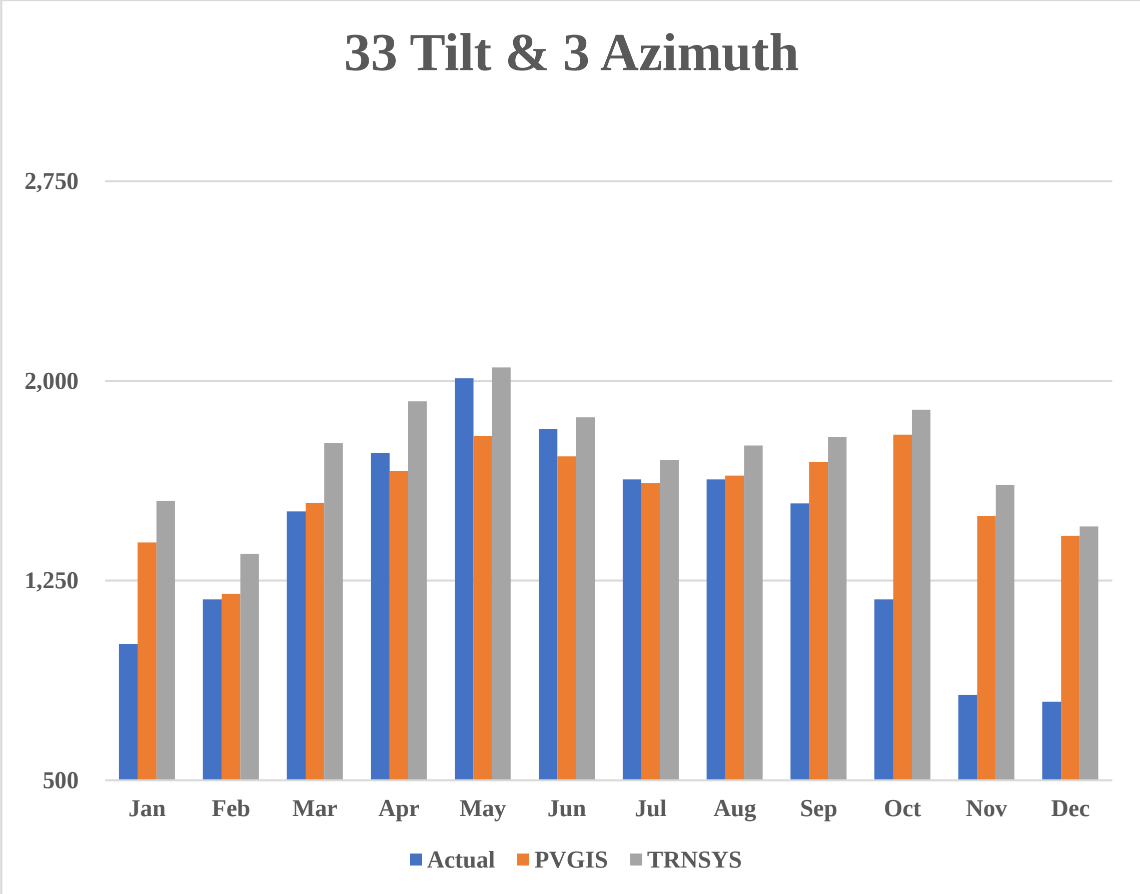


Figure 42: Actual Generated KWH (Case 1) vs. PVGIS & TRNSYS Simulated KWH(Case 8)

Figure 42 compares the actual monthly energy generation (KWH) of the installed Solar PV system (Case 1) with the simulation results from PVGIS and TRNSYS (Case 8).

Table 28 represents the actual monthly generated energy (KWH) by the Solar PV system as installed i.e. 8º Tilt and -38º (142^0 from North) Azimuth (Case 1), the simulation results of PVGIS and TRNSYS, and the % variants based on 0º Tilt angle and tracking on the Azimuth (Case 9), using the actual base case data as basis.

Table 28: Actual Solar Energy Generated (Case 1) vs. Simulation Results (Case 9)

0T & Tracking on A					
1		**9**			
Month	**Actual KWH**	**PVGIS KWH**	**Variant**	**TRNSYS KWH**	**Variant**
Jan	1,012	891	-12%	1,031	2%
Feb	1,180	901	-24%	1,027	-13%
Mar	1,510	1,328	-12%	1,525	1%

Apr	1,730	1,619	-6%	1,859	7%
May	2,010	1,910	-5%	2,172	8%
Jun	1,820	1,901	4%	2,054	13%
Jul	1,630	1,737	7%	1,830	12%
Aug	1,630	1,652	1%	1,783	9%
Sep	1,540	1,508	-2%	1,611	5%
Oct	1,180	1,361	15%	1,465	24%
Nov	821	980	19%	1,099	34%
Dec	795	857	8%	933	17%
Total	**16,858**	**16,644**	**-1%**	**18,389**	**9%**

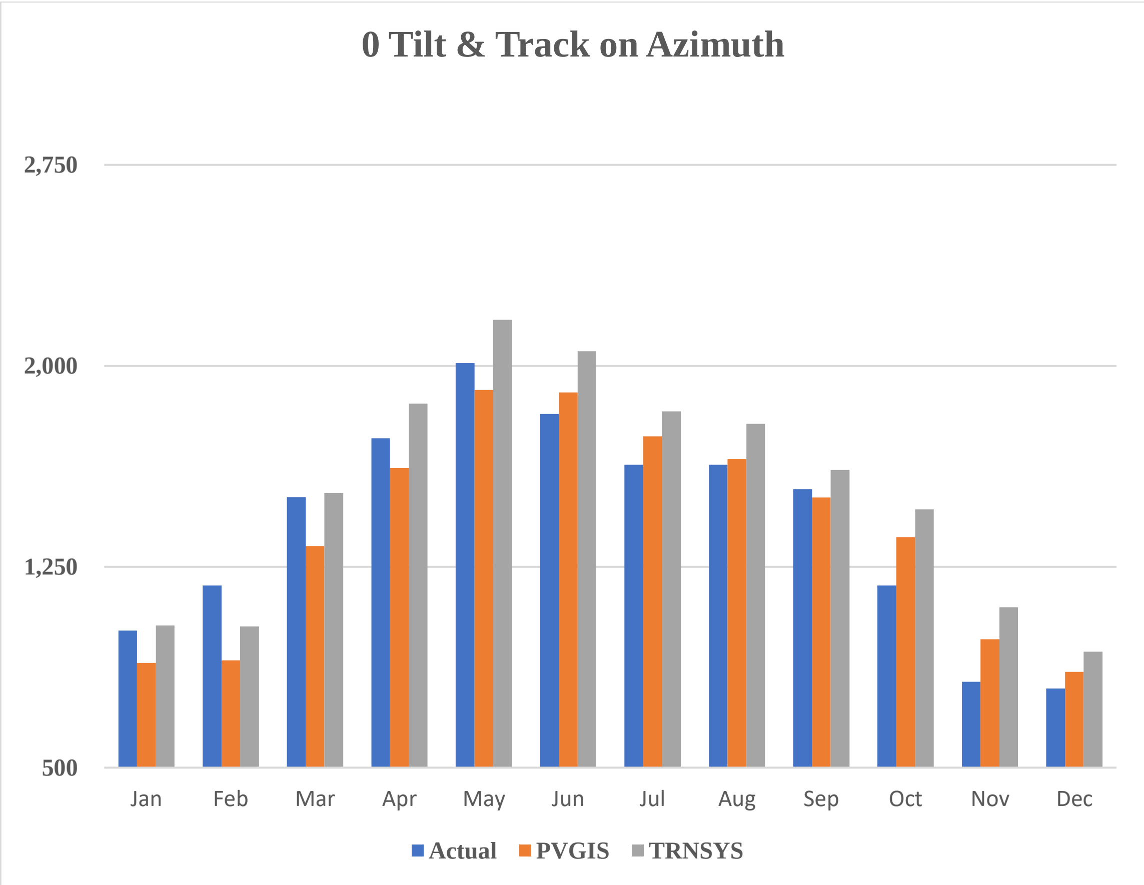


Figure 43: Actual Generated KWH (Case 1) vs. PVGIS & TRNSYS Simulated KWH(Case 9)

Figure 43 compares the actual monthly energy generation (KWH) of the installed Solar PV system (Case 1) with the simulation results from PVGIS and TRNSYS (Case 9).

Table 29 represents the actual monthly generated energy (KWH) by the Solar PV system as installed i.e. 8º Tilt and -38º (142⁰ from North) Azimuth (Case 1), the simulation results of PVGIS and TRNSYS, and the % variants based on 15º Tilt angle and tracking on the Azimuth (Case 10), using the actual base case data as basis.

Table 29: Actual Solar Energy Generated (Case 1) vs. Simulation Results (Case 10)

15T & Tracking on A					
1		10			
Month	**Actual KWH**	**PVGIS KWH**	**Variant**	**TRNSYS KWH**	**Variant**
Jan	1,012	1,152	22%	1,380	36%
Feb	1,180	1,607	-2%	1,278	8%
Mar	1,510	1,885	6%	1,805	20%
Apr	1,730	2,187	9%	2,140	24%
May	2,010	2,150	9%	2,449	22%
Jun	1,820	1,931	18%	2,283	25%
Jul	1,630	1,882	18%	1,999	23%
Aug	1,630	1,812	15%	1,998	23%
Sep	1,540	1,763	18%	1,897	23%
Oct	1,180	1,349	49%	1,855	57%
Nov	821	1,229	64%	1,463	78%
Dec	795	1,317	55%	1,274	60%
Total	**16,858**	**20,263**	**20%**	**21,821**	**29%**

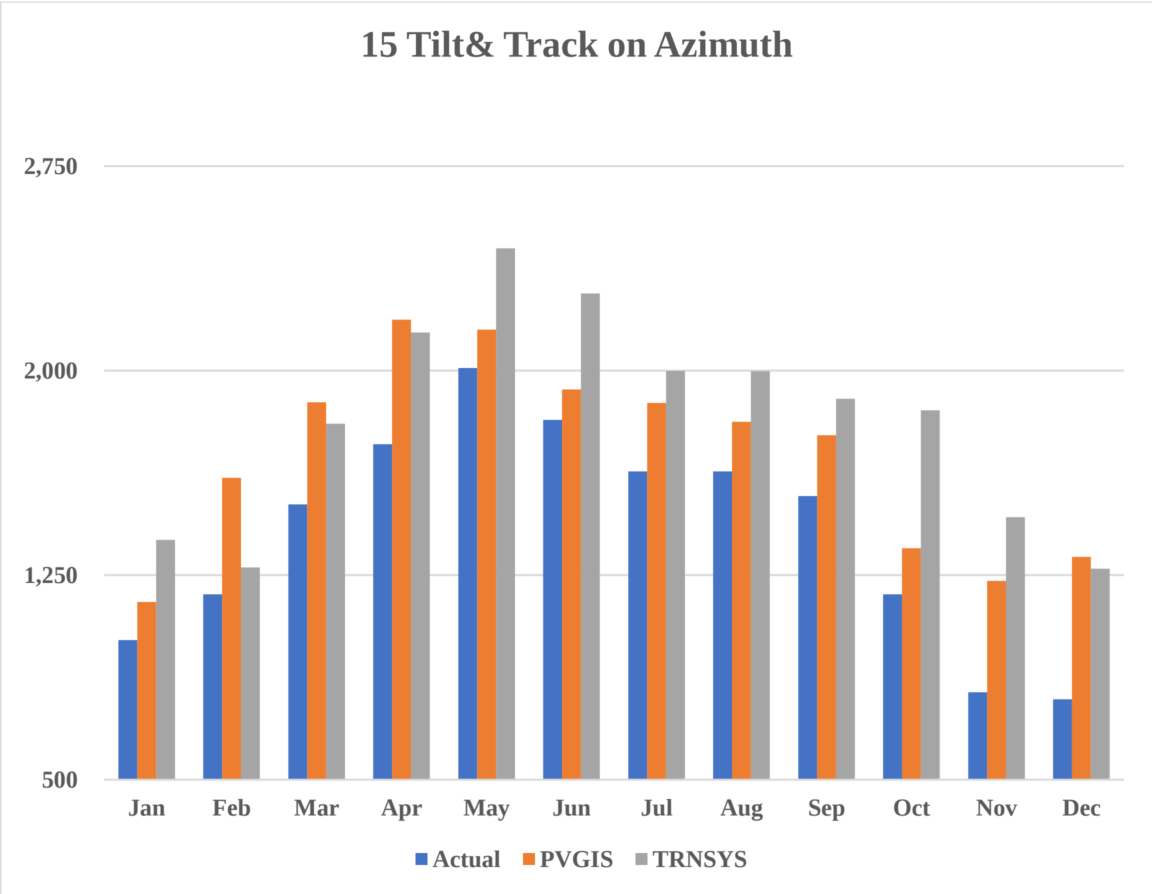


Figure 44: Actual Generated KWH (Case 1) vs. PVGIS & TRNSYS Simulated KWH(Case 10)

Figure 44 compares the actual monthly energy generation (KWH) of the installed Solar PV system (Case 1) with the simulation results from PVGIS and TRNSYS (Case 10).

Table 30 represents the actual monthly generated energy (KWH) by the Solar PV system as installed i.e. 8^o Tilt and -38^o (142^0 from North) Azimuth (Case 1), the simulation results of PVGIS and TRNSYS, and the % variants based on 33^o Tilt angle and tracking on the Azimuth (Case 11), using the actual base case data as basis.

Table 30: Actual Solar Energy Generated (Case 1) vs. Simulation Results (Case 11)

33T & Tracking on A					
1		**11**			
Month	**Actual Total KWH**	**PVGIS KWH**	**Variant**	**TRNSYS KWH**	**Variant**
Jan	1,012	1,528	51%	1,677	66%
Feb	1,180	1,357	15%	1,494	27%
Mar	1,510	1,821	21%	2,006	33%
Apr	1,730	2,071	20%	2,317	34%
May	2,010	2,366	18%	2,601	29%
Jun	1,820	2,303	27%	2,395	32%
Jul	1,630	2,043	25%	2,069	27%
Aug	1,630	2,033	25%	2,119	30%
Sep	1,540	2,042	33%	2,098	36%
Oct	1,180	2,091	77%	2,163	83%
Nov	821	1,663	103%	1,768	115%
Dec	795	1,548	95%	1,569	97%
Total	**16,858**	**22,867**	**36%**	**24,276**	**44%**

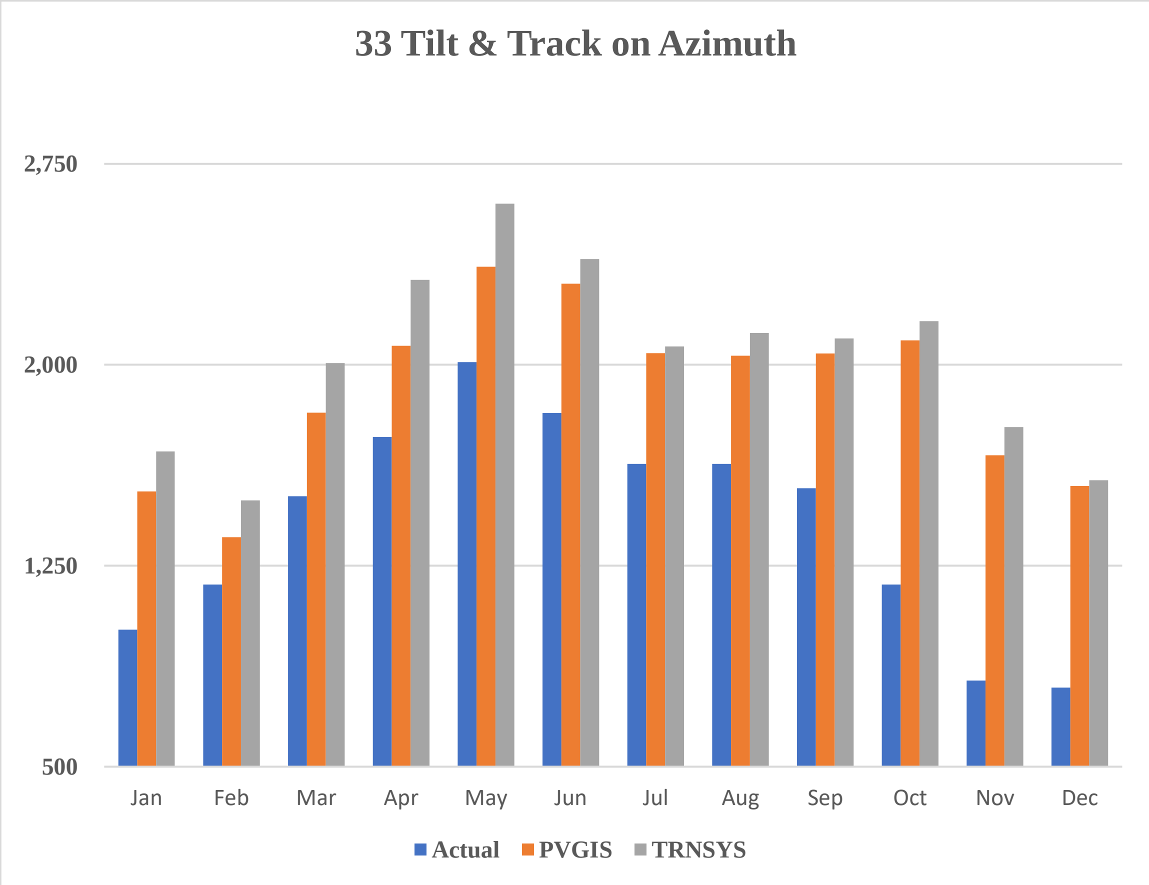


Figure 45: Actual Generated KWH (Case 1) vs. PVGIS & TRNSYS Simulated KWH(Case 11)

Figure 45 compares the actual monthly energy generation (KWH) of the installed Solar PV system (Case 1) with the simulation results from PVGIS and TRNSYS (Case 11).

Table 31 represents the actual monthly generated energy (KWH) by the Solar PV system as installed i.e. 8° Tilt and -38° (142° from North) Azimuth (Case 1), the simulation results of PVGIS and TRNSYS, and the % variants based on tracking on the Tilt and Azimuth axes (Case 12), using the actual base case data as basis.

Table 31: Actual Solar Energy Generated (Case 1) vs. Simulation Results (Case 12)

2 Axis Tracking					
1		12			
Month	Actual Total KWH	PVGIS KWH	Variant	TRNSYS KWH	Variant
Jan	1,012	1,729	71%	1,867	84%
Feb	1,180	1,477	25%	1,602	36%
Mar	1,510	1,935	28%	2,082	38%
Apr	1,730	2,169	25%	2,391	38%
May	2,010	2,480	23%	2,687	34%
Jun	1,820	2,412	33%	2,469	36%
Jul	1,630	2,113	30%	2,110	29%

Aug	1,630	2,111	30%	2,171	33%
Sep	1,540	2,162	40%	2,183	42%
Oct	1,180	2,291	94%	2,327	97%
Nov	821	1,880	129%	1,956	138%
Dec	795	1,779	124%	1,770	123%
Total	**16,858**	**24,538**	**46%**	**25,615**	**52%**

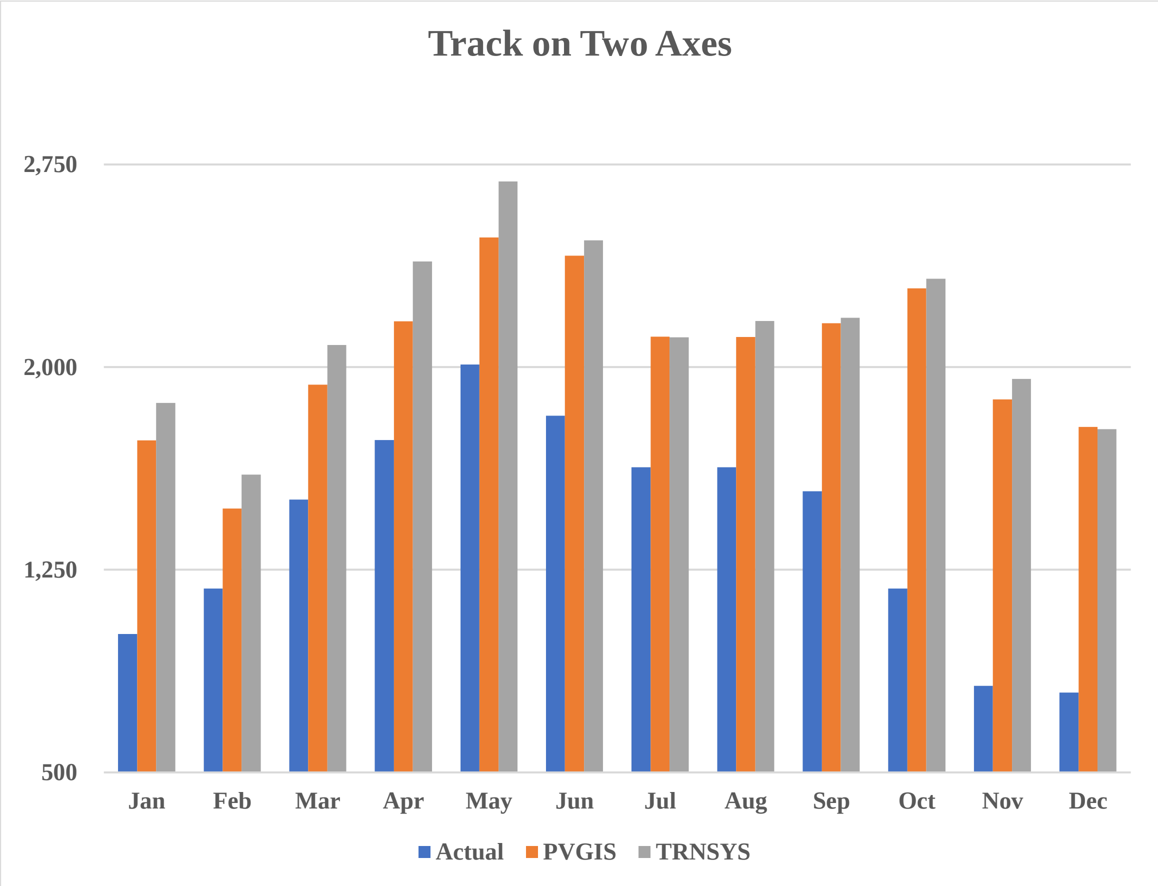


Figure 46: Actual Generated KWH (Case 1) vs. PVGIS & TRNSYS Simulated KWH(Case 12)

Figure 46 compares the actual monthly energy generation (KWH) of the installed Solar PV system (Case 1) with the simulation results from PVGIS and TRNSYS (Case 12).

Total Generated Solar Since January 2021 up to 31st December 2023 50,370 KWH. An average monthly of 1,399 KWH or Average Yearly 16,790 KWH.

Figure 47 shows a typical Solar PV System monthly generated Energy Saving Report highlighting the actual solar production, grid power consumed and solar exported electricity, also, the expected total savings. This particular report is for July 2022.

Solar photovoltaic (PV) sun tracking is not common due to cost, complexity, and maintenance challenges. Here are the main reasons:

- Tracking systems necessitate extra mechanical, electrical and electronic components, including motors, sensors, and control systems, which raise the initial installation cost.

- Can lead to frequent mechanical failures due to moving parts in trackers, resulting from wear and tear.

- It is less attractive for residential and small-scale application due to the need for regular maintenance.

- Active tracking systems consumes electricity for operation, resulting in slight reduction in the solar photovoltaic overall system efficiency.

- Require larger footprint since the tracking system, whether single-axis and dual-axis require more spacing between the solar photovoltaic panels, which less attractive for small PV installations.

- The recent drop in PV module costs has made it more economically viable to install more panels rather than invest in tracking systems.

- Advancement in bifacial panels and high-efficiency modules declined interest in tracking.

- Tracking is more justifiable for large utility-scale solar PV farms, where maximizing efficiency is crucial, unlike residential roof top applications.

SKYELECTRIC
Powered by Intelligence

Customer Name:	MAGDI RASHAD
Date Timeline:	13-June-2022 to 12-July-2022
System Size:	12.2kW PV x 10.0kW Inverter x 0.0kWh Battery
Billing Month:	July 2022
Due Date:	22-July-2022

Energy Savings Report

A detailed description of your SkyElectric Smart Solar System's solar energy production and grid utilization is given below:

1 SOLAR CONSUMED
58 Units consumed
Solar Consumption Savings: **Rs. 1,139.14**

2 GRID OUTAGES
Total No. of Grid Outages: N/A *
Total Grid Outages Duration: N/A *
Total Units Consumed during Grid Outages: N/A *
Grid Outages Savings: N/A *
Feature coming soon

3 SOLAR EXPORTED
1,336 Units Exported
at High Tariff Rate: **0 Units**
at Low Tariff Rate: **1,336 Units**
Solar Exported Savings: **Rs. 21,816.88**

4 COST SAVINGS
Rs. 22,956.02 Total Savings
Total Solar Consumption Savings: **Rs. 1,139.14**
Total Grid Outages Savings: **N/A**
Total Solar Exported Savings: **Rs. 21,816.88**

5 GRID CONSUMED
N/A
at High Tariff Rate: **N/A**
at Low Tariff Rate: **N/A**
Electricity Bill July 2022: **Rs. -64,862**

6 ENERGY SOURCES
Total Solar Production
100%
Total Grid Consumption:
0%

IESCO tariff rates * :	
High tariff rate	**Rs. 22.65 per Unit**
Low tariff rate	**Rs. 16.33 per Unit**

Government Tax / Surcharge Rates:	
GST	**17%**
NJ Surcharge	**Rs. 0.10 per Unit**
FC Surcharge	**Rs. 0.43 per Unit**

REPORT CALCULATIONS:

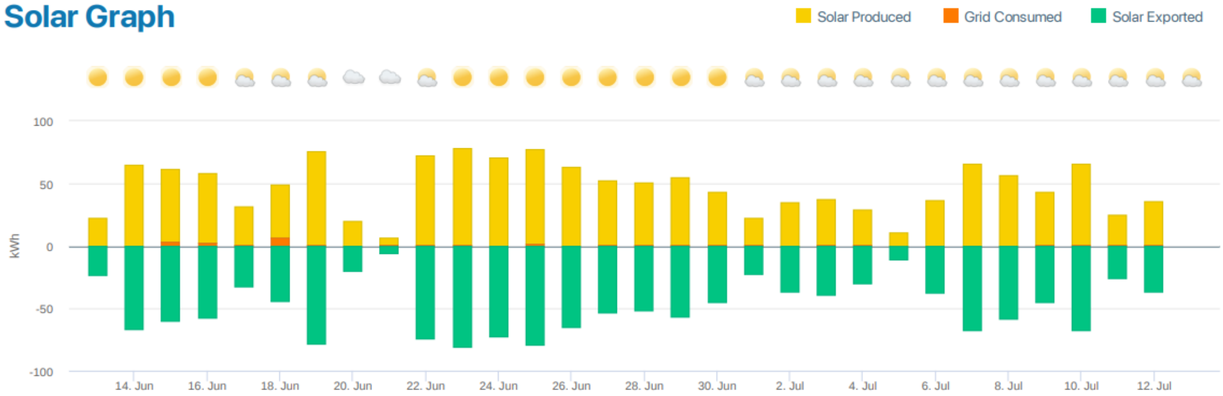
1 Solar Consumption Savings:
Savings secured from solar consumption by local loads are determined as follows:
Solar Units (High Tariff) x 22.65 + GST + NJSurcharge + FC Surcharge
(0 x 22.65) + 0 + 0 + 0 = **Rs. 0**
Solar Units (Low Tariff) x 16.33 + GST + NJSurcharge + FC Surcharge
(58 x 16.33) + 161 + 6 + 25 = **Rs. 1,139.14**
Total = Rs. 1,139.14

2 Grid Outages Savings:
Savings secured during Grid Outages are determined as follows:
Units Consumed during Grid Outages x Rs. 45
N/A Units x Rs. 45
N/A
Estimated generator per unit cost is **Rs. 45**
(@ Diesel Price of **Rs. 127.16/Ltr.**)

3 Solar Exported Savings:
Savings secured from solar export are determined as follows:
Solar Units (High Tariff) x 22.65
0 x 22.65 = **Rs. 0**
Solar Units (Low Tariff) x 16.33
1336 x 16.33 = **Rs. 21,816.88**
Total = Rs. 21,816.88

4 Total Cost Savings:
Below are the detail methodolgy and formula used to calculate the cost savings.
Solar Consumption Savings + Grid Outages Savings + Solar Exported Savings
1,139.14 + N/A + 21,816.88
Total = Rs. 22,956.02

Solar Graph



0800 77 759 (SKY) customer.care@skyelectric.com www.skyelectric.com

*These are reference rates and might be different from those used by the power companies to compute your bill

Figure 47 Typical System Generated Energy Saving Report

9. Research Investigation

9.1 Introduction

The research investigation took advantage of the many passive design features of the building chosen as the experimental rig. The building construction details are in Section 7. The reach investigation focused on studying the performance of the installed Solar PV system performance using TRNSYS and PVGIS to simulate 11 cases (2 to 12) of varying tilt and azimuth angles and comparing the simulation results with the actual data (Case 1) collected over a period of one year. The emphasis here is to study the performance of Solar PV in a low carbon footprint building, where the main consumer of electricity during the warm season is air conditioning, already less than half the average cooling capacity is needed, and during winter two electric boilers 140 Liters each.

A common misconception is that every location along the same latitude has the same optimal fixed tilt angle for solar panels. This assumption neglects important factors like different weather conditions and climate variations in regions along the same latitude. In fact, solar energy output varies uniquely with each specific set of latitude and longitude coordinates.

9.2 Research Investigation

It is vitally important to conduct error analysis when solar photovoltaic (PV) computer simulation tools are used to investigate the performance of solar systems at different tilt and azimuth angles, compare with actual data and to understand the accuracy and reliability of the simulation outputs. The error analysis will help identify and quantify the sources of inaccuracies and how to mitigate them. PV performance predictions can be greatly improved by enhancing input data quality, performing sensitivity analysis, conducting “what if” scenarios and increasing the accuracy of modelling techniques. Eventually, this results in better configuration of Solar PV systems intended for specific sites, and more accurately predictable financial modelling. All lead to enhanced decision-making process when designing and deploying Solar PV systems, as well as, improving the performance of existing ones.

One of the main challenges when conducting computer simulation of the up and running grid connected Solar PV was how to quantify the unaccounted production during grid power disconnection. This is one of the main drawbacks of grid connect Solar PV system with no energy storage i.e. battery-less system. The inverter in this type of installation requires voltage source, commonly from the power grid, for it to work. In the absence of power (blackout) the inverter will shut down. It was noticed throughout the period of data collections, which was over 2 years, grid power interruption was quite frequent, with no specific time of the day, sometimes during daytime and sometimes at night, and no specific duration, sometimes an hour or two or several hours. Nevertheless, the average daily production of a 12.18 KW_p system is 46.18 KWH, deduced by dividing the total annual generation of 16,858 by 365 days a year. This compares to the daily average 48.72 KWH [Ref], difference of 5.2%.

9.3 Error Analysis

There are many causes for errors which lead to uncertainty in the input data and lack of confidence in the output results.

1. Input Data Uncertainty

- Solar Irradiance Data

  Errors in the solar irradiance data used in simulation can lead to substantial impact on the simulation output accuracy. Common error causes: incorrect measurements, of time resolution and surrounding space variabilities i.e. change in landscape due to new constructions, tree plantation or grow higher.

- Meteorological Data:

  Low-resolution meteorological inputs, such as wind speed, temperature, rainfall, sky clarity i.e. clouds, pollution, dust due to construction or near roads activities, can all lead to erroneous performance predictions.

- System Component Specifications:

  Inaccurate recoding the manufacturer specifications for system components such the Solar PV panels and Inverter can result discrepancies.

2. Modelling Assumptions and Simplification:

- PV Module Performance Models:

  Ideal conditions are commonly assumed when modelling, not taking into consideration equipment degradation, surrounding landscape and the possibility shadow-cast by trees tall plants, creepers or nearby buildings that may not necessary been present at the time of installing the Solar PV system.

- Inverter Models:

  Energy prediction output may not be accurately predicted if all operational modes of the inverter are not properly modelled.

- System Losses:

  Significant errors can result from inaccurate system losses assumptions or output not accounted for as a result of blackouts (power disconnection), in grid connected systems (inverter shuts down in the absence of power).

3. Simulation Algorithms:
   - Time Step Resolution:

     Higher resolution of the time step used can affect the simulation results. While it can lead to recording and accounting for more detailed variations, more computational power is required.

   - Shading Models:

     The effect of shadows due to complicated shading surrounds on Solar PV output, requires more elaborate modelling for accurate representation.

4. Quantifying and Mitigating Errors
   - Sensitivity Analysis:

     System performance can be assisted by conducting sensitivity analysis. By identifying and varying the input parameters that most likely to have the biggest impact on the simulation results while keeping the rest unchanged, this helps identify which input parameters have the most significant impact on the simulation output.

   - Validation Against Measured Data:

     Simulation output comparison with actual results from installed systems is vitally important for validation. Inaccuracies can be identified and mitigated by calibrating the simulation models to reduce errors.

   - The longer the record of actual performance data the better as this helps in understanding the seasonal variations, other external factors that may affect accuracy as well as the impact of system components natural deterioration.
5. Improving Input Data Quality:
   - Errors can be reduced by using quality, high resolution irradiance and meteorological validated data.
   - Input data reliability can be improved by accurately characterizing all PV module components.
6. Enhanced Modelling Techniques:

- The use of more advanced simulation models such as TRNSYS, which can accurately simulate not just the PV module and system components, but also other physical parameters like thermal characteristics and surround shading elements results in more accurate output.

Table 32 is a summary of PVGIS and TRNSYS annual simulation results for case study 1 to 12. In Case 1 no adjustment has been made to account for the loss of production during blackouts (grid disconnection) due the absence of accurate record as well as the unpredictable time of the day when electricity gets disconnected. However. The comparison with TRNSYS is quite favourable. TRNSYS predicted a higher production, which if the production loses during blackout are accounted for, the margin of error, or rather variant would be even less than 2.8%, which is already well within the acceptable margin of error. PVGIS showed lower production with a variant of -7%, this was expected because the input data into PVGIS about the Solar PV system components are not specific to the actual brand used i.e. the logarithm are based on general manufacturing parameters.

Case 1is the actual Solar PV production as recorded by the PV system monitor, accounted for by the electricity smart net-meter, which the Electricity Board (ISECO) use to calculate the monthly bills.

Table 32 Annual Simulation Output Comparison Between Case 1 (Actual) Cases 2 to 12 (Simulated)

Simulation Cases 1 to 12	**Actual**	**PVGIS**		**TRNSYS**	
	KWH	**KWH**	**Variant**	**KWH**	**Variant**
8T-38A Cases 1 vs 2	16,858	15,673	-7.0 %	17,330	2.8 %
0T-38A Cases 1 vs 3		16,675	-1.1 %	17,487	3.7 %
15T-38A Cases 1 vs 4		17,871	6.0 %	17,591	4.3 %
33T-38A Cases 1 vs 5		18,188	7.8 %	17,344	2.9 %
0T3A Cases 1 vs 6		16,675	-1.1 %	17,488	3.7 %
15T3A Cases 1 vs 7		18,269	8.3 %	20,100	19.2 %
33T3A Cases 1 vs 8		18,975	12.6 %	20,710	22.8 %
0T & Tracking on A Cases 1 vs 9		16,644	-1.3 %	18,389	9.1 %
15T & Tracking on A Cases 1 vs 10		20,263	20.2 %	21,821	29.4 %
33T & Tracking on A Cases 1 vs 11		22,867	35.6 %	24,276	44.0 %
2 Axis Tracking Cases 1 vs 12		24,538	45.6 %	25,615	51.9 %

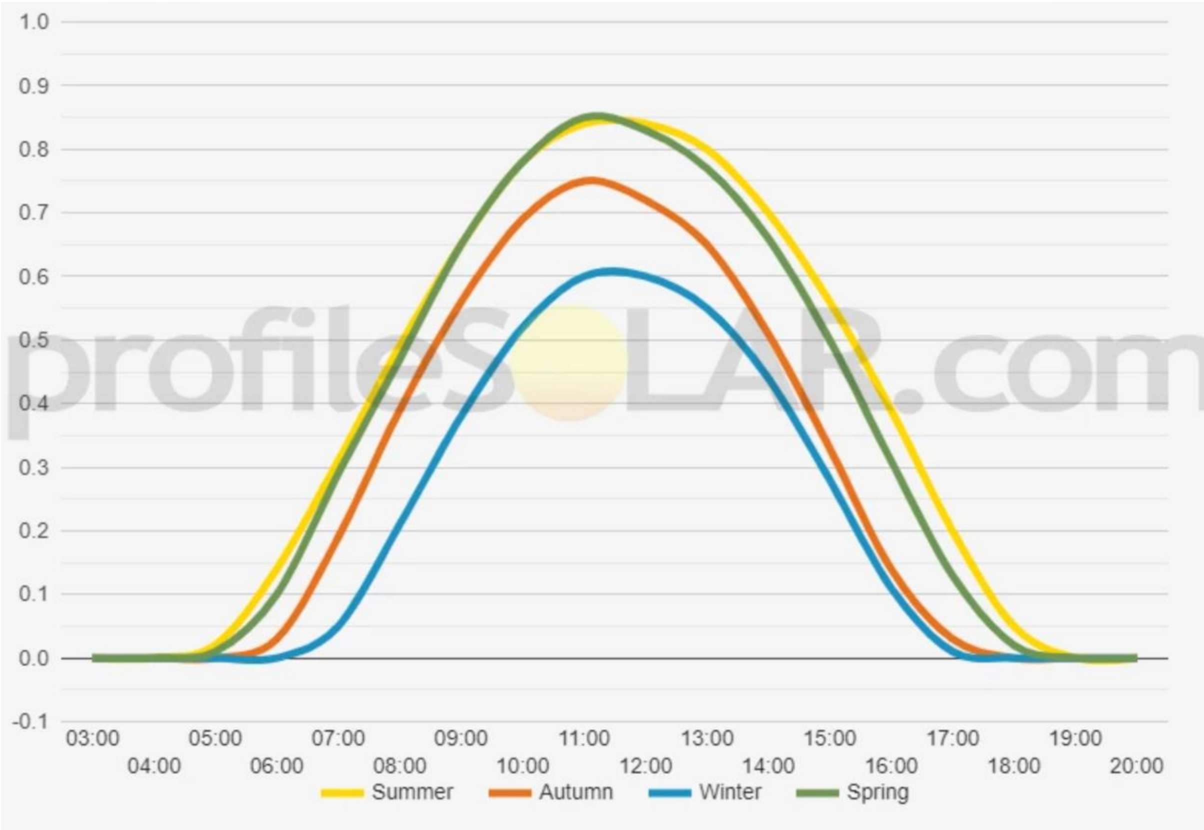


Figure 48: Hourly average electricity output per KW of Solar PV in Islamabad, Pakistan (by season) [104]

Figure 48 shows the average hourly output per KW of installed Solar PV in the Islamabad Region, during summer, autumn, winter and spring.

Here is a summary of the simulation results and how they compare with the actual obtained from the installed PV Solar system. PVGIS predicted the optimum tilt to be 33 and Azimuth +3 for the site. The optimum tilt is almost the same as the average of the optimum seasonal tilts for Islamabad, Aron Robinson [104].

The average daily KWH per KW_p for Case 1:

- Actual (as Installed) 3.8
- TRNSYS 3.9
- PVGIS 3.5

TRNSYS predicted a is closer Figure to the actual produced. This could be even closer if power blackout hours have been factored as actual and not estimated. The Solar PV is grid connected with no battery storage i.e. no production when the grid power is off because the inverter is not energized. PVGIS is as not accurate as TRNSYS because it relies on the geometry and general data product about the PV panels, but not specific data pertaining to the manufacturing data of the PV System components used. However, TRNSYS requires a typical TMY weather data file which was obtained from White Box USA and actual inverter and panel manufacturer's data.

KWH per KWp at Optimum Tilt & Azimuth Case 8:

- TRNSYS 4.7
- PVGIS 4.3

The exact Solar PV site location coordinates from Google Earth were inputted in both TRNSYS and PVGIS .

10. Conclusion

10.1 Summary of Methodology (Research Findings)

A comparison was made between the actual output of the installed 12.18 KW_p photovoltaic grid connected system and 12 simulated cases of different tilt and azimuth angles using TRNSYS and PVGIS. The Tilt and azimuth angles for each case is shown in table 33 below, including tracking on one and two axes.

Table 33: Annual % Output Comparison Between Case1 (Actual) and Cases 2 To 12 (Sumulated)

Case	Tilt	Azimuth	System Output Variant		Remark
			TRNSYS	PVGIS	
1	8°	142°N(-38°S)	-	-	Actual (as installed)
2	8°	142°N(-38°S)	2.8 %	-7.0 %	Simulation
3	0°	142°N(-38°S)	3.7 %	-1.1 %	Simulation
4	15°	142°N(-38°S)	4.3 %	6.0 %	Simulation
5	33°	142°N(-38°S)	2.9 %	7.8 %	Simulation
6	0°	183°N(+3° S)	3.7 %	-1.1 %	Simulation
7	15°	183°N(+3°S)	19.2 %	8.3 %	Simulation
8	33°	183°N(+3°S)	22.8 %	12.6 %	Simulation
9	0°	Tracking	9.1 %	-1.3 %	Simulation
10	15°	Tracking	29.4 %	20.2 %	Simulation
11	33°	Tracking	44.0 %	35.6 %	Simulation
12	Tracking	Tracking	51.9 %	45.6 %	Simulation

The photovoltaic system efficiency (production over total solar falling energy on the surface of the PV panel) as predicted by TRNSYS, ranged from 14.7%, in case 1 (as installed) to 16.7 % in case 12 (tracking on 2 axes). PVGIS predicted almost identical results, 14.7% in case 1 to 16.0 % in case 12. Using the installed solar photovoltaic panels actual production as the base numbers, TRNSYS and PVGIS production results were compared and the percentage difference, whether plus or minus, were deduced. TRNSYS predicted a higher output than PVGIS in cases 2 and 3, lower in cases 4 and 5, and higher in cases 6 to 12. In general, both simulation tools results predicted improvement in the production as the Tilt and Azimuth Angles approach the optimum position of 33° Tilt and 183°N(+3°S) Azimuth calculated by PVGIS and cross checked by Aron Robinson [104], which is a dedicated Solar PV error analysis web site which has calibrated NASA data, based on the demonstrated output of existing solar arrays of megawatts of capacities. TRNSYS simulation resulted are more accurate than PVGIS because of the elaborate input parameters needed when setting up the simulation model, which are manufacturer specific. In the case of PVGIS, the same parameters are based on general Solar PV panels design data. In addition, the actual data collected from the installed system is slightly lower due to the power interruption, during which the Solar PV production drops to zero because the inverter is not powered. Even though a modest allowance has added to the actual production, it is extremely difficult to accurately predict the exact losses as power interruption is sporadic and can happened during daytime as well night-time. In the case of zero tilt angle without tracking (Cases 3 and 6) both TRNSYS and PVGIS results were identical, + 3.7% in the case of TRNSYS and -1.1% in the case of PVGIS. This has given more assurance in the simulation results of both tools since the production is not expected to vary in the case of horizontally laid Solar PV panels. Significant improvement in the output in the case of tracking on one and two axes, TRNSYS predicted plus 44% and 51.9%, while PVGIS predicted 35.6% and 45.6%, respectively. This has proved that tracking on one axis would lead to lead to significant improvement in the output at an additional economical cost. The meagre improvement in tracking on two axes is not financially viable, as well as cumbersome.

While solar photovoltaic (PV) grid-connected systems have numerous advantages, they also come with some disadvantages:

1. Initial Cost: Setting up a Solar PV grid-connected system can require a significant upfront investment for the solar panels, inverters, mounting structures, and installation.

2. Intermittent Power Generation: Solar energy generation depends on sunlight availability, which can vary throughout the day and across seasons. Cloudy weather or night-time will reduce power output.

3. Grid Dependency: Grid-connected systems rely on the availability of the electrical grid. If there is a grid outage, the solar panels will not work unless there is a battery backup or other energy storage solutions.

4. Space Requirements: Solar panels require adequate space, which may not be feasible for everyone, especially those with limited roof space or living in densely populated areas.

5. Environmental Impact: The production and disposal of solar panels can have some environmental impact due to the use of certain materials and manufacturing processes.

6. Energy Storage Costs: To ensure continuous power supply during periods of low sunlight or at night, energy storage solutions like batteries are needed, which can add to the overall cost.

7. Efficiency and Performance: The efficiency of solar panels can decrease over time, which means their power generation capability may decrease gradually.

8. The Solar PV output from September to March drops by 60-70% of the average daily output during March to September. The research Solar PV system results, which its installed capacity is 12.18 KW_{p} , showed 65 KWH compared to 40 KWH, despite the cooler ambient conditions with help improve the performance of the Solar PV. This is attributed to the low position of the sun in the sky with lower arc in through the sky on the winter solstice on December 21st.

Despite these disadvantages, it’s important to note that Solar PV grid-connected systems still offer numerous environmental and economic benefits, such as reduced greenhouse gas emissions, potential cost savings on electricity bills and a step closer towards independent off grid power supply with the advancement in storage battery technology, particularly Li (Lithium ion) which are gaining traction in the residential solar photovoltaic market. All contributing to a more sustainable energy future.

10.2 Summary of Novel Contributions and Future Work

The research work shed the light on the energy in the residential sector that led to a few novel contributions in a region where the energy per capita is among the highest worldwide and lack behind in the implementation of pragmatic energy conservation strategies. The research rig, which is among the most energy saving dwelling in the whole of Pakistan due to the very strict self-imposed energy conservation measures applied by the builder, such as substantial thermal insulation in walls and roof, double glazing throughout and the provision of controlled natural ventilation, particularly during night time in summer (10 pm to 6 pm), enabled studying the impact of Solar PV net metering grid connected system on the energy cost, how to further improve the output yield, as well as integrate the this technology with others with ease for further reductions in energy consumption to move closer to zero net energy.

The emerging rooftop solar photovoltaic net metering market in Pakistan, where the research house is located in the capital city Islamabad, is estimated to generate an excess of 1,000 MW. This is pausing a challenge to the Government caused from having to buy back this excess energy from the net metering customers, which is the equivalent of £0.05 per exported unit (KWH) and having to pay a capacity charge to the IPP (Independent Power Producer) at the rate of £0.08, in a noticeable falling nationwide consumption, some put the estimate at approximately 14% this year compared to the same period last year. The drop-in consumption is attributed to the continuous upward adjustment in the electricity price, partly due to the increase in oil and gas prices, and partly due to the drop in the local currency value. At the same time, the relative drop in the cost of Solar PV, improvement in the power output of panels - 560 W_p per panel, compared for example with 435 W_p per panel, as installed in the research Solar PV this system in March 2021.

In pursuit of energy neutrality, upcoming plan is to take advantage of the flexible design of this the research dwelling which serves as a platform, simulating and validating energy-saving measures, to advance pragmatic, not ideologist, solutions to improve the energy-efficiency of existing residential buildings, and offer guidelines for designing new ones:

1. The conversion of the current grid connected Solar PV to independent off grid system.

2. Increase the Solar PV installed capacity.

3. To study the phenomena of Solar PV Duck syndrome and how to mitigate. This is when conventional power output and Solar PV power output peak, normally during peak hours, and consumption dips.

4. Solar thermal heating to reduce the electrical boiler left.

5. Solar air heating during winter to reduce dependence on gas operated hot water radiator system.

6. The mechanical induction of night-time ambient air to further enhance night-time ventilation air cooling during summer.

7. Further improvement to night-time ventilation by deploying an IEC (Indirect Evaporative Cooling) unit.

The study has revealed that extensive research work has been conducted in attempts to quantify achievable energy savings that will help in reducing dependence on gas and electricity in tropical and subtropical regions where indoor climate control, particularly during the warm seasons, is an expensive necessity. Also, the means of improving the performance of these strategies in a cost-effective way, when deployed either individually or in a hybrid configuration of more than one strategy, have been identified for existing houses as well as houses under design. It is revealed that there is a need for a real case study coupled with extensive filed data gathering over at least 12 months to cover all seasons of a contemporary passively designed houses in locations where meteorological conditions would permit the utilization of free ambient energy to help generate comfort (or near comfort) conditions, thus further improving the thermal performance of residential houses. Also, it is quite evident from the literature review that there is limited research work on an integrated approach of studying the deployment of the selected strategies with the objective to maximizing the benefit of free ambient energy throughout the year. In addition, there is an essential need for the use of an energy efficient HHVAC (Hybrid Heating, Ventilation and Air Conditioning) system, flexible enough to permit integration of the passive measures such as insulation, orientation, choice of finishing material, architectural shading elements and surrounding landscape, as well as being able to optimise the operation of these strategies either individually or collectively for an extended validation period. The HHVAC system design should take into consideration the predominant characteristics of the meteorological conditions for the region being studied. Also, how practical and cost effective it is to implement such strategies in existing houses should be considered and how the findings can enhance current design guidelines for new buildings. Not only comfort conditions should be the sole objective but also near comfort conditions, as well as full or partial relief to occupants during peak days in summer and cold winter nights. This will help in understanding better the complexities of how passively designed house thermal performance will improve by the implementation of the reviewed strategies.

Constantly rising energy prices and the desire to protect the environmental and help it to gradually recover by reducing pollutants emitted into the atmosphere, encourages the search for solutions to optimise building design, construction and electro-mechanical installations while maintaining users' comfort. It is well known that depending on the thermal insulation of the building envelope (and its value of heat transfer coefficient) the amount of energy supplied to the building will vary. In certain cases, internal heat-gain may be sufficient to cover much or all heating needs. However, including infiltration in the calculation indicates that heating of the fresh air supplied from outside is required and can significantly affects the total energy demand.

The research will in supporting the initiative to seek to bring about a gradual metamorphosis in a disadvantaged neighbourhood, home to approximately 3,000 residences. The goal is to cultivate a thriving green oasis, enriched with a diverse array of indigenous climbing plants. This ambitious project unfolds in two distinct stages, each designed to catalyse positive change and foster sustainable living.

In Stage 1, the focus is on prioritizing actions that elevate the quality of life for residents, enhance the aesthetic appeal of the surroundings, and lay the groundwork for the neighbourhood's evolution into a self-sufficient, green-built environment. This phase aims to create a holistic transformation that goes beyond mere beautification, fostering a community that is both environmentally conscious and socially empowered.

Moving into Stage 2, the initiative takes a bold step towards sustainable energy practices. A key component involves the installation of 3 to 5 KW_p grid-connected net metering Solar PV systems on the roof of each housing unit. This strategic move not only will reduce electricity costs for the residents but also contributes to a significant decrease in dependence on fossil fuels.

The overarching goal of this endeavour is to establish a paradigmatic project that transcends boundaries, offering a blueprint for global emulation. By positively impacting the lives of approximately one in four people worldwide, this initiative aspires to be a catalyst for widespread betterment. Through a combination of environmental sustainability, community empowerment, and educational enrichment, this project strives to be a beacon of positive change on a global scale.

11. Appendices

11.1 [1] The utilisation of useful ambient energy in residential dwellings to improve thermal comfort and reduce energy consumption

ABSTRACT

Energy consumption in the housing sector, is significantly high and continues to escalate. Urbanisation due to population growth and migration from rural areas to cities are two main reasons for this rising demand. With the uncertainty in the energy market and the increasing awareness of the impact of fossil fuels on the environment, research work in efficient building design has gained momentum. Energy conservation guidelines in many countries have become mandatory. However, more emphasis has been given to commercial, institutional, governmental and industrial buildings, which commonly employ more efficient HVAC systems than those deployed in houses. Thus, the push towards energy conservation in the residential sector is less noticeable. This is further compounded with the absence of will power to enforce the same energy conservation rules as the case with other sectors. In this paper five passive cooling and heating strategies have been reviewed (passive building design, night ventilation, nocturnal cooling, PCM (Phase Change Material) and IEC (Indirect Evaporative Cooling), solar thermal energy). The aim is to evaluate how to implement them better in a cost-effective way in existing and new houses. The literature review confirmed the need for further investigation of energy efficient HVAC systems with passives strategies solutions for contemporary residential dwellings is required to make a meaningful impact on the energy map of this sector. Also, the viability of an easy to deploy and configure HVAC system for retrofit and new applications for more benefits of these passive strategies either individually or in a hybrid configuration needs to be explored.

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Acronym

- BOE: Barrel of Oil Equivalent

- COP: Coefficient of Performance

- FCS: Free Cooling System

- GCC: Gulf Cooperation Council

- HVAC: Heating Ventilation and Air Conditioning

- IEC: Indirect Evaporative Cooling

- KWc: Kilowatt Cooling

- KWe: Kilowatt Electric

- MWc: Megawatt Cooling

- MWe: Megawatt Electric

- MWH: Megawatt Hour

- PV: Photovoltaic

- PV/T: Photovoltaic/Thermal

- RH: Relative Humidity

1. Introduction

The ever-growing demand for electricity and gas for air conditioning (cooling and heating) in residential buildings, the uncertainty in the energy market over the last 30 years and the growing awareness of the impact fossils fuels have on the environment are the driving force behind the increasing research interest in finding ways to reduce residential buildings footprint. This drive is gaining traction in both developed and developing nations, including those who rely heavily on oil exports as the only or main source of revenue. Dermot Gately et al. reported that the domestic oil consumption in 2012 in KSA (Kingdom of Saudi Arabia) reached nearly 3 million barrels per day with an estimated annual growth rate of 5.7% [1,2]. The Figure is approximately 4 million barrels today as reported by CEICDATA [3]. This number is likely to double over the next 10 years if the current rate of increase in electricity demand continues, the estimated annual increase being 5 % to 7% [2], with approximately 40% of this oil used to generate electricity [4]. The estimated electricity consumption in the residential sector in Kuwait is 60% of the total national power generated, particularly during peak summer months because of air conditioning [5]. This is a repeated scenario in the GCC (Gulf Cooperation Council) where temperatures can reach 50 °C or above in

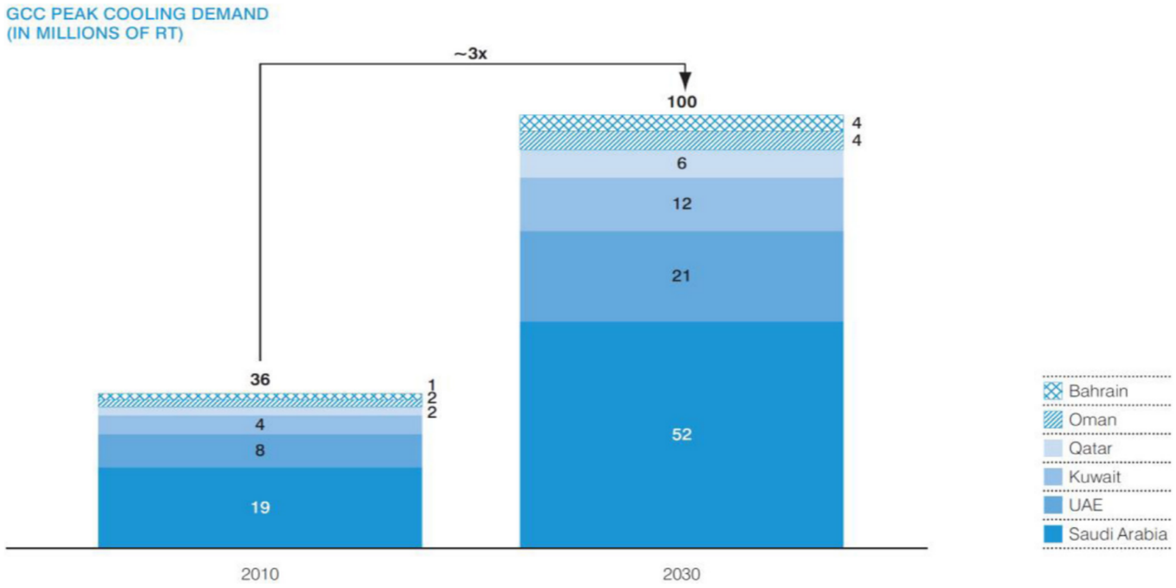

Fig. 1. GCC PEAK COOLING DEMAND in Millions of Refrigeration Ton [9].

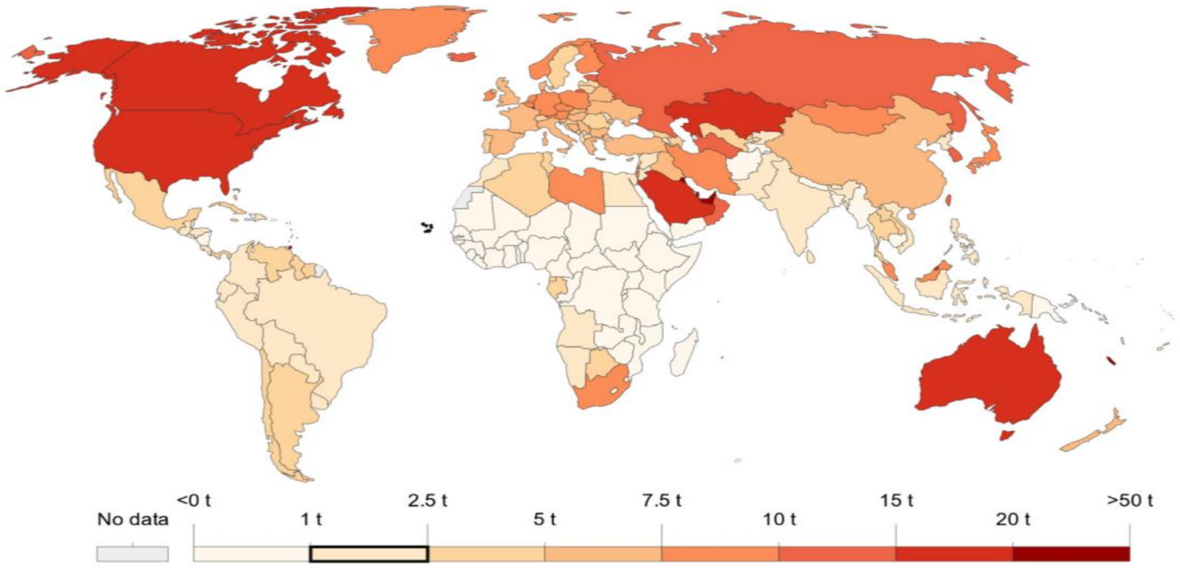

Fig. 2. Average carbon dioxide (CO_2) emissions per capita measured in tonnes per year. 2018 [12].

summer. In Kuwait on 16th July 2016 a record peak daytime temperature of 53.9 °C was recorded [6], while temperatures of 50 °C plus are a common occurrence in other cities such as Riyadh and Baghdad. While the cost of building power plants and transmission lines is in the region of £1.5 million per MWe [7], the cost of air conditioning is in the range of £50,000 to £100,000 per MWc [8] depending on the type of system i.e., central or unitary. Mechanical cooling (using refrigeration) is an expensive necessity in the GCC. Figure. 1 shows the demand for cooling in millions of RT (RT = Refrigeration Ton = 3.515 KWc) in 2010 and how it is expected to be in 2030 [9]. It is estimated that one MWH (Megawatt hour) of electricity requires 1.71 BOE (Barrel of Oil Equivalent) to burn [10] and each BOE results in the formation and emission of 390 kg of CO2 approximately [11]. The GCC along with many other countries where air conditioning is a necessity are among the highest contributors of GHG (Greenhouse Gases). Figure. 2 shows the CO2 emission per capita in 2011 [12]. Table 1 illustrates the average annual energy consumption, estimated Barrel of Oil Equivalent and CO2 emissions in a few countries [13]. Most of these countries are in the 53% global emissions red zone according to http://OurWorldinData.org/co2- emissions. Temperatures are less extreme in tropical regions, but humidity tends to be higher, and the warm season is longer or all year round. High humidity requires dehumidification, this is typically done either by subcooling the room air to saturation conditions as it.

Table 1
Annual average electricity consumption & CO_2 emission in some countries [13].

Country	Population	Average Electricity Consumption (MWh/Year/ Country)	Average BOE/Year	CO2 Emission Ton/Year
Egypt	94,666,993	142,947,159	228,715,454	68,614,636
Pakistan	211,995,540	85,858,194	137,373,110	41,211,933
Greece	10,773,253	52,993,632	84,789,811	25,436,943
Jordan	8,185,384	15,994,240	25,590,784	7,677,235
Lebanon	6,237,738	15,999,798	25,599,676	7,679,903

passes through the cooling coils in the air handling or fan coil units and then by re-heating back to the normal supply air temperature, or by desiccant dehumidification, which requires regeneration, to remove excessive moisture. Both solutions lead to more energy expenditure. In winter, space heating is essential in many countries. In Kuwait and the northern parts of Pakistan, for example, the yearly range (the difference between the highest and lowest temperatures) is 35-45 degrees Celsius [6], also, it is quite common to see temperatures tumble down to near zero at night and during the early hours of the morning. The Northern Region of Saudi Arabia and parts of Jordan, Syria and Lebanon have frequently experienced heavy snowfall during winter in recent years.

Passive cooling building design is gaining momentum through the necessity of improving the thermal performance of buildings and reducing their carbon footprint by increasing reliance on renewable energies. However, commercial buildings (6 floors and above), shopping malls, institutional and government buildings have received the lion share of these studies and the attention of public and private sectors, particularly those recently constructed. Existing commercial buildings have benefited from the vast experience gained and accumulated knowledge in sustainability as well as the viability of conducting and implementing the findings of energy audits. While commercial buildings, which are normally equipped with relatively more efficient HVAC systems and benefit from a wider diversity of cooling and heating loads (as high as 60% in the case of cooling) due to size and occupancy patterns, receive more attention, residential buildings (below 6 floors) and housing units (detached, semidetached villas and town houses) do not receive enough attention or practical incentives to improve their energy ratings as commonly seen in UK and Europe. In addition, most of these residential constructions are equipped with the least efficient cooling equipment such as window type air conditioners, mini-split, VRF (Variable Refrigerant Flow), package/split DX (Direct Expansion) and air-cooled chillers [14]. In contrast, commercial buildings are normally equipped with far more efficient cooling equipment such as water-cooled chillers or receive chilled water as a utility from town scale district cooling schemes. The problem is further compounded with the electricity consumption characteristic which tends to be more residential than commercial. In Kuwait, for example, up to 60% of the electricity consumption is in the residential sector [1518]. Similar electricity consumption characteristics can be found in the rest of the GCC and the MENA Region. In Saudi Arabia, the existing low-rise building stock is approximately 1.5 million units with a shortage of nearly 500 thousand; similar order of magnitude numbers can be found in other countries such as Pakistan and Egypt. Considerable research work has been carried out using a variety of passive energy saving strategies, either individually or in a hybrid configuration of more than one strategy. This research review paper looks at the state of the art of some of these strategies which have exhibited some degree of success with the intention of finding research gaps for further work. The aim is to evaluate how to implement them better in a cost-effective way in existing and new buildings.

Passive energy strategies considered:

- Passive building design.
- Night ventilation: the use of night-time ambient air when its temperature drops below a certain threshold by inducing it into buildings.
- Nocturnal cooling: night sky radiation exchange with building surfaces as well as cooling media such as water.
- PCM (Phase Change Material) and IEC (Indirect Evaporative Cooling): use of phase change material to increase the sensible cooling efficiency of evaporative coolers and use of water as a cooling medium whereby air is induced into the evaporative cooler through a controlled spray of water to lower its DBT (Dry Bulb Temperature) when ambient air conditions permit.
- Solar thermal energy.

2. Passive building design

The concept of a "house" evolved in the history of mankind through a process of trial and error motivated mainly by having to shelter from the climate adversity and for safety and security. From the humble beginnings of a temporary or permanent shelter (tree, cave, overhang, etc.) houses evolved to today’s complex mechanized buildings, not only protecting from the weather but also creating specific indoor conditions to meet specific needs all year round. Even the concept of indoor comfort itself changed with time from the basic need to keep dry, warm or cold to being accustomed to precise temperature, humidity and air quality conditions. People have become sensitive to the slightest variation in temperature and humidity, while the natural ability to climatize between the different weather patterns diminished, i.e., at the beginning of summer there is a tendency to feel warmer at lower temperatures while at the beginning of winter the tendency is to feel colder at higher temperatures. Also, social as well as clothing habits have added to the higher demand for better controlled indoor thermal conditions. All this led to the relentless rise in domestic energy demand compounded further with population increase and the need to house more people. The growing awareness of the energy efficiency features of the historical vernacular architecture led to many researchers look closely how they work and how they can adopt them to help improve the prospective energy requirements of contemporary architecture with the use of modern construction materials. Abdulkareem [19] correctly stated that "Dwellings are built to serve a variety of functions, but one of the most important is to create living conditions that are acceptable to their occupiers particularly in relation to the prevailing climates”. One of the outstanding examples of a successful historical traditional built form is the courtyard house. Many examples can be seen across the globe from China to the Indian Subcontinent, the Middle East, North Africa, southern Europe and Latin America. This was a successful example of how man learned to couple his complex needs for a shelter by building for and in harmony with the environment. As referred to by the same author in his paper [19], “The creation of shelter is our response to the environment and the context of our existence, which consists of a complex set of components." This form of house topography can be seen in its basic form as a simple house with a few rooms surrounding an open space (courtyard) as well as in much more complex and sophisticated forms of palaces, forts, temples, churches and mosques. While the best way to save energy is not to use it at all, which obviously is an impractical proposition, the courtyard house tends to score high on the scale of free ambient energy utilisation. It has many built-in passive energy measures, one of which is its fundamental principle of the open space right in the core of the house (the courtyard) and its ability to efficiently exchange energy with the night sky in what is known as nocturnal radiation exchange. The night sky absorbs the radiant energy emitted from the house walls, roof and courtyard surfaces, which was received the previous day. This results in these construction surfaces cooling down, the air in the courtyard also, and in addition some of the cooler denser air from the roof of the house sinks and collects in the courtyard. The cold air seeps into the living accommodation surrounding the courtyard during the early hours of the morning keeping it relatively cooler than outside the house a little longer during the day before the cycle repeats itself. Figure. 3 shows the actual temperature measurements taken in a courtyard house in Baghdad in the early 1970‘s. Other fundamental principles of the courtyard house are the minimal fenestrations on external walls, which reduce solar gains as well as the infiltration of warm ambient air, the high thermal mass of

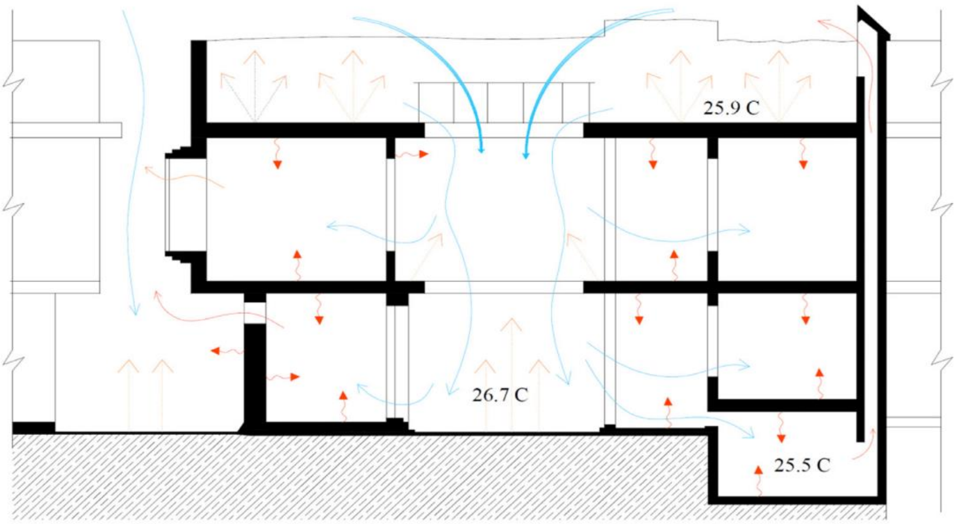

Fig. 3. Thermal performance of a courtyard house during the night in Baghdad [19].
Note: the measurements are effective temperatures that were recorded in a Baghdadi courtyard house in August 1972.

external walls, which increases the lag time between the maximum external and internal dry bulb temperatures, controlled ventilation openings at roof level (known as Badgeer), which allow the cooler night air to be transported directly into the living accommodation through masonry channels in the thick walls. Further enhancement to the indoor thermal comfort of the house was achieved by installing a fountain or ornamental water pools in the courtyard as well as vegetation. Obviously, the social movements shown in Figure. 4 and dress habits helped, for example, the Clo factor (clothes thermal insulation) of the traditional Arab garment known as dishdahasha or Jalabiya is less than half as much as for a typical light suit or shirt and trousers. Also, what helped was the tendency of occupants to accept indoor thermal conditions which may be perceived in our time as outside the typical comfort range of 16°C to 28°C [20]. Other examples of passive design elements of traditional vernacular architecture, which help reduce heat gains and/or losses:

Construction materials: natural stone, mud bricks and wood. These basic natural materials, characterised by high thermal resistance, which delays heat transfer through the building envelope, were extensively used in the pre-cement era. Mashrabiya in the Middle East: allows day light to cascade through the living accommodation as well as natural ventilation air but prevents glare and excessive direct sunshine, see Figures. 5 and 6. Sometimes porous clay pots filled with water are placed by the Mashrabiya to promote additional cooling through evaporation of the water that oozes out through the porous skin of the pot, keeping the outside surface wet and at the same time cooling down the rest of the water inside the pot for consumption [21]. Wind catchers (Badgir): induce ambient air naturally into the living space. This is done through a masonry shaft constructed from high thermal mass materials. The shaft traverses the full height of the building and rises above the roof level by several metres. As the relatively cooler air is induced into the building the warmer is purged out. It used to be quite popular in warm climates, particularly the Middle East [22].

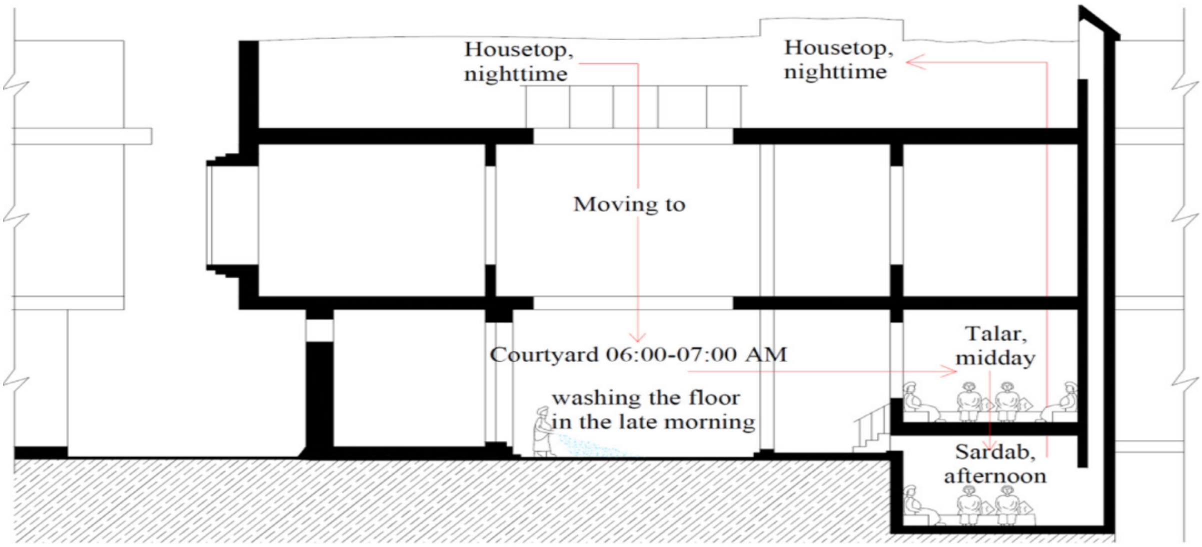

Fig. 4. Section of courtyard house, illustrating daily movement in the summer period [19].

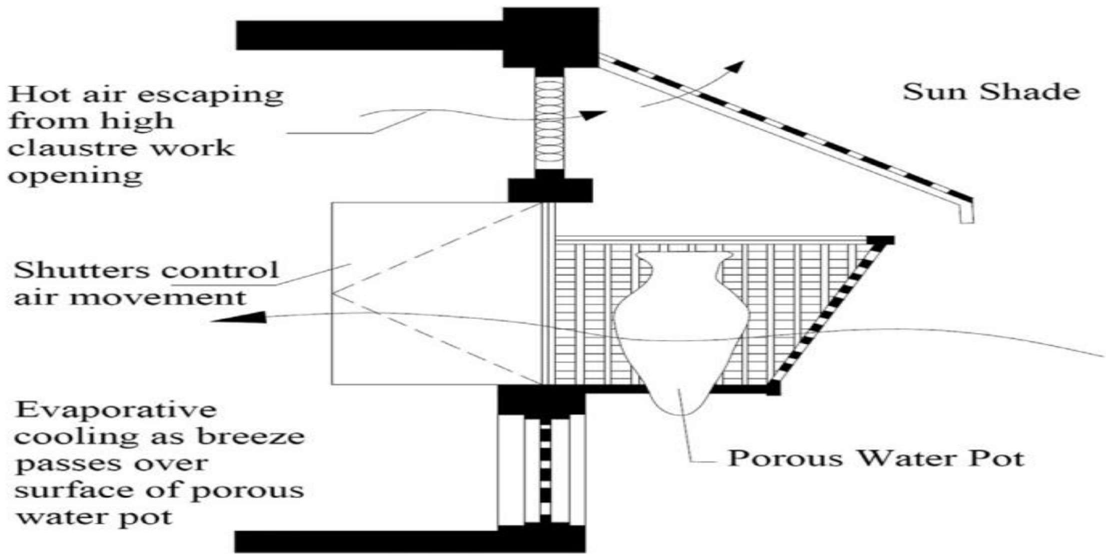

Fig. 5. Section illustrates integrating window with porous water Haval [19].

Zamani et al. [23] highlighted the sustainability aspects of the courtyard and how it can passively improve the thermal and microclimatic conditions, particularly in hot arid climates, and the need to accurately identify the influential factors which determine its thermal performance. The researchers looked at how the courtyard configuration and components in terms of geometry, construction material, proportion, orientation, shading elements, vegetation and water features can be utilized to improve the thermal performance of the courtyard in the context of solar gain, humidity and natural air movement. However, it is important to point out that, with the climate changes experienced in our time and the commonly unclear night skies due to pollution, the very fundamental principles by which the courtyard as well as exposed surfaces such as roofs cool down at night, through the exchange of longwave radiation with the night sky, has been inhibited (the night sky acts as a black body). The research highlights the importance of shading elements to reduce solar gains, a valid argument but only during daytime as the same elements will inhibit the ability of the courtyard to effectively exchange radiation with the night sky. Therefore, it is important to study the use of shading elements that can be deployed during the day and retracted during the night. The researchers highlighted the importance of natural ventilation and how it can be affected by the geometrical configuration of the courtyard, i.e., ratio of height to floor area and shape, and how it affects the thermal performance of the courtyard. While natural air movement may be desirable during mild/cool seasons, during the warmer season, it is best if it is encouraged at night, when the air temperature is lower, as the daytime air temperature in hot arid climates can be excessively high. Chen et al. [14], Song [15] and Gong et al. [16] highlight that typical passive design features, which would significantly impact building energy consumption, include layout, building fabric thermophysics and the extent to which buildings are airtight to minimise infiltration and/or exfiltration. In addition, building geometry plays a very important role in reducing envelope gains; for example, a circular building will have the least envelope area when compared with other building shapes with the same floor area, but circular buildings are not usually functionally practical. Also, the following are important: the ratio of window areas to wall areas, external wall and roof colours (lighter colours reduce thermal heat absorption), architectural shading elements, particularly on the south elevation in the northern hemi sphere, as well as vegetation approximately buildings. Chen et al. [14] conclude that considering as many passive design measures as possible early in the design stage will help in energy Optimisation. Dan et al. [25] stated that a passively designed house can generate improved indoor comfort with low energy consumption. A study was conducted on an energy efficient house in which passive energy measures were applied, such as extensive thermal insulation (polystyrene panel thermal insulation of thickness 300 mm in walls and 425 mm in the roof were used), advantageous orientation, heat recovery, and an air-tight envelope. The house was monitored for an extended period (2 years) and its design parameters and the results from monitoring were compared with those of a conventional house designed in accordance with the Romanian energy efficiency requirements. The measures applied to the passively designed house have resulted in a significant reduction in the energy consumption. It achieved a target of 15 KWH/m2 year cooling/heating demand and a total primary energy requirement of less than 120 KWH/m2 year. Zune et al. [26] highlighted in a study of vernacular architectural houses in Myanmar from a thermal performance perspective, that traditional passive design is not enough to achieve indoor thermal comfort due to the noticeable changes in the climate as a result of global warming. Further studies are needed to focus on exploring new ideas which will help mitigate the additional challenges brought about by climate change. Zaki et al. [27] simulated.

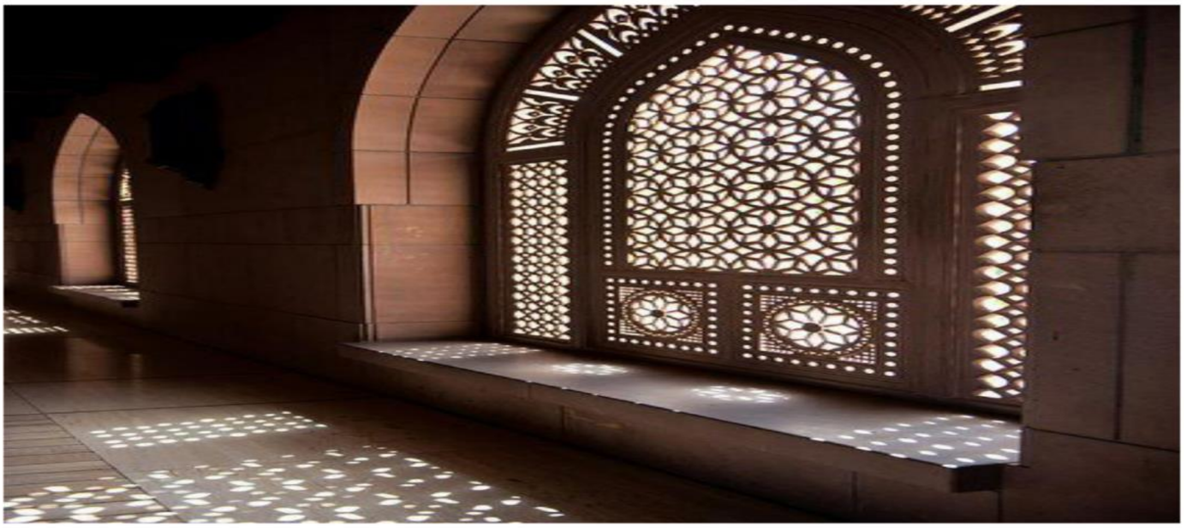

Fig. 6. Mashrabyia façade as seen from inside the living space.

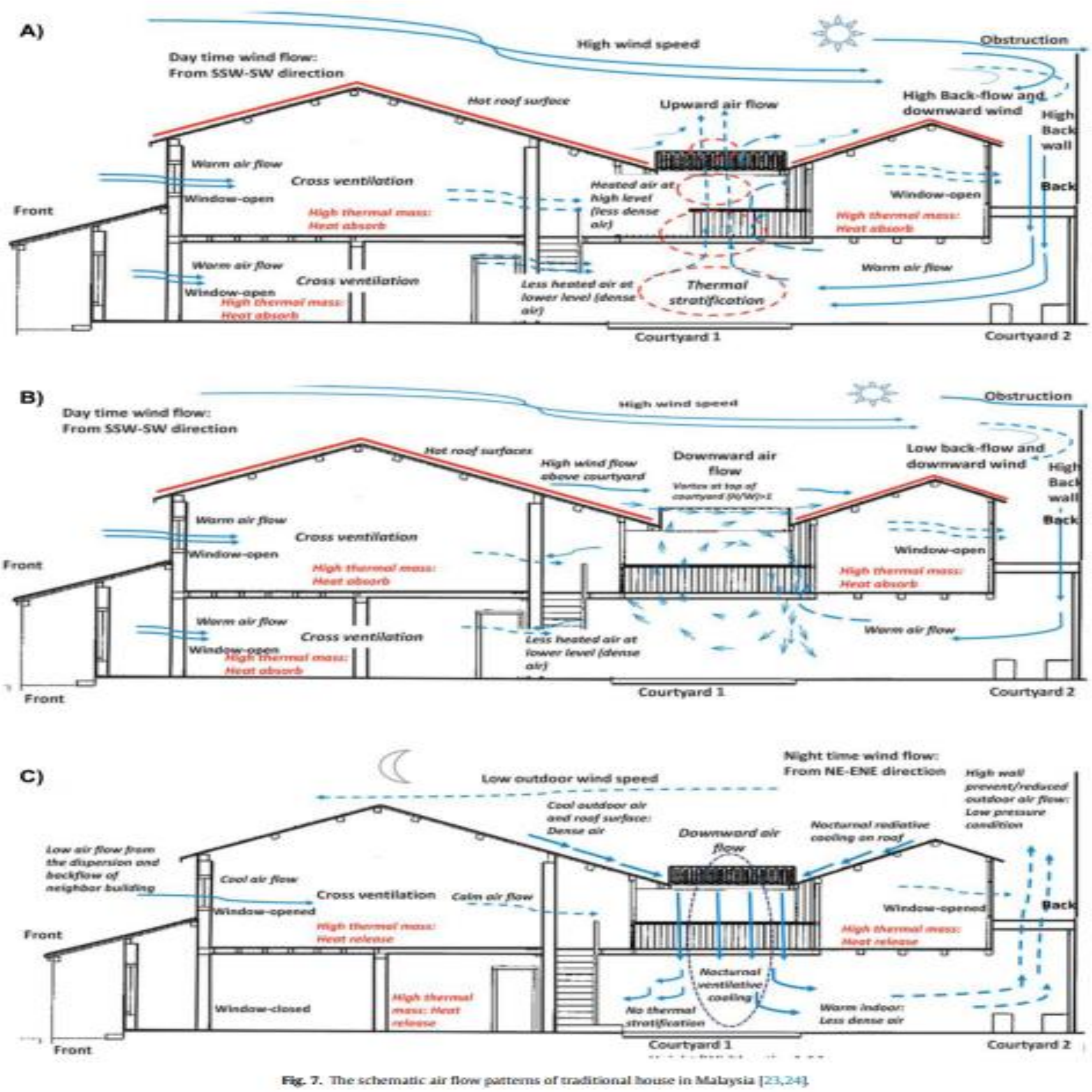

Fig. 7. The schematic air flow patterns of traditional house in Malaysia [23,24].

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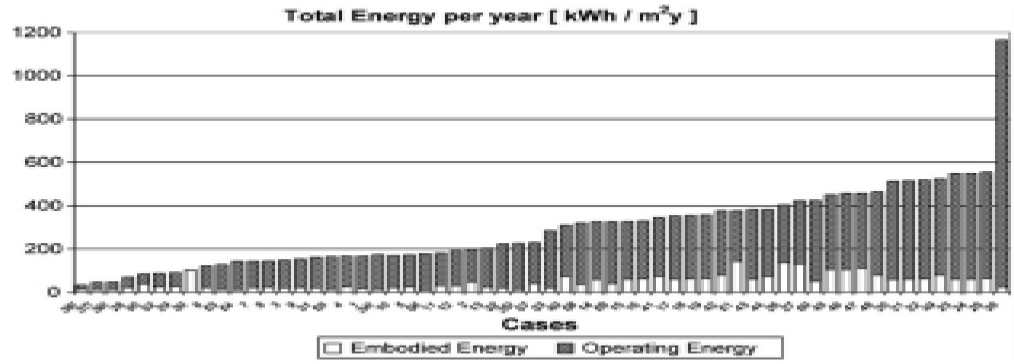

Fig. 8. Normalized total energy for the 60 cases [28]

two hypothetical terraced houses, a conventional traditional Malaysian terraced house and another in which passive architectural strategies were implemented. The aim was to explore ways of improving the thermal performance by adapting passive measures such as more appropriate orientation, thermal insulation, particularly in the roof, larger windows and adequate shading devices. The simulation work revealed that significant improvements in the indoor thermal comfort can be achieved. Sartori et al. [28] conducted a literature survey on the life cycle energy use of 60 buildings from 9 different countries. Two interesting findings emerged: a passively designed house outperformed an equivalent self-sufficient solar house in terms of energy efficiency and reduced the life cycle energy demand by a factor of 3 as well. The study also highlighted that operation represents the greater proportion of the total life-cycle energy consumption in conventional buildings, up to 90% to 95%, while the remainder represents the energy expended (embodied energy) in the manufacturing of construction materials, see Figure. 8. Wang et al. [29] in their simulation of a number of passive heating and cooling strategies, such as energy recovery ventilation (heating and cooling), pre-heating/cooling fresh air, pre-ventilation and night ventilation, in different weather conditions in passive buildings, found that it is quite possible to combine energy efficiency and acceptable indoor conditions. Roslan et al. [30] suggest that it is possible to maintain indoor thermal comfort all day long by minimizing the heat transfer through the building envelope, particularly the roof, as well as by removing internal hot air in hot humid regions. Taking into consideration the building orientation and local weather conditions, a reflective cool roof with an optimised pitch along with the ventilated roof can be introduced as design guidelines to help in improving the thermal performance of passively designed modern houses, Figure. 9.

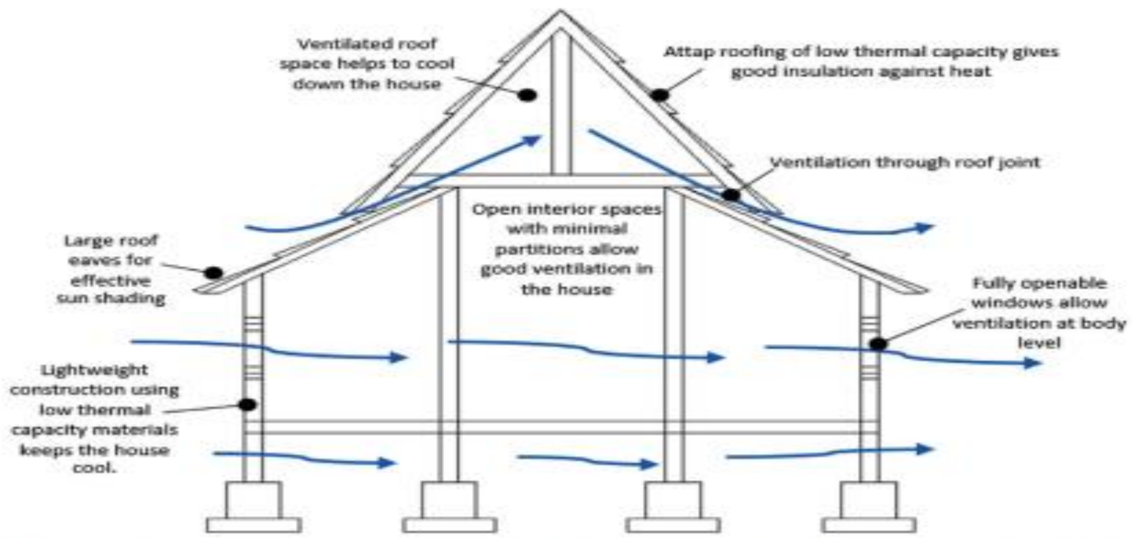

Fig. 9. Air movement for traditional Malay house. Source: The traditional Malay house, rediscovering Malaysia's indigenous shelter system [30].

3. Night ventilation (NV)

Night ventilation is the utilization of the nocturnal cooler air to drive down the temperatures of the building's internal air and surfaces (walls, floor, ceiling) to aid in cooling indoor spaces during the day in summer. Ebrahim Solgi et al. [31] defines night ventilation as ".... an effective passive cooling technique whereby the daytime heat gain of a building is released during the night through the intake of the cooler outdoor air." Air is induced into the building either naturally or mechanically through apertures in the building envelope, windows and/or dedicated ventilation openings. Depending on the thermal mass of the building, orientation, facade design, shading elements, ¸ particularly on the south elevation in the northern hemisphere and the adjacent external landscape, the effect of the nocturnal cooling will help increase the time lag between maximum external and indoor temperatures. According to the same source the longer the time lag, the lesser the number of hours needed to run the air conditioning, or to have to run the air conditioning at full load, particularly during peak summer hours, to maintain indoor comfort. Also, it is concluded that there is enough evidence to suggest that night ventilation strategies can be applied to most climate types but there is a need for Optimisation as well as integrating this passive energy solution with other passive strategies for more effective results, for example, indirect evaporative cooling and nocturnal radiation exchange. With climate change and the apparent evidence of globe warming [32], the fundamental parameters which govern the effectiveness of night ventilation, that is the diurnal range (maximum difference between the peak day time and minimum night-time temperatures) and the duration of the lower night-time temperatures, are not as common as before. Narrower diurnal ranges and shorter durations of lower night-time temperatures are more frequently experienced in regions expected to make full use of night-time ventilation. It is quite evident that night ventilation on its own as a passive strategy may not necessarily yield the expected results and further research work needs to be conducted to optimise the use of this very important passive energy strategy. As reported by Michael et al. [33] in a study on natural ventilation for cooling in a vernacular architectural building with high thermal mass in Cyprus, the maximum benefit can be achieved from cross ventilation at night. However, as the duration of the field measurement was limited to 27 days (7th July to 2nd August 2105), field measurements spanning a longer period, particularly during peak months, are recommended for more substantiated findings. This would allow more accurate measurements as well, by giving more time for the building to stabilise thermally between the various ventilation regimes adopted in the study i.e. (1) No Ventilation, (2) 24-hour ventilation, (3) Night-time Ventilation (21:00 to 07:00) and (4) Day Time Ventilation (07:00 to 21:00). According to Giovani [34], indoor thermal conditions can improve in an external temperature range of 28 °C to 32 °C with an indoor air movement of 1.5 m/s to 2 m/s. According to the same source, maximum benefits can be realised from night-time ventilation when the nocturnal air temperature is approximately 20 °C and the diurnal day fluctuation is more than 10 °C. More studies are needed particularly on contemporary passively designed buildings with common construction materials, which would make up for the desired high thermal mass found in vernacular buildings, e.g., composite external wall and roof structures with thermal insulation, high emissivity light colours to reflect solar heat and double glazing. Aste et al. [35] studied how well thermally insulated buildings will perform under the influence of the thermal inertia of external walls. The U value (Overall Heat Transfer Coefficient) should be in accordance with the international and local recognized energy conservation codes, e.g., in England - Wall 0.16 W/m2 K, Floor 0.11W/m2 K and Roof 0.11W/m2 K [36,37]. Kubpta et al. [38] and Jamaludin et al. [39] investigated different ventilation strategies and their impact on indoor conditions in residential buildings. Both concluded that night-time ventilation performed better than daytime or full day ventilation. Kololotrone et al. [40] concludes that night ventilation would be considered successful if the peak and average indoor temperatures are reduced the following day. Taleb [41] refers to the Wind Catchers in Dubai encouraging natural cross ventilation, particularly at night, a common vernacular architecture in many areas in the Gulf Region and Iran long before mechanical cooling had become readily available. Wind Catchers may have offered some thermal relief to occupants at a time when the perception about indoor comfort was totally different to that today. Careful consideration must be given particularly with the noticeable changes in the climate where higher day time temperatures and a narrower diurnal range are quite common. In addition, the increased dust storms, which demand effective filtration of external air prior to induction into the living spaces, would significantly inhibit natural ventilation. There is not enough evidence in the article to support the benefits of wind catchers. The researcher describes the UAE climate, particularly in Dubai, as predominantly arid with sufficiently low night-time air temperatures to make night-time ventilation effective with the help of Wind Catchers. Dubai is a coastal city at the northern part of the UAE with a seafront to the West/Northwest of the City. The prevailing wind direction in the Gulf Region is mostly North-Westerly coming from the Saudi Arabian/Iraq desert. During the warm season, the wind heats as it passes over the desert, increasing the capacity of the air to pick up moisture from the Gulf as it traverses the coastal cities on the eastern part of the Arabian Peninsula. This is one of the main reasons why most of the Western Gulf Coast Cities south of Kuwait i.e., Jubail, Dharan / Khobar, Doha, Manama, Abu Dhabi and Dubai, tend be hotter and more humid than arid. Dubai itself receives the lion's share of this humid air as it faces the Gulf from the North and Northwest as well as the Arabian Sea from East and Southeast, making it even more prone to humidity when the wind changes direction at the end of the warm season. The researcher suggests a 23.6% saving in energy if the passive strategies considered in the research paper are applied [42]. The basis on which this saving was calculated is not clear. Also, there is no evidence that the thermal performance of the experimental house was recorded before any of the various passive strategies discussed in the article were applied, including the Wind Catcher. Blondeau et al. [43] conclude that night ventilation has significant potential on its own to improve indoor thermal conditions and not necessarily the same potential can be realised by coupling night ventilation with other ventilation modes i.e., all day and daytime. They also highlighted that further research work needs to be carried out to understand how night ventilation would affect the whole building and not just the restricted experimental space within the building which was under investigation. While night ventilation as a passive strategy has great potential, it may on its own improve indoor thermal conditions only under certain meteorological conditions Givoni [44] concludes in his experiment to study the effect of ventilation on buildings with different thermal masses that night ventilation out-performed other modes of ventilation by lowering the indoor maximum temperature in high mass buildings in comparison with low mass buildings. Chyee et al. Toe et al. [45] demonstrate that high thermal mass houses with roof insulation and small internal courtyards would maximise the benefit of night ventilation in the Malaysian tropical climate, while Shaviv et al. [46] studied the influence of thermal mass when using night ventilation on the maximum indoor temperature in different locations in Israel. The results were turned into a design tool to help predict at the early stages of the design process the conditions most favourable for maximum benefit from night ventilation and thermal mass.

Landsman et al. [47] suggested that the most influential parameters that affect the thermal performance of night ventilation is the ventilation system set point; the higher the set point the higher the efficiency, as well as the number of hours of operation of the ventilation system; the longer the hours the more benefits can be achieved. Equally important is the outdoor night-time temperature, the lower the temperature, the greater the potential of night ventilation. The results of the study also showed that night ventilation in mild climates can maintain the indoor temperature within 80% of the acceptable comfort limit (indoor comfort range 17 C to 27 C and 50% + or 10% Relative Humidity). Chenari et al. [48] highlighted the importance of improving the efficiency of ventilation systems to reduce the impact of local and international guidelines pertaining to the requirements of outdoor air to maintain indoor air quality. They also highlighted the significant importance of hybrid mechanical and natural ventilation systems with control strategies to enable switching between the active and passive systems (that is, mechanical and natural), which will lead to accumulating savings in energy while maintaining indoor air quality. Omrani et al. [49] highlighted the importance of natural ventilation as a passive cooling strategy to reduce energy demand in regions where cooling is necessary. They proposed a process model that would help in evaluating as well as adopting the design of natural ventilation in multi-story buildings. Various evaluation methods were considered with the aim of developing a more cost-effective inexpensive method of evaluating the potential natural ventilation during the design stages of the building projects with more accurate methods to be used as the design develops further and during construction. TAS (an industry-leading building modelling and simulation tool) simulations were conducted during a number of thermal discomfort hours in a typical year. It was concluded that full day natural ventilation can improve the thermal comfort in the hot-humid climate of Singapore. This, coupled with a number of passive design measures, such as horizontal shading devices, increased window to wall ratios (0.24) and, surprisingly, no insultation in walls, can lead to better results (this requires further investigation). In addition, careful design of facades would help in gaining more benefits from natural ventilation [50]. Santamouris et al. [51], analysed the energy data from 214 airconditioned residential buildings using night ventilation to help reduce demand for energy. They reported that the potential contribution of night ventilation increased within buildings with higher cooling demands under specific boundary conditions and that an increased air flow rate is another potential contributing factor.

4. Nocturnal radiation exchange (NRE)

Nocturnal Radiation Exchange (NRE), also, known as Nocturnal Sky Radiation Cooling (NSRC), Passive Radiative Cooling (PRC) and Night Sky Cooling (NSC) is the cooling of building by rejecting heat to the night sky which acts as a heat sink. Flat surfaces such as building roofs absorb most of the solar radiation during the day. The surface temperature of sun-exposed surfaces in warm climatic regions can reach well above 70 °C and a record high black bulb temperature of 85°C has been reached. Provided the right meteorological conditions exist, i.e., a clear sky, a low moisture content in the air, the absence of dust or low dust levels, minimal pollution and a reasonable diurnal nocturnal temperature range, the night sky acts as a heat sink which absorbs longwave radiation from building surfaces, particularly those exposed to the sky, i.e., roofs of buildings, walls not obstructed by nearby buildings, hills, trees, etc. It is an old technique [52] which human beings gradually, through a process of trial and error that spanned centuries, learned how to adopt and make use of in their localities to reduce the impact of the adversity of the climate throughout the seasons. Being a passive strategy, it has gained a lot of interest by researchers over the last past 40 years and more so recently with the perceived changes in the climate due to pollution and the uncertainty of the energy market. The night sky plays the role of a heat sink exchanging radiation with hot surfaces on earth. This results in heat losses from building surfaces exposed to the night sky. The greater the exposure is, the higher the rate of heat rejection and the lower the surface temperature will drop. This phenomenon, if deployed on its own or in a hybrid HVAC system as a passive strategy, can help cool down buildings at night to near comfort range in some regions. The main challenge with nocturnal cooling is how to store the coolness at night for utilization as long as possible during the day and not just when the conditions are favourable for nocturnal radiation exchange at night. A hybrid NSRC system, which included a number of active components such as a heat pump and several pumps to move the cooling medium (water) across the various components of the system as shown in Figure. 11, was used in a research study by Amir et al. [53], in which it was concluded that a hybrid system employing more than one strategy (passive and active) will offer the maximum benefits and performance. Man et al. [54] used nocturnal cooling radiation in a novel nocturnal cooling radiator to aid the heat rejector of a conventional active cooling system, when meteorological conditions permitted, to improve its energy performance. The simulation results in a humid tropical climate proved that it is feasible to use nocturnal cooling to supplement as a heat sink the heat rejection capability of an active cooling system. Zhao et al. [55] experimented with a conventional PV panel modified to be operated as diurnal PV panel and a Nocturnal Panel. The PV-RC system schematic and the actual modified PV Panel can be seen in Figures. 12a and 12b. The PV panel face was covered by a transparent low-density polyethylene sheet while all other 4 sides and the bottom were well insulated with polystyrene thermal insulation to ensure no heat transfer or gain which might reduce the performance of the panel. The panel was installed on the roof a building and was only protected with the low-density polyethylene cover during the nocturnal cycle. He concluded that the PV panel thermal emission within the infrared wavelength band makes it a potential candidate for doubling up as nocturnal radiative cooling panel during the night hours. An average of 12.4% PV conversion and an average equilibrium temperature difference (Delta Tap) of 12.7°C for nocturnal RC process were achieved, which supported the idea of PV panel dual function (PV conversion during daytime and nocturnal cooling during night-time). He also demonstrated that the performance is significantly affected by water moisture in the air, which proved that low humidity regions allow for better performance. Also, a clear night sky is equally important to release the full potential of the nocturnal cooling strategy. With polluted skies due to burning of fossil fuels, nocturnal cooling on its own may not be the most rewarding solution. A hybrid system along with the deployment of other passive strategies would offer the best chance to achieve better results. Zhang et al. [56] demonstrated the potential of using a hybrid system combining Microencapsulated Phase Change Material (MPCM slurry storage) with nocturnal radiative cooling. Encouraging though limited results were produced showing a potential annual energy saving when this strategy is applied in low rise buildings. The savings ranged from 12% to 77% across five cities in China as can be seen in Figure. 10. Shuo et al recommended the use of this strategy in northern and central China where the metrological conditions are more favourable for nocturnal radiative cooling, being dry with low ambient temperatures at night. Bokor et al. [57] used a corrugated perforated metal plate as a radiant surface, as can be seen in Figure. 13, to study the potential of nocturnal cooling in four European Cities. He concluded that nocturnal cooling performs.

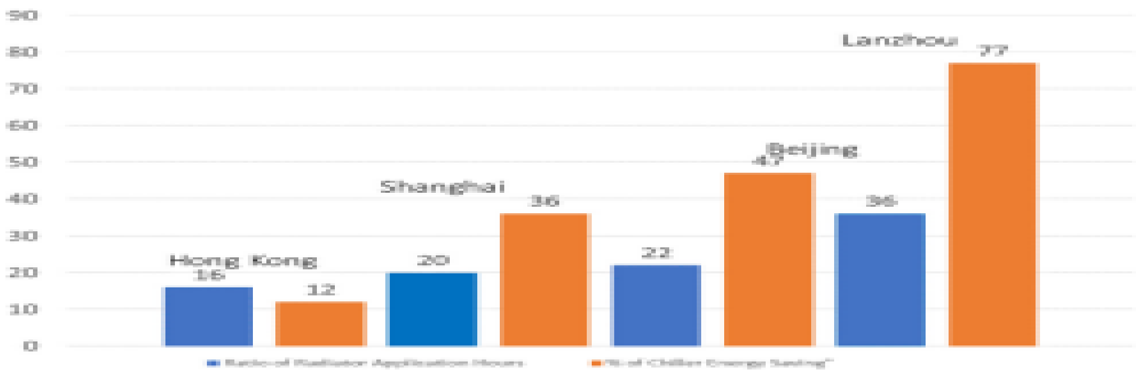

Fig. 10. % of chiller energy saving and the utilization ratio of nocturnal radiator [51].

better in locations with drier climates due to the absence of water moisture in the air, which impedes the radiation exchange with the night sky. In this paper the use of TSC (Transpired Solar Collector) is being suggested as means of doubling the benefit of a solar collector by using it for cooling the air through longwave radiation exchange with the night sky (i.e., Nocturnal Cooling) in the warmer months as well as a solar heater in winter. Encouraging results were produced but further research work needs to be carried out to test this approach and determine its feasibility as a strategy to aid active HVAC systems and in turn reduce their energy footprint. It may be worth investigating applying the same strategy with the use of purpose-built solar air heaters which permit the living space air to circulate through them (for winter heating), a technology evolved out of the Antarctic expeditions to heat tents in the harsh frozen conditions of the south pole. The same device can be used in reverse in summer to cool down the air at night and allow air circulation in the living space. Nwaji et al. [58] investigated a hybrid flat plate water heating solar collector that can double up as a nocturnal radiator to demonstrate the worth of investigating this passive strategy further. The finite element analysis of the dynamic performance of the solar collector in five Nigerian city temperatures produced impressive results. The difference between the maximum achieved during the diurnal period and that achieved during the nocturnal period was 73.55 °C, i.e., 93.67 °C in the case of diurnal heating and 20.12 °C in the case of nocturnal cooling. Further investigation is required. Wang et al. [59] developed a new numerical algorithm based on a solution of the energy balance equations in an attempt to characterize the complex thermodynamics of nocturnal cooling when applied to intensively urbanized cities. The complex urban development landscape surface and surrounding atmosphere with its multitude of interwoven parameters such as tall buildings, short buildings, masonry and glazed facades, flat and sloping roofs, asphalted streets, parks, etc., which lead to what is known as Urban Heat Islands (UHI), are but a few of the challenges met. Further work needs to be carried out to understand nocturnal cooling better and to attempt to quantify its benefits in the context of UHI. Lu et al. [60] reviewed the potential of different PRC (Passive Radiative Cooling) systems to assess their performance by simulations. It was concluded that the diurnal performance is limited when compared to nocturnal performance even under the most suitable meteorological conditions. It was also concluded that the commercialization of this passive strategy is heavily dependent on the discovery, reliability and availability of the coating materials, which themselves are subject to extensive research and development work. Hua et al. [61] looked at diurnal solar heating and nocturnal radiative cooling using a Solar Heating/Radiative Cooling Collector as illustrated in Figure. 14. A mathematical model to establish the performance of the collector in both modes was established. The thermal performance of the collector was investigated using parameters with different specifications and conditions, e.g., insulation thicknesses, wind velocities, ambient and inlet temperatures, water flow rates, precipitable water vapor amounts and solar irradiance. It was concluded that the multi functionality of the solar collector through its increased utilization was one of the main advantages when compared to traditional single mode solar thermal collectors. The heating and cooling gains varied across the four Chinese cities in which the collector was investigated. Parameters such thermal insulation, ambient temperature and wind speed impacted directly on the performance of the collector in both modes. Further research work is required to establish the practicality and cost effectiveness of such multifunction collectors under various meteorological conditions.

5. PCM and IEC

The application of thermal energy storage (TES) in a building significantly reduces energy consumption. It allows an improvement in the efficiency of systems by postponing the use of accumulated energy for use during the period of the highest demand [62]. One of the TES approaches are phase change materials (PCMs). These materials can be used in the construction of walls [63,64], ceilings [65], roofs [66], floors [67], as well as PCM-to-air heat exchangers for building envelope applications [68]. The incorporation of PCM allows a reduction in the temperature variation in the room, thus significantly improving the thermal comfort of users and increasing the building's thermal inertia [69]. As a result of phase change, depending on the properties of the PCM, a large amount of heat or

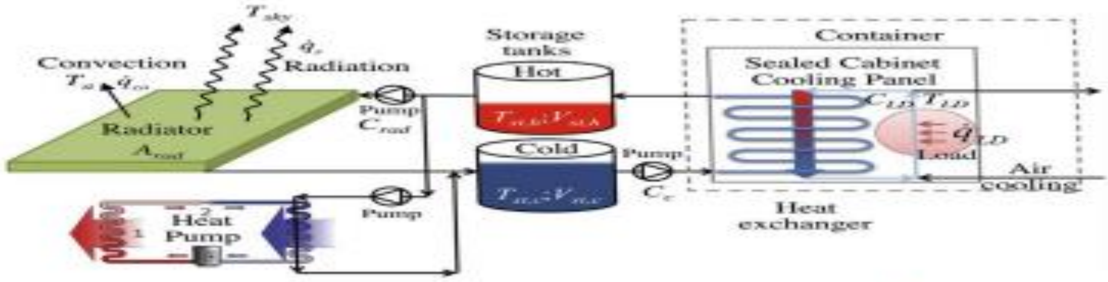

Fig. 11. Schematic layout of the hybrid nocturnal sky radiation cooling system [48].

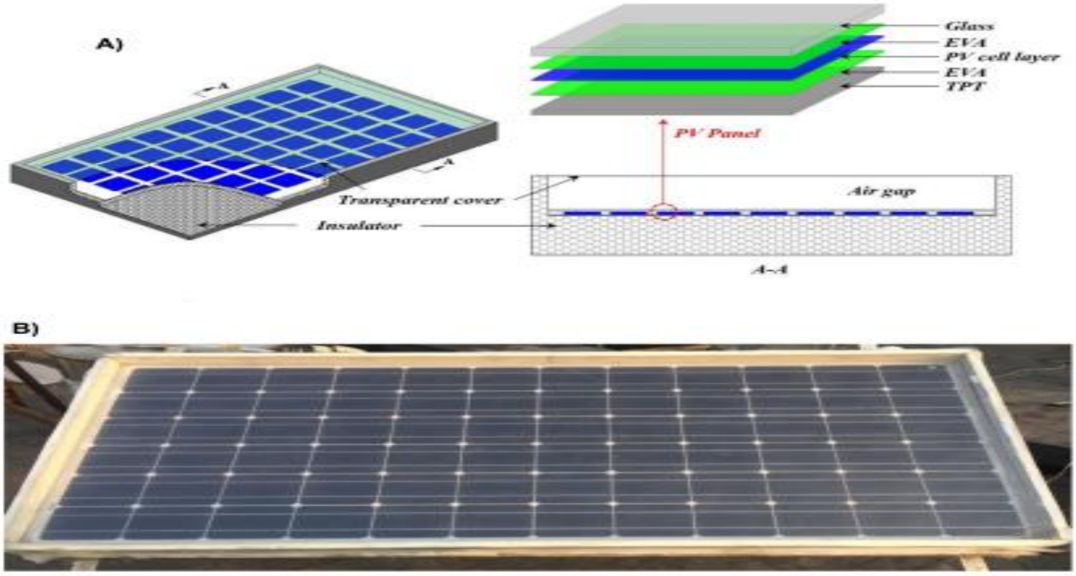

Fig. 12. A) Configuration of the PV-RC hybrid system – Schematic. B) Configuration of the PV-RC hybrid system. Actual panel [55].

cold can be stored as latent heat. Depending on whether additional air handling equipment is needed or not, passive or active cooling can be specified [70]. The PCM can be applied with natural ventilation as a free cooling system (FCS) to store the cold from the outside air during the night and release it during the day when the room temperature rises. At night the PCM is charged (solidification of PCM - when the outside air with a lower temperature than the inside air flows through the PCM storage) and during the day the PCM is discharged (melting of the PCM as a consequence of absorbing heat from the internal air and simultaneously lowering its temperature). The concept of free cooling is presented in Figure. 15. The three main parameters affecting the performance of PCM based free cooling are [70]:

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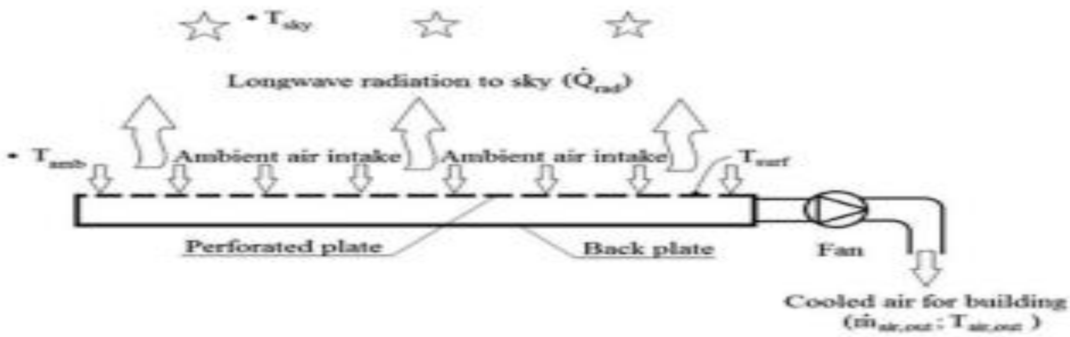

Fig. 13. Scheme of the Transpired Solar Collector setup for nocturnal radiation air cooling [52].

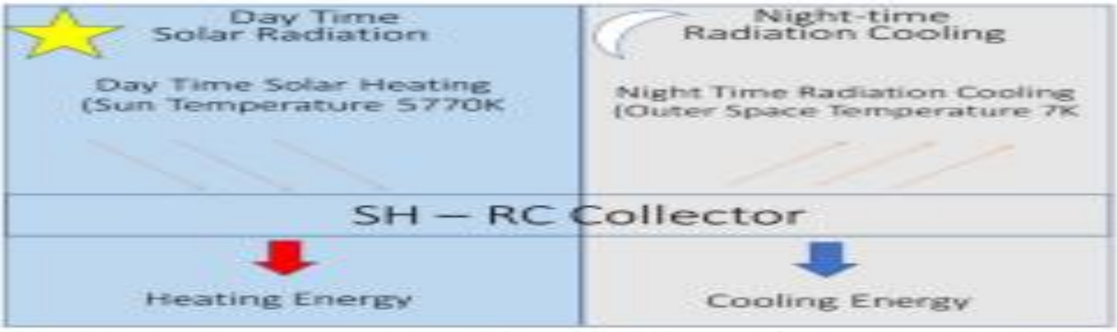

Fig. 14. Graphic representation of Diurnal Heating and Nocturnal Cooling [61].

local climatic condition, - thermophysical properties of the PCM and its phase change temperature range - inlet velocity and temperature of the heat transfer fluid as well as its thermo-physical properties. In a review article, Thambidurai et al. [71] have prepared a list of PCMs which could be used in free cooling, taking into account melting point, heat of fusion and density. The authors have compiled in tables eutectic, inorganic and organic PCMs and commercial PCMs applicable in free cooling. One of the main conclusions of the article was that free cooling works best in climate zones with low humidity and a large daily temperature range. In humid and warm climatic conditions additional air dehumidification is required, however, the authors do not indicate what additional design conditions for heat exchangers should be met. P. Rathore et al. [64] presented methods of applying macro-encapsulated PCM in building envelopes and in systems including free cooling. In one of the cases analysed, it was found that, in hot and dry climatic conditions, a lower flow rate through the air gaps under consideration within the PCM is required in order to maintain long-term thermal comfort, although a higher flow rate accelerates the PCM charging process. It was observed that the size of the air gap does not affect the thermal comfort. However, the range of thermal comfort parameters was not specified. Nada et al. [72], analysed the impact of outside temperatures and air flow rate on system performance and charging and discharging processes of SP-24E PCM with the melting temperature of 25 °C applied in a free cooling system in a laboratory experiment. The conclusions show that energy savings in the examined air conditioning system depend not only on the outside air temperature and fresh air flow rate but also on the amount of PCM plates needed. The same authors in [73] investigated the fresh air free cooling system for which the difference between the PCM (type SP24E) melting temperature and the air temperature is 24 °C (for three different air flow rates). They indicated that PCM solidification cannot be ensured overnight without additional requirements. At the same time, the results have proved that PCMs including SP24E are mixtures of compounds. Both articles have shown that in the airflow direction the temperature of PCMs plates goes down and the air flow rate needed at night decreases as the outside temperature drops. Panchabikesan et al. [70] proposed increasing the thermal performance of a free cooling system based on PCM by combining it with direct evaporative cooling (DEC) unit, Figure. 16. They conducted an experiment under Indian climatic conditions in real time in relation to PCM solidification, charging time, total and temporary heat transfer including different heat transfer fluid (HTF) inlet air velocities. It has been concluded that in the proposed system, the increase in HTF velocity has a negligible impact as opposed to a typical free cooling system. In addition, a significant reduction in charging time (28.7% and 34.8%) was observed regardless of the HTF velocities applied (2 and 1.5 m/s). In the continuation of the work, the authors propose to focus on the parametric analysis of the system, however, they omit the issue of other climate conditions. In article [74], the authors compared the FCS with the system coupled with the DEC unit under tropical Indian climate conditions throughout the year. They have estimated the monthly average cooling potential of the systems analysed and compared the results with those of the pilot-scale experiments in three cities with temperate, hot-dry and warm-humid climates. It was found that, regardless of local ambient conditions in hot and warm humid climates, the application of FCS with DEC reduces the duration of the complete PCM solidification process and doubles the possibility of using free cooling from May to August in a building. Furthermore, the authors do not recommend using PCM with a phase change temperature below 27 ° C in tropical climates. Figure. 17 presents the principle of FCS and FCS with DEC during the PCM charging process. It is worth noting that the authors state that in warm and humid climates there are small temperature fluctuations during the day, and then the temperature difference between the night-time outside air and the PCM is lower than 3 °C and the system will not work properly. Evaporative cooling requires much less electricity compared to a mechanical compression system [75] and has a very small impact on global warming [76]. The second method of evaporative cooling is indirect evaporative

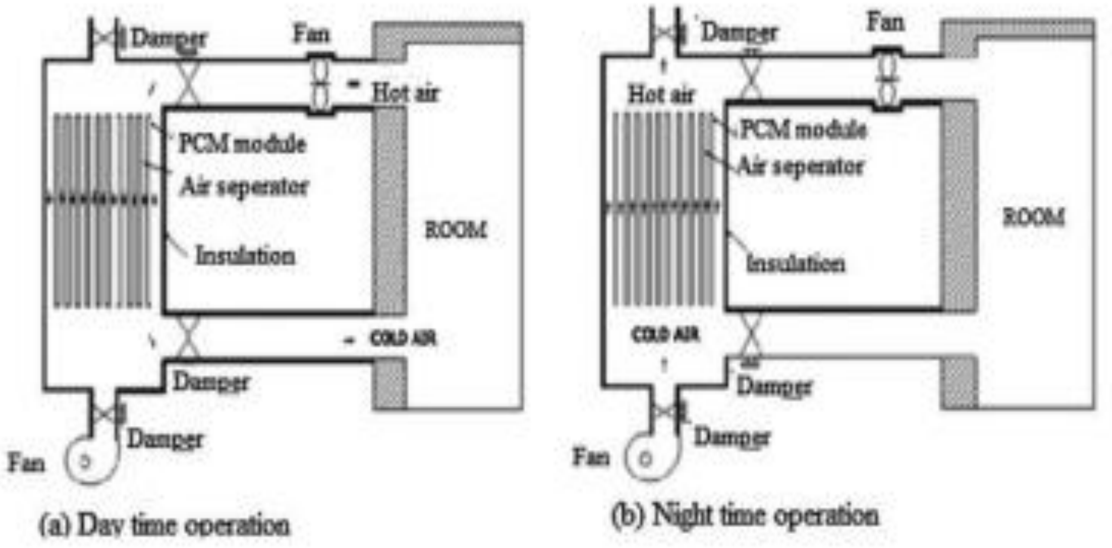

Fig. 15. The concept of free cooling [71].

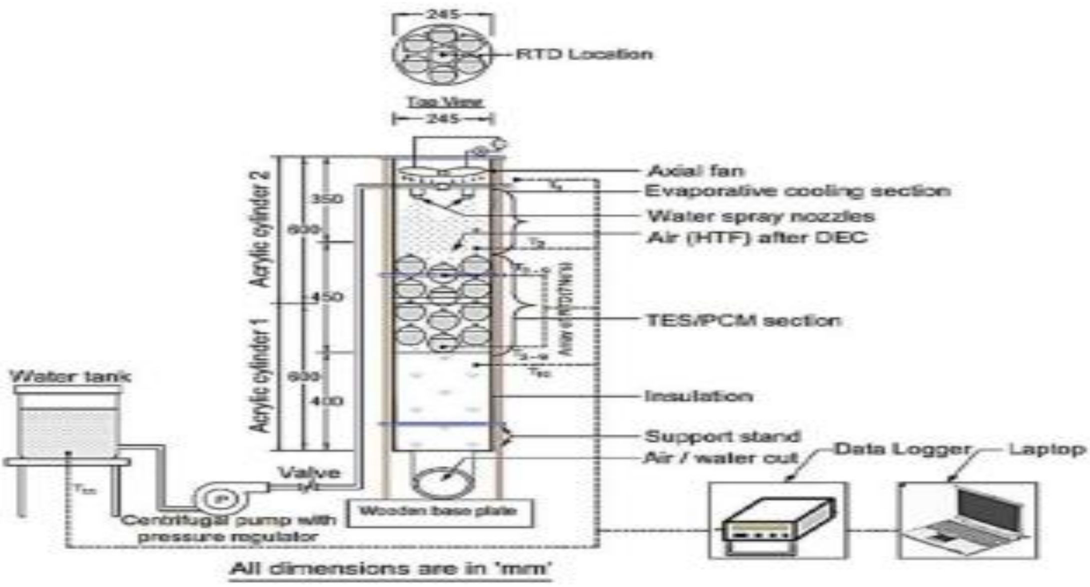

Fig. 16. Modified free cooling system integrated with DEC unit (reproduced from [70]).

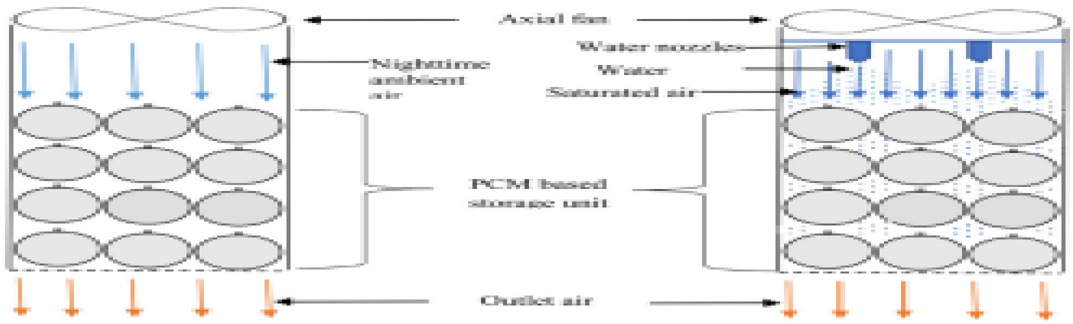

Fig. 17. PCM solidification – FCS (left) and FCS with DEC (right) operating principle [74].

cooling (IEC). In the case of direct cooling, the warm dry air was transformed into moist and cool air. The IEC consists of transferring heat and mass between two airflows, which are separated by a heat transfer surface. This process is based on heat absorption by evaporation of water to decrease the air temperature with no moisture added. Furthermore, it prevents contaminated water droplets from entering rooms, increasing health safety [77]. The difference between the two methods of cooling is shown in Figure. 18. Such an evaporative cooler consists of fans, heat and mass exchanger, a water distributor/a water basin and a water pump. In many publications, the authors focused on the analysis of the IEC system and on improving its performance. Xu et al. [77] analysed 6 samples of cloth fabrics and one sample of Kraft paper to examine their ability to wet areas, wick moisture, evaporation rates and diffusion rates. Huang et al. [75] analysed experimentally two types of heat exchanger (horizontal and vertical as shown in Figure. 19). Analyses have been carried out in five regions of China and it was found that in humid regions the use of a horizontal exchanger is not recommended due to an uneven distribution of the water layer in the exhaust air ducts. The specific energy saving parameter (d) defined in the article does not take into account the air supply parameters (air supply temperature, which may be too high) and assesses only the energy savings of the equipment. Thus, when IEC is used in the hot and wet area, it may necessitate additional processes for the supplied air. Zheng B. et al. [78] analysed a model for a crossflow IEC unit (Figure. 20) for a warm and humid climate to determine its performance. It was found that at a relative humidity of fresh air below 50% (especially at 30%-40%) condensation will not occur. Full condensation will appear when the relative humidity reaches over 80%. The total amount of heat transferred continues to increase due to the increase in the amount of latent heat transferred even though the amount of sensible heat is decreasing. It is possible to reduce primary air humidity in hot and humid climates by up to 36%. In their calculations, the authors do not specify to what range the values are different for each parameter under examination. Chen Q. et al. [79] considered the fact that, in hot climates, not only cooling but also fresh water is needed, and they proposed integrating the humidification-dehumidification desalination cycle (HDH) with indirect evaporative cooling according to Figure. 21. The results of the analysis showed that, under the same operating conditions, the connection to IDC increases the gain-output ratio (GOR) for HDH compared to

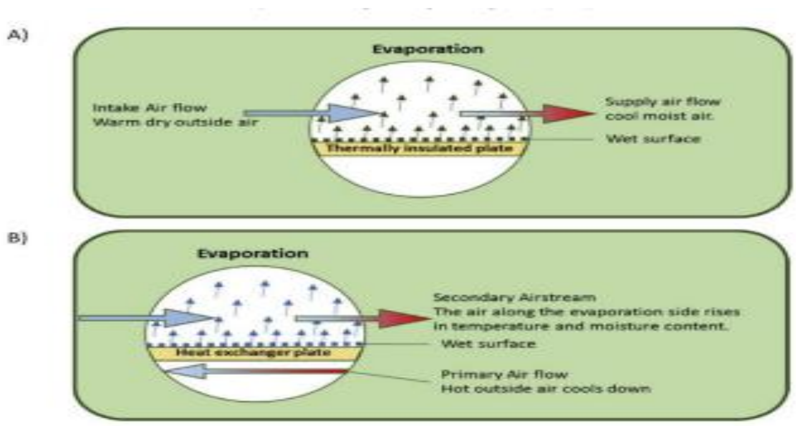

Fig. 18. Evaporative cooling: A) direct, B) indirect [77].

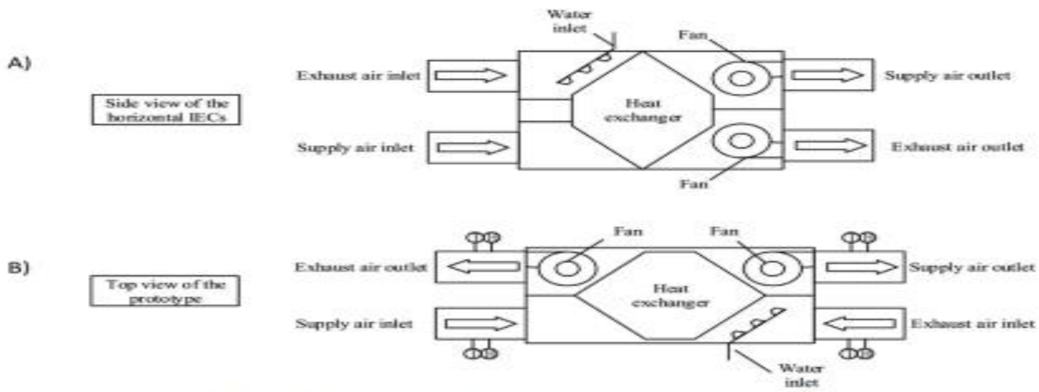

Fig. 19. Schematic of: A) side view of vertical IEC B) top view of horizontal IEC [75].

standalone HDH operation. Because of the marginal power consumption in the IEC cycle, the total COP of the coupled IEC-HDH cycle is close to the GOR of the HDH system. These results are based on the assumption that the outside air has low humidity in IDC. Otherwise, it is necessary to use a dehumidifier to maintain the efficiency of the IEC device. Rampazzo M. et al. [76] proposed coupling FC with an IDC system, Figure. 22. In order to analyse the work of the main element (evaporative heat exchanger) they built a First-Principal Data-Driven model in Matlab software. The simulations indicate a correct imitation of some basic thermal aspects of the IEC process. Al Horr et al. [80] proposed methods leading to energy savings, which can be implemented in the logic of automatic control of indirect evaporative cooling systems. The authors in their work answer the question which operating mode, water spraying, mist injection or a combination of them or dry mode will be best suited for the selected assessment environment conditions. Their analysis concerned an indirect/direct evaporative cooling unit in Qatar as presented in Figure. 23 but only for three air parameters: 26°C/55%RH, 38° C/55%RH, and 42°C/25%RH. In their studies, they have shown that, depending on the operating mode, the variation in cooling performance can differ by up to 41% and when IEC operates in hot climates, it can enable a decrease in the cooling load. Wet modes have been found to save up to 43% of the cooling demand compared to dry modes.

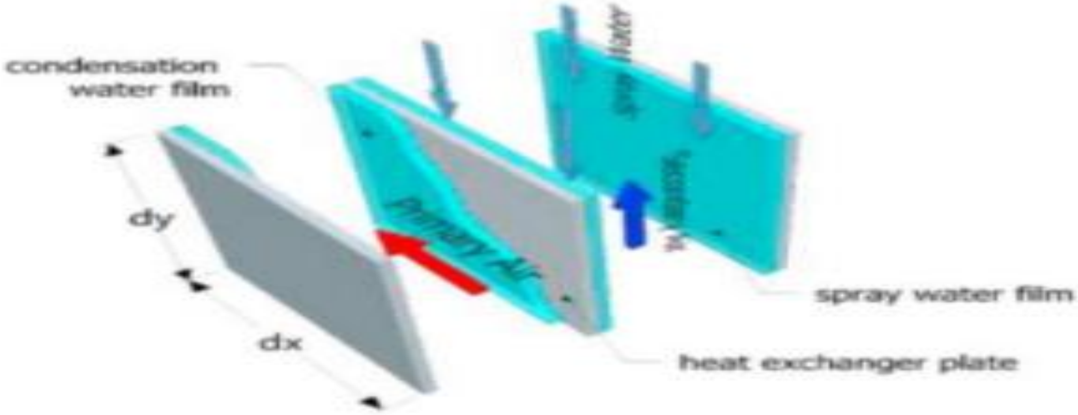

Fig. 20. Cross-flow IEC with condensation — model [78].

6. Solar thermal energy

Solar-energy can be harnessed as a green source of energy to provide electricity and heat and can improve the energy efficiency of buildings. This is primarily done by using conventional photovoltaic and thermal collectors or a combination of the two technologies, namely, as PV/T, on the envelope or roof of a building [81]. Extensive research has been conducted into improving the utilisation efficiency of harvesting solar energy and it indicates that the highest possible production of heat and electricity can be obtained using the PV/T technology. This is found to be mainly due to the fact that the heat absorbed from the photovoltaics cells by the thermal panel can actually increase the electricity generation, improving the overall energy output from the system and, as a result, delivering more energy to the building [82]. It is found that, generally, the efficiency of photovoltaic panels can drop by approximately 0.5%/°C increase in the cell temperature, which in results in a reduction of the electrical generation efficiency of the panel, which is, in any case, only in the range of 10-20% [82]. This has therefore led to much innovative research to discover new methods of developing state-of-the-art photovoltaic thermal technologies for use in buildings. For instance, and as can be seen from Figure. 24, Yu et al. [83] discovered that, by placing solar panels on the Trombe wall envelope of a building, electricity can effectively be generated with the highest conversion efficiency throughout different seasons of the year. The configuration can also be used to provide space heating with efficiencies of almost 12% and 37% in winter and summer subsequently, while degrading gaseous formaldehyde by circulating the air through the system. The PV cells are cooled using diverted flowing air or water, depending on the energy demand and output requirement of the building. Similar configurations of cooling techniques can also be used separately from the building envelope to absorb the thermal energy from the PV panels and deliver it to the internal environment. The above-mentioned techniques can include a fan, for instance, to improve the electrical efficiency from the PV panels, while increasing the thermal energy output from the system. As an example, Elminshawy et al. [84] connected a fan to a buried heat exchanger (BHE) to force ambient air underneath a photovoltaic panel. This configuration, as can be seen from Figure. 25, allowed the generation of pre-cooled air from the ground heat exchanger,

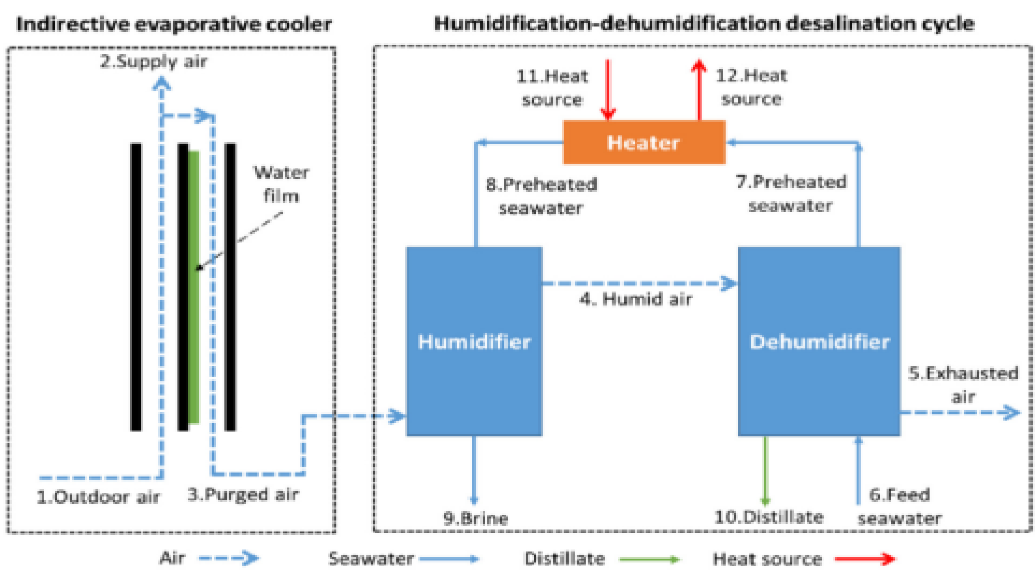

Fig. 21. Coupled IEC-HDH cycle- schematic [79].

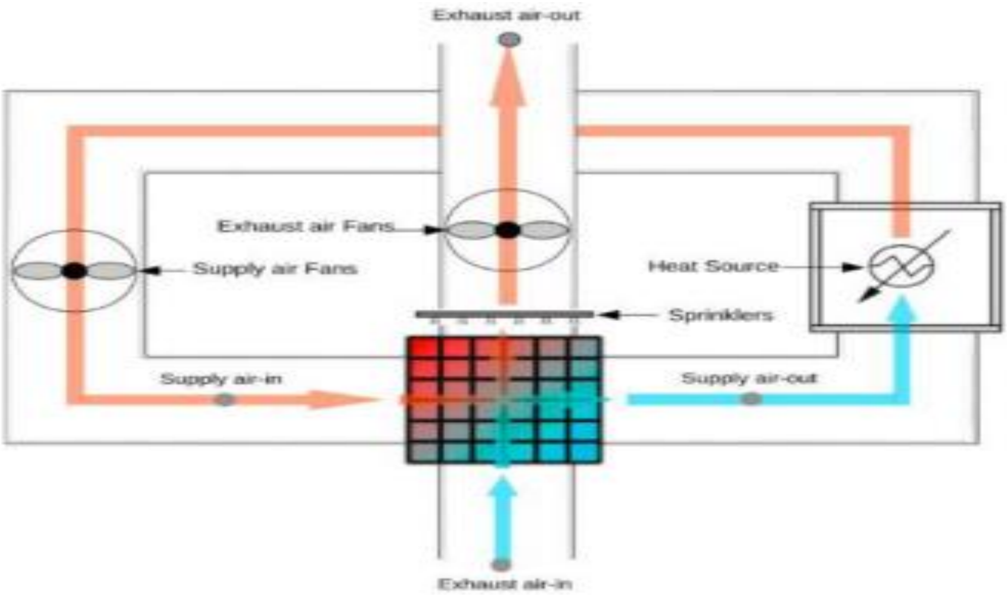

Fig. 22. IEC-FC system layout with the counter-flow configuration [76].

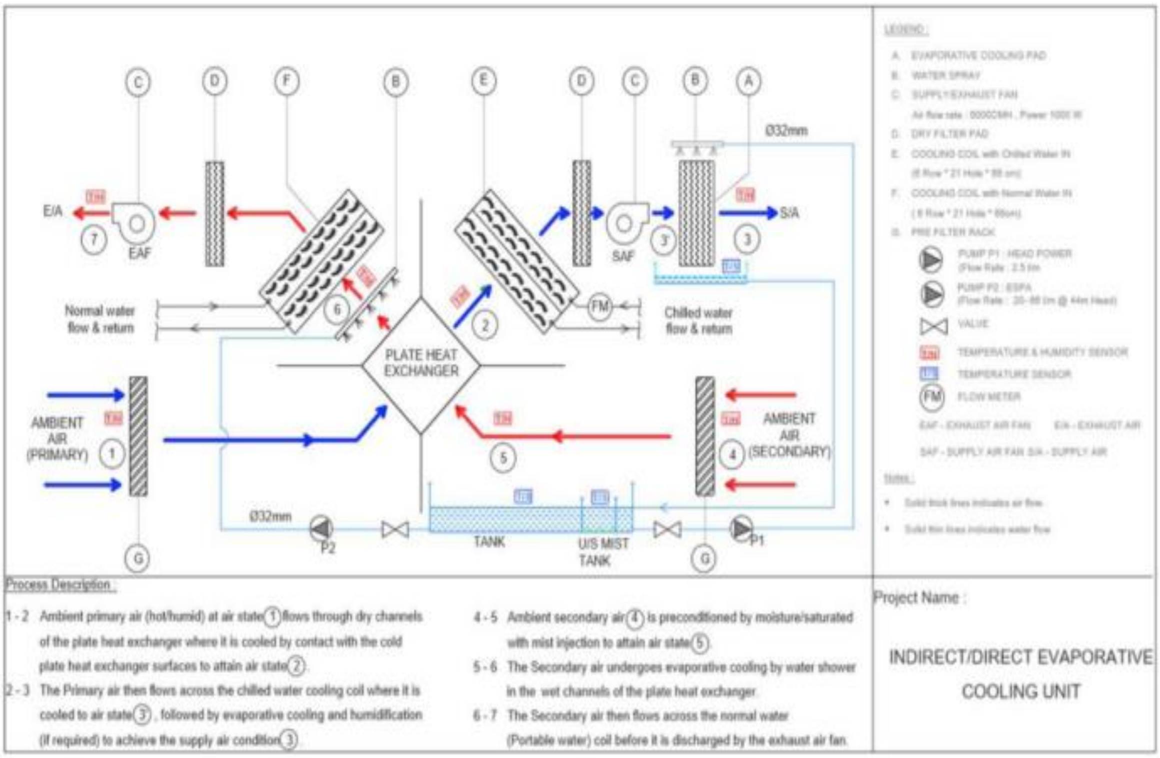

Fig. 23. Indirect/direct evaporative cooling unit [80].

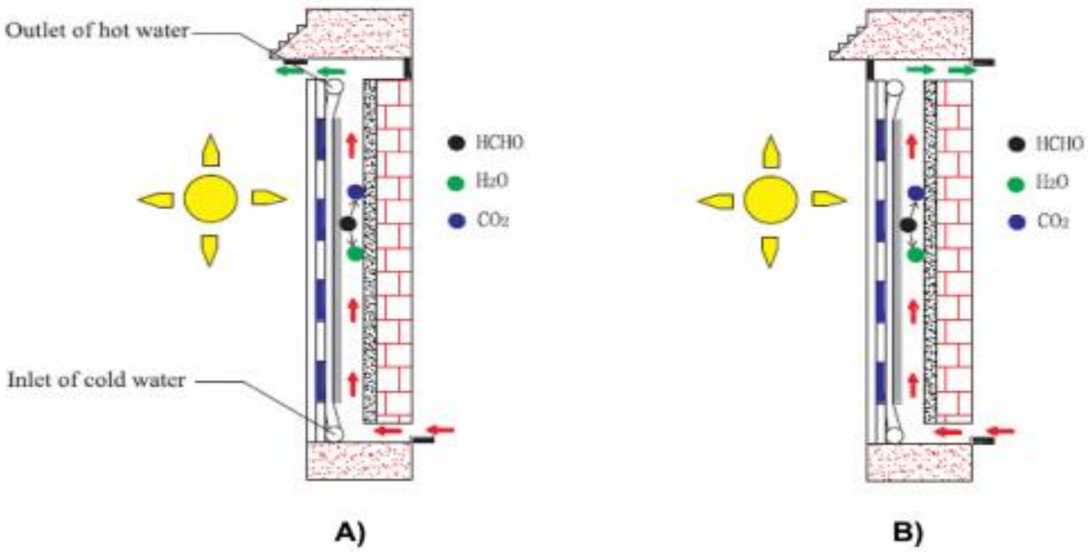

Fig. 24. Different arrangements of PV/T with Trombe wall for A) summer and B) winter [83].

which, in return, was supplied to the back of the PV cells to provide a temperature drop for the panel. The experiment was conducted at various ambient temperatures and the results indicated that the cooling technique can lead approximately to a maximum electrical efficiency improvement of up to 30%. The thermal efficiency delivered from the system was discovered to have increased to nearly 45%. It is important to note that the BHE`s thermal performance depends on the type of soil and its moisture. The method of thermal management employed for photovoltaic panels also depends on the location at which they are being used. For example, as Kabeel et al. [85] found, in a hot climate water cooling of PV yield the highest efficiency gain. However, in their research they do not give the temperature of the PVT panel cooling water but only the 12l/min flow rate. Nizetic et al. [86] used a manifold to spray water over the top and bottom surfaces of a PV panel and discovered that a maximum improvement in the power output efficiency of about 16% can be achieved using this method at peak solar irradiation. The test indicated that the temperature of the solar panel can be brought down to nearly 30°C from almost 54°C. The above studies do not take into account the fact that in hot climates water is very often lacking. The process of cooling water operation, especially in a closed system, will generate additional costs. Other techniques, such as the use of Phase Change Materials or PCMs for cooling, have also shown promising results in terms of efficiency improvement where there is stable solar radiation. For

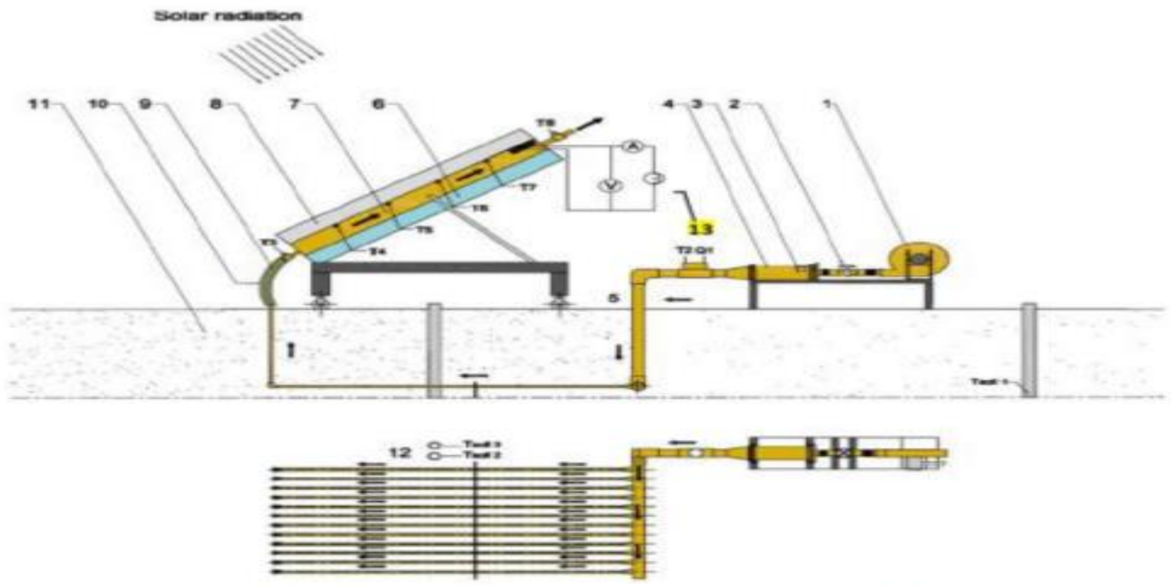

Fig. 25. PV panel with buried heat exchanger cooling arrangement [84].

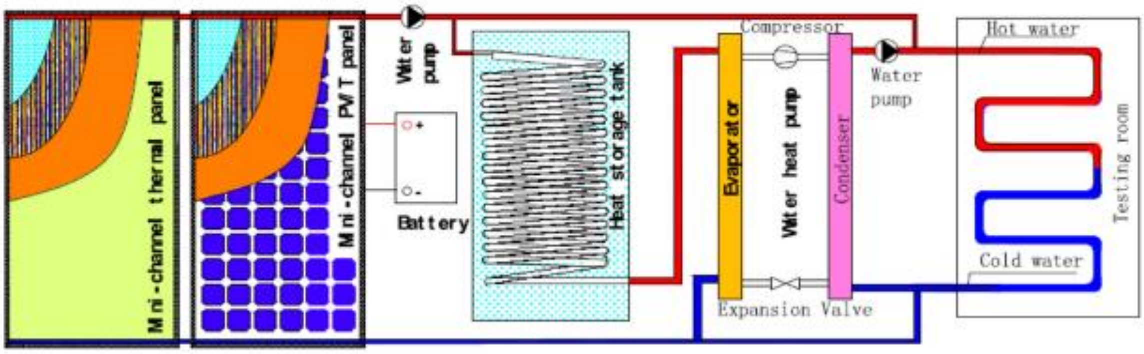

Fig. 26. Schematic arrangement of PV/T coupled with Heat pump [88].

instance, Hasan et al. [87] conducted an investigation into using different PCM materials, namely, salt hydrates and eutectic mixtures, for cooling PV cells in a cold and hot climate. The research let to the discovery that both PCMs can help to manage the temperature of the panel better in a hot climate. The salt-hydrate PCM achieved about a 4% higher temperature drop and improved the power output by almost 3%. However, in warm climates there is a problem with the removal of stored heat in PCMs. Because of the high temperature at night, the PCM does not solidify completely and, as the authors note, "coolant flow into the PCM to maximise heat extraction may be required". Thanks to the useful production of both electrical and thermal energy by PV/T panels, these systems can also be combined with other technologies such as heat pumps to generate and deliver energy in a more sustainable and efficient manner in areas with lower solar irradiation. For instance, Zhou et al. [88] coupled a heat pump with a PV/T system and discovered that space heating for buildings can be effectively generated in regions with low solar irradiation. For this system and, as can be seen from the Figure. 26, the pane is connected in a parallel configuration to a heat pump that is used as an auxiliary heating unit. The heat pump employs a compressor, an evaporator and a condenser to utilise and increase the temperature of the water in a storage tank that is connected to the thermal panel. The heat stored in the storage tank can then be used as useful thermal energy in a building envelope. In an experiment and using the developed system, it was found that the electrical, thermal and overall efficiencies of the heat pump incorporated PV/T system can reach almost 16%, 33% and nearly 50%, respectively, while keeping the room temperature at above the comfort level of 18°C. The COP of the heat pump was indicated to be 4.7 with the system fully functioning. The heat pump combined system can also be used for efficiency output management of the photovoltaic cells. For instance, Lazzarin and Noro [89] managed to employ a glazed PV/T system in combination with a ground source heat pump and discovered that, with this configuration, the thermal and electrical output efficiencies from the panel can be kept at an optimal level. The experimental set up included a refurbished building that comprised a dual source heat pump and used the ground as a heat sink and source, depending on the season of the year, to thermally manage

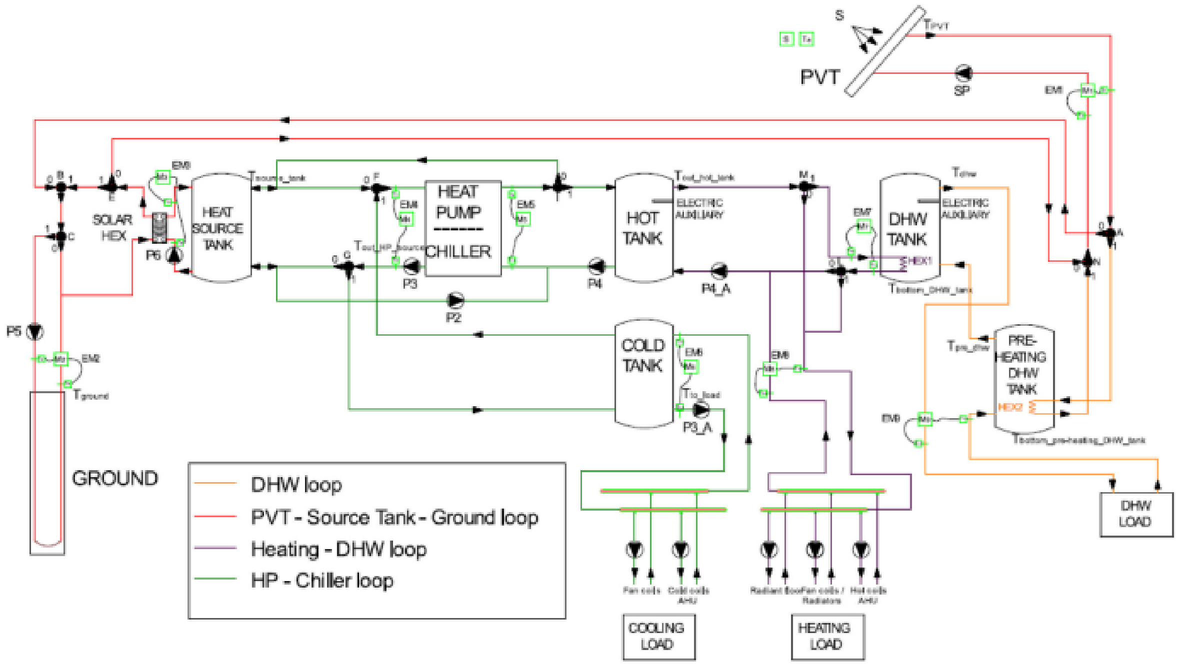

Fig. 27. Piping and instrumentation diagram of dual PV/T integrated heat pump system [89].

the temperature of the photovoltaic cells. The results from the experiment suggested excellent system performance, while the energy output was obtained with highest indicated efficiencies. Figure. 27 shows the piping and instrumentation diagram (P&ID) for the configuration of the system. Having reviewed the above investigations, it is noted that the use the use of heat pipe-based cooling techniques has also shown promising results in terms of both effective thermal energy delivery and efficiency improvement for PV panels. Yu et al. [90], for example, as can be seen from Figure. 28, used a micro-channel loop heat pipe as heat absorber and a tubular heat exchanger with water as heat sink to decrease the surface temperature of a PV panel. In this experiment, the heat pipes were filled with the refrigerant R134a as the working fluid and were placed under the solar panel to absorb and deliver heat to a cooling manifold where the heat exchanger was located. The working fluid in the heat pipes offers a rather low boiling point. Since the heat pipes are placed under the surface of the PV panel, a slight increase in temperature evaporates the working fluid within the heat pipe, which travels passively to the cooler section of the system where the water manifold is located. The working fluid then delivers its latent heat to the heat exchanger, condenses and returns to evaporate at the surface of the panel. This delivers the heat absorbed by the PV cells effectively and efficiently to the water flow [91]. The water flow can then be diverted to a thermal storage tank where it can be used as hot water for a household [92]. The results from the experiment showed that a peak solar thermal efficiency of almost 70% can be achieved through the use of micro-channel heat pipes, while the electrical efficiency maximised to nearly 18%. Jouhara et al. [93,94] took advantage of the benefits offered by heat pipes in an experiment and manufactured a building integrated PV/T solar roof, which improved both the electrical and thermal performances of the solar panel when compared to other state-of-the art technologies [82]. In this experiment and as can be seen from Figure. 29, PV panels were attached to the surface of a flat heat pipe, namely as a heat mat, and cooled through water which passed through a cooling manifold, transferring the absorbed heat from the cells. As shown in the Figure. 30, the manufactured heat mat panels were then placed on the roof of a demonstration building representing a small dwelling and the results obtained demonstrated that the overall system conversion efficiency is increased to approximately 50% while the PV electrical output efficiency is improved by about 15%. 7.

7. Conclusion

In this research paper the following passive energy strategies were reviewed in the of context of their application in residential buildings, a power-hungry sector, where a significant portion of the energy is spent on controlling the indoor temperature and humidity for the comfort of occupants:

- NV (Night Ventilation): the use of night-time ambient air when its temperature drops below a certain threshold, by inducing it into buildings.
- NRE (Nocturnal Radiation Exchange): night sky radiation exchange with building surfaces as well as cooling media such as water.
- PCM (Phase Change Material) and IEC (Indirect Evaporative Cooling): use of phase change material to increase the sensible cooling efficiency of evaporative coolers and the use of water as a cooling medium whereby air is induced into the evaporative cooler through a controlled spray of water to lower its DBT (Dry Bulb Temperature) when ambient air conditions permit.
- Solar Thermal Energy.
- Passive Building Design.

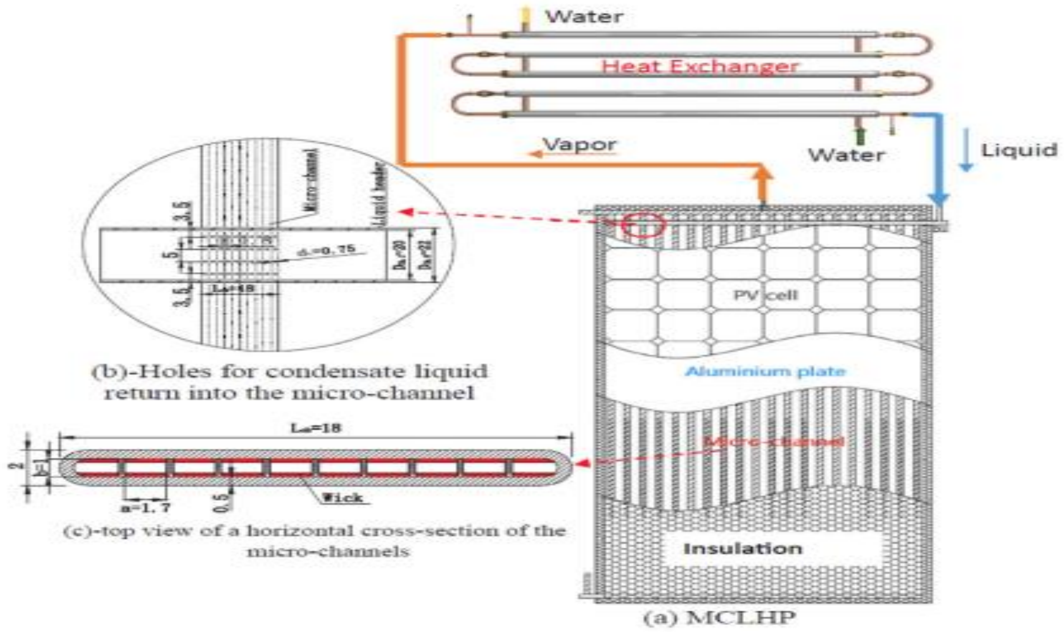

Fig. 28. Design layout of the micro-channel loop heat pipe PV/T system [90].

The review has revealed that extensive research work has been carried out in attempts to quantify achievable energy savings that will help in reducing dependence on gas and electricity in tropical and subtropical regions where indoor climate control, particularly during the warm seasons, is an expensive necessity. Also, the means of improving the performance of these strategies in a cost-effective way, when deployed either individually or in a hybrid configuration of more than one strategy, have been identified for existing houses as well as houses under design. It is revealed that there is a need for a real case study coupled with extensive filed data gathering over at least 12 months to cover all seasons of a contemporary passively designed houses in locations where meteorological conditions would permit the utilization of free ambient energy to help generate comfort (or near comfort) conditions, thus further improving the thermal performance of residential houses. Also, it is quite evident from the literature review that there is limited research work on an integrated approach of studying the deployment of the selected strategies in this review paper with the objective of maximizing the benefit of free ambient energy throughout the year. In addition, there is an essential need for the use of an energy efficient HHVAC (Hybrid Heating, Ventilation and Air Conditioning) system, flexible enough to permit integration of the passive strategies discussed in this review paper, as well as being able to optimise the operation of these strategies either individually or collectively for an extended validation period. The HHVAC system design should take into consideration the predominant characteristics of the meteorological conditions for the region being studied. Also, how practical and cost effective it is to implement such strategies in existing houses should be considered and how the findings can enhance current design guidelines for new. Not only comfort conditions should be the objective but as much as possible near comfort conditions, as well as full or partial relief to occupants during peak days in summer and cold winter nights. This will help in understanding better the complexities of how passively designed house thermal behaviour will improve by the implementation of the reviewed strategies.

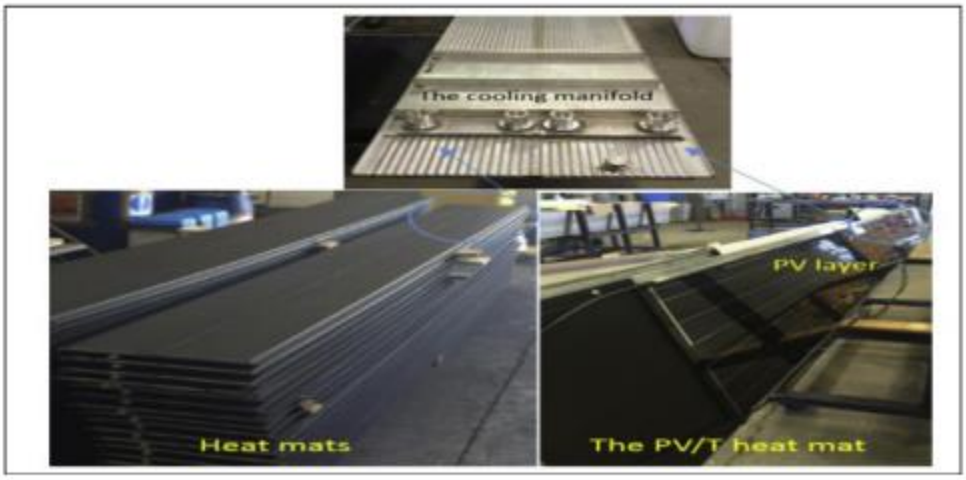

Fig. 29. Heat mat heat pipe technology [93].

Fig. 30. Heat Pipe Based PV/T System [94].

Declaration of Competing Interest

None.

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11.2 [2] Analysis of energy demand in a residential building using TRNSYS

ABSTRACT

Energy simulations of buildings complement or replace the static calculations used so far and provide detailed answers to questions such as: what is the energy demand for individual purposes in a building and how does it change over the course of a day, a month, a year and also enable a comparison of several design variants and the selection of the optimal one in terms of energy consumption. Therefore, energy simulations of buildings help make decisions to optimise architectural and installation solutions, leading to a reduction in electricity, gas and water demand for the designed building. They indicate to what extent individual factors affect the demand for heating, cooling and electricity. The results of the analyses can be used as a basis for design and system decisions, and also provide interesting feedback to the investor. This paper focuses on the year-round analysis of a three-zone building in TRNSYS. Attention is given to the values of the heat transfer coefficients through the envelope, heating and cooling demand, the effect of heat gains/losses on the energy demand of the building and thermal comfort. The article points out that the correct determination of the energy needs of a building influences the correct choice of renewable energy source and the lowest cost of installation.

1. Introduction

The demand for electricity is high and is increasing year by year. At the same time its production still relies heavily on fossil fuels, which has a negative impact on the environment. The increase in greenhouse gas production has prompted the world community to set ambitious targets to prevent global warming [1e4]. In the third quarter of 2021 total UK total energy production was 25.1 million tonnes of oil equivalent [5]. Compared to the third quarter of 2020, total final energy consumption was 6.4% higher. It is significant that the share of renewable energy sources in electricity generation is increasing, as can be seen in Figure. 1. The temporary decline in summer 2021 was due to maintenance work on the North Sea limiting renewable energy production as well as lower wind speeds. The share of photovoltaic (PV) systems recorded an increase to 6.2% in 2021, as illustrated in Figure. 2. In the UK, the domestic electricity consumption is one of the largest consumers [5] thus Solar PV systems for residential users are among the most preferred installations. PV systems allow electricity to be generated from 100% renewable solar energy [6]. The energy obtained can be used for the operation of household appliances, and/or for heating and domestic hot water [7]. Over the last 20 years, there has been a significant increase in the number of PV installations [8]. Ahmad L. et all [9]. extensively discussed the latest technological developments in the different types of solar collectors. UK Solar deployment by capacity and accreditation is shown in Figure. 3. According to the data presented, there is a total of 13,654 MW of installed solar capacity in the UK sited at 1,121,819 installations at the end of December

2021 [8]. The cost of the installation is a key issue for the individual consumer. Since 2013, detailed costs for small installations in the 0e4 KW, 4e10 KW and 10e50 KW ranges from the Microgeneration Certificate Scheme (MSC) have been posted on government websites [10] The MCS Installations Database contains information on certified small scale, low carbon installation in the UK since 2010 [11]. It should be noted that the data available [10] does not represent the cost to the householder. It is the cost per KW resulting from dividing the total cost (which include the cost of the photovoltaic generation equipment, the cost of installation and connection to the electricity grid and VAT) by the installed

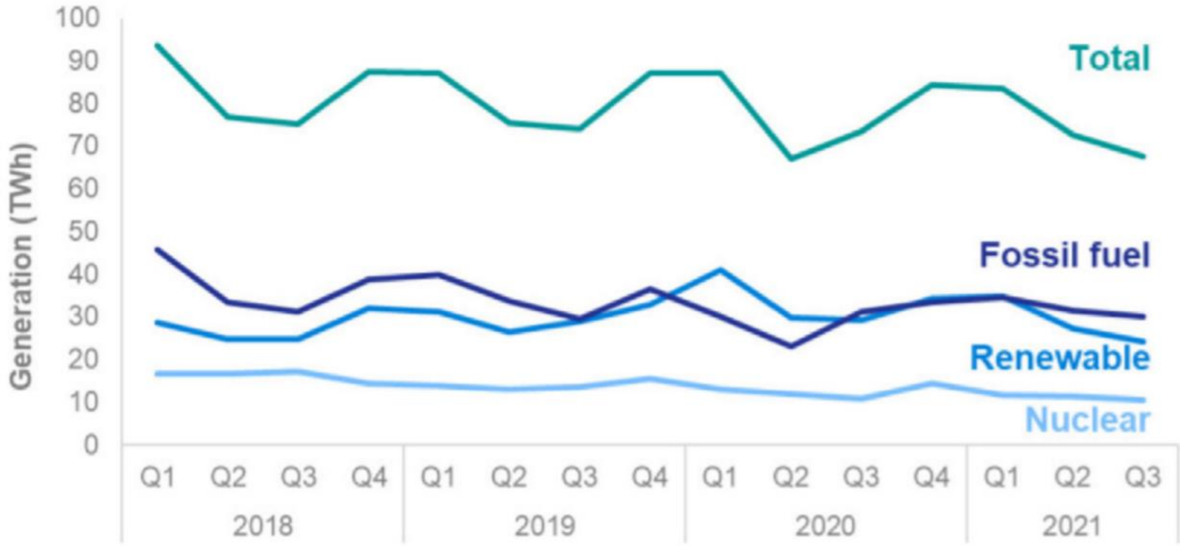

Fig. 1. Electricity generated, by fuel type in UK [5].

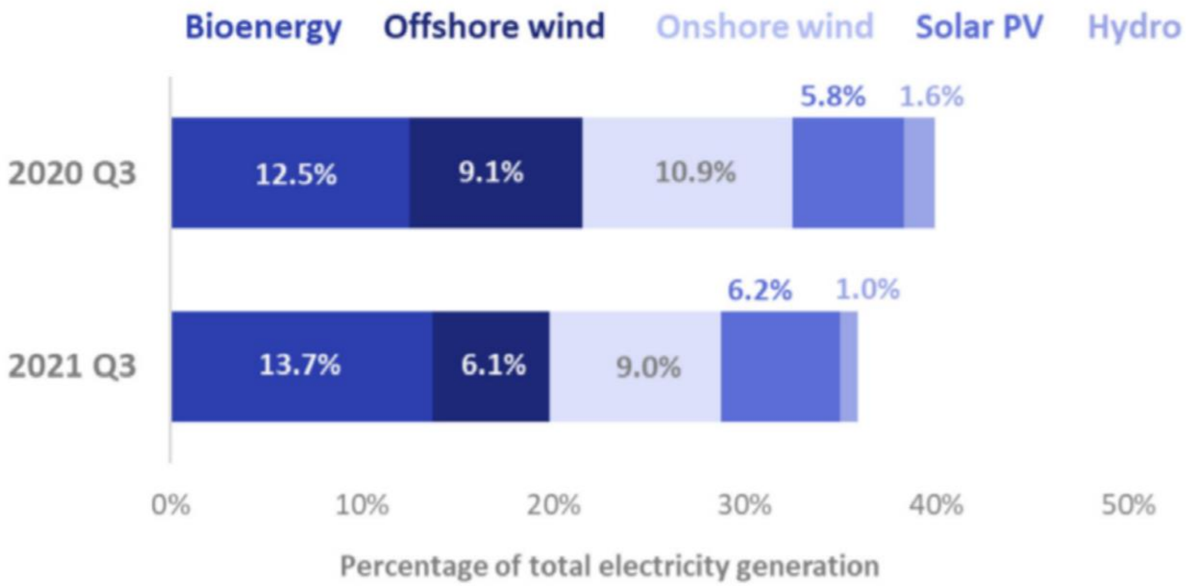

Fig. 2. Renewables' share of electricity generation – Q3 2020 and Q3 2021 [5].

capacity. 28,638 installations were included in the analysis between April 2019 and March 2020. According to the statistics, the average cost of Solar PV installations in 2020/21, despite an increase on the previous year 2019/2020, for 0e4 KW installations was 10% lower than in 2018/19 and 28% lower than in 2013/14 and was £1628 per KW installed. The average cost of a 4e10 KW installation was £1685 per KW installed in 2021/2022 and for 10e50 KW £1088. Currently, photovoltaic systems can be grid-connected (On-grid) or stand-alone (Off-grid) [12]. However, the cost of the installation is significantly influenced by the building structure, its location and occupancy [13]. In order to select a PV system, it is necessary to find out what the annual energy demand of the building will be. Energy simulation programs that take these factors into account can help to find the most energy-optimal building design and thus contribute to minimizing the PV installation costs. This article focuses on the building and the factors that have the greatest impact on energy demand. Therefore, a step-by-step construction of the building model in TRNSYS is presented. The phase of defining building geometry, wall structures, heating and cooling loads, infiltration, gains and schedules is described in detail. For each of these stages, the energy demand was investigated. In addition, the PMV and PPD values for the analysed building were examined.

2. Building energy simulation

Modelling the behaviour of a building under changing operating conditions enables detailed analyses to be carried out, which will contribute to key decisions being made both at the stage of designing a building and retrofitting an existing one. The energy simulations software's provide the ability to predict the performance of the designed building, the selected systems or both at the same time. They allow for a more complete description of those phenomena that cannot be characterised by simple static calculations such as the way a building reacts to solar heat gains or the accumulation in partitions. There are a number of software packages that can analyse either buildings, systems or both at the same time such as TRNSYS, EnergyPlus or IDA ICE. Each has its advantages and limitations. Each of these has been described many times in the literature [14-17]. In addition, M. Magni et al. [18] compared them with respect to modelling approaches and computational costs. The authors highlighted that it required many iterations to achieve good agreement in the representation of the building across the different programs. To assess compliance, statistical indicators were used among others. A. Chong et all [19]. addressed the issue of model calibration to improve the reliability of simulations. The article provides definitions of calibration, validation and verification according to the American Institute of Aeronautics and Astronautics (AIAA) guide and the article by T.G. Trucano et al. [20]. TRNSYS software allows the simulation of different types of solar collector, photovoltaics as well as photovoltaic-thermal (PV/T) collector [21,22], heat pipe heat exchangers [23,24], PVT-collector model and horizontal ground heat exchanger [25], solar-assisted ground-source heat pumps [26] as well as the building [27] or

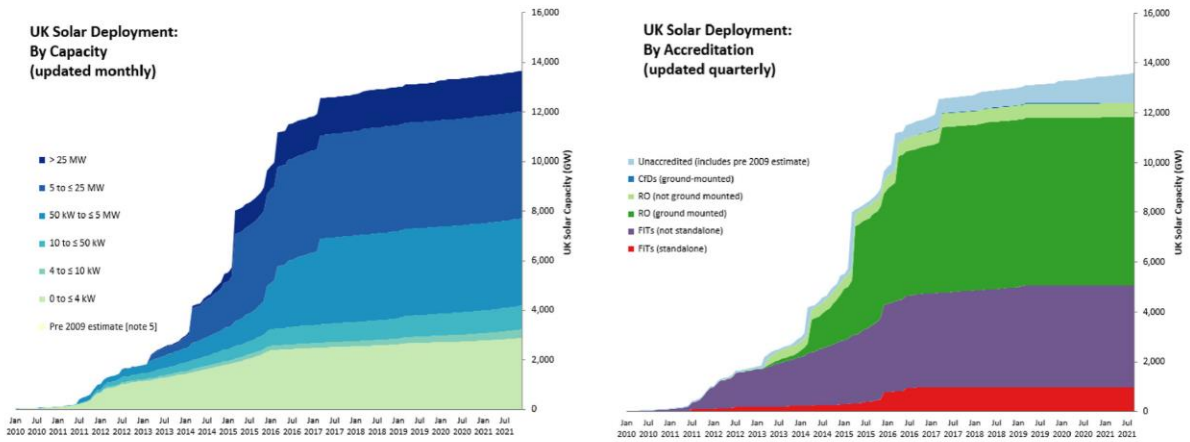

Fig. 3. UK Solar deployment by capacity and accreditation [8].

multiple radiative inter-reflections exchanges [28]. Both the system and the building can be configured and analysed separately. Researchers are interested in the potential of waste heat recovery in residential buildings [29], reducing the risk of disease transmission by analysing ventilation strategies [30] or using useful ambient energy [31]. However, a basic analysis of the energy needs of the building itself to maintain thermal comfort has not been widely investigated. After reviewing the various functionalities of each package, TRNSYS was selected for the building analysis. This article focuses on the building and the factors that have the greatest impact on energy demand. TRNSYS enables multi-zone building modelling with Type56 and TRNBuild. The user can map the thermal behaviour of a building divided into different zones and then assign heating, cooling, humidification, operating schedules, gains and much more to the model.

2.1. Building geometry

The modelling process begins by defining the geometry. The more complex the shape, the more difficult it is to represent it in the programme. For this purpose, the Trnsys3d plug-in for Google Sketchup may be used. This solution allows the elements of self-shading of the building to be taken into account or for radiation exchange internal view factors [32]. Correct definition of individual zones, windows, external and internal partitions in SketchUp speeds up the design process, and due to the visualisation, the whole process is user-friendly. The generated file with a.IDF (Intermediate Data File) extension can be imported into TRNSYS by creating a new 3D project (multizone). At this stage the following can be assigned: weather data file, building orientation, boundary temperatures of surfaces, static distribution factor of solar direct radiation or shading control. To modify a building in the TRNSYS project window, the building needs to be edited in TRNBuild. For the purposes of this article, a three-zone building was prepared in Google Sketchup and then imported into TRNSYS according to the above guidelines (Figure. 4A). The implemented geometry can be seen in TrnViewBUI as shown in Figure. 4B. In order to calculate the correct azimuthal angles of the surface orientation, the northern hemisphere was defined. London weather data has been assigned. The building is divided into three zones: on the ground floor North (SunZone) and South (BackZone) zones with a surface area of 20 m^2 each. Above them there is an unheated attic of 40 m^2. 2.4 m^2 of windows have been placed in the northern and southern walls.

2.2. Heat transfer coefficient

For the next stage of the building modelling process, an appropriate structure must be assigned to the individual building envelopes, taking into account the heat transfer coefficient U. This is one of the most important steps as it determines the amount of energy that needs to be supplied to the building in order to maintain the air temperature in each zone at the desired level. Maintaining thermal comfort indoors is crucial. Thermal comfort depends on the indoor air temperature and the surface temperature of the building envelope (preferably a difference of less than 3 K) as well as air speed (above 0.15 m/s giving sensations of draught) and humidity (the comfort range is 40-70%). Suitable insulation slows down the flow of heat through surfaces such as walls, attic and roof. The house stays warm in winter and at the same time in summer the insulation will keep the building pleasantly cool. Optimisation efforts start with the choice of envelope materials, glazing type or the entire façade, as these factors have a fundamental impact on the energy efficiency of the building [33-35]. Using simulation tools, the energy requirements for any configuration can be predicted. Every building, whether newly constructed, sold or rented out, should have an Energy Performance Certificate (EPC) indicating the energy efficiency of the building. Energy efficiency refers to the cost of the fuel that has to be supplied and the carbon dioxide emissions. The scores associated with each energy efficiency band are as follows [36]: band A-92 plus (most efficient); band B-81 to 91; band C-69 to 80; band D-55 to 68; band E 39 to 54; band F-21 to 38; band G -1 to 20 (least efficient). According to Office for National Statistic [36], by March 2021 the median energy efficiency score for residential dwellings in England was 66 which corresponds to band D. Median energy efficiency score by tenure and property type in England is shown in Figure. 5. In the simplified calculation method U value according to the standard [38] is described as:

$$U = 1/R_{tot} \qquad (1)$$

where: U, R_{tot} is the thermal transmittance ($W/(m^2\ K)$) and the total thermal resistance ($m^2\ K/W$) respectively. The total thermal resistance of a flat building element for which the heat flow is perpendicular to the stacked, thermally homogeneous layers can be defined as:

$$R_{tot} = R_{si} + R_1 + R_2 + R_n + R_{se} \qquad (2)$$

where R_{tot}, R_{si}, R_{se} is the total thermal resistance ($m^2\ K/W$), the internal surface resistance ($m^2\ K/W$) and the external surface resistance ($m^2\ K/W$) respectively. R_1; R_2,R_n are the design thermal resistances of each layer ($m^2\ K/W$); The thermal resistance of the layer can be described as a function of thermal conductivity (W/mK) and material layer thickness d (m): $R = d / \lambda$ (3)

For the purposes of this article, the requirements for external walls in terms of heat transfer coefficient for wall, floor, window and roof construction have been assigned as follows: external wall 0.16 W/(m^2 K), floor 0.11 W/(m^2 K), roof 0.11 W/(m^2 K), window 1.1 W/(m^2 K). The order of layers is precisely defined. For each wall construction material used the following is given: layer thickness [m], thermal conductivity [kJ/h m K], specific heat capacity [kJ/kg K] and density [kg/m^3]. Each wall can consist of up to 20 layers. In addition, for each partition it is possible to specify solar absorptance, longwave emission coefficient, convective heat transfer coefficient for both sides of the walls: front and back. In TRNSYS both the front and back of every wall are assumed to be black for internal radiative gains and for long-wave radiation exchange between the internal surfaces [39]. Type 56 also gives the option of defining to a specific wall area a specific energy flux. The results of the simulation with the defined partition structure taking into account the variation of ambient, ground, air and operative temperature in each zone are illustrated in Figure. 6. The results clearly show that the lack of a heat source, when appropriate values of heat transfer coefficients for London are used, does not allow the room temperature to be maintained at 20 C in any of the zones. The variation of the internal temperature follows the ambient temperature. Maintaining the required temperature in a room requires the supply of heat. The amount of heat to be supplied to each zone is precisely defined and independent of the type of heat source.

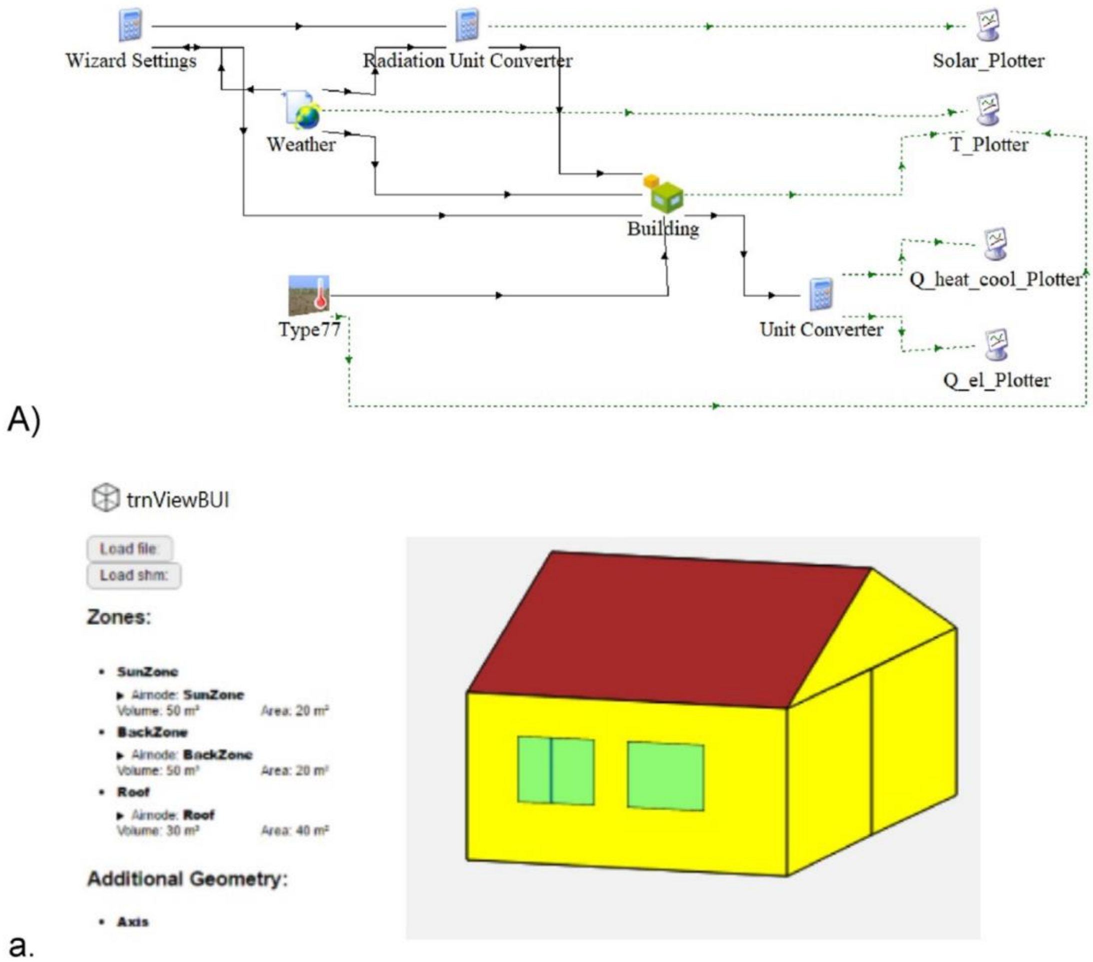

Fig. 4. View of A)Simulation Studio: TRNSYS project b)TRNBuild: 3 zone building in trnViewBUI.

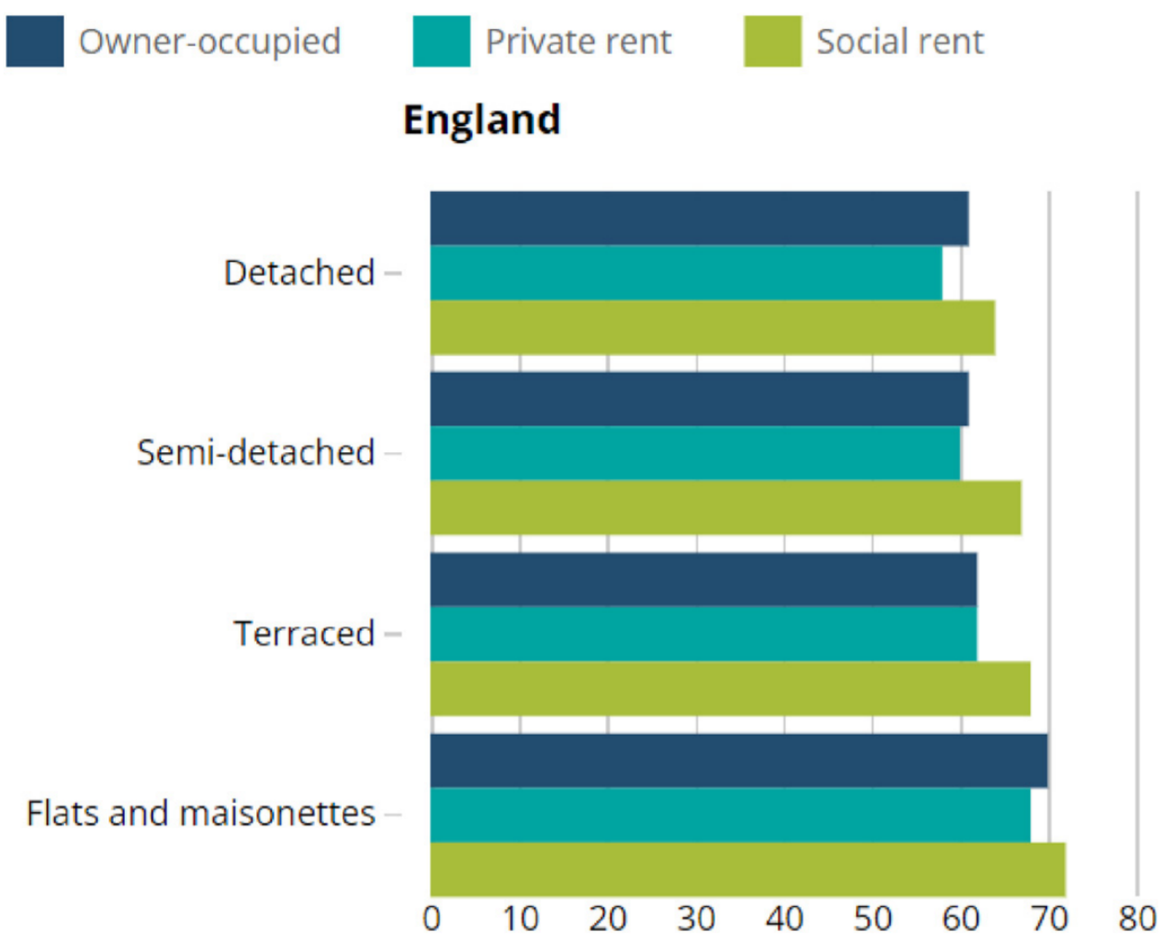

Fig. 5. Median energy efficiency score by tenure and property type in England [36]. Maintaining proper thermal and humidity conditions will be achieved by meeting the legal requirements for the energy performance of the building. In England the current standard is: The Building Regulations 2010 Conservation of fuel and power APPROVED DOCUMENT L Volume 1: Dwellings 2021 edition – for use in England [37]. Limiting U-values are presented in Table 1.

2.3. Heating and cooling load

The default setting for the heating and cooling control in TYPE56 is OFF. This means that in order to determine the energy required for heating or cooling in each zone the ideal control option must be activated. However, it must be remembered that in this situation the heating and cooling devices are not modelled outside the TYPE56 component. Otherwise, this function should not be used. In heating mode, the room setpoint temperature, the heating power with its radiative part, and the humidification of the air within the air-node can be determined. In cooling mode, the room setpoint temperature, cooling capacity and zone dehumidification can be specified. All variables can be defined as a constant, an input, or a schedule. Schedules are periodic functions [39]. Depending on the time of day and/or week, the output may change. In addition, TRNSYS allows the user to simulate heating devices that provide part of their power through convection and part via radiation. At these settings, a defined fraction of the radiating power of the heater is supplied as internal radiation gains and distributed to the walls of the zone. The software allows surface heating to be modelled, but this must be taken into account when defining floor, wall or ceiling constructions. For this article, the constant temperature is set to 20 C degrees in winter and 25 C degrees in summer. In more detailed simulations, the heating can be set according to a schedule, for example, the room temperature can be reduced at night. Figures. 7 and 8 show the simulation results for a building with unlimited heating and cooling. The Figure. 8 indicates that the northern zone does not reach the minimum temperature of 25 C in summer when the cooling system has to be activated. The cooling demand in the southern zone, where solar gains are higher than in the northern zone, is a maximum of 13.6 W/m^2. According to the simulation, the heat demand does not exceed 9.24 W/m^2 floor area. By using the TYPE 65c component in Simulation Studio, which allows data to be printed to a file, the exact values of the heating and cooling demand were investigated.

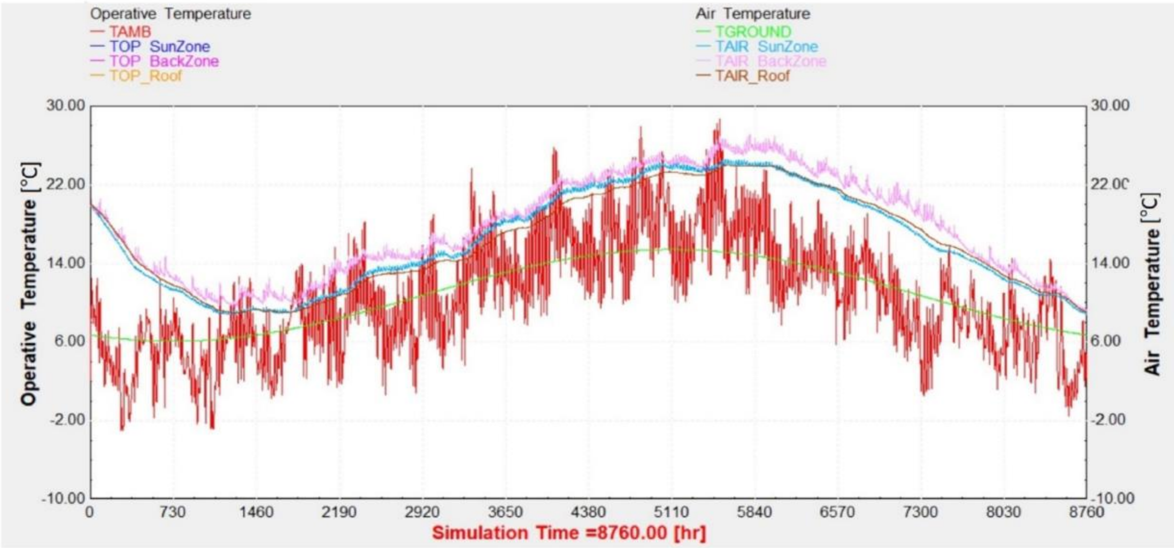

Fig. 6. The variability in ambient, ground, operative and air temperature in each zone.

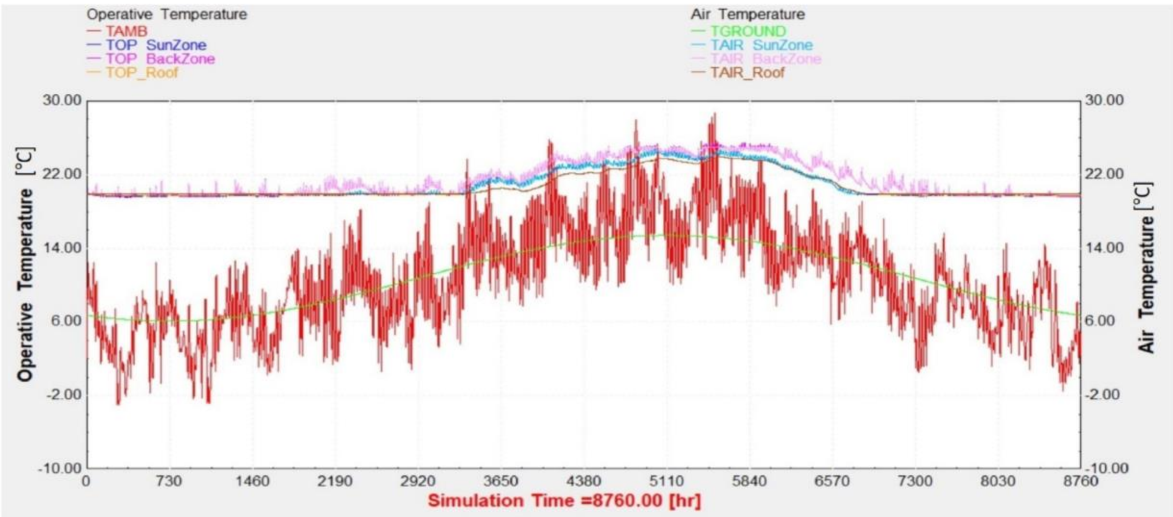

Fig. 7. The variability in ambient, ground, operative and air temperature in each zone with defined space heating and cooling.

2.4. Infiltration, gains and schedules

For a house, the total steady state design heat loss coefficient is determined by the sum of fabric (envelop) losses, infiltration and any ventilation loss, and is calculated in accordance with Heating CIBSE Guide B1: 2016 [40]. According to the guidelines, infiltration (Air infiltration allowance air changes/h) for houses depends on the type of room and should be adequate with the following values: living rooms 1, bedrooms 0.5, bathrooms 2, staircases and corridors 1.5. Steady state heat loss due to infiltration is described by the following formulae:

$$\phi_{inf} = q_{inf}\, \rho\, c_p(\theta_{ai} - \theta_{ao}) \qquad (4)$$

Where q_{inf} is the infiltration rate (m^3/s), ρ is the air density (kg/m^3), c_p is the specific heat capacity of air at constant pressure (J/kg K), q_{ai} and q_{ao} is the inside and outside air temperature (C).

Steady state ventilation heat loss is given by the:

$$\Phi_v = q_v \rho\, c_p(\theta_{ai} - \theta_{vs}) \qquad (5)$$

where q_v is the ventilation rate (m^3/s) and θ_{vs} is the temperature at which the air enters the room (C). The standard approach neglects any heat gains in the room that result from occupants, lighting and equipment. For rooms that are permanently occupied and used this is inappropriate. TRNBuild allows all these factors to be taken into account for the building under consideration and much more. As an example, the energy balance for zones (NTYPE 904) is described below [39]:

$$Q_{BAL} =- DQ_{AIRdt} + Q_{HEAT} - Q_{COOL} + Q_{INF} + Q_{VENT} + Q_{COUP}$$

$$+ Q_{TRANS} + Q_{GINT} + Q_{WGAIN} + Q_{SOL} + Q_{SOLAIR}\ [kJ/hr] \qquad (6)$$

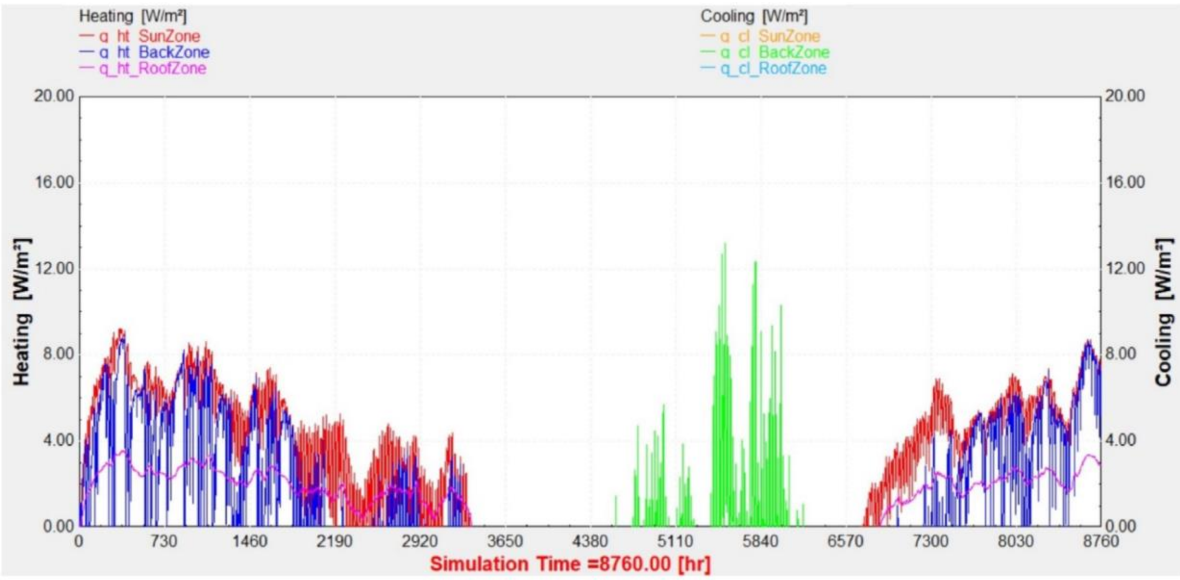

Fig. 8. Heating and cooling demand in each zone.

Where:

DQ_{AIRdt} - change of internal energy of zone (calculated with capacitance of air + additional capacitance which might be added in TRNBuild)

Q_{HEAT} - power of ideal heating (convective + radiative)

Q_{COOL}-power of ideal cooling

Q_{INF}- infiltration gains

Q_{VENT} - ventilation gains

Q_{COUP} - coupling gains

Q_{TRANS} - transmission into the surface from inner surface node (might be stored in the wall, going to a slab cooling or directly transmitted)

Q_{GINT} - internal gains (convective + radiative)

Q_{WGAIN} - wall gains

Q_{SOL} - absorbed solar gains on all inside surfaces of zones

Q_{SOLAIR} - convective energy gain of zone due transmitted solar radiation through external windows which is transformed immediately into a convective heat flow to internal air. For the concerned building, internal gains (including persons), electrical equipment and lighting, have been defined on the basis of a very extensive library which, for example, allows the determination of internal gains based on ASHRAE guidelines, EN13779, VDI2078 or SIA 2024. In addition, a separate time schedule has been assigned for each of the gains. It is assumed that the residents work between 9 a.m. and 5 p.m. and therefore use the lighting between 6 a.m. and 8 p.m. and 6 p.m. and 11 p.m. At weekends the household spend most of their time at home, leading a mostly sedentary lifestyle (according to ASHRAE Degree of Activity III - seated, very light work). No thermal comfort analysis was included in the considered building configuration. However, the software does allow for thermal comfort calculations

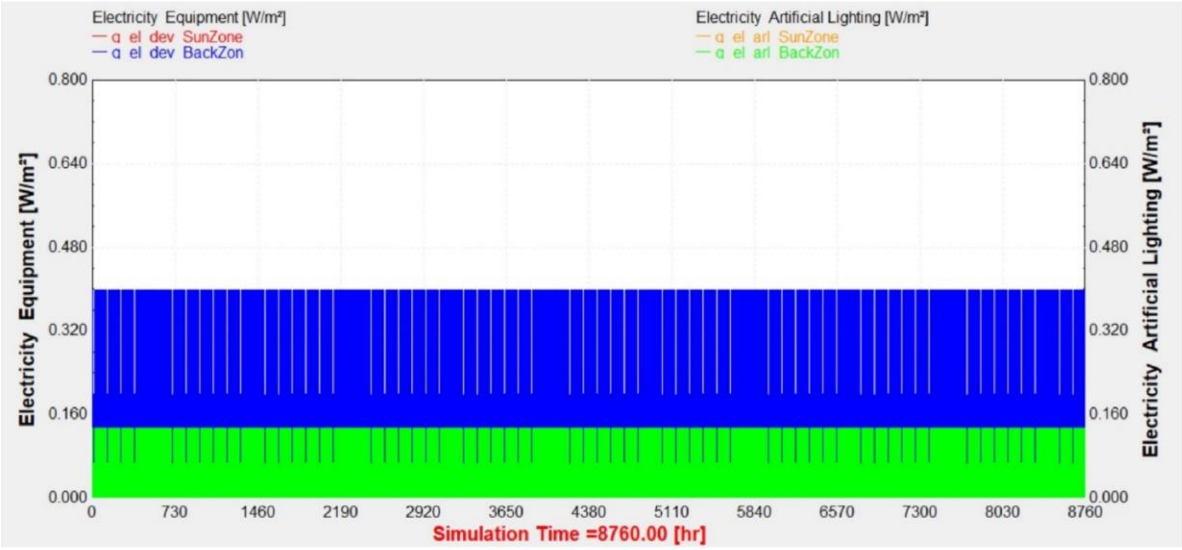

Fig. 9. Electricity demand in both zones.

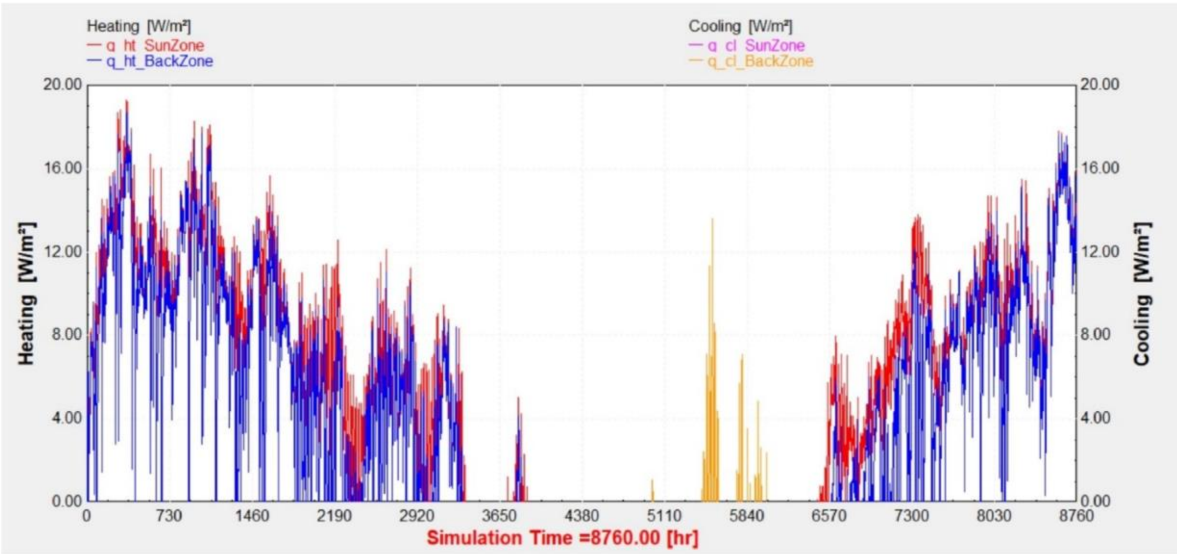

Fig. 10. Heating and cooling demand in each zone including internal gains and infiltration 0.6.

based on EN ISO 7730. Electricity demand is the same in both zones. Its level is shown in Figure. 9. For lighting is 0.135 W/m2 , for domestic appliances 0.4 W/m2 . Figure. 10 illustrates the heating and cooling demand taking into account the above-mentioned factors. In the next step of the analysis, it was investigated how the heat demand of a building would change when an infiltration of 0.6 AC/H (Air Change per Hour) was assigned in the model and then increased to 1. The results of the analysis carried out are presented in Figure. 11. As can be seen from Figures. 10 and 11 the amount of heat delivered to the rooms increases significantly as the infiltration rate increases.

2.5. Thermal COMFORT

The final step of the analysis focused on thermal comfort. Thermal comfort is a state of heat balance in which a person is neither too cold nor too hot [41]. The main factors that influence the feeling of thermal comfort are: air temperature, air velocity, radiant temperature, relative humidity as well as clothing, metabolic heat or level of activity, wellbeing and occupant health status. Thermal comfort is a subjective feeling and therefore a standard had to be created to which one can refer. Two thermal comfort indices based on EN ISO 7730 [20] are commonly used: the predicted mean vote (PMV) and the predicted percentage dissatisfied (PPD). PPD determines the estimated number of people who are dissatisfied with the thermal conditions and can be determined from the following formula [42]:

$$PPD = 100 - 95 \times (-0.3353 \times PMV^4 - 0.2179 \times PMV^2) \qquad (7)$$

PMV is an index which determines the average value of the votes of a group of users on a seven-point scale of thermal sensations (Table 2). According to the standard [43], it may be determined as follows:

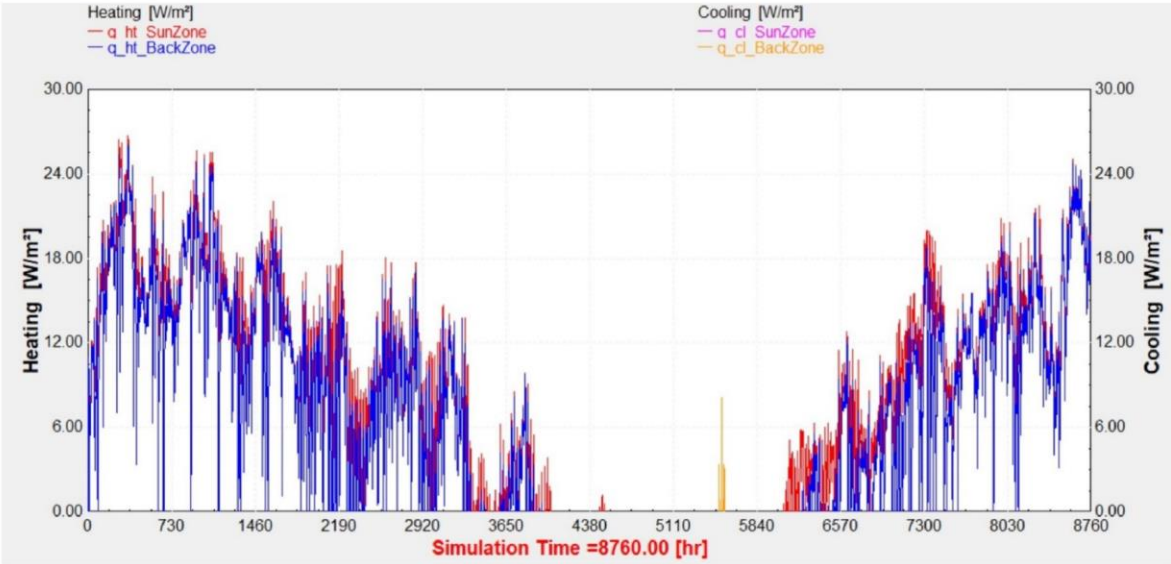

Fig. 11. Heating and cooling demand in each zone including internal gains and infiltration 1.

Table 1
Limiting U-values according to Ref. [37].

Element type	Limiting U-values for new fabric elements and air permeability in new dwellings	Limiting U-values for new fabric elements in existing dwellings	Limiting U-values for existing elements in existing dwellings (Improved)
	Maximum U-value W/(m²·K)	Maximum U-value W/(m²·K)	Maximum U-value W/(m²·K)
All roof types	0.16	0.15	0.16
Wall	0.26	0.18	Wall – cavity insulation: 0.55 Wall – internal or external insulation 0.3
Floor	0.18	0.18	0.25
Party wall	0.20		
Window	1.6	1.4 or Window Energy Rating Band B minimum	–
Rooflight	2.2	–	–
Doors (including glazed doors)	1.6	Doors with >60% of internal face glazed: 1.4 or Door-set Energy Rating Band C minimum Other doors: 1.4 or Door-set Energy Rating Band B minimum	–
Air permeability	8.0m³/(h·m²) @ 50Pa 1.57m³/(h·m²) @ 4Pa		

$$PMV = (0.303e^{0.036M} + 0.028)$$

$$x\ \{(M - W) - 3.05\ x\ 10^{-3}$$

$$x\ [5733 - 6.99\ (M - W)\ - P_a] - 0.42$$

$$x\ (M - W) - 58.15] - 1.7\ x 10^{-5}\ M(5867 - P_a)$$

$$- 0.0014M(34 - t_a) - 3.96\ x\ 10^{-8} f_{cl}$$

$$_x [(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl} h_c (t_{cl} - t^a)\} \quad (8)$$

Where:

$$t_{cl} = 35.7 - 0.028(M - W) - I_{cl}\{3.96\ x\ 10^{-8} f_{cl}$$

$$_x [(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl} h_c (t_{cl} - t^a)\} \quad (9)$$

$$h_{c\,=}\{2.38(t_{cl} - t_a)^{0.25}\ \text{for}\ 2.38\ x\ (t_{cl} - t_a)^{0.25} > 12.1\sqrt{(V_{ar})}$$

$$12.1\sqrt{(V_{ar})}\ \text{for}\ 2.38\ x\ (t_{cl} - t_a)^{0.25} < 12.1\sqrt{(V_{ar})} \quad (10)$$

$$f_{cl\,=}\{1.00 + 1.290 I_{cl}\ \text{for}\ I_{cl} \le 0.078\ m^2K/W$$

$$1.05 + 0.645 I_{cl}\ \text{for}\ I_{cl} > 0.078\ m^2K/W \quad (11)$$

where:

M is the metabolic rate [W/m^2]

W is the effective mechanical power [W/m^2] equal to zero for most activities

I_{cl} is the thermal resistance of clothing, [m^{2}K/W]

f_{cl} is the ratio of surface area of the body with clothes to the surface area of the body without clothes

t_a is the air temperature, [C]

t_r is the mean radiant temperature, [C]

V_{ar} is the relative air velocity, [m/s]

P_a is the water vapor partial pressure, [Pa]

h_c is the convective heat transfer coefficient, [W/m2C]

t_{cl} is the clothing surface temperature, [C]

Based on EN ISO 7730 [20], the values for the building under consideration were assumed:

- the clothing factor of 0.6 was chosen: Light working ensemble (Athletic shorts, woollen socks, cotton work shirt, work trousers).

- metabolic rate: 1.2 seated, light work (office, home, school, laboratory).

- external work: 0

- relative air velocity: 1

An internal calculation - simple model was selected in which the calculation is based on an area weighted mean surface temperature of all surfaces of a zone [39]. Moreover, the calculation of PMV and PPD does not take into account the effects of diffuse or direct solar radiation on room occupants. In the developed model, in order to verify the PMV and PPD values, additional outputs were defined for TYPE56. The variability of PMV and PPD over the year is shown in Figure. 12. The results of the conducted simulations are summarized in Table 3. As can be seen, there is no difference in the amount of power needed to heat the rooms after the implementation of the heat comfort module. However, at the same time, Figure.12 indicates that the indoor conditions in the analysed rooms are not within the expected range of - 0.5 to + 0.5 for comfortable (ideal) conditions. Hence, the percentage of people dissatisfied (PPD) in the least favourable period of time is 15.2% and 15.14% for the Sun-Zone and Back-Zone, respectively. PMV values range from - 0.7 to 0.7.

Table 2
Level of PMV and PPD [44].

PMV	[−3, −2.5]	[−2.5, −1.5]	[−1.5, −0.5]	[−0.5, +0.5]	[+0.5, +1.5]	[+1.5, +2.5]	[+2.5, +3]
PPD Thermal perception	95–100% Cold	50–95% Cool	10–50% Slightly cool	0–10% Neutral (Comfortable)	10–50% Slightly warm	50–95% Warm	95–100% Hot

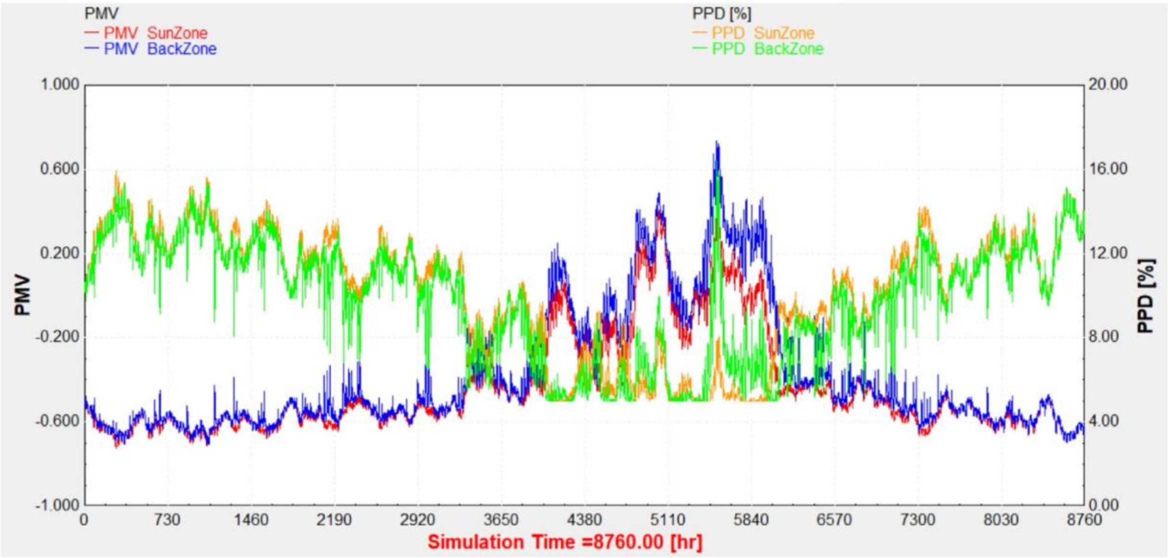

Fig. 12. Variability of PMV and PPD.

Table 3
Energy maximum peak value.

Scenario analysed	Heat demand Sun-Zone W/m^2	Heat demand Back-Zone W/m^2	Cooling demand Sun-Zone W/m^2	Cooling demand Back-Zone W/m^2
2	9.24	8.98	0	13.6
3	5.42	5.09	8.28	18.39
4	8.43	7.90	5.40	15.35
5	19.32	18.74	0	11.39
6	26.75	26.12	0	6.08
7	26.75	26.12	0	6.08

Table 4
Annual heating and cooling demand.

Scenario analysed	Heat demand Sun-Zone W/m^2	Heat demand Back-Zone W/m^2	Cooling demand SunZ-one W/m^2	Cooling demand Back-Zone W/m^2
2	24565.70	14884.11	0	1262.42
3	6713.16	2831.78	6997.02	13128.95
4	13320.83	7405.64	2469.57	6781.20
5	49129.12	37434.65	0	219.73
6	74698.11	61699.71	0	31.20
7	74698.11	61699.71	0	31.20

3. Conclusions

Constantly rising energy prices, and additionally the desire to reduce environmental impact by reducing pollutants emitted into the atmosphere, encourage the search for solutions to optimise building structures and installations while maintaining comfort for users. It is well known that depending on the thermal insulation of the building envelope (and its value of heat transfer coefficient) the amount of energy supplied to the building will vary. In extreme cases it can happen that the internal heat gains may be sufficient to cover all heating needs. However, including infiltration in the calculation indicates that heating of the fresh air supplied from outside is required and significantly affects the total energy demand. This paper analyses the energy demand of a detached single-family building with an unheated attic. The definition of the building model in TRNSYS software is presented step by step. Then, 7 scenarios of heating and cooling demand in the northern and southern zones were analysed:

1. Building geometry with assigned construction of partitions

2. Scenario 1 + assignment of ideal heating and cooling,

3. Scenario 2 + heat gains from people, lighting, and equipment,

4. Scenario 3 + schedules,

5. Scenario 4 + infiltration 0.6,

6. Scenario 4 + infiltration 1,

7. Scenario 4 + the impact of defining thermal comfort.

The maximum peak value is presented in Table 3. In contrast, the annual heating and cooling demand is presented in Table 4. The differences in total annual energy demand that occur between the different scenarios confirm how important it is to accurately determine the building's construction and occupancy. This has a huge impact on the choice of energy source for the building. Between the first and last scenario analysed, the difference in total annual energy demand for heating and cooling is 70.16%. The results presented did not take into account the energy needs for hot water preparation, which in a real building should be taken into account when selecting the heat source. In addition, consideration should be given to how to improve thermal comfort so that as few people as possible feel discomfort within the room. Since photovoltaic systems for domestic users are among the most preferred installations further research will focus on the selection of a PV and PV/T systems for the building under consideration. In addition, it will be verified that the selected PV and PV/T installation is capable of making the building energy self-sufficient under London's climatic conditions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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11.2 [3] District Cooling an Energy Conservation Technology- Science Talk May 2024 (Submitted)

ABSTRACT

It is going to take a long time for the world to wean itself off fossil fuels, but it is imperative we reduce GHG emissions as a matter of urgency. The only way to do that is to use energy more efficiently whilst we are trying to minimise the impact of fossil fuels on the environment.

Governments, industry and people need to stop wasting energy. This can be achieved through adopting energy efficiency measures in all aspects of our lives by introducing combined heat & power; waste heat recovery; better insulation; better use of BIM systems, and, especially in the Middle East – the greater use of District Cooling.

This talk will answer the following questions:

1. What is District Cooling?
2. Why is it more efficient, more reliable, more cost effective, and better for the environment than alternative methods of cooling?
3. Why GCC governments should encourage District Cooling through direct action?

Keywords:
District Cooling
Utility
Energy
Refrigerants
Grid congestion
Power
Oil
GHG (Greenhouse Gases)
LEED (Leadership in Efficient Energy Design)

Figures and tables

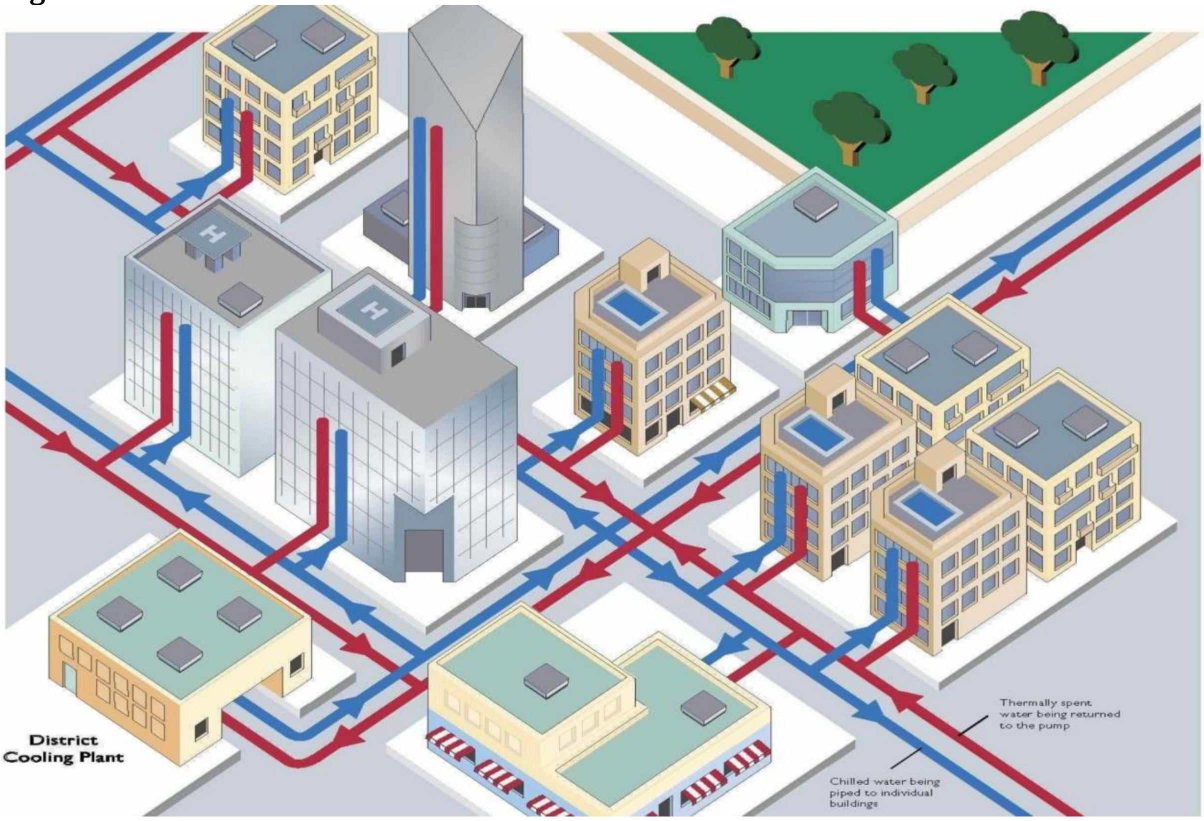

Figure 49: Centralized production and distribution of chilled water to a range of buildings

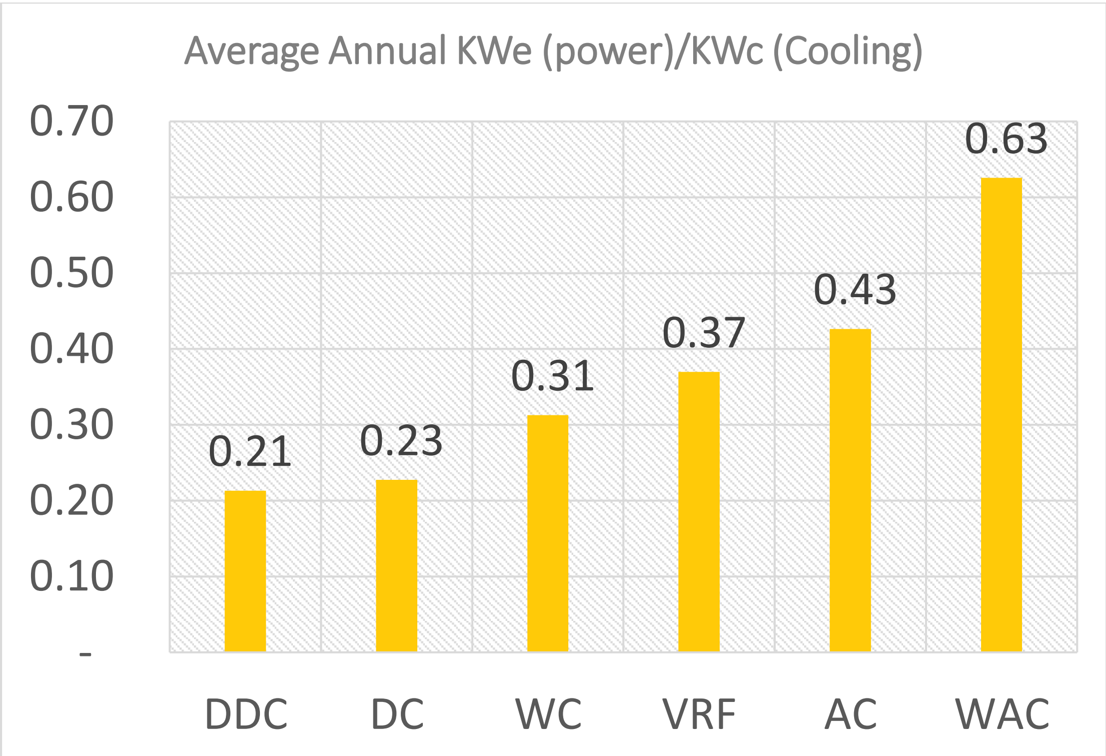

Figure 50: District Cooling is significantly more efficient than other conventional cooling methods

Table 1 highlights the coincident demand in Ton of Refrigeration and power consumption in KW for a 60,000 Ton (211 MW) district cooling plant hour by hour during a typical peak day. Plant power consumption with TES (Thermal Energy Storage), without TES and for a similar plant capacity, but with air cooled chillers (conventional) are also shown. The data is presented graphically in Figure 3.

Typical: Peak Day Power Consumption

Time	**Power Consumption (KW)**			**KW/TR**	
	With TES	**Without TES**	**Conventional**	**DC**	**Conventional**
1	39,193	31,437	55,015	0.81	1.41
2	39,003	30,489	53,355	0.80	1.40
3	38,550	29,799	52,148	0.79	1.39
4	39,116	29,322	51,313	0.80	1.41
5	40,662	34,369	60,147	0.84	1.46
6	41,683	36,412	63,721	0.86	1.50
7	41,398	36,450	63,787	0.85	1.49
8	40,297	38,985	68,224	0.83	1.45
9	39,968	41,212	72,121	0.82	1.44
10	38,579	36,254	63,445	0.79	1.39
11	38,340	35,409	61,966	0.79	1.38
12	39,922	38,093	66,663	0.82	1.44
13	39,224	42,290	74,008	0.81	1.41
14	42,081	49,702	86,978	0.86	1.51
15	42,435	51,535	90,186	0.87	1.53
16	42,366	51,837	90,715	0.87	1.52
17	41,834	53,152	93,016	0.86	1.50
18	41,405	49,097	85,920	0.85	1.49
19	41,448	49,396	86,443	0.85	1.49
39,033	37,265	65,213	0.80	1.40	1.45
38,255	36,389	63,680	0.79	1.38	1.43
22	38,608	39,643	69,376	0.79	1.39
23					
24					

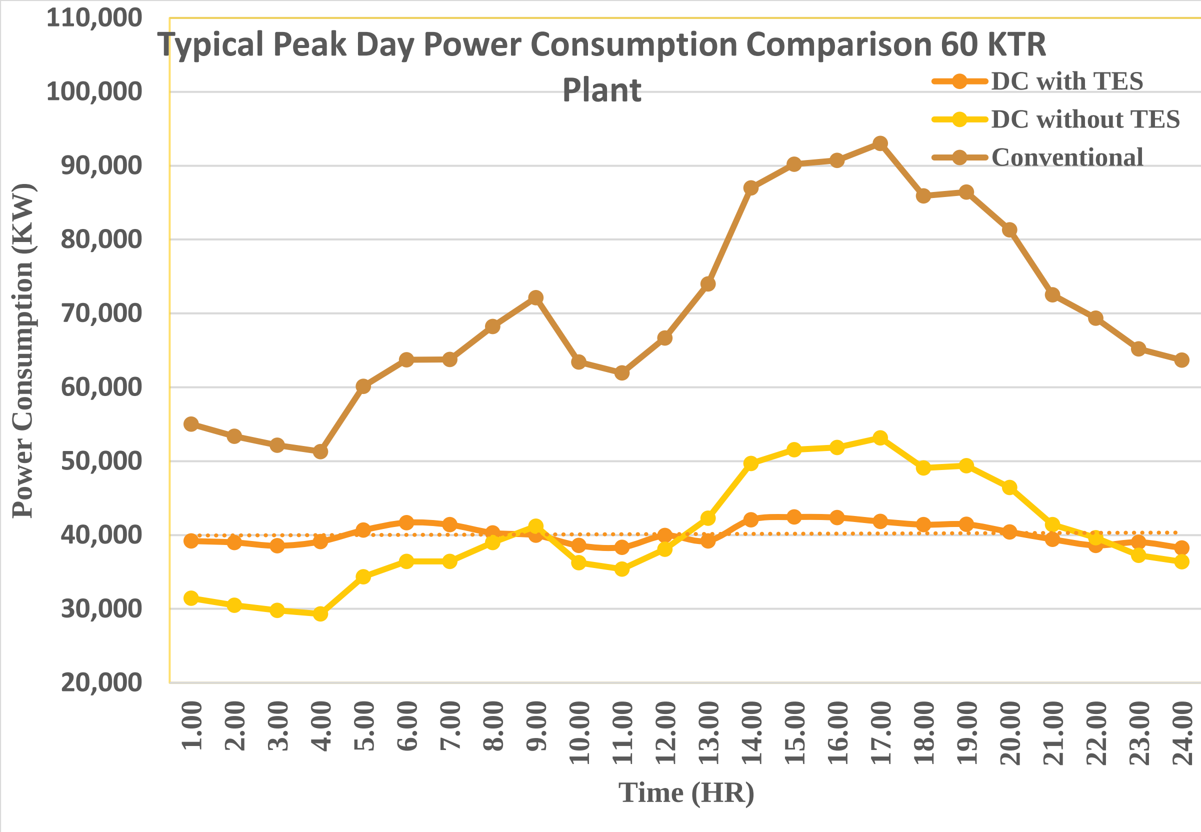

Figure 51: Typical Peak Day Power Consumption Comparison

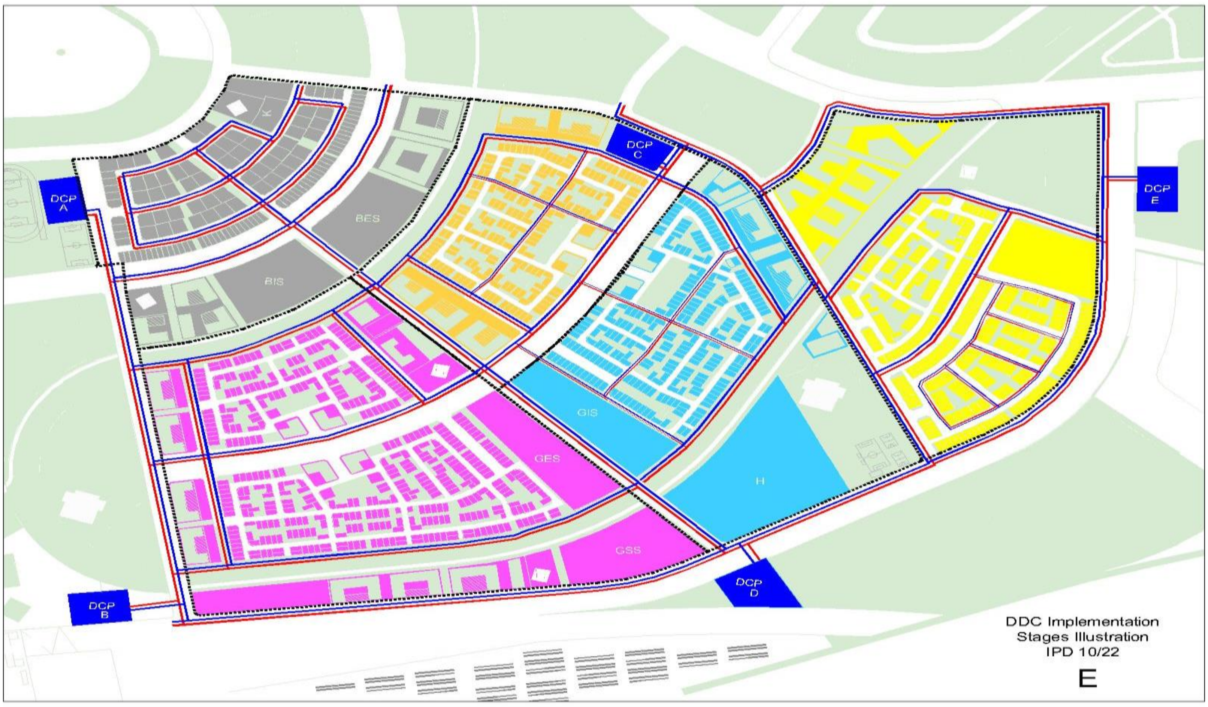

Figure 52: Distributed District Cooling Illustration

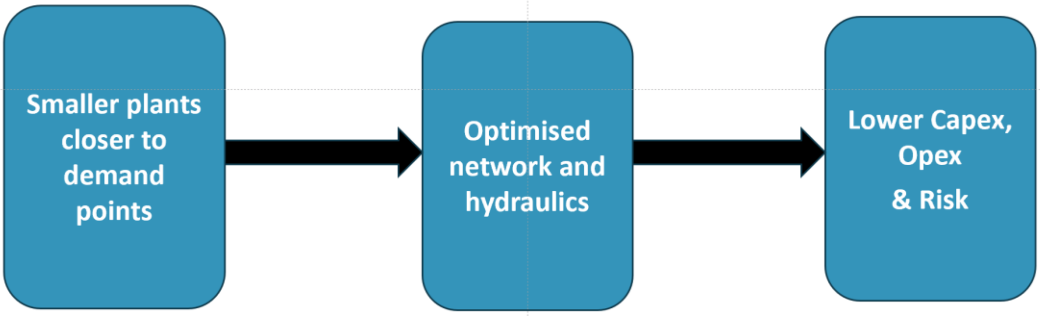

Figure 53: Distributed District Cooling (DDC) Major Benefits

Project	1	2	3	4	5	6	7	8	Total
Installed Capacity (MWc)	330	2,540	90	250	220	415	250	180	4,275
Connected Power (MW)	78	600	21	60	50	98	60	42	1,009
Savings (MW)	**75**	**575**	**20**	**57**	**50**	**94**	**57**	**41**	**969**

Figure 54: Sample DC Projects

CRediT authorship contribution statement Magdi Rashad: Conceptualization, Investigation, Writing – original draft. Dr Alina Zabnienska-Gora: Draft review, Prof Hussam Jouhara: Final review, editing and overall support.

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Declaration of interests

The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

Further reading

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