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Modelling an Optimisation Selection Method for Buildings Design Toward Environmental & Economic Objectives

Including a case study for building design guidelines in Kuwait, trading-off energy, cost, and emission objectives

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Declaration

The work presented in this thesis is original. Where information has been derived from other sources, it has been indicated in the thesis.

Table of Content

List of Tables

List of Figures

Dedication

الحمد لله الذي بنعمته تتم الصالحات

This journey wouldn’t have been completed without the support of my family and loved ones. Every success is theirs as much as it’s mine, and I’m blessed with all the support and love they provide.

To my advisor, thank you for being the light as I navigate through the dark corners of science. Your guidance was essential to reach my destination.

Abstract

Improving the performance of buildings based on their energy consumption is a challenging task. The main contributing factor to the amount of energy a building consumes is associated with maintaining the satisfaction of the building's users, by controlling the conditions within a building's envelope. Two main design factors control the overall buildings energy performance, the Heating Ventilation and Air Conditioning (HVAC) system design and building envelope design. There are several studies aimed at finding optimum solutions, evaluating these factors individually. The researches focused on the HVAC system design, has limited number of variables going into it, comparing different systems, operation set ups and fuels. As for the researches focusing on the buildings' envelop design, a large number of envelope's design variables can influence the building's energy consumption, such as its shape, geometry, material composition, elevation, and location, lead to different energy consumption rates.

This research systematically investigates how three main building envelop design variables (Orientation, Aspect ratio/compactness and Window to Wall ratio) impact the overall building's energy performance, including the potential of integrating sustainable energy generation systems, in search for optimum buildings designs than can achieve an environmental and economic balance. The first component is specific to the analyses of buildings' energy performance/consumption, based on the three building's envelop design variables. The energy performance considers different building geometries (from a square to a rectangular aspect ratio that is of length twice the width). Then, orienting those different forms at different directions. Further, varying the external walls composition at different window to wall ratios. The results are used to calculate the net yearly energy consumption rates and understand the patterns of energy consumption influenced by those three variables. All simulations are specific to the climate condition of Kuwait's geolocation, to develop an informed perspective of the climate influence on energy patterns. The results obtained have unique patterns that do not particularly agree with the general conclusions cited by other researches, specific to the relationship between buildings compactness and the energy consumption.

With the growing concerns of climate change effects on the environment, it's no longer enough to aim for passive mitigation solutions by reducing the energy consumption. The goal is to push for active ways to generate energy using sustainable resources, when possible, in the most economically feasible way. Hence, the second component of this research, focused on the opportunities to utilise the envelope for energy generation. By integrating sustainable energy generation systems within the buildings' façade, the dependency on the power from the grid, that is

mostly generated using fossil fuels, can be reduced. The climate characteristics of the Gulf Cooperation Council (GCC) countries impose specific challenges on buildings' energy performance as well as the efficiency of sustainable energy generation systems. Specific challenges such as the effect of dust on the most productive sustainable source for energy generation, solar photovoltaic systems, must be considered. Accordingly, a prediction model is created to quantify the regional effect of dust on the productivity of PV systems. Then, given the specific building variables used in the buildings' energy consumption calculations, the energy generation potentials are calculated.

The last component of this research aims to optimise the objectives of lower energy consumption rates, higher energy generation potentials (Lower emissions), and lower investment costs. A model is created to find optimum solutions that can balance those contradicting objectives. The results are obtained to provide guidance to the designers toward environmental and economic decisions, through a set of different possible design combinations.

Impact Statement

This research addresses certain gaps in literature, specific to the regional impact of climate on energy and buildings. Where some publications aimed to improve buildings' energy consumption, and others maximised the potentials from renewables to generate energy; This research explore a trade-off between the two, infusing renewable energy systems (RES) within the building's envelope design. A model is presented to find optimum solutions, suggesting envelope design variables, balancing between the objectives of minimum energy consumption and maximum potentials from RES's, in consideration of the regional climate challenges. The research will have an impact on the way buildings are designed, considering the user's requirements and local limitations, in three main parts.

First, the uniqueness of the buildings' energy consumption patterns emphasises on the importance of having regional research that can explore and challenge the specific climate conditions within the GCC. The simulated energy consumption rates determine the impact of the form, material used (windows and walls), and orientation on the buildings' overall energy performance. The analysis provides proper understanding of how each building envelope design variable affects each other and the overall energy consumption.

Second, the integration of RES's, and specifically Photovoltaics (PVs), within the building is explored; Using the same building envelope design variables, analysed for their effects on energy consumption patterns. As the productivity of PVs is highly influenced by their tilt and orientation, multiple positions/orientations of PVs were simulated. Building on the available literature, a new dust factor model is created to adjust the values of energy generation potentials. The model reflects the impact of dust and the scheduled times to remove it (cleaning). It's designed to provide a realistic prediction of PVs potentials, considering one of the dominant environment/climate factors within the region.

The Final part details the process of building an optimisation model, combining the above two parts. The output of the model balance between the building's energy performance environmentally and economically. The objectives are defined using five functions that calculate the fiscal impact of building construction, RES/PV investment, energy consumption rates, energy generation rates, and emissions. The model generates multiple Pareto optimum solutions, that allow the user to compare and decide on the envelope design variables that are most suitable to their case.

Chapter 1

This chapter introduces the problem this research is attempting to resolve, and discussing the current regional efforts taken to address them.

1.0 Improving Buildings' Energy Performance

The idea of developing a model that can provide guidance when it comes to buildings' design decision, starts with the goal of improving the current guidelines. Some of the available buildings design guidelines are developed aiming toward structural integrity, safety, energy performance, or environmental sustainability, in line with the regional laws and policies. In this research, the objective is to improve the building's energy performance while including environmental/sustainable energy systems, and in consideration of the fiscal feasibility. The start is with understanding the current situation today, exploring the global and local environmental challenges, and identifying the gap in research, needed to support new guidelines. Design guidelines can deliver environmental objectives through either the reduction of buildings' energy consumption by improving the selection of some design/construction elements, the integration of sustainable energy production systems within the building, or both.

The influence of climate on buildings' energy performance is significant. Cooling and heating requirements are the dominant factors in making buildings design decisions, through understanding the associated energy demands. Cooling and heating energy loads are a response to the heat balance between the external and internal spaces of buildings. Climate measures such as temperatures, humidity and solar radiation have major roles in controlling the energy consumption patterns throughout the year. These consumption patterns vary regionally and behave differently at each season within a year. By understanding regional climatic characteristic's, an analysis of the possibilities to enhancing the buildings' designs toward less energy consumption can be achieved. Moreover, exploration of the potential energy generation opportunities, harnessed from renewable resources, as well as the challenges facing their applications can be estimated.

Given the regional restrains, and how the results are highly impacted by the climate, this research will focus geographically on the Gulf Cooperation Council (GCC) region and specifically Kuwait. The buildings' consumption patterns and the productivity of sustainable resources to generate energy are the bases for understanding the need of improving buildings' designs within the GCC region; highlighting the importance of such research in the face of climate change and the growing population contributing toward it.

2.0 Role of Climate Change

Climate Change is described as "an environmental problem with global causes and consequences" where human contribution to carbon dioxide (CO_2) emissions alter the global climatic conditions, likely causing substantial harm to ecosystems and humans in the future (Jang and Hart, 2015). Evidence of climate change is reported continuously in many scientific and political outlets, aiming to find ways and encourage global efforts to reduce CO_2 emissions and Green-house gases, consume less fossil fuels, and optimise all natural resources' consumption. All of which can be linked to human activities that are subjecting a substantial impact to ecosystem and the sustainability of life and resources in future (Reay *et al.*, 2007). Evidence of climate change appears in many forms, with it being associated with the human contribution toward it. The link between climate change and its association with the increase of the average regional ambient temperatures, the severe drop in precipitation levels, as well as, the extreme weather events that are becoming more frequent is well established (Al-Maamary *et al.*, 2017).

Within the gulf cooperation council (GCC) in the Arabian Peninsula region, a 4^oC increase the average temperatures was recorded since the 1960's, along with a severe decline in the precipitation levels. This region went through a major industrial growth in the production of fossil fuels within the past hundred years. Recently, it was recorded that the GCC countries were found to be emitting more than four times other countries' average per capita. Environmental researches marked the increase of green-house gas (GHG) emissions to about 121% just between the years 1994 to 2005 (Atalay *et al.*, 2016). The effect of climate change has a direct impact on the air and water qualities (sea and ground water).

The world bank and the Institute for health metrics and evaluation, in the year 2013, estimated that the number of lives lost due to diseases associated with air pollution (indoor/outdoor) were about 125,000 within the Middle East and North Africa countries. According to the studies conducted in Kuwait, Qatar and Bahrain in recent years analysing the air quality and pollutants nature, it was concluded that vehicles and power generation were the main sources for particulate matter (PM). While industries, refineries and power generation sectors were found to be the major sources of sulphur dioxide (SO_2), nitrogen oxides (NOx), volatile organic compounds (VOC), and carbon monoxide (CO) (Eastnorth *et al.*, 2016).

Natural water sources are of a major importance to the GCC region. There is a dependency on the gulf's water for residential and industrial water consumption and power (Chowdhury and Al-Zahrani, 2013). Climate change has a direct impact on the water salinity through temperature increase. Also, indirectly, as the temperatures are rising, the demand for power is increasing through exhaustive consumption for air conditioning, resulting in the increase of distillation rates and GHG emissions.

The decrease of precipitation levels has a direct impact on growing crops as local wells is one of the main sources for irrigation. Although food security within the GCC was not being recognised to be of a great concern, climate change effects have been associated with yield loss in the region (Chakraborty and Newton, 2011). A survey, using a quantitative evaluation, on the increase of CO_2

and its influence over yield rates indicated that with the variance of emission scenarios and time intervals, yield loss would increase as an impact of climate change (Parry *et al.*, 2004). Considering the climate nature of this region, this is adding another complexity to an already challenging environment for yields' production.

Sandstorms and floods are not foreign to the GCC region. Extreme weather events have been recorded thought-out history and their devastating impact on the environment and the societies. However, the frequency and intensity of those events is on the rise. Better understanding of these events is essential to plan the way for selecting the most efficient sustainable solutions. The GCC region's exposure to the high-velocity northern winds leading to sandstorms was of significance in the last couple of years (WMO, 2013) . The meteorology records indicating the increase of regional sandstorms, having the arabic term *"Haboob; A penetrating sandstorm or dust storm with violent winds, occurring chiefly in Arabia, North Africa, and India"* added in **The American heritage® dictionary of the English language, 4th edition** describing such intense sandstorms now known globally. These events have been known to cause respiratory problems, significantly reduction in visibility, and hindering traffic operations (Baddock *et al.*, 2013; Bennion *et al.*, 2007; Garrison *et al.*, 2014).

The subject of sustainable solutions is not only important because of its direct influence on the GCC region's economic dependency on fossil fuels production and usage. Opting alternative renewable and environmental solutions is becoming more of a necessity to sustain human life, and the ability to maintain an acceptable living quality based on the conditions of air, water, and food (Parry *et al.*, 2004).

3.0 Current Efforts in the GCC

There are many efforts taking place in the GCC countries, acknowledging climate change as a global challenge that requires every state's attention. In the year 2012, The united nations' 18th climate change conference was held in Doha, Qatar. One of the main objectives was to address the challenges of air pollution with the GCC countries (Omidvarborna *et al.*, 2018). Since then, each country is exploring the use of sustainable solutions and technologies as an international

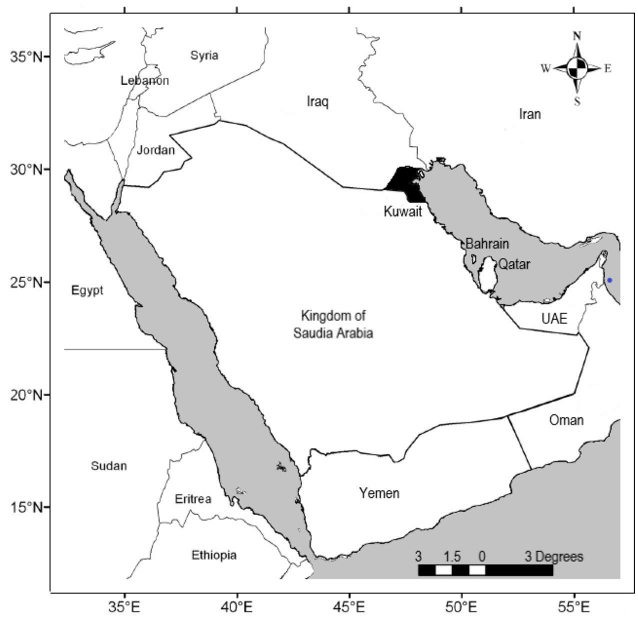


Figure 1 - Arabian Peninsula

commitment. Facing climate change, they committed to invest in renewable sources of energy, despite the availability of more economical resources (fossil fuels). **Figure-1** outlines the Arabian peninsula and highlights (in black) the specific location of Kuwait.

Kingdome of Bahrain

The kingdom of Bahrain is the smallest country within the GCC, a group of 35 islands, 24 km away from the east coast of the Kingdome of Saudia Arabia (KSA). The average temperatures reach 38^{o}C as highest during the summer, combined with mean daily maximum relative humidity from 79% to 83% between the months of May and August. In winter, the average temperatures can get as low as 14^{o}C within January (Alnaser and Flanagan, 2007). From 2013's electricity end-use annual records, the residential sector dominates the energy consumption with 48%, the commercial, industrial and agriculture sectors follow with 36%, 15% and 1% respectively (Krarti and Dubey, 2018).

Bahrain's dependency on fossil fuels for generating electricity is 100% (85% through natural gas and 15% through oil), 60% of which is consumed for air conditioning (Al-Maamary *et al.*, 2017). Bahrain is the second ranking country in emitting CO2 (per capita) in the GCC at 0.4% (Alnaser and Alnaser, 2009). In recognition of the increasing demand, earlier in 1999, the government adopted an energy efficiency code for commercial buildings stating specific requirements for walls/roofs thermal insulations and windows glazing, attempting to minimise buildings' energy consumption. This was then extended to all building types in 2013 (Krarti and Dubey, 2018). In 2006, with the aim of reducing the emitted pollution, Bahrain's government took on the Kyoto Protocol and the statute of IRENA (the international renewable energy agency) as an international commitment. Further, establishing their designated national authority considering clean development mechanisms in future energy projects (Al-Maamary *et al.*, 2017).

The characteristics of Bahrain's climate categorise it with high solar energy potential and moderate winds. Yet, it seems there is a gap between the policies and the investors, as well as a lack on advertised knowledge about the benefits and capabilities of sustainable systems. One of the first attempts for the use of sustainable solutions in Bahrain was in the world trade center; Three wind turbines with a capacity of 0.66 MW supplying 11–15% of the consumed energy by the building. In 2008, the government, in collaboration with the world bank aid, took initial steps toward the development of alternative energy sources. A budget of 900 million US$ was planned for producing 1000 MW through renewable energy projects by the year 2020 (Alnaser and Flanagan, 2007). Till the date of writing this research, there has been no record of a major investment producing energy through renewable resources.

Oman

The Sultanate of Oman is located at the South-Eastern corner of the Arabian peninsula, with shores extending over more than 2,000 kilometres along the Arabian sea. Between all GCC countries, Oman has the warmer temperatures in winter and among the coolest during summer, with a high relative humidity (Yousif *et al.*, 2019). Similar to the other GCC countries, Oman depends mainly on the fossil fuels for energy. Based on data reported in 2016, the industrial sector consumed about 52% of the power generated, followed by the transportation sector with 20% and then the residential sectors with 16%; with 83% of the electricity consumed specifically by buildings. (Enerdata, 2018a).

In 2005, the Kyoto protocol was signed committing to carbon gas emission reduction. Further, establishing their own designated National Authority working toward the Omani clean development mechanism for encouraging renewable energy utilisation (Al-Maamary *et al.*, 2017). Aiming toward the mitigation of climate change and economic diversification, a target of sustainable energy dependency of 10% was set by the year 2025 (Enerdata, 2018a).

Although there were many applications of sustainable efforts done on a smaller scale for solar power lighting systems, water pumping, and seismic monitoring stations and water pumping systems in remote areas (Al-Maamary *et al.*, 2017). On a larger scale, site preparation and the construction of a 1,021 MW Miraah solar concentrated solar power (CSP) plant started at the end of 2015 at the Amal West oil field. It was designed to supply power to extract heavy crude oil. Also, the first wind power plant launched by RAECO and Masdar with a capacity of 50 MW; was planned to be commissioned in 2017; records mentioned some delays due to commercial reasons (Enerdata, 2018a).

Qatar

A small semi-island sharing land borders only with KSA. With an economy that is fully dependent on hydrocarbons production, Qatar has the highest growing power sector among the GCC. Since 1997, their natural gas production was on the rise against their demand; in 2009 exceeding their demand by more than 2700 MW in production capability while reducing their pollutant emissions by 38% due to the cleaner characteristics of using natural gas. On another hand, being one of the top three natural gas producers in the world, 2005 records reported the highest levels of carbon emissions produced per capita and it only went up from there (Doukas *et al.*, 2006).

Evidence of climate change can be linked to the recorded increases in sea levels, groundwater salinity, and a decrease in air quality; common in most GCC countries. Qatar has the added challenge of limited land for industrial and residential growth. The dependency on energy intensive thermal processes for desalination, combined with the increase in water demand are highly linked to the increase in desertification in the mainland (Blank *et al.*, 2007).

A national development strategy was developed with a vision to diversify the energy sources; The aim was to supply 20% of the energy demand from renewable sources by 2030 with the capability of producing 1,800 MW through solar systems by the year 2020 (Enerdata, 2017a). Al-Kharsaah Solar plant is designed to generate 800 megawatt-peak (MWp), and to be completed by 2025. It was awarded to a consortium of Marubeni (51%) (a local Qatari Company) and Total (49%), being the country's first solar tender (Zeedan *et al.*, 2021).

Kingdome of Saudi Arabia (KSA)

In KSA, the challenge is more complex, with an area of 200 million km^2 in size (approximately 80% of the Arabian peninsula). The attempt to diversify the utilisation of land and resources require more understanding of the surrounding environmental parameters. Between one of the largest deserts on the planet, to forests covering up to 2.7 million hectares, pastures of 171 million acres, 35 km^2 of mangroves and 1480 km2 of coral reefs (Al-Maamary *et al.*, 2017). While KSA depends on fossil fuels as the major source of income being the top crude oil exporter in the world, the government is looking into their current activities with an objective to mitigate the alarming indications of their contribution toward climate change (Enerdata, 2018b). In 2012, the government funded a project for injecting 40 million cubic feet per day (ft^3/day) of CO_2 in one of their largest fields. In 2007, king Abdullah allocated $US 300 million funds to be invested in support of more efficient and cleaner oil techniques, such as carbon capture and storage (CCS). The government's efforts were also considering food security; In 2009, the king announced the "food safety initiative", with funding of about 800 million US$ to support investment in KSA private sector companies in agricultural projects in recognition of the impact of climate change and its impact on the agriculture sustainability (Al-Maamary *et al.*, 2017).

As for the sustainable solutions opportunities, in 2010, KSA developed a desalination plant with a capacity of 10 MW using solar power. Later, two more plants were initiated considering the success of the first one. Furthermore, a solar village project was developed with an area of about 67,180 m2 producing 350 kW of direct current (DC), distributing 1–1.5 MW/d of electrical power to three rural village (Yamada, 2016).

UAE

The united Arab Emirates UAE has a hot weather and ranked among the highest in humidity levels within the GCC at 85% (Alqubaisi and Al-alili, 2019). In 2012, UAE certified their green growth strategy, the first of its type in the region (Salahuddin and Gow, 2014). Earlier in 2010, Abu Dhabi completed its environment Vision 2030. Further, putting in place their environment strategy for years 2010–2014 focusing on climate change, air quality, water resources, waste, biodiversity, public awareness, hazardous materials, and environmental health and safety (Ministry of Energy (UAE), 2012). Also, in 2012, Abu Dhabi started the construction of their first nuclear reactor, with a plan to build three more. The plant was designed with a total capacity of (5.6 GW) to meet 20% of UAE's power requirements (Tolba and Saab, 2009).

When it comes to renewable energy, Dubai has set a target of generating at least 1% of their energy demand through renewable sources of energy by the year 2020, then to increase that to 5% by the year 2030. While in Abu Dhabi the target is to depend on renewable sources of energy to produce 7% of their demand by the year 2020. Their plan also included diversifying their power resources for domestic use, UAE's vision extended to plan a modern city (Masdar City) being fully sustainable, powered entirely by renewable energy sources.

Kuwait

Located at the Northeast corner of the Arabian peninsula, sharing borders with KSA and Iraq. Kuwait has an arid climate, generally known for its long and very hot summers with average temperatures ranging from 38 to 46 °C while temperatures over 50 °C are not uncommon. It also lacks rainfall with an average of 22 wet days a year with a mean annual rainfall of 119 mm. During summer, hot wind blows from the Northwest (locally known as "Shamal") dominating about 60% of the total wind directions (Al-Awadhi and AlShuaibi, 2013).

Kuwait's economy is highly dependent on the production of oil and gas. It is among the world's top 10 oil producers with 8% of the world's conventional oil reserves and considered the third largest oil exporter among OPEC member countries (Enerdata, 2017b). Oil and gas are also the main source of generating Energy in Kuwait through the process of transforming energy of the fuel into electrical energy using power stations (and water desalination plants). These power generation plants use different types of fossil fuels, natural gas, heavy fuel-oil, crude-oil and gas-oil. Depending on boiler design, the fuels are utilised with priority given to natural gas within the limits of the available quantities (MOE&W, 2019).

The year 1934 was when the national electricity company constructed the first small Direct Current (DC) electric plant in Kuwait. Production started with two (30 kW) generators and the power was distributed by +200 V DC line. Within 6 years, the number of consumers jumped from 60 to 700 by the year 1940, while increasing the installed capacity to 340 KW to meet that demand increase. The statistical yearbook issued by Kuwait's ministry of electricity and water recorded the population in the year 2017 as 4,500,476 (nationals and foreigners), with an average energy consumption per capita of 14,413 kWh/person. The mean annual rate of growth over the last 10 years was 1.5%. The government has plans for expansion and upgrading the energy generation utilities and so far, the energy production/supply utilities are keeping up with the growing population and demand (MOE&W, 2019) as the capacity of energy increased 75% within the last 10 years (Enerdata, 2017b).

Kuwait has recently commenced several utilities using alternative energy (solar and wind power) to produce energy. It's a part of a national commitment to generate 15% of the electricity demand from renewable energy sources by 2030 (Enerdata, 2017b; MOE&W, 2019). Further exploration with nuclear power was initiated through Kuwait's national nuclear energy committee, established in 2009 to develop a nuclear programme in cooperation with international organisations. Then, with the growing safety concerns after the Fukushima accident, all nuclear plans were reconsidered and the programme was transferred to the Kuwait institute for scientific research (KISR) for further study (Enerdata, 2017b). Al-Shygaya Power Plant is the first major project operating in 2018, using sustainable resources to produce energy. The government also reported future projects and expansions in diversifying energy production resources (Statistics Department & Information Center, 2021).

4.0 Problem Statement

Climate change is a global challenge that requires individual and state-wise actions toward minimising the human contribution toward it. It was recorded that only 0.6% of the world's populations lived in the GCC countries, yet the region contributes to 2.4% of the GHG emissions (Reiche, 2010). In recognition of these climate challenges, many initiatives took place in the GCC Region to address the industrial choices and the governmental roles in contribution to pollution and climate change (Eastnorth *et al.*, 2016). In 2012, Doha, Qatar hosted the 18th UN climate change conference at which commitments had been made toward environmental consciousness.

From the global energy market research data (Enerdata, 2017a, 2017c, 2017b, 2018c, 2018a, 2018b), **Figure-2** summarises the distribution of electricity consumption within the GCC. Between the residential, industrial and services sectors, the residential sector within the GCC dominates most of the electricity consumption in four out of the six countries. The residential sector mostly consists of buildings and their energy consumption mostly attributed toward HVAC utilities.

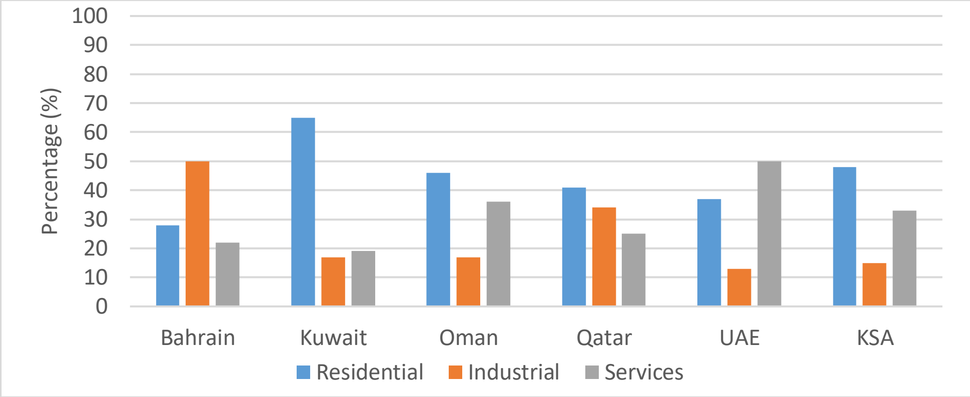


Figure 2 - GCC electricity consumption distribution summary

Further to this breakdown, buildings are not just a part of the residential sector, the electricity consumption classified here for the industrial and services sectors also involve buildings in support the function of each. For example, in Oman, the residential sector consumes 46% of the electricity generated. However, 83% of the electricity consumption is attributed to buildings (Enerdata, 2018a).

Although many design choices nowadays are more than an artistic building expression or a functional layout serving users' objectives, designing a building can be one of the most complex processes. The skills required to design a building are beyond the art and the visual appeal, it requires managing multi-disciplinary engineering functions and objectives. Energy, water, and emissions are now taking a major lead in deriving the design choices considering the international efforts facing the global concern of climate change. Buildings' energy consumption can be effectively reduced considering different design configurations to select the optimum design, according to the specific characteristics of the building's objectives, materials, construction methods and location (Baglivo *et al.*, 2017).

With the advances in the sustainable solutions industry, the solar potential in the GCC area measured to be one of the highest in the world; yet limited number of applications are taking place considering such solutions in the region. Wind and solar applications face multiple challenges in performance mainly due to the extreme high temperature, high humidity levels and dust accumulation (Khalfallah and Koliub, 2007; Sarver *et al.*, 2013; Sayyah *et al.*, 2014).

The governments in the GCC countries have been encouraging the use of sustainable solutions, adapting international guidelines, mobilising academic and scientific institutions/resources, and supporting green initiatives. However, there is still a lack in information published pertaining to the concentration of air pollutants within hot and arid regions as in the GCC, as well as their influence on the sustainable technologies (Omidvarborna *et al.*, 2018). Not to overlook the fact that the main source of energy from fossil fuels is not expensive within the GCC. The change towards alternative and renewable energy sources, and away from fossil fuel sources, must be prioritised in the GCC despite being the world's biggest producer of oil and gas (Abdul-Wahab *et al.*, 2015).

In order to understand this problem, and quantify the benefits from exploring several environmental and economic design alternatives, this research will aim to answer the following questions:

- How would the building design choices influence energy consumption?
- What design characteristics can improve a building performance in energy consumption?
- What efforts have taken place to promote the use of sustainable solutions?
- What are the climate characteristics that have caused a performance drop and reliability concerns about such technologies?
- What can be done to mitigate such performance drop causes?
- Can the mitigation suggestions be integrated with the design choices aimed toward reducing the energy consumption?
- Can the environmental objectives be achieved in an economically feasible way?

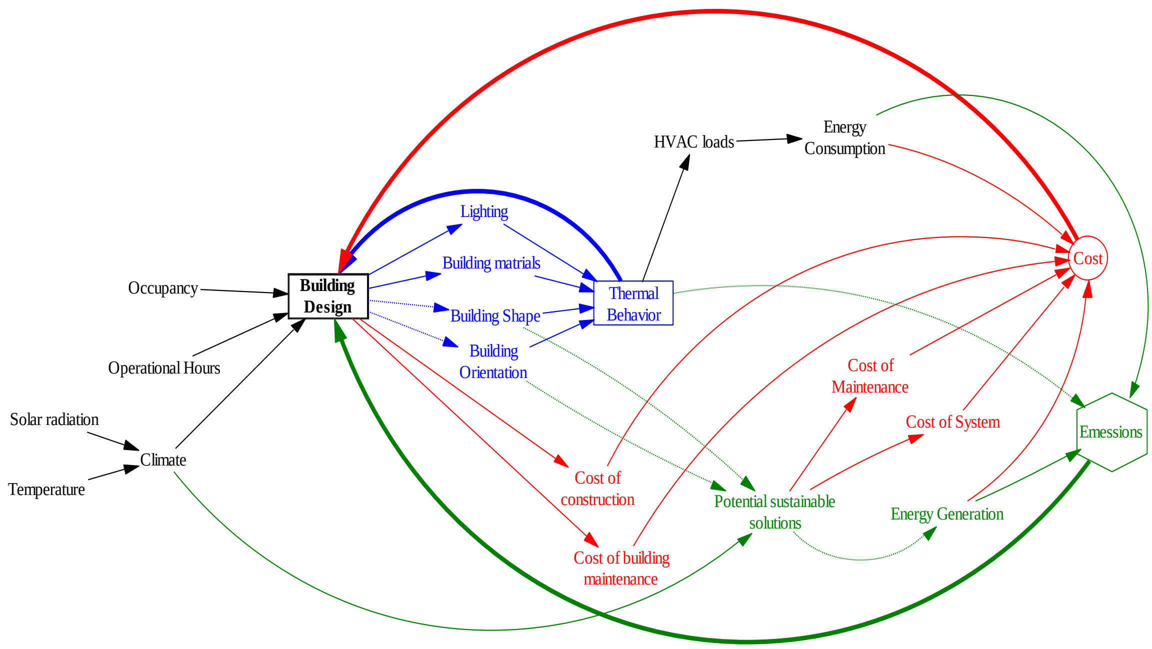
5.0 Research Objectives

The objective of this research is to develop a decision support system for buildings designs, based on the answers of the above questions, considering the user's scope limitations, building operation and the location characteristics. This is achieved by analysing the components in the following sections:

- Section 1: Buildings thermal behaviour
    - Define the design characteristics that have influence on the building's energy consumption and understand their significance (orientation, shape, building materials and lighting).
    - Calculate and define the optimum design characteristics and the efficiency/ performance variance in range from peak values.
    - Analyse the building's thermal behaviour which is directly influencing the HVAC loads and energy consumption.
- Section 2: Emissions
    - Define the potential sustainable solutions that can be integrated within the buildings design, based on the location's limitations and the regional climate conditions.
    - Identify the energy generation potentials and emissions' reduction utilising such technologies.
    - Analyse the possible solutions based on the location characteristics and performance concerns. This is based on manufacturers data and the associated studies made to analyse these systems' performance and efficiency.
- Section 3: Cost and solutions' feasibility

- Calculate the costs from energy consumption, linked to the HVAC loads and the building's thermal behaviour.
- Calculate the capital costs associated with the building materials and variables in section 1.
- Calculate the material and installation costs for the selected sustainable solutions in section 2.
- Calculate the potential costs saving through energy generation from the selected sustainable solutions in section 2.
- Finally, optimise the overall performance of the building considering the parameters in Section 1, 2 and 3; Producing a set of design/investment considerations that guide the building design toward environmental and economic objectives. It is essential that the conclusion out of this system is produced in way that can lead decision makers toward supporting the output. The guidelines are better displayed with emphasis on how smaller changes in efforts of reducing consumption or generating energy from renewable resources can make a significant contribution toward a better environment.

6.0 Research metrics Selection



____ Building design variables ____ Emission influences ____ Cost influences

____ Building and Regional conditions

Figure 3- Building variables and their influences

To tackle the design challenge, of finding optimum solutions based on multiple objectives, the influences from design variables are highlighted in a causal diagram (**Figure-3**) to show the relations and interactions. With this research the attempt is to optimise the following objectives:

A. Lower energy consumption by controlling the thermal behaviour within the building's envelope.
B. Reduce emissions through the introduction of sustainable solutions for energy generation.
C. Balancing the cost of the building construction/installations and the operational costs.

Figure-3 highlights the link between building's design and the influences of the thermal behaviour, cost, and emissions in loops. Once a variable change in any loop, the overall design is affected and with that the other loops are impacted.

Within this research, the selection of objectives is focused on lowering the energy consumption of buildings leading to the reduction of emissions. Considering that the main source of energy is delivered by an electrical grid connected to a desalination plant. This research is specific to buildings in Kuwait, the emissions are calculated based on these plants, operated by using fossil fuels. The objectives also consider the feasibility of integrating sustainable solutions within the building's envelop, validating the cost/benefit level and the performance efficiency of such solutions in the selected climate.

To generalise the objectives of this study, the analysis is chosen to be unrestricted by specific land conditions (no effect from shadowing of adjacent structures). Also, it considers a typical building form of a symmetric shape/aspect ratio that results in different behavioural patterns, due to the variance in the forms' orientation from a Zero degree (facing North) to 180 degrees (facing South). Due to symmetry, North facing and South facing orientations shall give the same energy consumption results.

The focus is on understanding the building's geometry effect on its overall thermal performance, in line with the other objectives. The difference in the aspect ratio, while keeping the floor area constant, leads to variance in the buildings surface area and the form compactness. The Aspect ratio as a variable, is chosen to have a simple rectangular geometry. With constant building's floor area and volume, the width to length ratio is to be varied from 1-to-1 ratio (square) to 1-to-2 ratio (rectangle with of length twice of its width). The increase in the building's surface area between those to ratios is about 6%.

The window to wall ratio analyses is within a range between 20% and 80%. It takes in to account the thermal performance of the building, leading to the energy consumption rates based on the envelop surface composition, as well as the associated cost of the material at each configuration.

The thermal insulation factor of a standard wall sections is typically greater than most external windows (Rashdi and Embi, 2016). If the objective is only focused on improving the thermal behaviour, it's safe to assume that the function will lean toward a minimum window to wall ratio. However, this variable is also affected by the need of sunlight inside the building if found to be important for the user's comfort level (depending on the operating objective of the building). Users' comfort levels can become an objective maximising that ratio in the calculations(Yang *et al.*, 2017).

With the customised nature of lighting design, the lighting loads in this research will be simulated with standard pre-defined settings, as the other variables change. This decision will make the results focused on the selected variables' contribution toward energy, making the sought guidelines more generic at the early design stages.

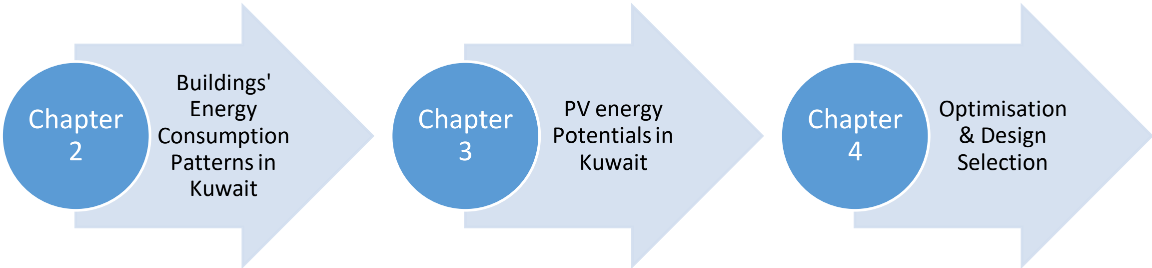
To assess the use of renewable energy/ sustainable resources, the research considers energy generation systems that can be integrated within the buildings' envelope such as photovoltaic (PV) panels. This decision is governed by the building design variables and influenced by the other objectives stated earlier. The following points explain the thought process and potentials from considering wall mounted PV systems:

A. It's a significant space/area of the building that can be better utilised.
B. Building's roofs are usually used for HVAC units and water storage/handling utilities.
C. Roof mounted panels require proper access and spacing for cleaning and maintenance.
D. Considering all buildings are constructed with window cleaning utilities, the same systems can be used for cleaning and maintenance accessibility to wall mounted system.
E. Dust accumulation is at its lowest when the panels are installed vertically .
F. Potential benefits of additional layer on the wall, improving the thermal quality of the buildings' envelope.

The analysis will consider the calculations of potential renewable energy, generated based on the direction/orientation and the tilt of PV panels, corresponding to the solar radiation throughout the year. This naturally linked to the orientation of each external wall and the wall area available at each side as variables. Some studies have explored the potentials from vertically installed solar panels (Austin, 2018; Haroldson, 2017; Mohammadi and Khorasanizadeh, 2015). This research shall validate the potentials, while recognising the regional challenges, to optimise the chosen objectives and variables.

In this research, design choices, from specific building orientation, to aspect ratio, and window to wall ratio, are evaluated for their impact on the cost of building materials and yearly energy consumption. Some regional parameters are quantified based on local measurements and regional simulations, such as the local rates of fuels, construction materials, climate characteristics and policy guidelines. The evaluation of energy consumption cost is based on the regional prices of fossil fuels vs. the cost of the energy generated through sustainable solutions. This shall lead to find optimum solutions, based on specific values from the analysed variables to achieve the defined objectives.

The structure of this research analyses the building's envelope impact on energy consumption and the potential for energy generation separately. Then the last chapter details the optimisation model, created to find a set of solutions, that can harmonise between the contradicting objectives:



The following chart contains a process summary. It breaks down the main steps designed to achieve the research's objectives and how the chapters intersect.

Chapter 2 Energy Consumption
Process Flow Chart
Chapter 3 Energy Generation
Lower Energy Consumption
Define Objectives
Higher Energy Generation
Building's Orientation
Building's Aspect Ratio
Window to Wall Ratio
Define Variables
Orientation of panels
No. of Solar Panels based or AR & WWR
Tilt of installation
Building's Volume
Building's Materials
Operation Settings
Define Simulation's Parameters
Renewable Systems
Climate impact
Operation Settings
N, NE, E & SE
1:1, 1:1.25, 1:1.5, 1:1.75, & 1:2
20%, 40%, 60% & 80%
Define Simulation's Variables' Ranges
N, NE, E, SE, S, SW, W, & NW
1:1, 1:1.25, 1:1.5, 1:1.75, & 1:2
20%, 40%, 60% & 80% of Wall
Panel's tilt 90º, 85º and 80º
DesignBuilder: Building's Geometry & Operation's setting modelling
EnergyPlus: Simulation of Building's Energy Consumption
Data Generation
solarninja: Regional solar energy simulation platform
Data from previous relevant literature used to create a model
Plotting Results
Calculating Variances
Data Analysis
Plotting Results
Calculating Variances
Repeat the Analysis with up-scaled Building Geometry
Results Validation
Prediction accuracy evaluation metrics
Discussion & Summery of Findings
Indications & Patterns
Discussion & Summery of Findings
Chapter 4 Optimisation

Chapter 2

This chapter is focused on the effect of buildings envelop design on the overall energy consumption in Kuwait, quantifying the impact of the orientation, aspect ratio and window to wall ratio as variables.

Key aspects of this chapter have been published in a paper titled:

“Climate, Buildings’ Envelope Design and Energy Patterns: Improving Energy Performance of New Buildings in Kuwait”

1.0 Background and Literature Review

1.1 Energy and Buildings

It is important that at the early design stage of a project, the designers comprehend the user's requirements. Within the budget defined, the designers must interpret the scope, deciding on its engineering components such as the building's structure, material, operating systems and control systems (Tiene *et al.*, 2018). To optimise these components, designers need to evaluate them based on their contribution toward the building performance as well as their cost (Fesanghary *et al.*, 2012). The components while being individually analysed, they are also evaluated for their impact on one another. Several research efforts analyse the pre-defined design parameters for their optimum performance using different sets of financial and non-financial objectives (Nguyen *et al.*, 2014). The old/conventional practice of isolating design disciplines (such as architects, electrical engineers, mechanical engineers, civil engineers) resulted in fragmented solutions. That approach led to conflicts, especially when different objectives derived from similar variables are contradicting (Leistner *et al.*, 2022). By integrating those design disciplines, synergy between the performance and cost can be achieved. The search for an optimum design always starts with proper identification of the scope. Optimum choice is mainly a function meeting specific objectives corresponding to specific variables. Proper definition of objectives and variables is key for a successful optimisation process.

An example of the conflicts that need to be addressed, is how a building subjected to a high level of solar/thermal gains through its envelop during winter has a positive effect on its energy consumption due to the lower rate of energy used for heating (Ferrara *et al.*, 2015). Meanwhile in summer, that same building envelope design results in an increase of energy consumption due to higher rate of energy use for cooling. In that example, the designers were trying to find a trade-off between lower energy and comfort by varying the wall/roof/ceiling construction typology, glazing characteristics, thickness of external insulation on external walls/roof, dimensions of glazed area, depth of overhang and vertical fin shading system. It was found that those variables also influenced the lighting required to maintain a desired visual comfort, taking in to account the daylight analysis and the associated electrical loads required to maintain it, using artificial lighting sources.

As the number of variables affecting the building's energy performance is composed of every material and system within the building, different variables exert conflicting influences (Chantrelle *et al.*, 2011; Mahdavi and Mahattanatawe, 2003; Wang and Jin, 2000). Researchers identify variables of interest, their range of variance then analyse the buildings performance within those boundaries. Their objective is to report ways that can help designers in decisions that can improve the performance of their buildings (Evins, 2013). Improvements on buildings' energy performance can reach further than their consumption. The objective of improving buildings' thermal performance while varying the envelop profile and material layering can be coupled with the objective of including a type of renewable energy system (Albatayneh *et al.*, 2018). The optimisation problem then expands by determining which combination of envelope profiles could provide the greatest energy savings, while considering the least cost of investment in a renewable system that can generate the most energy.

The climate of the region, where a study is conducted, is an important parameter when the focus is to understand the effect of specific envelop design variables on its the thermal performance and energy demand (Choi, 2017). In a study specific to a new residential building in Southern Italy, the thermal performance is evaluated considering the design of walls, ceilings, roof, windows and shading as variables (Baglivo *et al.*, 2017). It emphasised on the climate being one of the key parameters to decide on a specific design. One of the general findings is that within colder climates, insulation and building air tightness have more influence on the building's thermal behaviour, maintaining the indoor desired comfort levels. While for buildings located in warm areas, solar radiation and heat gains lead to internal overheating, highlighting the requirement of proper ventilation and air circulation.

Building's geometry can also be considered as a design variable to optimise the buildings form and its component with the objective of having less heat gain and eventually lower cooling load. In a case study, the simulation of different building forms, based on the weather characteristics of Malaysia, reported different energy consumption rates (Rashdi and Embi, 2016). That variance is due to the form/shape (architectural perspective) and the geometry of buildings being influenced by the solar energy it receives based on the amount of surface area its exposed to. That requires analysing the amount of energy consumption due to the power consumed by cooling systems; a requirement that is geographically specific. The case study cited that in Malaysia, most of the commercial office building's cooling systems consume (in average) about 70% of yearly total energy consumption. Their results indicate that, the selection of an optimum form, orientation, and envelope configuration has the potential to reduce the building's energy consumption by almost 40%.

The influence of building envelope variables can amount to more a proportional effect on the thermal load than on either capital cost or usable area of a building (Gero *et al.*, 1983). That conclusion was made based on a case study in Sydney, Australia. The analysis took in to account the building's orientation, number of floors, window to wall ratio, glazing material specifications as variables. Kept as constants are the overall building's volume, floor's height, and HVAC settings.

In this research, the focus is on the climatic characteristics of Kuwait and the impact of its seasonal weather; extreme and long hot summer, a short mild cold in winter and the common dust events (Al-Awadhi and AlShuaibi, 2013). The patterns of energy loads and their distributions, that are mostly consumed to balance the thermostatic conditions between what is within the building's envelop and the external environmental elements, are analysed.

1.2 Buildings Design Metrics

In line with the stated research objective, defining the main contributing factors toward buildings' energy consumption is essential as a first step in developing a guidance system (Chapter 1, Fig. 3). Literature analysing these factors is key to understanding their significance and contribution in conserving, consuming, or generating energy.

a. Thermal Behaviour

Buildings electricity consumption, At the EU level, buildings accounts for approximately 50% of energy consumption, resulting in 40% of the carbon emission determined by their direct energy use (Tronchin *et al.*, 2018). Buildings have been enlisted at the top of districts energy consumption records and in Kuwait it's no different. As per Enerdata's Kuwait energy report, most of the electricity generated is consumed by households (65%), followed by services (19%) and industry (17%) (2016) (Enerdata, 2017b). The records show that heating and cooling systems account for the majority of building's energy consumption. Opportunities have been shown, that building's consumptions can be significantly reduced, evaluating different building configurations at the design stage, then selecting the most appropriate ones according to the specific characteristics of the building usage, operations and location (Baglivo *et al.*, 2017).

The start must be in understanding the variables that can directly affect the energy consumption. Fundamental design decisions such as the orientation, shape, building materials and lighting are the envelop components responsible for a building's behaviour responding to cooling, heating, and lighting energy loads.

i. Orientation:

A building's orientation is a significant design decision, restricted by many factors. The decision for choosing a specific orientation is restricted by the land's dimensions, topography, infrastructure, surrounding structures and the building's purpose/operations. If the building's thermal behaviour is considered as a reaction to the climate conditions, the balance between the indoor and the outdoor must be governed by the difference between the two, as well as the specifications of the medium separating them. Energy is consumed to maintain the indoor ambient temperature at the user's comfort level, against the outdoor ambient temperature, affected by solar radiation, wind, elevation and humidity.

By analysing the effect of the orientation on a building with a rectangular aspect ratio of a length twice the width, the optimum energy performance is recorded when the building's longer span is facing North (Aksoy and Inalli, 2006). That conclusion is specific to the relatively cold climate of Elazig, Turkey. The energy simulation compared the heating required, based on their specific regional requirements.

Other analysis considered many other building forms, reporting that the variation of orientation has a moderate effect on the cooling loads (Rashdi and Embi, 2016). It also generalised that orientating the longer axis of a building to face North would be the best alternative. In that simulation, the results are specific to the weather conditions in Malaysia and might differ if simulated in a different region.

The general notions argues that buildings with more surface areas are prone to more sun radiation and required more energy for heating/cooling, given the orientation at which the buildings thermal behaviour is mostly impacted. It's important to highlight that based on the environment of region, buildings may require seasonal heating, cooling, or both. By reviewing literature with objectives and variables exploring the impact of orientation over building's energy consumption, the orientation of a building is usually linked to the definition of its form, the dimensions of its aspect ratio and the positioning of its walls. It is noticed that the building orientation is not fond to be analysed independently from other variables such as the building's form and its walls/roof compositions (Aksoy and Inalli, 2006; Rashdi and Embi, 2016).

ii. Shape

The building's geometry contribution toward energy consumption is a function of the surface area exposed to the external environment, considering the volume requiring thermal control. This can be referred to as the building's thermal behaviour toward its compactness. The building's geometry relates to the surface area exposure to external temperatures, solar radiation and its angle, area and direction of each external surface and its position (Marks, 1997). When it comes to buildings within hot regions, its reported that buildings with lower surface to volume ratio (more compact), require less cooling loads (Rashdi and Embi, 2016). The same conclusion was also reached by comparing the heating loads associated with the building's within a cold climate (Aksoy and Inalli, 2006); Comparing two building geometries, it was found that the more compact form of square shaped aspect ratio performed better than the rectangular shaped aspect ratio of a length twice the width.

The impact of a building's shape can also be compared based on different elevations. The Analysis of buildings of the same volume, but with different number of floors, showed that the energy consumed for thermal control is at its lowest for buildings with a single floor, and energy rate increases as the number of floors increases (Gero *et al.*, 1983). In that particular case, the simulation was done based on the weather conditions in Sydney, Australia. It's important to restate that such conclusions are location sensitive and would be highly impacted by the nature of the dominate climate conditions.

The way geometry is defined may take the results in a different direction, even if the objectives are the same. When the shape of the building is allowed to vary in a wide range, other design factors can be highly impacted such as its cost and utilised areas. In a research investigating the design of a free-form shaped building, the objective was not limited to finding the minimum yearly energy loads (for heating), the analysis also searched for the minimum building costs (materials and construction) (Marks, 1997). The building's form was set as a function with constant building volume and height. The analysis aim is to optimise the form of the building to improve its energy performance, while varying the shape and orientation. The restrain about the shape is to be formed of two arbitrary curves and symmetrical on an x-y plan (the x axis where the two curves intersect, and the y axis perpendicular at the middle of the 2 points of intersection). In such case, the practicality of the design might not be the main objective, the cost in this case was a function of the quantities of the materials used for each possible design. The climate of the selected region, as an input, affects the heating requirements. The variance in optimum shape changes from a polygon (within areas of long heating periods) to a regular octagon (within areas of short heating periods).

iii. Building Materials

Selecting the most suitable building materials is not an easy task. Many factors go into the process of defining the envelope's surfaces materials/profiles and composition. To achieve a desired architecture look, materials selection can have an impact on the building's energy consumption. With the many parameters that can affect a building's performance, in many cases different parameters exert conflicting influences (Huang and Niu, 2016). The window to wall ratio, shading, thermal insulation performance of the façade material of choice and the thermal insulation performance of roof design are some of the major contributors to a building's thermal behaviour.

Again, these variables effect on the energy performance is highly linked to the chosen climate. In the process of optimising the performance of a building, different design recommendations might be given, suggesting different materials compositions, if investigated within different climates. The existing literature mainly selected a limited number of variables that are a part of the building's envelope (architectural and structural), to investigate their effect on the energy consumption.

When the objective of the analysis is focused on investigating a specific element of building's envelope materials, the analysis will probably overlook the impact of other design elements and other key objectives. On one hand, in a case where the walls, roof, shading, and windows properties are the focus, a single objective can be chosen, such as, optimising the building's thermal performance (Baglivo *et al.*, 2017). The results can help identifying which element is more critical to that objective, given the climate of a certain region. On the other hand, multiple objectives can be considered while investigating the impact of selected building envelop design variables, such as lowering energy consumption and lowering the building's construction cost. For example, one study selected specific wall modules (cavity brick, insulated cavity brick, insulated brick veneer and insulated reverse brick veneer) to determine which type could provide the greatest energy savings with the least construction cost (Albatayneh *et al.*, 2018). While in another study, variables such as the glazing material specifications were the focus, analysed for the same objectives (Gero *et al.*, 1983). One of the key conclusions in those cases that the effect on the thermal load as an objective is more proportional than it was on the cost as an objective.

Other cases considered additional objectives such as the thermal comfort of the users (Delgarm, Sajadi and Delgarm, 2016). The thermal comfort as an objective, defined in the ASHRAE Standard (55–2013) as "Thermal comfort is the condition of mind that describes satisfaction with the thermal environment" that is highly associated with the health, well-being, and productivity of occupants. The *ASHRAE Standard 55* for thermal acceptability of indoor environments requires that more than 80% of the occupants need to be satisfied with the building's thermal conditions.

iv. Lighting

There is a considerable amount of opportunities in designing a building's lighting system with the objective of minimising the energy consumption (Cassol *et al.*, 2011). Its highly linked to the illumination from natural resources, the latest lighting technologies, the lighting management systems as well as the design/distribution of lighting. The art of lighting design and distribution is usually customised to the building's layout and its operation's philosophy. It's also dependant on the amount of sunlight penetrating the envelop at the set operational hours. Linked to the lighting design, is the natural sunlight within a space, through windows and transparent glazed roofs, and in association, the glazing sizes and the material's light transmittance qualities.

Addressing the lighting design choices require defining specific details further than the building location, shape, orientation, windows/glazing details. Lighting design varies based on the internal spacing dimensions, walls/dividers, and windows positioning. Those aspects can be assessed for their influence over the users' visual comfort level, the building's energy performance and construction/material/installation costs (Marks, 1997).

The details needed to consider the lighting design opportunities as one of the variables for minimising the building's energy consumption are more advanced to the level of decision guidance this research is aiming to provide.

b. Emissions

Controlling emissions is a global responsibility most countries take seriously. International platforms are set yearly to discuss scientific advances in reducing emissions and the latest technologies for generating sustainable energy such as **The UN's climate change conference**[1]**, The sustainability summit**[2]**, The conference and exhibition on emissions monitoring**[3]**, The international conference on energy and sustainability**[4]. Topping the most important air pollutants is carbon dioxide (CO_2), further are carbon monoxide (CO), particulate matter (PM), nitrogen oxides (NOx), volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), persistent organic pollutants (POPs), ozone (O_3), and sulphur dioxide (SO_2) (Omidvarborna *et al.*, 2018). Based on the national ambient air quality standards, maximum allowable concentrations have been set based on the human health and/or environmental criteria. It also explained how those pollutants are a major health concern, according to the world bank and the institute for health metrics and evaluation, an estimated that for the year 2013, 125,000 lives were lost because of diseases associated with outdoor and indoor air pollution in the Middle East and North Africa countries only.

[1] https://unfccc.int/cop25
[2] https://events.economist.com/events-conferences/emea/sustainability-summit-london
[3] https://www.ilmexhibitions.com/cem/?gclid=EAIaIQobChMI972G4pqr5wIViLPtCh3KsQF2EAMYAiAAEgJKlfD_BwE
[4] https://www.wessex.ac.uk/conferences/2019/energy-and-sustainability-2019

As the emissions produced by any country has a global effect, the solutions each country could attempt differ based on their own contribution toward the problem, their available resources, and the climate resources/challenges they have. The solutions usually take place as mitigation efforts to consume less energy, managing the dependency on certain fuels toward cleaner alternatives and/or utilising renewable resources to generate energy.

There are many methods for sustainable energy generation, famously, using solar, thermal and wind power. Most of the sustainable energy generating systems are created to be independently installed, operated, and maintained. Such systems usually require being considered in the project's budget as an investment and allocating an area within the project for harnessing energy (solar panels, wind turbines).

The scope of this research focuses on the efforts possible within a building project's design and planning in the state of Kuwait. It considers maximising the opportunity of generating energy through sustainable resources as an objective. The optimisation process is planned to be solved as a multi-objective problem, by lowering the emissions through increasing the reliability on sustainable energy sources as well as lowering energy consumption through the building's envelop design within the earlier stated variables corresponding to the thermal behaviour.

Furthermore, the use of solar power in the GCC area have been in the focus of many studies and experiments (Alnaser and Alnaser, 2009; Doukas *et al.*, 2006; Reiche, 2010; Salahuddin and Gow, 2014). Although, sun as a resource is promised to deliver with high performance considering the solar radiation and concentration in the GCC region. The application of such technology is facing many challenges to sustain their performance due to the frequent wind/dust activity and extreme heat waves (Al-Awadhi and AlShuaibi, 2013; Flowers *et al.*, 2016; Khalfallah and Koliub, 2007; Sarver *et al.*, 2013; Sayyah *et al.*, 2014; Yamada, 2016). The next chapter will include further breakdown over the effect of the surrounding environmental challenges in the face of sustainable energy solutions.

c. Cost

In most organizations, the decision to proceed with a project (or set of actions) is concluded based on the response of two questions, "How much it costs?" And "Can we afford it?". The availability of a financing method and the decision to proceed are always binary, if you have the means you can proceed, if you don't you can't. The minimisation of cost as an objective in building projects (new and refurbishment), can be addressed within two stages; the objective can be focused on lowering the capital cost of material's selection during the construction, making design choices that can lower the building's energy consumption (as an operational cost) or a combination of the two. The optimisation of building design parameters, for lower consumption, mostly conflicts with other scope objective mostly pertaining user's comfort (Albatayneh *et al.*, 2018; Marks, 1997; Pernodet *et al.*, 2009; Torres and Sakamoto, 2007). It's found in these studies, that the objective of minimising the cost is challenged by the increase in the cost of construction and material composition while attempting to maintain the user's comfort thermally and/or visually. Standards as the *ASHRAE Standard 55*, state the limitations of what the minimum user's visual and thermal comforts are. It's one of the main boundary conditions the designers use to make sure that their optimisation efforts within the cost and environmental objectives are not conflicting with the occupants' satisfaction. However, it's been proven that the energy consumption of a building project can be reduced by evaluating different design configurations and selecting the most appropriate ones according to the specific characteristics of the building scope and the characteristics of the site (Baglivo *et al.*, 2017).

Furthermore, when the designers opt to consider renewable energy generation system, the cost objective can be challenged with the feasibility of the selected energy generation system factoring its efficiency, maintenance and environmental contribution against the other economical alternatives mostly applied (energy through fossil fuels). As the objective of emission reduction can be maximised through the increase of the size of the system (i.e., increasing the number of solar panels), to constrain this objective, limitations must be specified such as the space available for system installation. Furthermore, other objectives can work in contradiction to the emission reduction, such as the objective of capital cost minimisation. The sustainable systems are weather dependent, the problem of balancing the mismatch between inflexible production and inelastic demand better be considered economically (Tronchin *et al.*, 2018). The feasibility of renewable systems, cost wise, is measured throughout the years of used. The payback period can be calculated based on the amount of energy savings from the overall energy cost, compared to what would have been the expenditure on energy if it was completely sourced from the local grid (depending on fossil fuels) (Flowers *et al.*, 2016).

1.3 Energy Consumption Simulation

A building is naturally a system of interrelated engineering components such as its physical shape/form, structure, material, HVAC systems, occupancy rates, operating schedules, and its location's climatic conditions (Rashdi and Embi, 2016). The interaction between such variables, often nonlinear, is extremely complex for the wide range of variables and their variations to be optimised (Damerau *et al.*, 2016). Buildings designers (engineers and architects) often use energy simulation programs for building performance simulation (BPS) such as DOE-2 (Caldas and Norford, 2002), IDA ICE (Hamdy *et al.*, 2011), EnergyPlus (Wright and Mourshed, 2009), Integrated environmental solutions (IES) (Azhar *et al.*, 2010) and TRNSYS (Fong *et al.*, 2006). They evaluate and optimise the performance of buildings in variation of specific parameters, defining an (or a set) objective(s) (Delgarm, Sajadi and Delgarm, 2016). These simulation platforms have different approaches in calculating the estimated energy consumption rates; the result sometimes vary, but the general input requirements are almost the same. The concept of optimising the building envelope based on simulations was first introduced in 1992 (Sullivan *et al.*, 1992). The results of these simulation systems have been tested by several studies and the reliability on their performance was assessed (Zhou *et al.*, 2014, 2008). The reliability of results from such simulation depends on the quality and accuracy of input data (Dodoo *et al.*, 2017). Moreover, the modellers' experience and their competency contribute significantly to the quality of simulation model and its output (Choi, 2017; Imam *et al.*, 2017a; Mirsadeghi *et al.*, 2013; Simões *et al.*, 2014; Ward *et al.*, 2016), considering the over-simplification of complex systems. Yet, some studies modelled the same building and carefully mapped the input parameters using different simulation platforms, then ended up with differences ranging from 17% to 67% between the total energy consumption predictions (Al-janabi *et al.*, 2019).

The capabilities of 20 different energy simulation softwares have been compared (Crawley *et al.*, 2008). Table 1 summarises the diverse potentials from these simulation platforms.

Table 1 - Contrasting features and capabilities between 20 energy simulation platforms

	SIMULATION PROGRAM	**SIMULATION FEATURES AND CAPABILITIES (NO. OF FEATURES CROSS-CHECKED)**			
		Zone Load (9)	Building envelope, Daylighting & Solar (9)	Infiltration, Ventilation, room air & multi-zone airflow (9)	Economic Evaluation (4)
1	EnergyPlus (26/31)	8	8	6	4
2	IES /VES (24/31)	9	5	7	3
3	ESP-r (20/31)	5	6	8	1
4	Tas (20/31)	8	4	6	2
5	DeST (19/31)	6	3	7	3
6	IDA ICE (18/31)	7	4	5	2
7	TRNSYS (18/31)	5	3	6	4
8	BSim (16/31)	4	3	6	3
9	TRACE (16/31)	5	6	1	4
10	PowerDomus (15/31)	4	2	5	4
11	eQUEST (12/31)	4	2	2	4
12	HEED (12/31)	6	1	1	4
13	DOE-2.1E (11/31)	5	1	1	4
14	SUNREL (10/31)	3	2	5	0
15	Ener-Win (9/31)	4	1	3	1
16	Energy Express (9/31)	6	0	1	2
17	HAP (8/31)	4	0	1	3
18	BLAST (7/31)	4	2	1	0
19	ECOTECT (6/31)	3	1	1	1
20	Energy-10 (5/31)	2	1	1	1

Not to argue that having a wide range of features and functions lead to a better platform; some of the less diverse simulation programs can have more specific focus on a certain energy/performance aspect, able to produce more accurate results related to that specific function. However, EnergyPlus and IES are in the lead when looking for a wholesome single platform that is able to factor in different aspects of energy parameters.

Some of these different BPS tools are available for free (i.e., EnergyPlus) or as commercial products (i.e., IES). EnergyPlus is considered a "new generation" whole-building simulation software that can simulate multiple building systems using a network of nodes; This offers considerable flexibility in modelling a building's energy system (Al-janabi *et al.*, 2019). IES is another comprehensive whole-building simulation tool that allows the user to interact with a single software for a detailed assessment and optimisation of buildings parameters and system designs (Crawley *et al.*, 2008). The two simulation platforms have been contrasted, evaluating their performances and highlighting the variances in their results; In a case study, it was found that the difference in predictions of heating energy consumption between the EnergyPlus model and the IES model is less than 1%. Whereas the difference in predictions of cooling energy consumption is less than 10% (Al-janabi *et al.*, 2019). There was no definitive conclusion to which is more accurate or better in general. Its highly dependent on the user's objectives and skills. 108 modellers from different engineering and architectural firms took part of a survey regarding their work in the design process of national and international projects, 80% of participants selected IES as the simulation software they used for energy analysis (Imam *et al.*, 2017b). This can be attributed to the fact that IES is a multi-functional software that allows the modellers to sketch, render, and process the building energy performance. While EnergyPlus, with all its open-source capabilities, require files to be processed through other softwares (i.e. buildings layouts and material rendering) before being uploaded for energy calculations and performance analysis.

2.0 Methodology, Buildings Simulation and Modelling

2.1 Selection of Simulation tools and Software

For this research, the decision is to use EnergyPlus as the main energy modelling platform. This choice is made in consideration of the literature reviewed in the prior section, and for the fact that EnergyPlus allow for script addition/modification. EnergyPlus has a wide range for outside surface convection algorithms and it's supported by many common programmes, used for data entry/ results processing (Crawley *et al.*, 2008). DesignBuilder is one of the commercial softwares that are built to interact with EnergyPlus as a simplified building drafting and zone classification platform. With the variables chosen for this research, DesignBuilder has pre-set data for building characteristics such as building materials, operating schedules, occupancy heat gains, and heating/cooling systems. The availability of these pre-defined parameters makes the process of analysing the contribution of the selected variables much easier, ensuring that the energy consumed in each case is the result of a single variation at a time.

Before demonstrating the capabilities of such simulation software, the mathematical sequence of how the loads are calculated shall be explained. Some of the main energy consumption systems for buildings are associated with the heating, cooling, interior lighting, exterior lighting, interior equipment, exterior equipment, fans, pumps and water facilities. For the objectives chosen in this research, the emphasis is on the energy consuming systems that are affected majorly by the variables defined. Cooling and heating loads are taking over the largest share of the energy consumed by buildings, especially when the climate under study is of a seasonal extreme (hot/long summer – cold/long winter). The energy consumed through interior/exterior equipment (such as lighting) and water facilities (such as plumbing) are mostly calculated/simulated as a function of the building floor area and occupancy rates. By fixing the buildings floor areas and zones/building volume, the energy consumed by interior/exterior equipment and water facilities can be assumed to be constants in the different buildings configurations (the simulation results shall prove the same).

The key concept in simulating a building's energy performance for cooling/heating is through understanding the heat and mass balance (EnergyPlus: Getting Started Manual, 2018). Analysing the performance can be done through a complex and computationally intensive process of simulating the fluid (Air) movement within a zone referred to as computational fluid dynamics (CFD). In carrying on such complex process, some assumptions are made to simplify the calculations, such as considering uniform surface temperatures, uniform long and short-wave irradiation, diffuse radiating surfaces and internal heat conduction. The dynamic simulation run multiple modules simultaneously, the main 3 components simulated are surfaces heat balance, air heat balance and building systems/utilities management.

With the surfaces heat balance simulation, the calculations are mostly considering the atmospheric conditions, the shading effect, the daylight influence and the window/glass characteristics. The goal is to simulate the inside and outside surface heat balance, subject to the interconnections between heat balances and boundary conditions, conduction, convection, radiation, and mass transfer effects. For the air heat balance simulation, mass streams such as ventilation air, exhaust air, and infiltration are accounted for their direct convective heat gains considering multi-zone airflow, infiltration, indoor contaminant, and ventilation calculations.

Simulating the building systems is carried out to control HVAC systems/electrical systems, equipment and components while updating the multi-zone-air conditions. The simulation process of building systems is designed with the objectives of being fully integrated in simulating the loads, systems, and plant (heating/cooling source). It also has a modular and extensible structure; Using input file templates for the each of the major system types, it provides an easy starting point, allowing for simulating the selected system components with different configurations form the "default" configurations.

EnergyPlus processes the three of the major parts, building, system, and plant, simultaneously (EnergyPlus: Getting Started Manual, 2018). This integrated simulation method forces the parts to interact as a series of functional elements connected by fluid loops, delivering physically realistic results. The loops have two sides, supply and demand; The solution scheme generally relies on the successive substitution iteration to balance the supply and demand using the **Gauss-Seidell** method of continuous updating ("EnergyPlus: Getting Started Manual", 2018). Also known as a point-wise iteration method or the successive displacement method, this method is named after Carl Friedrich Gauss and Philipp Ludwig von Seidel (Yang, 2018). The **Gauss-Seidell** method has a strong resemblance to the **Jacobi** method (improved), instead of always using previous iteration values for all terms of the right-hand side of an equation, whenever an updated value becomes available, it is immediately used during the iterative procedures (Mazumder, 2016).

Starting with the zone and air system integration the solution scheme starts with a heat balance on the zone air, balancing energy and moisture for the zone air, and solve the resulting ordinary differential equations using a predictor-corrector approach. Details of the functions used in simulating the energy performance using EnergyPlus are attached in **Appendix-I**.

The calculations of the energy consumed through interior/exterior equipment (including lighting) and water facilities (such as plumbing) in EnergyPlus are mostly governed by the building's floor area and the occupancy rates/hours. The decision to fix the buildings' floor areas, the zones/building volumes, and the occupancy rates/hours, allow for the assumption that the energy consumed by interior/exterior equipment and water facilities are constants, in all different buildings' geometry and orientation configurations.

The software calculates the air system output (Q), for cooling or heating, considering four heat transfer functions, as per the following equation:

$$\mathrm{Q} = \sum_{i=1}^{\mathrm{Nsl}} \mathrm{SL}_i + \sum_{i=1}^{\mathrm{Nsurfaces}} ZS_i + \sum_{i=1}^{\mathrm{Nzones}} ZM_i + I$$

where, (SL) represent the convective internal loads from each source inside a zone (equipment and/or occupants), (ZS) represent the convective heat transfer from the surfaces (internal/external walls and windows) defining a zone, (ZM) is the heat transfer due to inter-zones air mixing and (I) is the heat transfer due to infiltration of outside air into a zone.

When the number of zones, the number of internal loads within the zones, and the number of infiltration points in all buildings are constants, (ZS) is the only variable with direct correlation to the change in the surface area of the zones. (ZS) is calculated using the following equation:

$$ZS_i = \mathrm{H_i A_i}(\Delta \mathrm{T}_i)$$

where, H is the height of the zone, A is the floor area of the zone and ΔT is the temperature difference between the surfaces' temperature and the air within the zone's temperature.

EnergyPlus's algorithm is based on time steps, to update the zone's temperature using a predictor-corrector approach (Mazumder, 2016). As the surfaces composition is changing (varying the window to wall ratio), the rate of ($\Delta \mathrm{T}$) will change, explaining the focus of this research on the three main envelope variables (orientation, aspect ratio, and window to wall ratio).

2.2 Energy Simulation Parameters

The variables selected for the analysis are the building's orientation, aspect ratio (compactness), window to wall ratio, and the potential of using sustainable energy generation systems, integrated within the façade [**Table 2**]. **Figure-1** presents a visual explanation of the geometry and orientation variations analysed:

Table 2 - Research variables

	VARIABLE	RANGE	UNIT
1	Orientation	N, NE, E, SE and S (equivalent to N due to symmetry)	Degrees
2	Aspect ratio (W:L)	1:1, 1:1.25, 1:1.5, 1:1.75, and 1:2	Ratio
3	Window to wall ratio	20%, 40%, 60% and 80% (equally distributed on each wall)	Ratio
4	Solar panels integration	20% to 80% of the building's surface area (wall area)	m^2

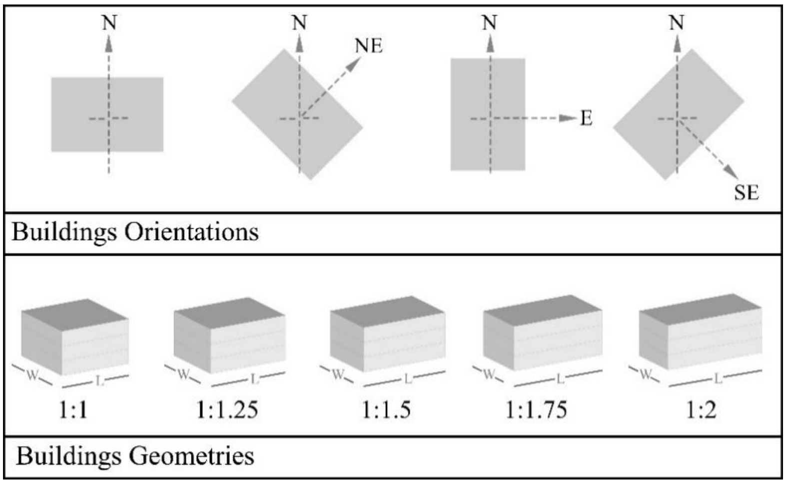


Figure 1 - Simple Representation of Orientation and Geometry Variance

The first three set of variables are the building's envelope elements evaluated for their contribution toward energy consumption. The fourth variable considers the potential for energy generation, corresponding to different placing scenarios (Single wall vs. multiple walls at 8 possible orientations). With these defined variables and their ranges, the number of possible cases is the multiplication of the variables' ranges, 4 x 5 x 4 x (4 x (4!=24)), A total of 7680 potential cases.

Such large number of cases to simulate and analyse would be very time consuming. The number of these cases can be significantly reduced by understanding the significance of each variable. Hence, a simulation of the energy consumption is independently explored in detail, in this chapter; Then, the potential for energy generation in Chapter-3.

3.0 Results and Analysis

3.1 Simulation Results

To understand how the building's envelope design variables affect the energy consumption, the Latin hyper-cube (Sheikholeslami and Razavi, 2017) sampling approach is used to analyse 80 cases. Each building is simulated with a specific composition of orientation, aspect ratio, and the window to wall ratio, using DesignBuilder. The buildings are analysed for their energy consumption, to evaluate the effect of each variable. Other building design parameters are kept constant, such as the floor area, number of floors, floors heights, building materials, HVAC operating system, HVAC temperatures setting, building operating hours and building lighting system [**Table-3**]. The buildings simulated cover a range of typical buildings' geometries in Kuwait, and wall/windows compositions that can help in evaluating the impact of each variable.

The geometry of the building is varied with a constant floor area and building's height (H). The length (L) and width (W) of each building, considering the different aspect ratios/forms shown in **Figure-1**, are calculated while maintaining the floor area at 400 m^2.

Table 3 - Simulation parameters

	Parameter	*Value*	*Unit*
1	Weather Parameters	Kuwait City	-
2	Number of floors	3	No.
3	Floor area (A)	400	m^2
4	Floor height (H)	4	m
5	Building materials	Project construction template	Standard template
6	HVAC operating system	Fan coil unit (4-Pipe), Air cooled chiller	Standard template
7	HVAC heating temperatures setting	Set back T 12°C, set 20 ° C	Degree C
8	HVAC cooling temperatures setting	Set back T 25°C, set 22 ° C	Degree C
9	building operating hours and	Generic Office Area	Standard template
10	building lighting system	Reference	Standard template

The initial building floor area is a square, with equal length and width (L1 = W1 = 20 m). Then the geometry is varied, solving for (L) and (W) with the initial condition of a fixed floor area at each aspect ratio:

$$W_2/L_2 = 1/1.25 \ ; W_3/L_3 = 1/1.5 \ ; \ W_4/L_4 = 1/1.75 \ ; \ W_5/L_5 = 1/2$$

Accordingly, the buildings' volumes (V) remain constant within at each form. However, the variance in (L) and (W) have an impact on the buildings' surface areas (SA). This can be explained by the difference in the relationship between (L) and (W) while calculating the shape's parameter being linear, relationship between (L) and (W) while calculating the shape's volume as non-linear.

$$SA = (2L + 2W) * H \quad ; \quad V = \ L * W * H$$

The roof's area is constant as it matches the floor area in each building. Hence, the difference in the building's external surface area is a result of the variance in the building's sides (walls/windows area). The maximum difference while varying the buildings' aspect ratio is about 6%, between the most compact floor plan (square) and the least compact floor plan (a rectangular form with a 1:2 aspect ratio). Since the construction materials are constant in each case, selected from the built-in template within the simulation software, the differences in construction materials' quantities (at each window to wall ratio) are limited to the change in the buildings' SA (less than 6%). The standard practice in Kuwait, centralised HVAC units are typically installed on the roof of buildings or on the ground, depending on the size of the building/44system and the available areas for their installation.

As indicated in EnergyPlus's equation for calculating the buildings' yearly energy consumption, the patterns can be associated with the variance in surface areas, and the solar radiation contributing to the heat gains and losses, at the different buildings' orientations. **Figure-2** display the 20 buildings' behavioural patterns of 20% window to wall ratio. The x-axis represents the orientation of the building, starting with the case of the longer span facing North (0), then changing as 45˚ intervals to face North-East, East, South-East and South. The y-axis represents the ‘Net site energy’, marking the yearly energy consumed by each building case in kWhx10^3.

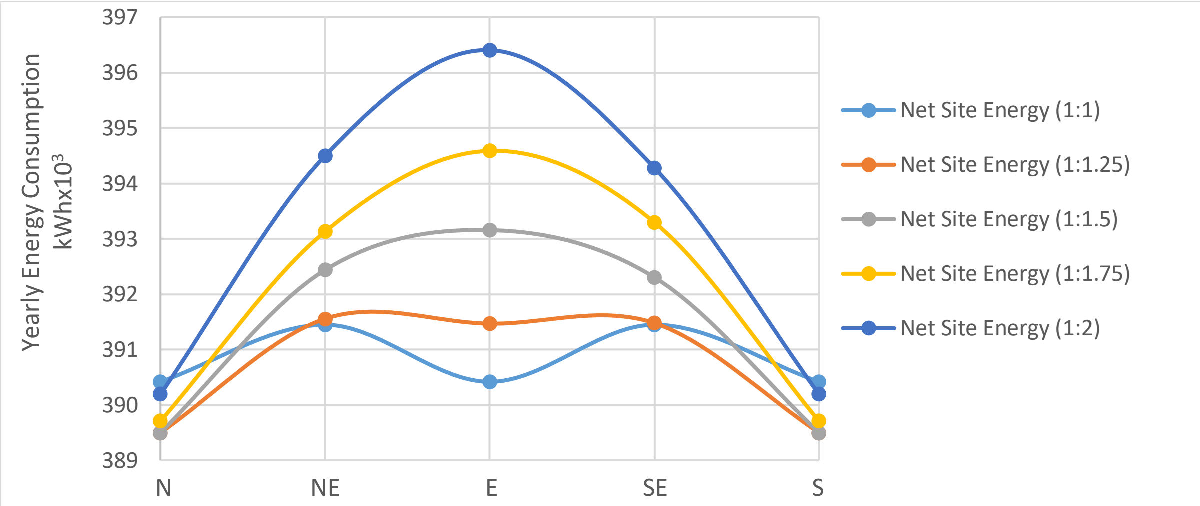


Figure 2- Net site energy for buildings with a 20% window to wall ratio

Buildings are also simulated with 40%, 60% and 80% window to wall ratios at each aspect ratio and facing the different orientations. The data can be presented from different perspectives. **Figure-3** shows the energy consumption of buildings with a compactness (length to width ratio) of 1:1.5, while varying the window to wall ratio against different orientations.

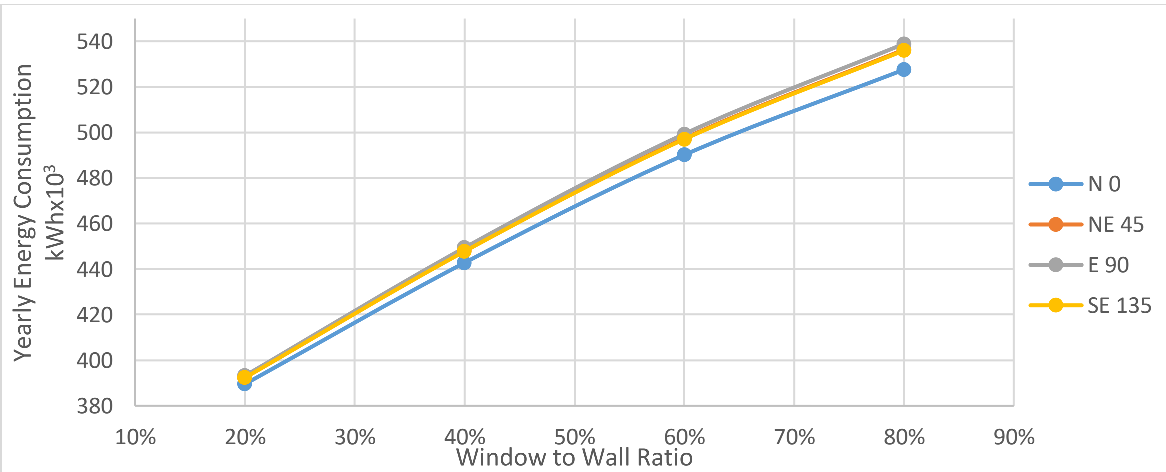


Figure 3 - Net site energy for buildings with a 1:1.5 compactness ratio

The output from the simulation also details energy consumption calculation, particular to the internal lighting loads, water heating loads, cooling/heating peak loads as well as estimates for water consumption. Across all buildings, the water consumption and the water heating loads are almost constant. At each window to wall ratio, it’s observed that the lighting loads and water heating loads are constant while varying the orientation. Across the different aspect ratios, the simulation indicates a variance of less than 0.5%. The slim advantage is recorded for buildings with 1:2 aspect ratio over every other form.

Across the different window to wall ratios, buildings with lower window to wall ratio recoded lower peak cooling loads; the difference in the peak cooling loads between buildings with 20% and 80% window to wall ratios is 31%. However, buildings with 20% window to wall ratio recoded higher peak heating loads than buildings higher window to wall ratios; the difference in the peak heating loads between buildings with 20% and 80% window to wall ratios is 28%. The design of HVAC systems has to operate with capacities higher than the peak heating and cooling loads. Different window to wall ratios lead to significant differences on peak loads. Accordingly, designers shall take into account the variance in buildings' window to wall ratio, to the extent that between 20% and 80%, a range of 30% increase in the HVAC system capacity requirement is to be considered.

By comparing the cooling loads to the heating loads, simulated using the same parameters in **Table-3**, the amount of energy consumed for heating during the cold days within a year does not exceed 0.15% of the energy consumed for cooling. The simulation is run for the same 80 cases Given how minimal is the impact of the heating loads, the analysis will not include further details on the heating patterns. **Figure-4** is an example of 20 building cases with 60% window to wall ratio while varying the aspect ratio and the orientation.

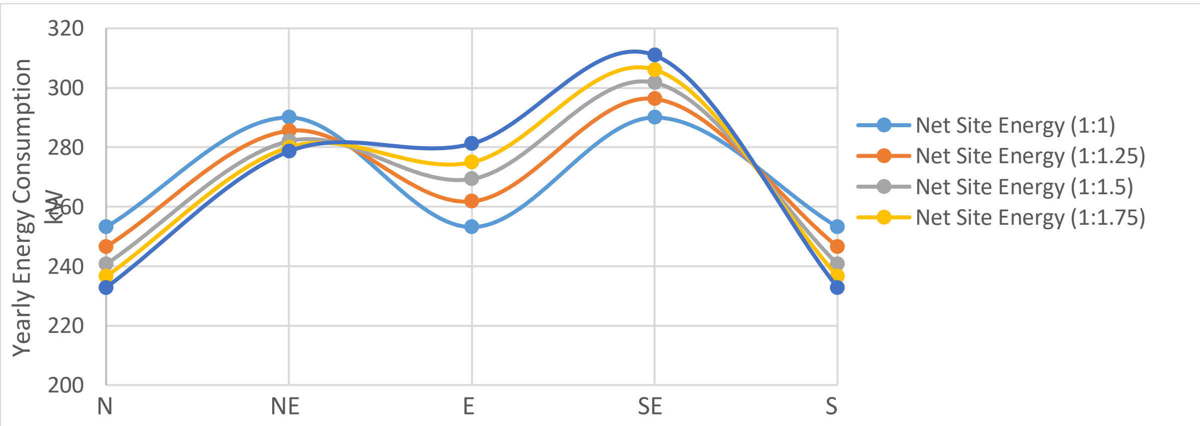


Figure 4 - Yearly energy consumption for heating buildings with 60% window to wall ratio

This makes sense as the energy consumption data are very specific to the climate conditions of Kuwait, which as a short winter season, with few weeks that require indoor thermal heating. However, the energy loads are mostly consumed for balancing summer heat gains through cooling units/systems. Further use of this analysis shall take into account the source of energy feeding the buildings. In this case, as in most construction projects in Kuwait, the assumption is that the buildings are fed through the local grid, connected to a desalination plant, operated using fossil fuels.

3.2 Indications and Patterns

The results of buildings simulations and energy generation calculations are to be optimised collectively; But first, it's important to understand the influences of each part independently. Starting with understanding how the selected design-build variables contribute toward energy consumption and the range of variance in performance attributed to these variables.

The 80 cases simulated are visualised in **Figure-5**, each chart plotted [A, B, C & D] represent 20 cases of buildings with 20%, 40%, 60%, and 80% window to wall ratios, respectively. These charts demonstrate the yearly buildings energy consumption values while varying their orientations and aspect ratios.

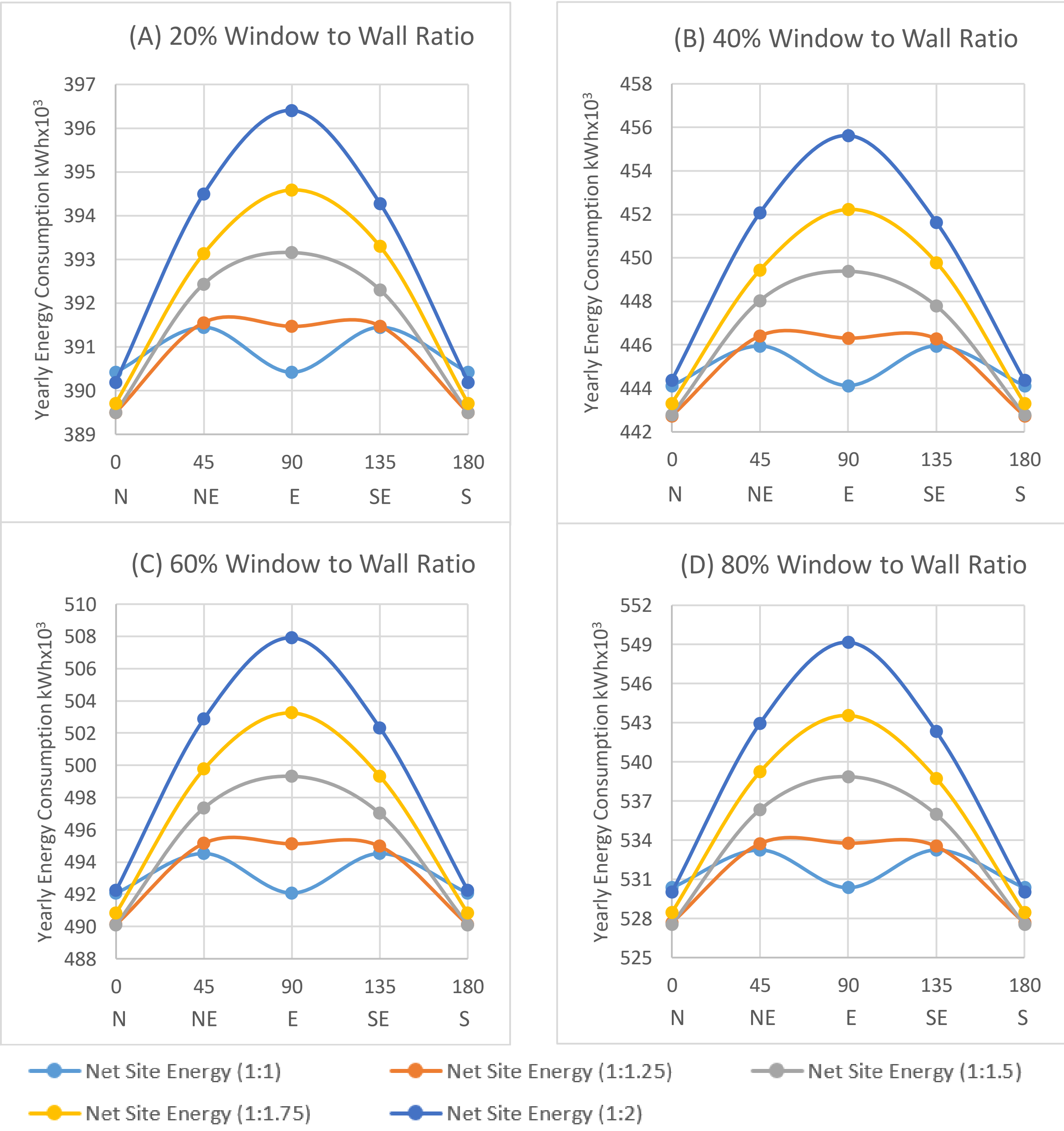


Figure 5 - [A, B, C &D] - Net Energy consumptions, varying the orientation, Aspect ratio, and at 20%, 40%, 60% & 80% window to wall ratios

These results show that in all configurations, while varying the orientation, the more compact abuilding is (higher width to length ratio), the lower energy the building will consume; Except when the longer span is facing North. This is a result of the heating and cooling loads, balancing the solar contribution toward the building's heat gains/losses. **Figure-6** [A, B, C & D] show the energy patterns of the 20 buildings that have their longer span (L) facing North.

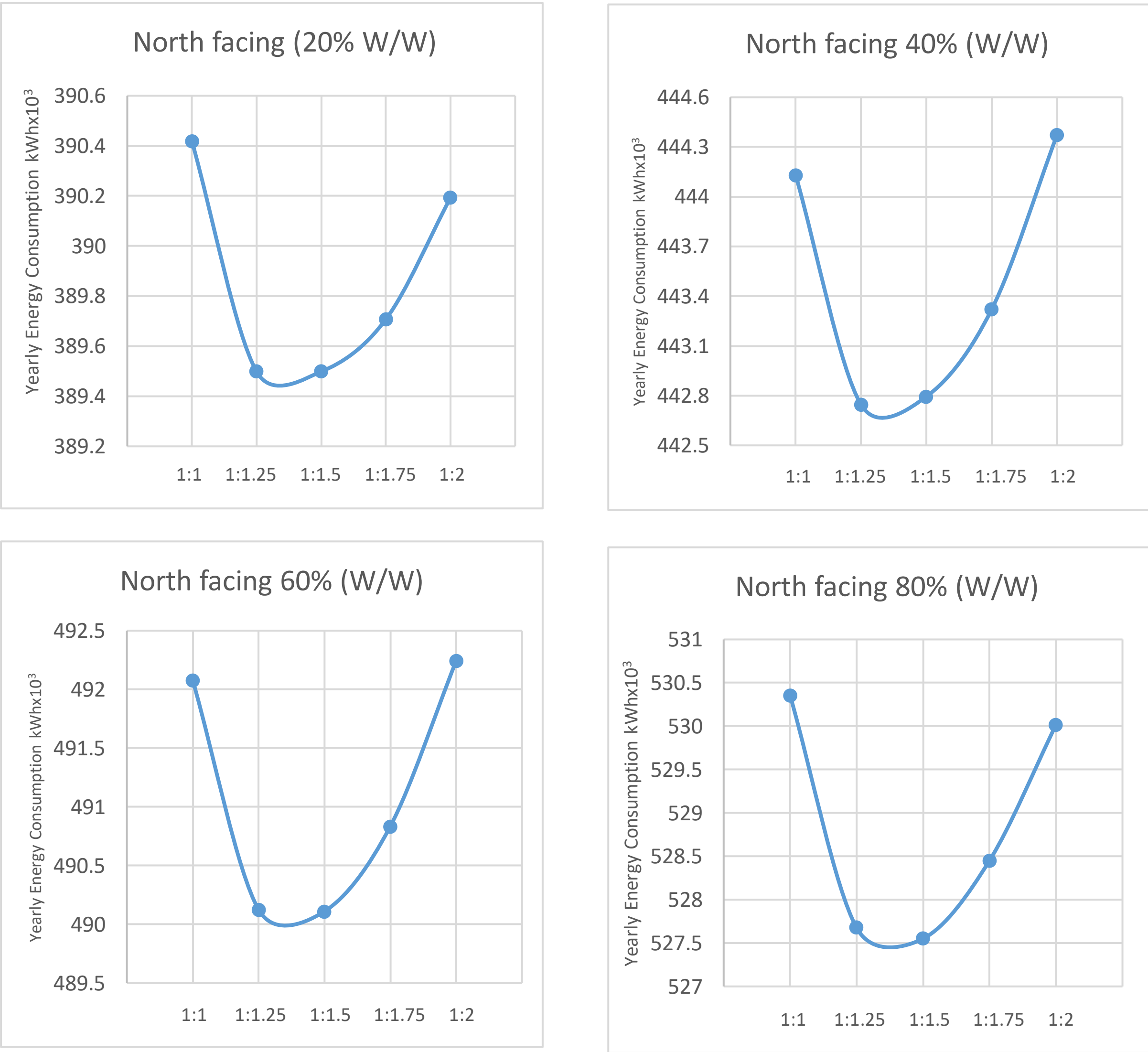
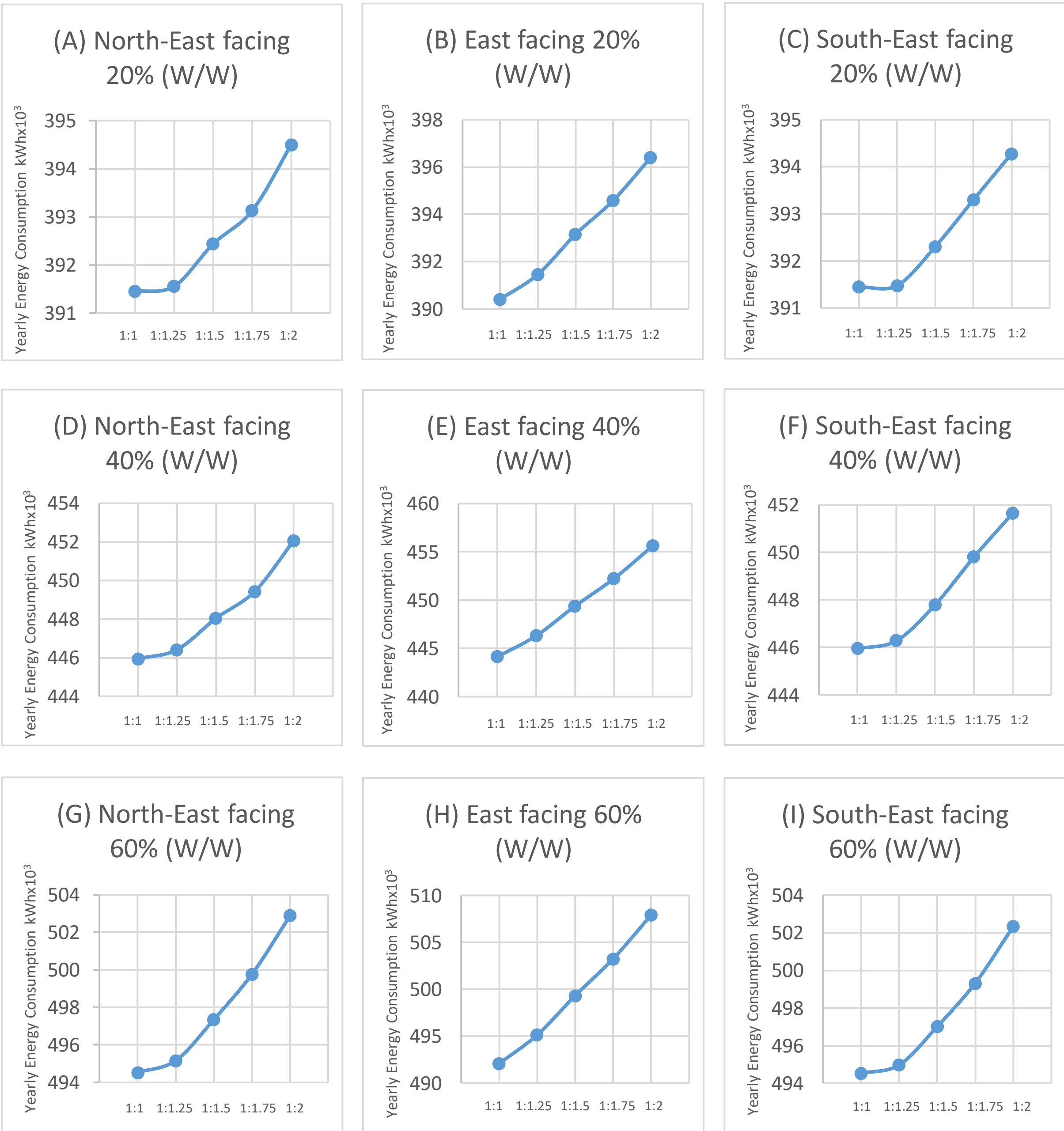


Figure 4 - [A, B, C & D] - Yearly energy consumption of North facing buildings at different Aspect ratios, and at 20%, 40%, 60% & 80% window to wall ratios

In all variations of window to wall ratios, the aspect ratios of 1:1.25 and 1:1.5 are performing best when the longer span is facing North. With buildings of 20%, 40%, 60% and 80% window to wall ratios, the differences between the best performing aspect ratio and the worst, based on their yearly energy consumption, are 0.24%, 0.37% 0.43% and 0.50% respectively. The main reason for the increase in variance is the increase of window to wall ratios. More glazing affect the buildings' heat gains and losses; As the difference is found to be getting higher when the buildings are having more windows. The thermal conservation factor of windows within the building envelop is generally less than it is for a wall. In this simulation, the thermal qualities of windows and walls were selected from DesignBuilder's built-in templates as a constant parameter throughout all configurations. It's also noticeable that, the values of buildings energy consumption with aspect ratios of 1:1 and 1:2 are the highest and close to each other's values while facing North.



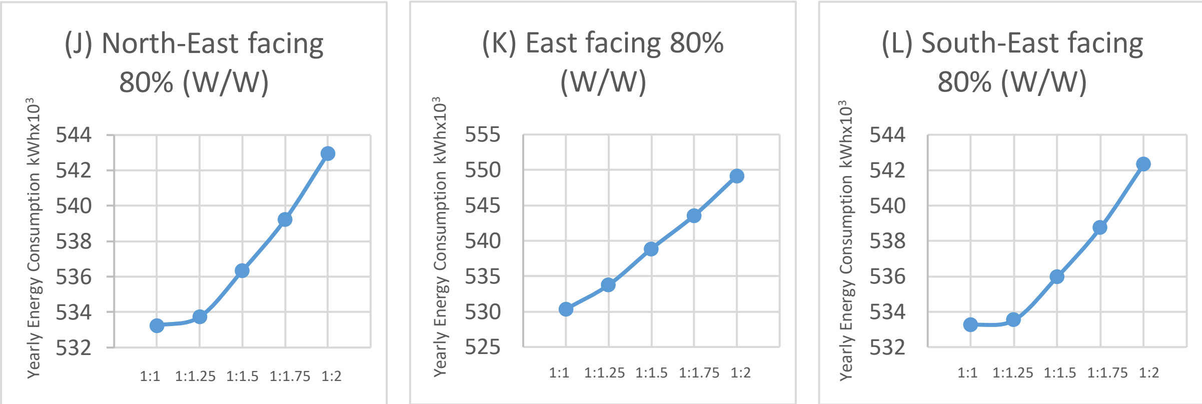


Figure 7 - [A, B, C, D, E, F, G, H, I, J, K and L] - Aspect ratios vs. window to wall ratios at different orientations

All other orientations have an ascending pattern of energy consumption with the lowest value attributed to the most compact form of buildings with aspect ratio of 1:1. The Energy consumed and the convexity changes as the window to wall ratios are increasing (**Figure 7** - [A, B, C, D, E, F, G, H, I, J, K & L]).

3.3 Results validation

To validate the results and patterns analysed, the simulation is replicated with similar constructions/ operation parameters at a different scale. The scale of the building is increased, to verify that the energy patterns are not majorly affected while considering different scales, and a scale change can be used to predict the change in energy values. The changes in the building's scale parameters are shown in **Figure-8**.

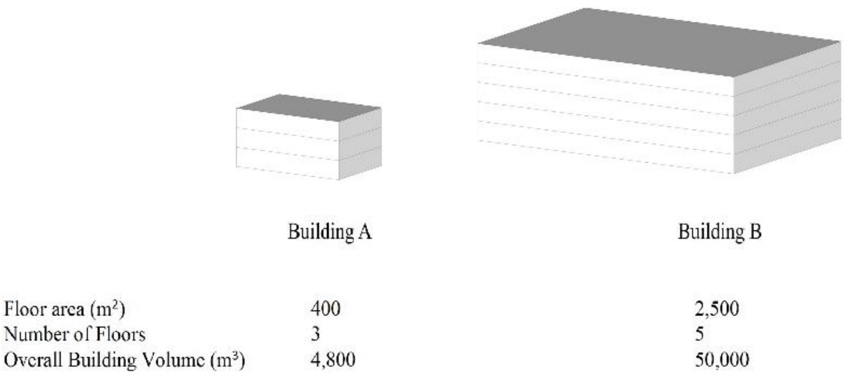


Figure 8 - Buildings' scales, Analysis (A) vs. Validation (B)

Building-A represents the scale used in our detailed analysis, and Building-B represents the new scale used for validation purposes. For Building-B, the validation analysis considers 20 cases for a building with 20% window to wall ratio. Similar to the original analysis, Building-B's aspect ratio is varied at 1:1, 1:1.25, 1:1.5, 1:1.75 and 1:2 of its width to length floor plans, as the longer span is oriented at North, North-East, East and South-East directions.

The new 20 cases display similar pattern to results analysed for Buildings-A, with higher values of overall energy consumption rates (**Figure-9**). The increase in the overall yearly energy rates is attributed to the fact that the validation results are for buildings ten times bigger than the original parameters used in the previous analysis.

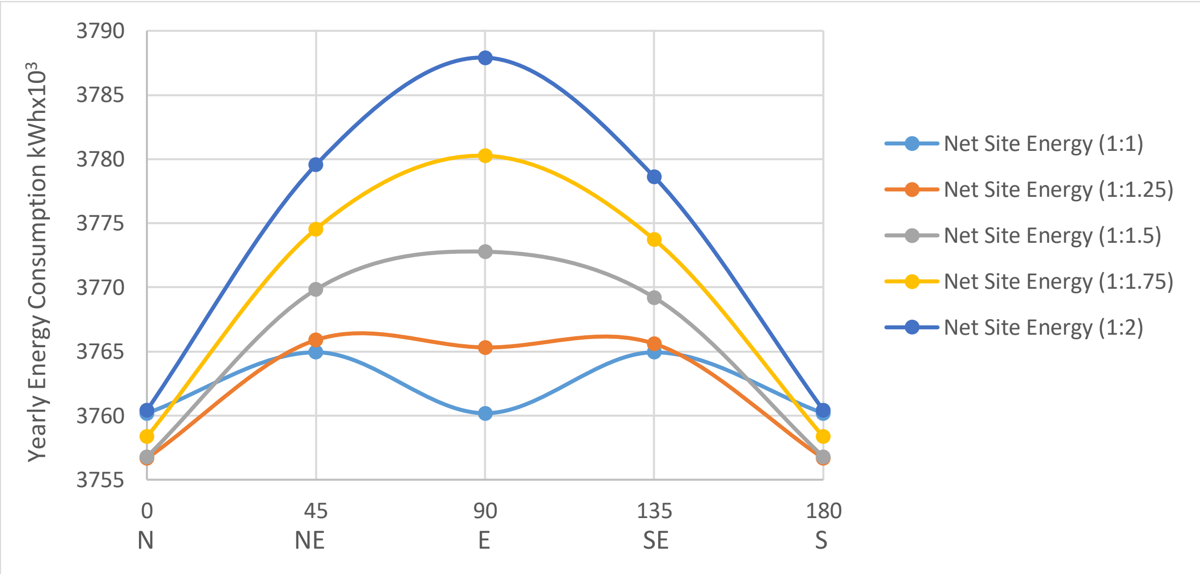


Figure 9 - Net Energy consumptions, varying the orientation and compactness at 20% window to wall ratio

Taking a closer look at the energy pattern for the different aspect ratios of Building-B while the longer span facing North, the energy consumption values at compactness ratios between 1:1.25 to 1:1.5 are the lowest and very close to each other. While the values of buildings' energy consumption with compactness ratios of 1:1 and 1:2 are the highest and close to each other (**Figure-10**). This pattern is also consistent with the patterns analysed for Building-A, considering the increase in energy consumption values given the scale increase.

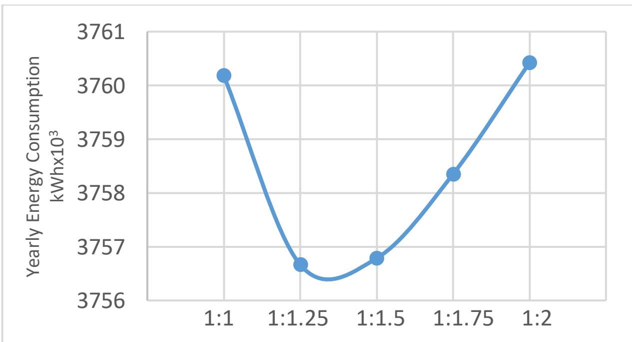


Figure 10 - North facing buildings with a 20% window to wall ratio

Similarly, **Figure 11** [A, B and C] show all other orientations having an ascending pattern of energy consumption, the lowest value attributed to the most compact form with an aspect ratio of (1:1).

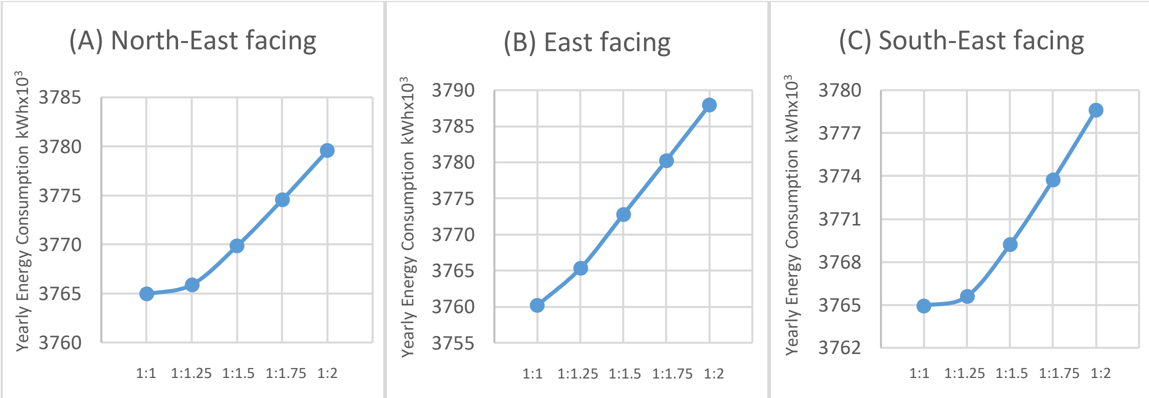


Figure 11 [A, B and C] – 20% window to wall ratios building, varying compactness ratios at different orientations

4.0 Discussion

Based on the analysis, the results indicate that the window to wall ratio is the most critical variable, for having to most impact on the buildings' total energy consumption. For buildings with aspect ratios of 1:1.25, 1:1.5, 1:1.75 and 1:2, the least energy consuming composition is when the buildings have 20% window to wall ratio and while their longer spans are facing North. As for buildings with aspect ratios of 1:1.25, 1:1.5, 1:1.75 and 1:2, the most energy consuming composition is when the buildings have 80% window to wall ratio and while their longer spans are facing East. At the different aspect ratios of 1:1.25, 1:1.5, 1:1.75 and 1:2, the difference between the least and the most energy consuming configurations are 37%, 38%, 39% and 40%, respectively. The square form of a 1:1 aspect ratio though, due to its symmetry, North and East facing orientations have the similar values and generally consume a little less energy than North-East and South-East orientations. The variance due to the increase of window to wall ratios (from 20% to 80%) at the different orientations is almost the same at 36%.

Comparing buildings at each window to wall ratio, The most consuming configuration is for buildings of 1:2 aspect ratio, while the longer span is facing East (except when the aspect ratio is 1:1, North and East facing orientations have the similar values and consume less energy than North-East and South-East orientations).The change in orientation, considering the different aspect ratios, can lead to variances in the energy consumption up to 1.8%, 2.9%, 3.6% and 4%, for buildings with window to wall ratios of 20%, 40%, 60% and 80% respectively.

Most of those results fit with the conclusions from previously publications, focusing on similar variables (Baglivo *et al.*, 2017; Ferrara *et al.*, 2015; Gero *et al.*, 1983; Rashdi and Embi, 2016). For example, the results supports the general notion addressed in one of the previously reviewed publications (Rashdi and Embi, 2016), that for buildings with similar geometry, buildings while their long axis is facing North have better energy performance than any other orientation. Furthermore, their simulation gives guidance that, the more compact the building's form is, the lower the cooling load the building would consume. However, in that study, the focus was on the energy usage specific to cooling, considering their regional climate requirements. In contrast to their results, this research focus is on Kuwait's climate, and the simulation considers cooling loads as well as the heating loads. The results rank building that are not the most compact in geometry (with aspect ratio of 1:1.25 and 1:1.5) while their long span is facing North, to have lower energy consumption loads than the most compact geometry of 1:1 aspect ratio. Even when the cooling loads are isolate from the heating loads, the dominant cooling loads are controlling the patterns, leading to the same conclusion.

Furthermore, the results from the analysis show that the behaviour between the most compact form of an aspect ratio of 1:1 and the aspect ratio of 1:2 is of significance. As one of the earlier studies compared the energy performance between buildings of those two aspect ratios only (Aksoy and Inalli, 2006), their conclusion was that the most compact design lead to lower heating demands. While within the analysis discussed in this research, when the longer span is facing North, buildings with geometries within those two ratios have lower cumulative cooling/heating loads than both forms. Also, given the short winter season and the limited heating required based on Kuwait's climate, when the longer spans of buildings are facing North or North-East, they all perform better than the most compact form.

One of the key objectives achieved by regional studies, further to the validation of concepts and conclusions, is quantifying the regional significance of the selected variables. This research focuses on the effect of envelope design variables on the net energy consumption and the cooling/heating, which govern the HVAC systems' capacity. Based on the peak loads' calculations, the variance in the cooling and heating system's capacities can vary within a 30% range, at the different window to wall ratios analysed. The identification of those values help the building's user/designer in trading off the advantages of increasing natural light, and the corresponding increase in the system's capacity, leading to increases in the cost of HVAC system as well as the yearly energy consumption.

The analysis presented in this research, combined with the literature reviewed concerning the same topics, emphasise on the importance of understanding the input parameters effect on conclusions and guidance. Input parameters, pertaining climate and the definition of building geometry, may lead to different outcomes, and different recommendations, to what an optimum design might be. The international energy conservation code 2018, ASHRAE Standard 90.1, GB50189 design standard for energy efficiency in public buildings, and The national construction code (NCC) are few examples of engineering guidelines, used in major countries such as USA, China and Australia, recommending building design aspects that can improve the buildings' energy performance (Ma and Airah, 2017). However, those guidelines can specify different limitations; as for the window to wall ratio, some recommended that it better not exceed 30%, while others recommended it must not exceed 40%. Exceptions to exceed those recommended values are also explained, influenced by the type of glazing material used and the operation philosophy of the building. These standards combined with the results here can help in directing local institutions/individuals within the GCC, and Kuwait specifically, to set their specific/regional recommendations and guidelines based on simulations built on local data.

5.1 Conclusion

The climatic conditions a building is subjected to play a key role in influencing the energy consumption patterns throughout the year. By analysing the energy performance of buildings with typical forms (Rectangular/ Square) in Kuwait, the general energy consumption patterns while varying the buildings Orientation, aspect ratios and window to wall ratios can be explained. The results display a unique pattern, especially when the buildings at an orientation placing their longer span at the North direction. The energy consumption patterns are compared with the general conclusions found in previous literature, highlighting the novelty in this chapter. Especially as the simulation indicates that buildings with aspect ratios of 1:1.25 and 1:1.5 can perform better than the most compact from with aspect ratio of 1:1.

If a single objective is concentrated on the building envelope variables toward minimising the energy consumption, the design decisions would be easy to reach. From the simulation, informed decisions can be made, as the window to wall ratio has the potential for net energy consumption savings up to 40%. Furthermore, the HVAC system capacity design can be guided by the peak loads calculation, given that the envelope design variables analysed can impact the building's overall energy consumption by 30%. The analysis indicates that the window to wall ratio is the dominant factor on the building's energy consumption. The maximum differences attributed to the change in orientation and aspect ratio are less than 5% each, at the different window to wall ratios analysed. Access to such details is of a great importance, to make early design decisions, specific to the analysed variables, for buildings in Kuwait.

This chapter on its own is limited to providing guidance about buildings envelope variables, formulating design decisions about the building's orientation, aspect ratio, and window to wall ratio, toward lower energy consumption. Yet, with the current climate change concerns, the efforts toward energy saving and lowering emissions must be pushed further. The next chapter explores opportunities in using energy generation systems, powered by sustainable resources. The integration of those systems considers the same building's envelope variables, to make overall design recommendations based on economic and environmental objectives.

Chapter 3

This chapter is focused on the Potentials from PVs in Kuwait, introducing a model that considers the effect of dust while simulation PVs power output. To minimise the impact of dust, the model is used to evaluate different tilts for installation, and the performance of wall mounted PVs.

The introduction of a prediction model that can estimate the losses in transmittance from PV surfaces due to dust has been published in a paper titled:

"Modelling the regional effect of transmittance loss on photovoltaic systems due to dust"

1.0 Background and Literature Review

This chapter investigates the effect of climate within a region, being a key factor in quantifying the potential energy generation by renewable sources, as it does affect the energy consumption patterns of buildings. Given the conditions and capabilities within the GCC region, addressed in Chapter 1, this chapter starts with detailing the current efforts in Kuwait, as well as the future ones, investing in renewable systems to produce energy. Then, the effect of the main regional climate challenge (Dust) is quantified, to realistically predict the potentials from photovoltaic systems to generate energy. Finally, the building variables investigated in Chapter 2 are used to calculate the potentials within the building's façade. The outcome from this chapter will be the link, introducing energy generation potentials as an objective, to the multi-optimisation model built in this research.

1.1 Renewables vs fossil fuels in Kuwait

In terms of potentials, based on a performance comparison of the annual average daily final yield from similar PV systems in different countries (Germany, Japan, Cyprus, India, Ireland, Norway, Spain and Oman), Kuwait's system ranked the second-best performance with 4.5 Wh/kWp/day, after Oman's 5.1 kW h/kWp/day, while the lowest was Germany, at 1.8 kWh/kWp/day (Al-Otaibi *et al.*, 2015). However in terms of application, the ministry of power (MOP) in Kuwait issues a yearly report detailing each year's electricity generation and consumption statistics (Statistics Department & Information Center, 2021); and as of 2020, only one power plant (Al-Shygaya Power Plant), operates using renewable resources to produce energy. The plant generates electricity, relying on solar [photovoltaic (PV) and concentrated solar power (CSP) technologies] and wind as sustainable resources. A recorded in the report, Al-Shygaya plant started operating in 2018 and its current production nearly at 0.02% of Kuwait's total electricity generation. The grid is mainly fed by other 8 power plants, operating on fossil fuels, using gas turbines and steam turbines. The government is targeting to increase the capacity/production of electricity from renewable resources up to 15% by 2030; **Table 1** summarises the current and future projects planned to achieve that target:

Table 1 - Renewable Energy Projects in Kuwait

PROJECT STATUS	*NO. OF PROJECTS*	*TOTAL PROJECT SYNTHETIC CAPACITY (KW PEAK)*
Renewable energy projects executed	5	4552
Renewable energy projects initiated and under construction	46	216841
Future and planned renewable energy projects	93	4800170

The report includes details of the 5 executed projects, and few details for only 16 out of the 46 projects initiated; all of which produce energy, using PV panels. Al-Shygaya plant and one other future plant are the only projects designed to operate using CSP and wind power, in addition to PVs.

Some of the main concerns, highlighted in the report, are the high initial investments cost of sustainable technologies/systems and the inconsistency in energy production from such systems within the days and the seasons. The monthly peak electricity demand and the maximum electricity production data are key performance measures, essential for planning and investing in power production. It's important that the energy production capacity stays higher than the energy demand. **Figure 1** compares Kuwait's electricity production capacity to the peak loads in the year 2020.

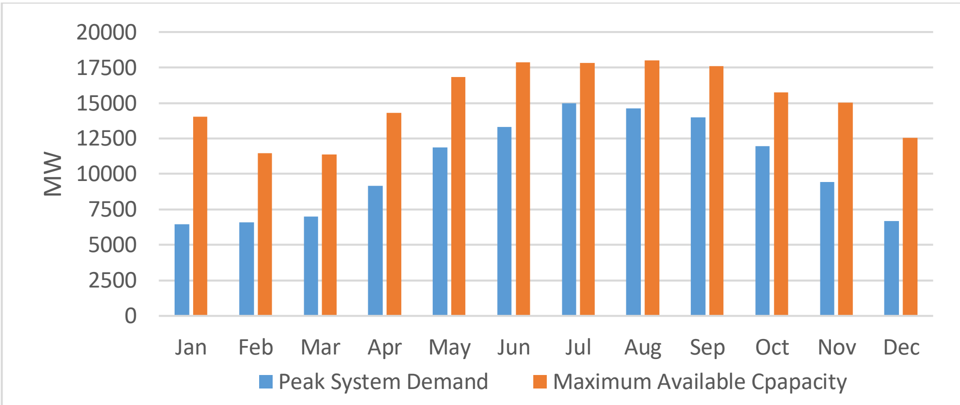


Figure 1 – Kuwait's Peak load demand vs. Power Production Capacity during 2020

It makes sense that the demand for energy is higher during the summer season, peaking on Jun, July, and August. The fact that the maximum available capacity has been consistently above the peak demands indicate the government was able to supply electricity to the users without failure.

As for 2020's monthly data from Al-Shygaya plant energy production, the monthly energy generation data from the plant shows a dip in energy production during the month of July (**Figure 2**). This is a major concern, given the fact that the peak demand for energy in Kuwait was registered in July. However, the report does not explain the reduction in energy production in July. The climate effect or scheduled/non-scheduled maintenance can be some of the reasons behind such drop. However, this in-line with the concerns mentioned in the report about the reliability of sustainable systems and renewable resources, keeping up with the electricity demands. Theoretically, July is one of the months with the highest potential for energy production from solar radiation, positioned at the optimum tilt, in Kuwait.

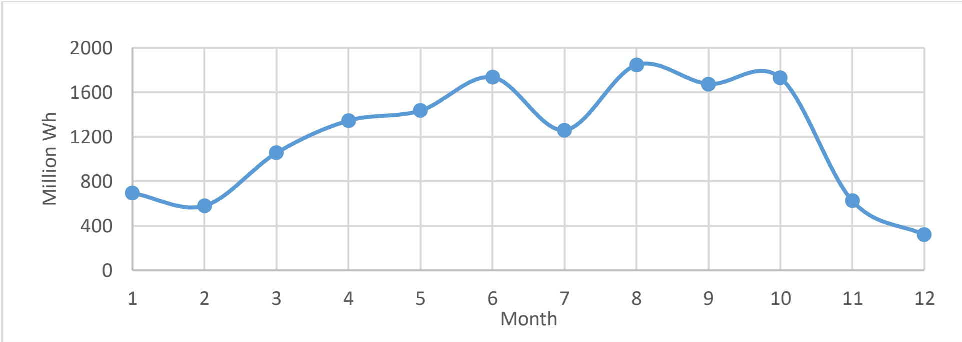


Figure 2 - Al-Shygaya Power Monthly Production (Solar - Wind - CSP) in the year 2020

Based on Kuwait's load distribution breakdown of electrical energy demands during 2020, it's consistent with the data discussed in Chapter-1, indicating that buildings are the dominant energy consuming sector. Based on the reported data (Statistics Department & Information Center, 2021), the sectors with the largest share of energy consumption are associated with buildings (Private buildings 53% and investment buildings 19%)**.** Including the public housing sector (1%), the energy consumed by buildings sum up to 73%. In addition, while the governmental sector consumes 7% and the commercial sector consumes 7%, those percentages include the energy consumed by buildings needed to operate their functions. The same can also be assumed for the industrial sector (13%) and the agricultural sector (4%) **Figure-3.**

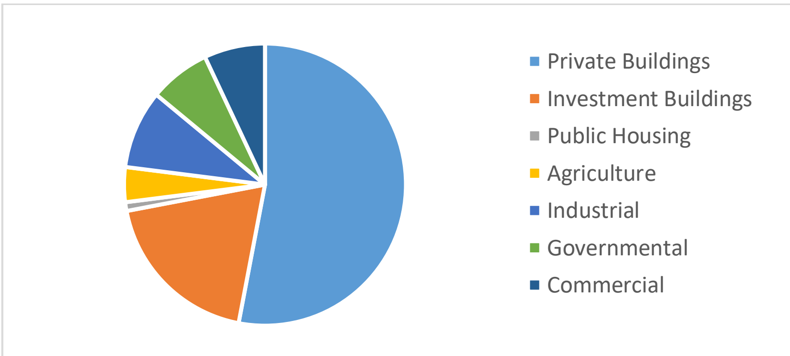


Figure 3 - Sector-wise energy consumption distribution

1.2 Renewables vs. Kuwait Climate

Solar power is considered one of the main renewable resources in Kuwait, given that all planned and executed projects are investing in at least one form of PV or CSP systems (Statistics Department & Information Center, 2021). While the MOP report highlighted concerns about the reliability of renewable systems, it did not cite the dust as the primary concern when solar systems for generating energy are being proposed. However, many publications reported significant drop in performance after dust events, as well as potential permanent damage to the surfaces of solar collectors panels (Goossens and Van Kerschaever, 1999; Sarver *et al.*, 2013; Sayyah *et al.*, 2014). The precipitation of dust happens normally due to a passing sandstorm or sand particles carried by local wind from open desert areas within the region. In Kuwait, a 17% drop in PV power was recorded due to sand accumulation over only six days (Sulaiman *et al.*, 2011). Kuwait's institute for scientific research (KISR) in collaboration with the local meteorology department record the yearly dust events along with the monthly precipitation levels (in tons). The average of dust-rising wind events between the years of 1962 and 2014 are plotted monthly (**Figure-4**).

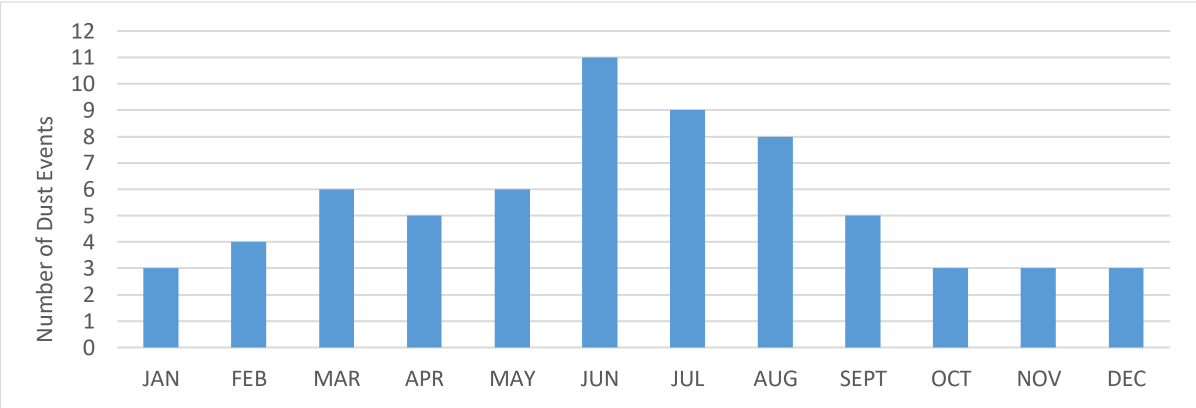


Figure 4 - Average number of monthly dust events in Kuwait between 1962 and 2014

The average number of dust events in Kuwait is 62 events per year, while the highest number of dust events in a single year is 111 events. Summer months (June, July, and August) record the highest averages of dust events within a year, with 11, 9 and 8 events respectively. The maximum recorded number of dust events in a single month are 18 events, registered in June, July, and August at different years. The average number of dust events during winter months (November, December, and January) are 3 events. The effect of these events on PV systems is not limited to the duration of the dust event within the day. The density of the dust wind/sandstorm obstructs the system from generating power at its highest capacity during the dust events, then the obstruction continues due to the accumulation of dust particles on the collector's surfaces. The system can only operate again at in maximum capacity when the dust particles are removed naturally by wind, or artificially (manual or automated cleaning).

1.3 Dust impact on PVs

To better understand the effect of dust on PV systems, a review of the literature available, that has analysed the significance of dust and how it can impact the energy produced by solar systems, is a good start. This is to analyse the relationship between the amount of dust accumulating on the PVs' surfaces and their productivity. Key factors such as the amount of dust suspended, the wind load, the chemical/physical composition of dust particles, the material of the surface and the tilt at which the panels are installed can all have an impact on the PVs' performance. The revision of the relevant publications is presented based on the region/environment of the outdoor experiments. Also, detailing the ones conducted in laboratories and under controlled conditions.

The Americas

The very first publication found to investigate the impact of dust on solar systems was published in 1942 (Hottel and Woertz, 1942), and it reports the performance of flat plate solar heat collectors and the particular impact of dust on their efficiency. Their analysis shows that for uncleaned panels, exposed to the natural conditions, in Boston (USA), set at a 30° tilt from the horizontal level for the duration of 52 days registered a maximum drop in incident solar radiation of 4.7%. In 1963, another publication reported the performance of solar energy systems in New York, USA weather conditions (Dietz, 1963). Their analysis was specific to surfaces exposed to the outdoor environment, at 0° tilt (horizontal to the ground level) for 10 days, reporting 5% loss in radiation. It's important to mention that for those two studies (Dietz, 1963; Hottel and Woertz, 1942), the locations where the data was collected, are not known for frequent dust events. On the contrary, the frequent rain events and the recorded precipitation levels were attributed for the lack of need for manual or artificial cleaning of the collectors' surfaces.

The correlations and recommendations, suggested in most literature, are specific to the data used and the location from which it was obtained. When PVs are considered, understanding the different conditions from multiple locations, can improve the prediction of their performance (Kimber *et al.*, 2006). Data from four different locations, in California and the Southwest region of the United States, was used to develop a prediction system that can evaluate the losses due to dust on grids connected to photovoltaic systems. The data was collected from multiple locations during the dry season of 2005, chosen from various climates. The four locations where California central valley, Northern California, Southern California, and an aired location out of the city described as a desert. The solar system was equipped with a tracking system, changing tilt throughout the day to maximise energy production.

Key observations were highlighted, such as a loss of 27% in efficiency can be predicted, within the last 30 days of the dry season. Also, rainfall events are key contributors in system efficiency recovery, on the 5th of December 2005, a recorded 20 mm of rain cleaned the system, resulting in an increase of 40% of its peak production, and registering a system's efficiency jump from 7.5% to 12.5%, measured before and after the rain event. The author argued that, based on their data, the recorded rainfall events, of levels a little above 5 mm, were not sufficient to clean the system and recover much of its efficiency, and the efficiency kept dropping, when other publications assumed rainfall events of 5 mm would be enough to clean the panels.

As different climates result in different losses from PV systems' productivity, it has been also proven that different PV modules might be affected differently by dust within the same climate (Cabanillas and Munguía, 2011). A study explored the effect of dust on three different types of photovoltaic systems, a monocrystalline module, a polycrystalline module, and an amorphous module. The study was specific to the weather conditions in Sonora, Mexico; a region known by its high level of solar incidence as well as an elevated presence of dust. All modules were mounted on solar tracking platform on a building's roof to maximise the radiation captured, while exposed to the natural condition. Form the data collected, a correlation was found to calculate the maximum power, based on the module used:

$$P_{MAX} = \text{a}\, R^{b}\, T_{Mod}^{c}$$

where, (R) is the is the solar radiation incident to the normal plane of the surface of the modules and (T_{Mod}) is the temperature of the module. The coefficients (a, b, and c) are materials factors associated with the PV type.

With the use of a tracking system, the value of (R) is assumed to be constant and equals to 1, corresponding to the solar radiation captured at a perpendicular angle on the PV surface for maximum performance, hence, the value of the coefficient (b) has no effect on the power. Based on the temperatures of the three clean modules, differing based on their material's properties, the value of the coefficient (c) is measured. Therefore, the variance in the value of coefficient (a) can be directly associated with the effect of dust on the power output.

Table 2 - Power coefficients for three types of PV modules

	POWER COEFFICIENTS	
	a - (Before dust exposure)	c
AMORPHOUS	0.066	- 0.18978
POLYCRYSTALLINE	0.28159	- 0.52089
MONOCRYTALLINE	0.2822	-0.4029

The values of coefficient (a) in **Table-2** are for clean PVs. The three PV types were tested for five runs/periods, each running a duration of 15 days without cleaning. From the five runs, the coefficient (a) for the amorphous module is calculated between 8.1 and 11.8, for the polycrystalline module between 4 and 6.4, and for the monocrystalline between 3.9 and 6.3. Accordingly, the equation the maximum power can be used to evaluate the losses due to dust, found to be 8% to 13% for the amorphous module, and between 4% to 7% in the monocrystalline and polycrystalline PVs.

Europe

In an attempt to understand the effect of dust on larger scale PV systems (plants), data form two solar pants were used to analyse their performance and the losses endured due to soiling (Massi Pavan *et al.*, 2011). The two plants are located in the countryside of Puglia, South of Italy. Both plants have panels set at the same orientation (South facing) and with a tilt of 25°. In each location, the panels were segregated into two groups, one is cleaned periodically during seven weeks of operation and the second was kept uncleaned for eight weeks of operation. Two different methods were used the clean the systems, Plant-1 was cleaned using high pressured water while being brushed, Plant-2 was cleaned with high pressured water only. The data collected was used to mathematically simulate the performance of a selected PV system using a generic polynomial regression model. The power (P) follows the formula:

$$\mathrm{P} = \mathrm{A} + \mathrm{B}\,\mathrm{T}_{mod}\,\mathrm{H}_i + \mathrm{C}\,\mathrm{H}_i + \mathrm{D}\,\mathrm{H}_i^2$$

where, (T_{mod}) is the temperature of the PV model, (H_i) is the in-plane global irradiance and (A, B, C and D) are the cleaning state-relevant polynomial constants calculated by from the data collected.

The power at each condition is referenced to those of the standard test conditions (STC: irradiance: 1000 W/m^2, cell temperature: 25 ℃ and solar spectrum: AM 1.5). Plant-1 recorded a difference in power of 6.9% between the cleaned and uncleaned models, while in plant-2 the difference is 1.1%. The difference in power loss percentages was attributed to the fact that plant-1 was installed on top of a land with loose sand, whereas plant-2 was installed on compacted soil. Furthermore, in comparing the clean state between the two plants, it is reported that plant-1 (being cleaned by water and brushing) generates higher power than plant-2 (being cleaned by water only). To put those power loss values in an economic representation, 34,800 €/year is the corresponding difference between the energy produced by plant-1 and plant-2.

Also in Europe, an experiment was conducted to assess the radiation losses due to soiling on photovoltaic models, based on the system's performance in Malaga, Spain (Zorrilla-Casanova *et al.*, 2013). Two identical photovoltaic cells, tilted at 30°, were used, where one cell was manually cleaned daily, and the second was kept uncleaned for the whole duration of the experiment. The experiment was planned for one year, to ensure exposure throughout all seasons, and the daily irradiation losses percentages (HL) were calculated using:

$$HL = \frac{H_{CC} - H_{DC}}{H_{CC}} * 100$$

where, (H_{CC}) is the measurement of the daily irradiation, from the daily cleaned cell, and (H_{DC}) is the measurement of the daily irradiation from the uncleaned (dusty) cell, both in Wh/m^2.

The records of rain events and the precipitation levels (in mm) helped explain the recovery of irradiation losses. A correlation is reported between the precipitation levels, the frequency of rain events and the irradiation losses registered. During the months of June, July and August, no rain events had taken place; during which, the highest monthly average irradiation loss reached 17.3% during in August, with a maximum recorded daily loss of 20%. Whereas rain events of precipitation levels as low as 5 mm helped recovering some of the losses, recording lower irradiation losses at 5%. The average monthly irradiation losses were between 0.4% and 3.2% for all the months, except the months of June, July, and August. Those three dry months impacted the yearly average irradiation loss, to be at 4.3%.

It's important to point out that the low levels of rain's ability to clean the cells is highly dependent on the characteristics of dust precipitating on those surfaces at the studied location. The data analysed based on the conditions in California, USA, indicated that only an event with 20 mm of rain was able to clean the system and recover the irradiation losses (Kimber et al., 2006), which is four times the level recoded in Malaga, Spain that was sufficient to significantly reduce the losses.

East and South Asia

One of the earliest publications in a region known for frequent dust events was published in 1974 (H. P. GARG, 1974). The objective was to analyse the effect of dirt on the transparent covers of flat plate solar energy collectors. The study took place in India and the duration of exposure was a month. The surfaces were set at different tilts, from 0° to 90° at 10° increments. After 30 days of exposure to the natural conditions without cleaning, the reported loss in transmittance was at its highest (69%) on the horizontal surfaces, while it was at its lowest (12%) is on the vertical surfaces. The Author highlighted, that the loss in transmittance becomes significantly higher when the tilts of plates are less than 40°; All plates tilted at 40° and beyond had a loss in transmittance of less than 23%.

In another study also conducted in an arid area located in India, the effect of dust on the transmittance of glazing materials (Glass, Acrylic and PVC) for solar collectors have been reported (Nahar and Gupta, 1990). A monthly analysis of the system's performance is reported for the three selected materials at three different tilts, 0°, 45° and 90°. The study investigated the impact of dust on the transmittance of the glazing materials, due to the particles accumulating on the surfaces as well as the permanent damage caused by those particles. The average monthly losses in transmittance for surfaces cleaned daily and weekly are summarised in **Table-3**.

Table 3 - Transmittance loss data for different PV cover materials

(MATERIAL) TILT (DEGREE)	LOSS IN TRANSMITTANCE (%)	
	Yearly Average / Daily cleaned	Yearly Average / Monthly cleaned
GLASS		
0	4.26%	15.06%
45	2.94%	9.88%
90	1.36%	3.28%
ACRYLIC		
0	5.27%	17.10%
45	3.98%	11.08%
90	1.78%	6.47%
PVC		
0	7.15%	-
45	5.16%	12.78%
90	2.35%	8.38%

Those results indicate that even with a periodical cleaning (Daily/Monthly) the material of the surface used have a significant impact on the transmittance. In the case of PVC covers, the weekly cleaned covers lost their transmittance and became damaged permanently. Similar damage is also reported for the other 2 sets of panels, based on their performance within a long-term exposure in 2 periods (winter and summer) without any cleaning. The transmittance patterns described in the research showed a direct fluctuation on rainy days and days of dust storm events during the investigation period. The study report losses in transmittance values at the end of each period, summarised in **Table-4**.

Table 4 - Transmittance losses within periods of long-term exposure without cleaning

(MATERIAL) TILT (DEGREE)	LOSS IN TRANSMITTANCE (%)	
	Uncleaned from 20 Jan / Till 18 Jul (179 days)	Uncleaned from 21 Jul / Till 15 Sep (56 days)
GLASS		
0	10.20%	37.50%
45	5.50%	14.10%
90	4.20%	5.20%
ACRYLIC		
0	21.40%	47.60%
45	7.17%	18.90%
90	5.70%	7.80%
PVC		
0	-	55.90%
45	-	44.50%
90	7.60%	20.70%

From those reported values, although the period from January 20th till July 18th is more than triple the investigated period from July 21st till Sep 15th, all materials and tilts recorded more losses in transmittance in the shorter summer period (56 days) compared to that of the longer winter/spring period (179 days). This can be attributed the days recording precipitation levels enough to clean the surfaces. Key conclusions from this research are the fact that glass cover surfaces outperform the other investigated materials. Also, the surfaces set at a 90° tilt has the lowest loss values in transmittance in all materials. Further, PVC as a cover material is not practical, considering the damage found, the lifetime of PVC covers is less than one year.

In another focused research, the effect of dust on the transmittance using low density polyethylene as a cover for solar panels was quantified (Mastekbayeva and Kumar, 2000). The study took place in Thailand, within a region specified for having a tropical climate. The panels were placed at a 15° tilt and the initial transmittance of the clean cover is measured to be at 87.9%. The panels were exposed for 30 days without cleaning, then the transmittance was recorded. The transmittance after exposure was 75.8%, resulting in a total loss in transmittance of 12.1%. It's important to mention that this experiment was conducted during the months of April/May 1998, with no recorded rain events taking place during that period. Using the data obtained, a dust correction (DC) factor formula was introduced, defined as the ratio between the estimated transmittance after exposure for (N) days divided by the initial transmittance of the clean surface:

$$DC = 0.0001N^2 - 0.0082N + 0.999 \quad , 0 \leq N \leq 30$$

It's key to know that this formula is specific to the low-density polyethylene PV covers, in a tropical region, and within number days of exposure being less than or equal 30 days.

Based on the weather conditions of Taxila, Pakistan, the efficiencies of two types of photovoltaic modules, a monocrystalline (c-Si) module and polycrystalline (p-Si) silicon module were evaluated (Hafiz *et al.*, 2017). The experiment was to analyse the performance of two sets (by two different manufacturers of each module), and the modules were set at a 50° tilt. The results compared uncleaned panels though out the whole experiment period (11 weeks) with periodically clean ones. Dust samples were collected and weighted, and I-V curves were measured twice a week, at three different times during the day (9 AM, 12 PM and 3 PM). For each, the output power (P) and module efficiency (η) are calculated using:

$$P = I * V \qquad , \qquad \eta = \frac{P}{G * A}$$

where, (G) is the global solar irradiance and (A) is the area of the solar panel. In this experiment, the c-Si module is about 15% bigger than the p-Si module.

The initial measurements of the modules' efficiency showed that for the clean panels, the p-Si modules perform better than the c-Si modules. Furthermore, results of the same module type, but from different manufacturers, did not have any significant variance in efficiency. After 11 weeks of exposure, the dust weight, accumulating on the surface of the panels, was 0.9867 mg/cm^2. Based on the composition and particle size-distribution of the sample, 32% was fine sand, of a diameter greater than 0.06 mm, 60% was silt with diameters between 0.06 and 0.002 mm, and 8% was clay of a diameter less than 0.002 mm. The relationship between the modules efficiencies and the increasing dust densities with time were found to be linear. The reduction in efficiency is 3.55% for the c-Si modules and 3.01% for the p-Si modules, for panels covered with dust of 0.9867 mg/cm^2.

Based on the output power distributions, recorded at different times during the day, the clean c-Si modules are slightly outperforming the clean p-Si modules in the weekly recorded output power. However, the uncleaned c-Si module was performing similarly if not lower than the uncleaned p-Si module. Furthermore, the output power measurements showed that the p-Si modules recorded lower reduction than the c-Si modules, comparing clean panels with unclean ones at the three different times of the day for the same module type. As for the efficiency of the two modules at the different times during the day, the weekly efficiency measurements show the clean p-Si modules outperforming the clean c-Si modules in most days of exposure. Also, the efficiency of the p-Si modules recorded lower reduction than the c-Si modules between the unclean models and the clean modules of the same type.

GCC and West Asia

In an attempt to understand the impact of dust on different solar systems, an experiment was conducted in 1981, comparing the performance of thermal flat plate collectors and photovoltaic flat plate collectors (Nimmo and Said, 1981). The location of the experiment was in KSA, and the two types of collectors were exposed to the natural conditions for 6 months. The uncleaned thermal collectors recorded losses of 26%, while the PV collectors recorded 40% loss. Such results are indicative of the transmittance significance, impacting the solar PV collectors' efficiency at a higher level. Furthermore, the importance of maintaining clean collector's surfaces for optimum performance for both systems.

The first publication that has analysed the performance of solar systems and their power generation potentials in Kuwait was in 1981 (Wakim, 1981). At that time, limited data were available reporting the performance of renewable systems. The study reported major loss in PV performance within few days, a loss of 17% in efficiency was recorded after only 6 days of exposure to the natural conditions. Following that research, another study in 1985 analysed the performance of flat surfaces solar devices in Kuwait (Sayigh *et al.*, 1985). The surfaces were tilted at 0°, 15°, 30°,45° and 60°, being exposed to the natural conditions for 38 days, reported transmittance losses of 64%, 48%, 38%, 30%, 17%, respectively. One key observation is that the horizontally placed panel (0° tilt) registered a 30% loss in transmittance after only 3 days. Both publications (Sayigh *et al.*, 1985; Wakim, 1981) gave clear indications that when the collectors are placed at tilts closer-to be (or are) horizontal, a significant loss in efficiency/transmittance is to be expected within a period less than a week.

On a larger scale, the performance of PVs was evaluated using data from an actual PV plant in KSA (Salim *et al.*, 1988). A conference paper compared the results between sets of PV panels periodically cleaned and uncleaned, being exposed to the natural conditions for a duration of 8 months. The PVs in the solar plant are tilted 24.68°, a yearly optimum for energy production in that location. The recorded efficiency loss due to the accumulated dust was 32%, a loss that can be avoided by maintaining frequent cleaning schedule (Salim and Eugenio, 1990).

Another study also compared the performance of three different solar systems, quantifying the effect of dust and compare the results of cleaned and uncleaned PV panel, double-glazed flat-plate collector, and an evacuated-tube collector with cylindrical reflectors (Said, 1990). The systems were tilted at 26°, facing South in Dhahran, KSA. The period of exposure without cleaning was different for each system. The double-glazed flat-plate collectors were uncleaned for 4 months, recording a reduction in the optical efficiency of 27%. The evacuated-tube collectors were uncleaned for 7 months, and their optical efficiency was reduced by 26%. As for the PVs, their surfaces were first uncleaned for 6 months, recording more the 60% drop in peak efficiency, marking an 11% reduction every month. Then the PVs were cleaned, and the test repeated starting in May, for a year, registering a 7% reduction per month. The monthly averages varied throughout the study period, as summer months has shown higher losses compared to winter months, due to the higher number of dust events during the summer season.

Multiple studies were published using data, form a plant powered by thermal collectors in Abu-Dhabi, UAE, collected between the years 1986 and 1990 (El-Nashar, 1990, 1994). One mainly focused on the effect of dust accumulation on the performance of evacuated tube collectors (El-Nashar, 1994). The uncleaned collectors recorded maximum reduction in peak heat collection between 60% to 70%. Data recoding the monthly efficiency fluctuation for the year 1986, of uncleaned collectors, was discussed in the publication **Table 4**.

Table 4 - Monthly record of efficiency loss from heat collectors

MONTH	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**
EFFICIENCY LOSS (%)	2.5	9	10.5	5	6	12.5	15	28.5	31	33	27.5	6.5

It’s important to note that, the collectors were tilted at 21° and data was collected at the end of each month (noon time), with no cleaning to the exposed surfaces of the collectors. The frequency of rain and the occurrence/intensity of dust events impact the losses in heat collection. The cumulative increase in efficiency loss correlates with the accumulation of dust on the collectors over time. When the values of the efficiency loss drop (on April, November, and December), its attributed to precipitation events at that month, in levels enough to recover some of the transmittance lost due to dust on the collector’s surface (natural cleaning).

Through different set of experimental and analytical variables, a new study, by the same author (El-Nashar, 2003), processed new data obtained from the same desalination plant located in Abu-Dhabi, UAE. The new publication assessed the effect of dust deposition on the transmittance and the performance of their designed solar system. As mentioned earlier, the solar system is meant to operate a in an area described as an arid desert. The field of 1064 evacuated tube thermal collectors with a total absorber area of 1862 m^2 was divided into two blocks. One was cleaned several times per week by a high-pressure water jet cleaning tool, while the other was subject to longer periods of exposure without cleaning (from one month to a whole year). The transmittance of the clean glass covers was initially measured/recorded (0.98).

From the measurements taken from the collectors’ covers, and the records of the power output from the collectors, the correlation between the loss of transmittance and the drop in efficiency due to dust is quantified. It’s reported that dust accumulation can lead to a drop in transmittance up to 30% from the uncleaned surfaces, and collectors operating with such surfaces, having a 0.7 transmittance value, recorded a 60% drop in power efficiency. Additionally, when the dust result in a drop in the transmittance of 0.7, it leads to the plant consuming 38% more power, due to more automatic start-ups and shutdowns while operating with such unclean collectors. Furthermore, the monthly recorded transmittance values show direct responses to dust and rain events. The frequent dust events and the cumulative nature of particles on surfaces lead to a continuous reduction in transmittance. While the rain events can be cited as the reason for transmittance recovery when an instant peak in the transmittance value is recorded or a cleaning has taken place.

It’s not unusual that authors refer to their previous work and shed a light on different aspect, using the same set of data. Data from the same desalination plant, powered by evacuated tube solar collectors, in Abu Dhabi, UAE, used in earlier reviewed publications (El-Nashar, 1990, 1994, 2003), has been further explored to understand the seasonal effects on the plant’s performance (El-nashar, 2009). This latest study is structured to focused on the seasonal effect and the loss in energy production due to the loss of transmittance. The data represented the seasonal effect in two periods summer (from May till August) and winter (from September till April). Sample evacuated tubes were set identically to the plant tubes, subjected to the same weather conditions and at cleaning frequencies intended to measure the short-term and long-term effect of dust. Voltage measurements were taken using a supporting plate, one taken in the middle of the sample tube (V_2) and the other outside the tube (V_1). The supporting plate is positioned at the same tilt of those in the plant, and solar sensors measurements were taken simultaneously. With those measurements, an equation is derived to predict the transmittance loss (τ):

$$\tau = C_s \frac{V_1}{V_2}$$

Where, C_s is a calibration constant. The long- and short-term effects of dust were measured based on two scenarios. The first scenario evaluates the short-term effect, by following a typical cleaning frequency of a monthly water wash, using a high-pressure plunger pump throughout a year. The second scenario evaluates the long-term effect, by keeping the tubes exposed without cleaning during the whole testing period (one year).

As the initial transmittance of the clean glass is 98%, the results out of the first scenario indicates that the seasonal loss in summer months are the highest, recording losses in transmittance between 6% and 16%, while the winter seasonal transmittance losses were between 2% and 4%. As for the data collected based on the second scenario, the uncleaned tubes for a whole year recorded a maximum loss in transmittance of 40%. Collectors losing 40% of their transmittance, can result in up to 60% loss in energy production; a ratio calculated by factoring the energy production rate of dusty collectors to the production rate of clean ones.

It was also observed that further to that direct impact of the loss in transmittance has on the plant's energy production, the plant's specific power consumption (SPC) varies based on the level of transmittance of the collector's covers. The correlation between the transmittance and the SPC ratio was presented as:

$$\frac{SPC}{SPC_o} = 0.1556\,\tau^2 - 1.4096\,\tau + 2.2327$$

Where the SPC is the dusty collector's annual average specific power consumption and the SPC_o is the clean collector's annual average specific power consumption. At the maximum recorded loss of transmittance (40%), This correlation measures the plant's increase in SPC at 45%.

Furthermore, based on the reported water consumption data and the frequency of cleaning's impact on the overall plant water production, the author notes that, although daily cleaning of the system will result in the highest energy production and the lowest SPC, daily cleaning might not be the optimum operating setup based on the overall plant performance. A single cleaning process consumes about 6.4 m^3 of water and requires 6 hours to be completed. Accordingly, it was suggested that when the plant undergoes a weekly cleaning program, optimum performance can be achieved, considering the plant's water production rate and the water consumed for cleaning. Therefore, it is important to compare the seasonal losses in transmittance that would occur between cleaning periods, the associated energy loss due to dust and the resources required for cleaning when deciding on the frequency of cleaning and the allocation of resources to achieve overall optimum performance.

As the wind and dust can mix with the surrounding pollutants emitted from industrial facilities, one research looked into the seasonal energy generation potentials, and the effect of tilt angle and local air pollution on the performance of photovoltaic systems (Asl-Soleimani *et al.*, 2001). The experiment took place in Tehran, where one group of panels were positioned at five different tilts 0°, 23°, 29°, 35° and 42° for seasonal analysis. In addition, two other group of panels were positioned at 45°, to analyse the impact of pollution. From the analysis of the first group of panels, the output power was measured at the start of every season; In summer, the zero tilt panels recorded the highest value compared to other tilts and was also the highest value between all other seasons. Looking at the cumulative values of all seasons, the panel with tilt of 29° had the highest overall energy value. The power outputs were measured at the beginning of the season, and the panels are not cleaned again until it's time to be measured again at the start of the next season. Traces of residue from bird droppings covered the surface of some modules, leading to differences between the theoretical maximum power output (assuming clean panels production rate) and the actual our output measured at site.

As for the pollution evaluation, the power output, for the 45° tilted panels, was measured on different days within the same season. Two days within the month of December were compared, the 14th of December 1999 was described as clean, partially cloudy, and windy; while the 22nd of December 1999, was described as one of the most polluted in the year. The description of clean weather usually given to days following a day with rain or snow, in precipitation levels enough to reduce the concentration of suspended particles. The results reflect the severity of the air pollution's impact on the power produced. The amount of energy produced by the module on a "clean" day and vs. a day with high air pollution are 179 Wh/d and 92 Wh/d, respectively. The overall reduction in power can reach 60%, comparing days within the same season classified as clean or polluted.

In a publication specific to Kuwait's climate, the performance a PV system was evaluated (AlBusairi and Möller, 2010). Two sets of flat cadmium telluride (CdTe) PV panels were set in six different tilt angles 0̊, 15̊, 30̊, 45̊, 60̊, and 90̊ and were exposed to the outdoor natural conditions. The first set of panels was cleaned daily to ensure maximum performance, while the second set of panels was cleaned once every month (start of the month). By the end of each month, and before cleaning, the glass samples were removed for spectroscopy analysis, evaluating the exposure's effect on the amount of radiation captured. The study linked some of the yield losses to a combined effect between humidity, rain, and dust.

The highest loss value recorded, was in the month of May, with 4% loss for the vertical panels (90̊ tilt) and 37% loss for the horizontal panels (0̊ tilt). The results, from panels positioned at 30̊ tilt, show that during the month of May, the system recorded the highest yield loss of 25%. Also during the month of May, the precipitation level was 12.5 mm. The month of June recorded the lowest yield loss of 6.6%, with 0 mm precipitation (no rain events). Moreover, the months April, July, and August recorded yield losses between 10% and 12%. While the month of April had the highest precipitation level recorded, at 16 mm, the months of July and August had 0 mm precipitation with no rain at all. This indicates that the limited rain events were not sufficient to recover the lost performance due to dust.

From the recorded performance of the daily cleaned, 30̊ tilted, panels during the month of July, the data indicates that the presence of humidity, at a high level, led to an increase in the yield losses on such days. While on following dry windy days, the yield losses were lower. From those observations, it can be assumed that dry dust can be easily blown off the panels, sustaining high performance throughout the day. Accordingly, it was recommended that the system cleaning better takes place after a combination of dusty days, followed by high humidity or light rain. Wind can improve the system's performance by blowing off the dust from the surfaces if dry. It was also suggested that soft brushes and water spraying might be needed to properly clean the panels.

In a different approach, one research used lab results and results obtained from outdoor exposure to study the impact of dust on the performance of PVs (Ibrahim, 2011). The first part of the study, a lab experiment, using a halogen lamp to simulate the solar energy, and a silicon monocrystalline solar panel of a 100 cm^2 area for producing electricity. Using standard test conditions (STC) for maximum output power as reference, considering irradiance of 1000 W/m^2, cell temperature of 25 ̊C and solar spectrum of AM 1.5. The corresponding measurements of the STC recorded a short circuit current (I_{SC}) of 200 mA, an open circuit voltage (V_{OC}) of 2.2 V, and a maximum power point (MPP) of 0.330 W. The aim of the first part is to understand the effect of shadowing casted by surrounding objects. Different parts of the solar panel were covered, and the corresponding I_{SC} and V_{OC} in each case was reported.

The second part of the study was focused on measuring the effect of dust on the photovoltaic system's performance, by determining the rate of dust deposits on solar panel's surface and the corresponding reduction rate of I_{SC} and V_{OC}. The same panel used in the first part of the study was installed outdoor, being exposed to the natural weather conditions for ten days in KSA. The maximum recorded I_{SC} and V_{OC} for a clean panel at the start of the experiment were 211.85 mA and 2.2 V, respectively. The reduction values within the first 10 days displayed linear patterns, and the losses can be calculated based on the number of days (t) the PVs has been tested without cleaning.

$$I_{SC} = 211.85 - 5.5612\, t$$

$$V_{OC} = 2.2 - 0.0192\, t$$

The functions are limited to 10 days of exposure, and the maximum reductions in I_{SC} and V_{OC} recorded were 26.25% and 8.73%, respectively. It's important to note that the outdoor experiment was conducted during the month of December, and the recorded measurements did not mark any peaks or drops in I_{SC} and V_{OC}. It indicates that no significant dust events nor rain events have taken place during that period and the derived linear rates are specific to that region, season, and system.

In a study focused on the characteristics of dust in Kuwait, the correlation between the quantity of dust and the performance of PV systems was investigated (Qasem *et al.*, 2014). Two sets of data were collected for two objectives. The first set was used to analyse dust samples, based on solid particles' size and chemical composition, and the transmittance levels of the glass samples covered with dust, measured using a spectrophotometer. The samples were collected after every 30 days of exposure between May 2010 and May 2011. The second set of data were collected to evaluate the effect of tilt on the dust deposition. The data was collected from South facing PVs, at tilt angles of 0°, 15°, 30°, 45°, 60° and 90°, between September and October 2009. After the exposure, the glass samples were encapsulated and sealed with epoxy for transmittance measurements. The effect of dust on the transmittance was quantified by measuring the area under the spectral transmittance curve (A_t) at different parts of the panel (Top, middle and bottom), to calculate the transmittance's non-uniformity on a panel:

$$Non - Uniformaty\ (\%) = \left(\frac{Max(A_t) - Min(A_t)}{Max(A_t) + Min(A_t)}\right) * 100$$

The first part of the results was of the dust samples, showing that the dust samples contained 44% of fine and very fine Silt and 20% of clay, with 90% of the particles below the 63 μm in diameter. The glass samples with different dust densities were tested at different wavelengths. The results show that the dust affects the lower wavelengths more significantly. By averaging the transmittance/dust density curves, wavelengths greater than 570 nm recorded a reduction in transmittance of 2.5%, while wavelengths less than 570 nm recorded a reduction of 11%.

The second part of the study addressed the non-uniformity calculations, showing that panels with a 30° tilt recorded the highest non-uniformity of the investigated tilts, with 4.4% non-uniformity between the top, middle and bottom of the panel. The lowest non-uniformity was recorded at 90° tilt at 0.2%. the reason of that behaviour is attributed to the gravity effect on displacing the dust particles after reaching the surface and the friction of the panel’s surface resisting that displacement. By averaging the amounts of dust at the different placements used for the non-uniformity analysis, the amount average amount of dust collected at the different tilts are enlisted in **Table-6**.

Table 5 - The amount of dust on PVs at different tilts

TILT (DEGREE)	DUST DENSITY (MG/CM^2)
0	3.37
15	2.30
30	1.93
45	1.30
60	1.17
90	0.23

Further, the reduction in spectral transmittance was quantified for four photovoltaic modules, crystalline silicon (c-Si), amorphous silicon (a-Si), copper indium gallium (di)selenide (CIGS) and cadmium telluride (CdTe). Glass samples, covered with different dust densities (1.2, 4.25, 14, 19 and 30 mg/cm^2) are evaluated. The reduction in spectral transmittance for the a-Si panel was the highest at all investigated dust densities. While the CIGS panel recoded the lowest reductions at all dust densities. The average reduction of spectral transmittance between the different modules at the different dust densities is summarised in **Table-7**.

Table 6 - The reduction in spectral transmittance at different dust densities

DUST DENSITY (mg/cm^2)	SPECTRAL TRANSMITTANCE REDUCTION (%)
1.2	9.675
4.25	30.05
14	61.78
19	72.93
30	98.03

Also in Kuwait, data from two sets of PVs were used to evaluate their performance against the weather challenges (Al-Otaibi *et al.*, 2015). The PV modules has identical operating characteristics and specifications, both roof-mounted, but different number of panels. The first location (Azda) was set with 567 PV's (array of 607 m^2). While the second location (Sawda) was set with 144 PV's (array of 154 m^2). Both systems were copper indium gallium diselenide (CIGS) thin film oriented to face the South and tilted at a 20°, set away from any objects that might cast a shadow or obstruct solar irradiation. Sensors were used to record the conditions, the data stored were concerning solar radiation, ambient temperature, wind speed, and temperature. Furthermore, an energy monitoring system was used to log the power output, ambient temperature, and the modules' temperatures at five-minute intervals for a whole year. In both locations, an automated cleaning system was set to clean the PV's by spraying water every week, and once a month spraying water with soap. It's noted that during the months of October, November and December the cleaning system was not used to evaluate the effect of soiling.

The performance of the systems was evaluated by calculating the performance ratio (PR), using the recorded data of the total output energy (Ps) in kW h, the irradiance (I) in kW h/m^2, the area of array (A) in m^2, and the efficiency of the module (Es):

$$PR(\%) = \frac{Ps}{I * A * Es} * 100$$

The initial observation out of the sensor's recorded data shows an alignment between the monthly irradiation and the amount of power generated; With the highest amount of power generated during the months of July and August, recording the highest amount of irradiation as well. However, as the PR percentage is calculated, July and August were some of the highly impacted with reduction in performance. This is attributed to the energy loss due to the higher ambient temperature, and the corresponding PV temperature, as well as the reduction in energy generated due to dust accumulation during the days in between cleaning events. The monthly PR ratio, during the year, for both locations is between 0.7 and 0.85. During the three months (October, November and December), when the cleaning system was not used, the average monthly Performance ratio reduction in Azda is 15.2% and in Sawda is 14%, with a cumulative loss due to soiling of 45.8% and 42%, respectively. With the average weekly performance loss due to soiling between the scheduled cleaning events found to be less than 1.7%, the author question if the cleaning events are better being scheduled further apart, considering the amount of water used/wasted for cleaning.

North Africa

One publication focused on evaluating the effect of dust on the transmittance of surfaces (Hegazy, 2001), as well as compare their results with the results of two other publications with similar objectives, in different regions (reviewed earlier) (H. P. GARG, 1974; Sayigh *et al.*, 1985). The analysis was specific to PV panels with a glass cover, tilted at 0˚, 10˚, 20˚, 30˚,40˚, 50˚, 60˚, and 90˚. The panels were exposed to the natural conditions, located near some agricultural fields in Egypt for a year. As the panels were cleaned by the end of every month and the measurements were analysed, the effect of dust (dust transmittance factor, F_d) is expressed as a ratio of the transmittance of a dusty panel (t), to the transmittance of a clean one (t_{clean}).

$$F_d = t / t_{clean}$$

The corresponding dust transmittance factor values for the different tilts installed 0˚, 10˚, 20˚, 30˚,40˚, 50˚, 60˚, and 90˚, averaged for each 30 days of exposure, are: 0.73, 0.77, 0.79, 0.815, 0.84, 0.85, 0.88 and 0.965; converting those values to transmittance loss percentages, the losses are 27%, 23%, 21%, 18.5%, 16%, 15%, 12% and 3.5%, respectively. The results also included data showing the relationship between the dust disposition (w) in g/m^2 and the different tilt angles. It concluded that surfaces at 90˚ tilt (vertical) accumulate less than 1 g/m^2, while surfaces at 0˚ tilt (horizontal) accumulate up to 6.8 g/m^2 after 30 days of exposure.

The comparison showed that Kuwait's F_d is higher than the F_d in Egypt and India, for surfaces with tilts higher than 15˚. Furthermore, the F_d for India and Egypt got closer in value for tilts above 50˚. Based on the three different sets of data, the general recommendation by the author was that for panels with tilts less than 60˚, a minimum cleaning frequency of one time every week is required, in order to maintain the effect of transmittance loss at a low level.

To assess the impact of dust on different solar panels, two types of solar panels were subjected to the environmental condition in Helwan, Egypt, evaluating the effect of airborne dust on their performance. (Hassan *et al.*, 2005). Some of the characteristics about the location referenced high concentrations of suspended particulate matter from natural sources (desert) and industrial sources (transport operations and cement plants). The first test was of amorphous silicon solar cells (a-Si), set at a 0˚ tilt (horizontal) and exposed to the natural condition without cleaning for six months. The second test was of polycrystalline silicon solar cell (Poly-Si), set at a 0˚ tilt (horizontal) and exposed to the natural condition, while being cleaned every day for six months.

For the a-Si system test, the efficiency was found to be dropping by 66% after six months without cleaning. Also, after the six months of exposure, the panels were cleaned and tested again. Comparing the results with clean panels that had not been exposed before, a 10% reduction in efficiency had taken place, a result of permanent damage due to the accumulation and scratching of the cells cover from dust. As for the Poly-Si system test, the first observation is that the daily amount of dust accumulating of the panels was higher in summer month than winter months; That corresponds to the recorded efficiency which found to be dropping in summer (13.2% at July) compared to winter (14.5% at December), a 9% reduction in efficiency between the two seasons. Since each type of panel had different conditions of exposure and cleaning, the conclusions are not comparable and each provide information specific to the module used (a-Si or Poly-Si).

In one of the more comprehensive studies, the effect of dust on the transparent cover of solar collectors was evaluated with respect to different orientations and tilts (Elminir *et al.*, 2006). The experiment took place in Egypt using 100 glass samples positioned at 8 orientations, North, North-East, East, South-East, South, South-West, West and North-West, and 7 tilt angles 0°, 15°, 30°, 45°, 60°, 75°, and 90°. The study also included analysis for the chemical composition of the dust particles dispositioned on the glass samples throughout the exposure period. The transmittance of the glass samples was measured periodically and after every rain event for a period of 7 months. Some of the glass samples were cleaned every month, after measuring the effect of dust on the transmittance and the weight of dust on those samples (by subtracting the weight of a clean sample from the weight of a dusty one after exposure). Other glass samples were kept uncleaned during the whole testing period.

One important observation from this research was that the mineralogical composition of the particles, collected from the glass samples, varied between the months of testing. The dust particles included minerals and pollutants attributed to transport operations and the large number of industrial facilities nearby.

The data indicated that the dust disposition did not vary in significant amounts between the different orientations, for each tilt. **Table-8** includes a summary of key data extracted from that study, comparing the averaged transmittance loss of different orientations, at each tilt, for samples cleaned every month (average of measurements for 7 months) and samples exposed to the environment without cleaning for 7 months. As well as the amount of dust accumulating on the surfaces (in g/m^2) after the whole period of exposure without cleaning.

Table 7 - Dust impact on surfaces positioned at different tilts

TILT (DEGREE)	DUST WEIGHT AFTER 7 MONTHS (G/M^2)	TRANSMITTANCE LOSS (%)	
		7 months exposure	30 days average
0	15.84	52.54%	27.62%
15	12.5	44.75%	20.18%
30	12	44.50%	18.47%
45	12	42.63%	15.96%
60	10.625	39.00%	13.62%
75	7.25	29.00%	10.82%
90	3.4375	14.38%	6.32%

The data shows that if the surfaces are uncleaned, the maximum loss in transmittance, reaching up to 52.54%, are of glass covers, positioned **horizontally**, and the minimum loss in transmittance, of 14.38%, are of glass covers positioned vertically. Finally, the author was able to formulate a correlation that can measure the reduction in transmittance ($\Delta\tau$), from the dust disposition weight (ρ_D in g/m^2) values:

$$\Delta\tau = 0.0381\ \rho_D^4 - 0.8626\ \rho_D^3 + 6.4143\ \rho_D^2 + 15.051\ \rho_D + 16.769$$

Another phenomena was also reported, indicating that when the surfaces are exposed to long periods of humid weather, or subjected to precipitation levels that are not enough to fully remove the dust accumulating on the glass surfaces, a layer of dissolved then re-crystallized minerals accumulate on the glass covers. Those layers were found visible on the covers that were not cleaned during the whole period of testing.

Lab experiments

To understand the correlation between direct beam solar radiation received by a photovoltaic panel and the sand/dust accumulating on its surface, a lab experiment was designed (Al-Hasan, 1998). The experiment is designed to replicate the movement of dust against fixed surfaces, using a duct box, a sand/dust blaster, and an air pressure regulator to control the high-speed air and allow the sand particles to be suspended inside the box. After the dust movement is simulated, the particles are allowed to be deposited on horizontally placed glass surface inside the duct. The glass surfaces were subjected to different runs, and the amounts of radiation beaming through were measured corresponding to the different amounts of dust disposition on each surface. The results from this experiment showed that when the average size of sand/dust particles is 6.44 µm with sand particles density of 2.65 g/cm^3, the relationship between the transmittance and the amount of dust particles accumulating on a surface is liner (while the loss in transmittance is less than 50%). The transmittance after exposure (τ_b) can be calculated using:

$$\tau_b = 1 - 2N\pi r^2$$

Where, (N) is the number of dust particles on one cm^2 surface and (r) is the sand/dust particle size radius. When the transmittance loss exceeds 50%, the sand/dust particles start accumulating on top of each other and that linear correlation is no longer applicable. The work in that publication is based on specific conditions, such as the sand/dust particles size and density as well as limited chemical composition of used particles in the experiment. In nature, the dust particles vary in size/density and includes solid particles that might be organic and non-organic. While the correlation was quantified, in real applications, the assumption that the dust particles are consistent in size and density reduced the reliability of the outcome based on that function.

Further to that publication, the correlation between the efficiency of photovoltaic panels and the amount of dust accumulated on their surface, based on the voltage and current measurements, was evaluated (Al-hasan and Ghoneim, 2005). The new lab experiment (by the same author) compared two sets of panels tilted at 30̊, one was kept clean while the other was subjected to sand particles, suspended in the air by a fan. The fine sand (dust) particles were collected from the desert and cleaned of other particles. The weight of sand particles accumulating on the surfaces was measured, and the associated current (I), voltage (V) and system efficiency were recorded at different weight values.

Based on the lab conditions, the maximum loss in short circuit current reached 40%, while the open circuit voltage did not register any sensitivity due to dust accumulation, and the power output loss can reach up to 34% of the system's maximum output power. A liner relationship can represent the system's efficiency and the weight of dust accumulation up to 1.5 g/m^2 with a reduction rate of 33% to every 1 g/m^2. The degradation rate in transmittance after 1.5 g/m^2 of dust becomes less, as the sand particles start to accumulate on top of each other beside accumulating on the other clear parts of the glass surface.

It's important to mention that the use of the correlations concluded from the lab based experiments (Al-Hasan, 1998; Al-hasan and Ghoneim, 2005) must be with caution, and in consideration of assumptions made and reflecting the specific conditions highlighted by the author(s).

A similar investigation, of same three PV modules (monocrystalline, polycrystalline, and amorphous) tested in Mexico (Cabanillas and Munguía, 2011), the impact of airborne dust deposition on the PVs performance was evaluated with an experimental setup (Jiang *et al.*, 2011). An experimental testing chamber was designed with three main components, a sun simulator, an airborne dust generator, and measurement systems. The temperature and humidity were controlled inside the chamber (Panel Temperature was 25̊ C and the relative air humidity was 60%). The dust used had a specific weight of 2.65 g/cm^3 with chemical components mostly of SiO_2 and Al_2O_3. The panels were fixed horizontally (0̊ tilt) to capture radiation at a perpendicular angle.

The open circuit voltage (V_{oc}) and the short circuit current (I_{sc}) of the three PV modules were measured using an I-V curve tracer. The results show that as the dust density increases on the surfaces of the panels, the I_{sc} output is decreasing. While no significant differences between the performance of the three models, it was reported that when the dust deposition density (ρ) reaches 22 g/m^2, the I_{sc} is reduced to 78% of its maximum value and 6% for the V_{oc}. It's worth mentioning that the monocrystalline panel slightly outperformed the polycrystalline and the amorphous models before the dust density have reached 20 g/m^2. Simple normalised power output efficiency calculations were made to assess the impact (Reduction) using:

$$E = \frac{Output\ power}{Input\ Sun\ Power} = \frac{V_{oc}\, I_{sc}}{G\ A} \qquad \& \qquad \frac{E_{Reduction}}{E_{Clean}} = \frac{(E_{Clean} - E_{Dusty})}{E_{Clean}}$$

where, (G) is the reference irradiation and (A) is the area of solar module.

That led to a calculated power output reduction of 26% for panels with 22 g/m^2 of dust. The reduction rate of the modules' efficiency was fitted in linear relationships with the dust deposition density for each model as:

$$E_{Reduction} \big/ E_{Dusty} = k\ \rho_{\text{depostion}}$$

where (k) is the material constant calculated, being 0.0115, 0.015 and 0.0139 for monocrystalline, polycrystalline, and amorphous modules, respectively.

During that experiment, it was recorded that for the same duration of exposure, the polycrystalline silicon cells covered with epoxy surface accumulated more dust than the other two models. Moreover, the larger the dust particles are used, the more unrecoverable damage the panel surfaces have endured.

In a different lab experiment, one type of PV system was tested to evaluate the impact of two types of artificial dust (Suliman *et al.*, 2012). In the experiment, a couple of spotlights were used to simulate the solar radiation and measure the effects of dried mud and talcum powder on the system's performance. The author justified his decision, in avoiding natural conditions/dust, as an effort to avoid the non-uniformity in dust distribution on the panel's surface. The output voltage and current produced by the panel were recorded using three radiation levels (340 W/m^2, 301 W/m^2, and 255 W/m^2), in four conditions; using plastic sheets covered with dried mud, using plastic sheets covered with talcum powder, using a clean plastic sheet, and without the plastic sheet. The efficiency (η) was calculated using:

$$\eta = \frac{V\ I}{P\ A} * 100$$

where, where (I) is the electrical current and (V) is the voltage produced by the solar panel, (P) is the power of the incident solar radiation and (A) is the surface area of the solar panel.

The measurements taken with the clean plastic sheets and without the plastic sheet, had a slight difference, the PVs performed better without the clean plastic cover. Based on the three radiation levels tested, the maximum reductions in peak power were found when the radiation was at 255 W/m^2. Furthermore, the higher the radiation value is, the lower reduction in peak power is recorded. The highest efficiency values were reported when the system was tested with or without the clean plastic sheets, at 4.82%. When the PVs were tested with the plastic sheets covered with mud, the efficiency was 3.95%, and when the PVs were tested with the plastic sheets covered with talcum powder's efficiency is 4.03%. The overall reduction, compared to the clean condition, is 18% for the dry-mud covered sheets, and 16% for the talcum powder covered sheets.

In a publication that had no outdoor or lab experiments, a comprehensive analysis based on previous publications evaluated the efficiency of photovoltaic systems in the presence of dust, humidity, and wind (at air velocities that can improve or hinder the performance) (Mekhilef *et al.*, 2012). When impact of dust, humidity, and wind on PV panels and their performance are evaluated separately, the general correlation between the quantity of dust disposition and PV performance, is that more dust result in lower performance. As for the humidity, systems exposed to higher levels of humidity had generally shown lower performance. The drop in performance due to humidity was explained as a result of either the effect of water particles on the amount of radiation captured by the system, the penetration of water into the enclosure of the photovoltaic panel, or both. Light hitting the condensate particles forming on the photovoltaic panels cause it to be refracted, reflected, or diffracted; when that happens, a significant drop in the short circuit current has been reported, while lower effect on the open circuit voltage is noticed. The presence of humidity at high levels for long periods is reported to cause encapsulate delamination, leading to permanent damage to the system. Moreover, hot humid weather is reported to expedite the system's deterioration. As for the wind velocity, the effect of wind on the photovoltaic performance is indirect. Wind velocity can significantly lead to an increase or decrease the panel's temperature, which is a key parameter to evaluate the reduction from optimum solar conversion efficiency.

The combined effect of the three factors (dust, humidity, and wind velocity) was evaluated, as each has resulted in an effect on the other. The results indicated that in hot and humid regions, wind at higher velocities can help lowering the PV module's temperature and improve its efficiency. Meanwhile, in hot dry regions, high wind velocity is the main reason for dust suspension that leads to efficiency drop. Furthermore, presence of dust and humidity together cause more dust coagulation which reduces the efficiency, is harder to clean, and might result in permanent damage to the panel's surface (depending on the module's material).

2.0 Methodology

The knowledge accumulated from reviewing the regional conditions and challenges, specific to PVs applications, is the bases for understanding their potentials in Kuwait. The main objective of using PVs is to generate energy from available/renewable resources that has minimum levels of emissions.

The objective of this research is to further investigate the productivity of PVs, integrated within buildings' façades. The methodology in this chapter focused on two main components. The first component is building a prediction model that can quantify the impact of dust, as it has been reported by the reviewed literature to have a significant impact of PVs productivity in Kuwait. The second component is simulating the performance of PVs, in Kuwait, at different positions (tilts and orientations), to compare the results based on the effect of dust's accumulation rate and the frequency of system cleaning. That includes the simulation PVs at positions suitable for installation on buildings' walls.

2.1 Transmittance loss Model

By comparing the conclusions from the different literature reviewed, the transmittance loss by dust disposition clearly varies based on the region, and the characteristics of dust particles associated with it. An experiment designed to quantify the amount of transmittance loss at different tilts for a defined period, is affected by the time of the year when its conducted, and the spontaneity of dust events occurring during that time. Alternatively, prediction models can quantify the transmittance loss, at various tilts through time, using the available regional data. A model built based on data collected from multiple studies with similar regional/ environmental characteristics can strengthen the model's reliability; as the data is collected from different seasons, using different methods aimed at a similar objective (quantifying transmittance loss).

First, the data available from studies of PVs and dust, conducted/exposed to the environment of Kuwait is grouped (AlBusairi and Möller, 2010; Hegazy, 2001; Sayigh *et al.*, 1985; Wakim, 1981). The data chosen is specific to surfaces that were not cleaned during the experiment, or recorded losses before cleaning and when it took place. Second, data specific to hot/arid regions, similar climate and environmental conditions in Kuwait (Egypt and India), are also considered to increase the data points, and ensure convergence in the model (Elminir *et al.*, 2006; H. P. GARG, 1974; Hegazy, 2001; Nahar and Gupta, 1990).

The data used cover a range of surface tilts between 0̊ and 90̊, with measurements of dust accumulation on uncleaned surfaces span from one day to 210 days. The data used is specific to the transmittance loss recorded from glass surfaces only, being the most commonly used/productive PV material in hot and dry regions. Forty data points are used to generate a model that can estimate the transmittance loss percentage within 30 days, at any tilt between 0̊ and 90̊.

The objective from the model is to predict the loss in transmittance due to the cumulative impact of dust on flat surfaces. The positioning of those surfaces (tilt and orientation) are the initial variables to be selected when PV systems are being considered. Two publications evaluated the relationship between the orientation of PVs and the amount of dust accumulating on them (Elminir *et al.*, 2006; Kimber *et al.*, 2006), both reported that the orientations do not influence the soiling rates in a significant way (less than 2%). The transmittance loss model is not focused on the energy generation potentials from each orientation at this point. Accordingly, the model is assumed be applicable to all orientations, predicting the cumulative transmittance loss within 30 days of exposure, at tilts between 0° and 90°.

The prediction model is built based on the Kriging method, as the data used has regional/geographical nature (Sacks *et al.*, 1989). Kriging is specifically useful as predicting model for data at different spatial location while capturing the regional variabilities of each data set (Cressie, 1988). The Kriging method uses covariate information to accurately capture the relationship between multi-variables data sets and is made of two components: the regression model $f(.)$ and the correlation model $\mathcal{R}(.)$. In this case, the Kriging predictor looks like:

$$TL(t,d) = f(t,d) + \varepsilon(t,d) \qquad (1)$$

as a function of two variables, the tilt (t) and the days of exposure (d). (ε) have zero mean and covariance related to the correlation function $\mathcal{R}(.)$:

$$\mathcal{R}(\theta,x) = \prod_{j=1}^{n} \mathcal{R}_j\,(\theta,x_j) \qquad (2)$$

where, (θ) is the correlation parameter, and (x) represents the data value at set (*j)*. As a rule of thumb, the Gaussian, or the spline functions fit better when the function is continuously differentiable, likely showing a parabolic behaviour near the origin. A linear, or an exponential function perform better, if the prediction displays a linear behaviour near the origin. (θ) is optimally found using the variance of data set and the determinant of $\mathcal{R}$ (Sacks *et al.*, 1989).

The prediction model is operates with linear regression for $f(t,d)$ and Gaussian correlation function $exp(-\theta x^2)$, at tilts between 0° and 90°, and within days of exposure up to 40 days. In the regression models, the shape and structure of the model is pre-defined within the polynomial class of functions, which is not always an accurate shape for a given data set. However, the Kriging interpolation adapts itself nonlinearly to the data set given the extra component in equation (1) using the covariance of data in a Gaussian process (Lophaven *et al.*, 2002).

In the module its assumed that the prediction of dust accumulation follows the same trajectory every month and can be reset once the PVs are cleaned. In real-life, dust events cannot be accurately predicted nor follow the same occurrence frequency every month. However, the data used in building the prediction model are from different seasons/years, representing the yearly impact of dust on the performance of PVs.

The accuracy a prediction model can be measured by calculating the coefficient of determination (R^2), the MAE (mean absolute error), and the MSE (mean squared error). Those three metrics can measure the strength (goodness of fit) of the model. R^2 is function of the regression sum of squares (SSR) and the total sum of squares (SST):

$$R^2 = SSR/SST \qquad (3)$$

where, SST can also be calculated by the summation of SSR and the sum of squares of errors (SSE). Accordingly, the value of R^2 is between one and zero. The closer the value of R^2 to 1, the stronger the prediction is (as the value of SSE will be closer to zero).

The MAE is calculated by averaging the summation of the absolute values of the model's errors:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|e_i|, \qquad (4)$$

And, the MSE is calculated by averaging the summation of the model's error squared values:

$$MSE = \frac{1}{n}\sum_{i=1}^{n} e_i^2. \qquad (5)$$

The MAE and the MSE values range between one and zero as well. The closer their values to zero, the better competency in prediction the model has.

2.2 PV potentials

To reflect the impact of dust and tilt selection on PVs through the proposed transmittance loss prediction model, the solar energy generation potentials in Kuwait must be measured. Commonly, ground measurements of the solar radiation are calculated hourly, daily, weekly, and monthly, based on the sun's position and the location where its being measured from. For renewable energy applications, satellite derived solar radiation measurements are considered to be a good alternative to ground measurements (Ineichen, 2014). The output of the GIS model used for PV energy calculations has been the subject of analysis and validation, reportedly providing the best statistics among six models designed to estimate irradiance components.

GIS solar modelling technology[5] can calculate the optimum tilts for energy production by PVs for any given location (longitude and latitude). The optimum positioning (tilt) of PVs can be calculated based on the yearly performance, or the seasonal performance. In Kuwait, the optimum orientation for PVs is when the panels are facing the South direction, and the tilt providing the highest yearly energy generation potential is 29°. When the tilts are evaluated seasonally, the optimum energy producing tilt in summer is 6°, in winter is 52°, and in spring/fall is 29°.

[5] GIS model provided by www.solargis.com

Satellite based simulations have also been used to estimate the potentials from energy generation systems, powered by renewable resources (solar and wind) (Pfenninger and Staffell, 2016; Staffell and Pfenninger, 2016). To calculate the PVs potentials, the size of the system is an input of the energy simulation model[6]. As the size of the model going to be a variable in the next Chapter, the daily potential solar energy output is simulated for a 1 kWh system, considering the regional conditions on Kuwait. It's important to highlight that the solar energy simulation platforms, uses hourly recorded satellite measurements at any selected location within a full year. Accordingly, the energy values consider the fluctuation in energy generation due to any detected environmental factors that can affect the amount of solar radiation measured, such as clouds, or dust.

The simulation calculates the energy production of a 1 kWh PV system, at multiple tilts that can be classified in three groups. The first group is specific panels facing South, at optimum tilts for the highest energy generation potential, 6° during Summer, 52° during Winter, and the overall yearly optimum at 29°. The second group is for three additional tilts of PVs facing South, to analyse the trend-line of energy generation potential at different tilts between 0° and 90°. The third group consists of the PVs potentials at the 8 different orientations (North, North-East, East, South-East, South, South-West, West and North-West), each at three different tilts 90°, 85°, and 80°. It was argued in two independent publications (Elminir et al., 2006; Kimber et al., 2006), that the PVs orientation does not greatly influence the dust accumulation rates. Hence, the prediction model created to quantity the transmittance losses can be factored in the energy generation potentials, simulated at each orientation.

The three tilt angles, at the eight different orientations, in the third group were chosen for two main reasons. First, to quantify in the opportunities within a building envelope, utilizing the wall areas for energy production. PVs can be wall mounted, structurally fitted on external walls, and placed between/ above windows at all four sides of a building. Second, as concluded from the reviewed literature, surfaces with tilts close to the vertical levels have lower potential of dust accumulation; Hence, less maintenance (cleaning), leading to better reliable energy generation output and minimum losses due to dust. This chapter is focused on the opportunities at each case; building up the data needed for the following chapter, evaluating the losses in energy values at those three tilts, compared to the highest potentials from PVs, that could have been achieved if installed at optimum angles.

Finally, a link must be established between the transmittance losses model and the simulated energy generation potentials. The loss in transmittance, as a percentage over days of exposure, does not

[6] Renewables calculation model provided by www.renewables.ninja

equal the losses in power (watts) through the same days of exposure, at the same rate (El-nashar, 2009; Paudyal *et al.*, 2017; Shah *et al.*, 2020). Based on the reported performance losses in the publications that correlated the transmittance losses with the power losses, different PV systems had different rate of loss between the transmittance and the power. Accordingly, It's the user's choice to select the correlation that suits the PV system chosen.

3.0 Results and Discussion

3.1 Transmittance loss model

Following the methodology detailed in section 2.1, the prediction model can estimate the transmittance losses, at tilts from 0̊ (horizontal to the ground level) to 90̊ (perpendicular to the ground level) and within 40 days of exposure (**Figure - 5**). The transmittance losses are at their lowest when the tilt is closer to 90̊. At each tilt, the transmittance losses increase with time. The model also indicates that the rate of loss in transmittance becomes lower, as the tilts increase. The two-dimensional views highlight the transmittance loss data vs. the model's prediction during the days of exposure (**Figure – 6.a)** and against the different tilts (**Figure – 6.b)**. One key observation is the difference between the transmittance loss at tilt 0̊ and tilt 90̊ by day 30, reaches almost 50%.

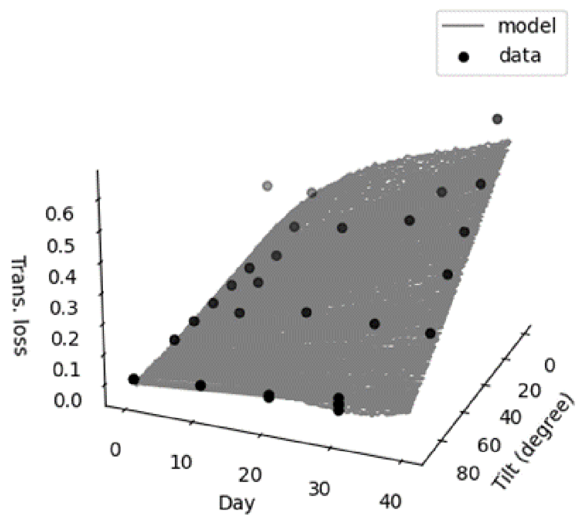


Figure 5 – Prediction model of transmittance loss at different tilt

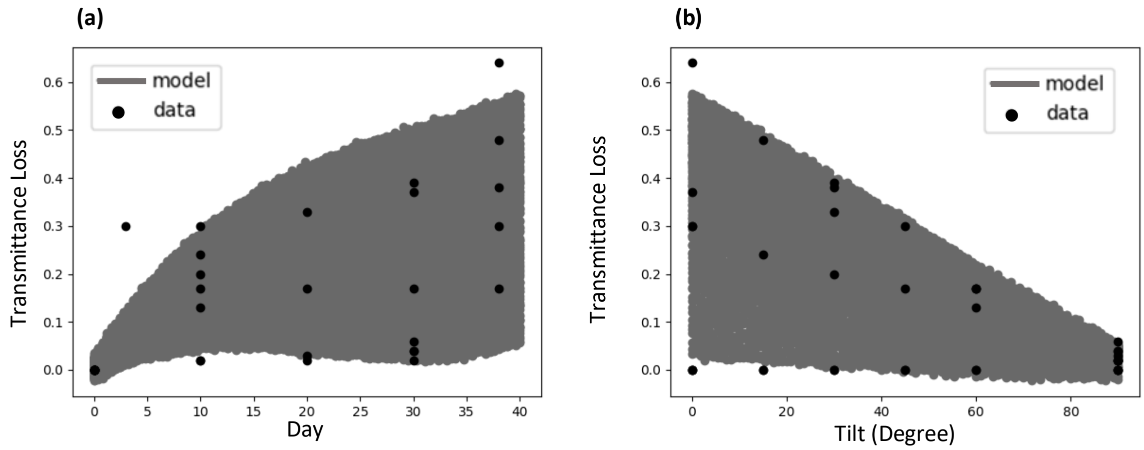


Figure 6 - Two dimensional views of the transmittance loss data vs. prediction (a) Transmittance loss vs. days of exposure, (b) Transmittance loss vs. tilt

From **Figure 5 and Figure 6 (a-b),** the prediction model visually appears to converges with most of the data point. The strength of the prediction can be measured by calculating the values of R^2, the MAE and the MSE. The value of R^2 is 0.928, very close to 1, indicating a strong fit between the data points and the prediction model. The value of the MAE is 0.026 and the value of the MSE is 0.002, both are close to zero, indicating that the errors between the data points and the predictions are very minor (**Table 9**).

Table 9 - Prediction model strength indicators

	Accuracy Indicator	Value
1	R^2	0.928
2	MAE	0.026
3	MSE	0.002

Based on the indicators' values, the prediction is strong, and the model is considered reliable in predicting the loss in transmittance, at different PV tilts, during 40 days of exposure to the regional environment (Kuwait) without cleaning. The use of this prediction model depends on the objectives of the user. The loss in transmittance can be used to calculate the potential losses in energy generation and/or the drop of efficiency of a PV system. However, the correlation between the transmittance and power output/efficiency is a user input, based on the specifications of the PV system selected.

3.2 Simulation of PVs potentials

Based on the PVs tilt, the loss in energy generation potentials, due to transmittance losses by dust, can be evaluated. The tilt of solar panels has a dominant effect on the amount of energy generated by the system. Similarly, the amount of loss in transmittance is highly impacted by the tilt of PVs. The simulation of PVs monthly energy generation potentials in Kuwait, for the first group of tilts (the overall yearly optimum at 29̊, the summer optimum at 6̊, and the winter optimum at 52̊), are plotted in **Figure-7**, specific a 1 kW PV system, facing South.

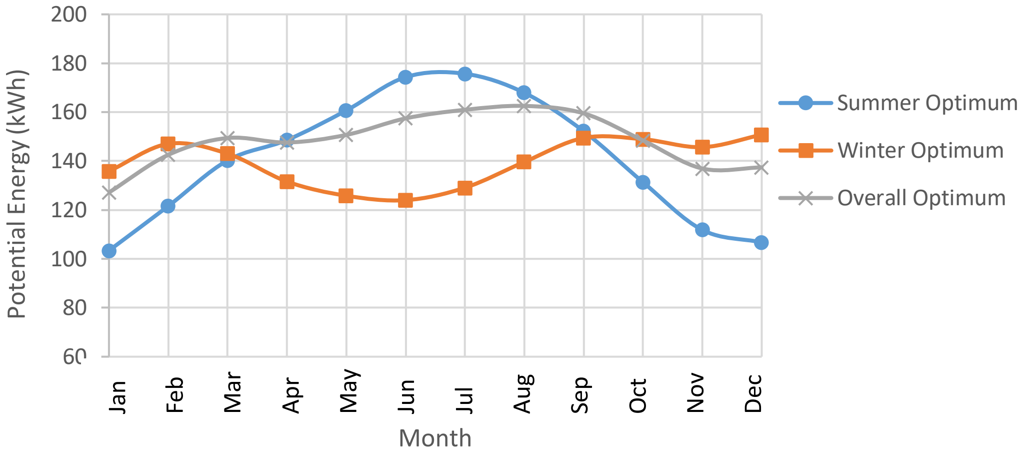


Figure 7 -Monthly energy generation rates at Kuwait's optimum PV tilts

Based on the yearly energy production rates from those three different tilts, the summer optimum tilt generated 5% less energy than the overall optimum tilt, while the winter optimum tilt generated 6% less energy than the overall optimum tilt. The simulation of the second group of tilts, combined with the yearly energy production from the three optimum tilts, presented in **Figure-7**, are used to analyse the pattern of yearly energy generation potential corresponding to PV tilts between 0̊ and 90̊. The pattern of yearly energy generation potential at different PV tilts is presented in **Figure-8**.

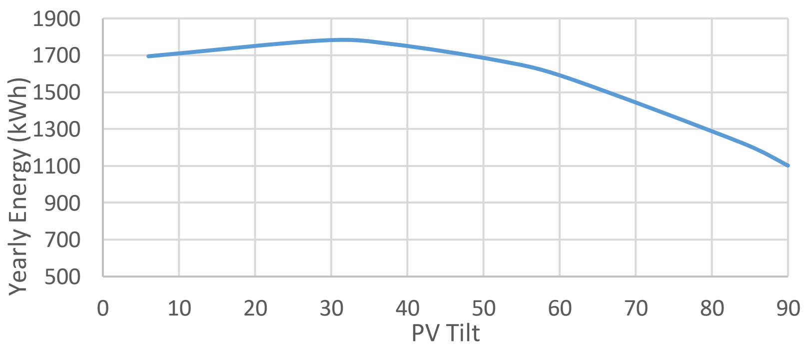


Figure 8 - Yearly energy potentials of South facing PVs in Kuwait, at different tilts

It's important to restate, that those measurements are simulated while assuming clean surfaces of the PVs at all the time. The immediate impact of weather parameters, that could've impacted the amount of irradiance reaching the surfaces of PVs such as clouds and dust events are reflected in the daily satellite-based simulation. The dust prediction model can be used to account for the accumulation of dust due to the surfaces' exposure to the environment (in Kuwait), until a cleaning event takes place. Accordingly, the application of the dust reduction model requires definition of the frequency of cleaning. A cleaning event would be reflected in the use of the model as a reset to the losses accumulating due to dust. By factoring in the relationship between transmittance losses and the corresponding energy losses from PVs (El-nashar, 2009), three PVs cleaning scenarios are analysed:

- Scenario 1: PVs are cleaned once at the end of every month
- Scenario 2: PVs are cleaned twice every month, once after 15 days, then again by the end of the month.
- Scenario 3: PVs are cleaned by the end of every week

Figure-9 highlights the differences between the monthly energy production rates of the simulated for the optimum tilts (presented in **Figure-7**), and the consideration of Scenario 1 while applying the reductions from the Dust Factor (DF).

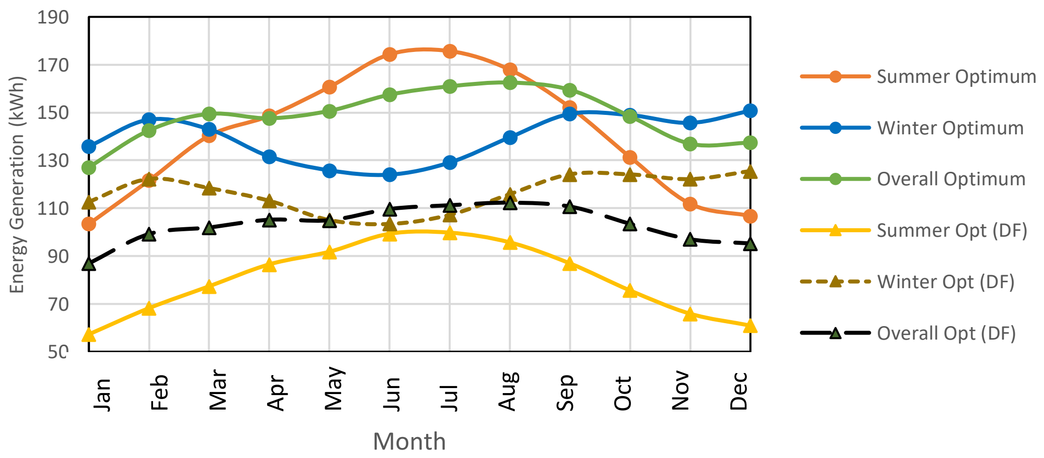


Figure 9 - Monthly energy comparison for optimum tilts (Scenario 1)

By comparing the amount of yearly energy production to those with losses from dust exposer and cleaned every month (Scenario 1), the differences are 43%, 30% and 17% corresponding to the optimum PV tilts 6̊, 29̊ and 52̊ respectively. In that case, the winter optimum tilt is estimated to outperform the summer optimum tilt and the overall optimum tilt. The difference in the total yearly energy production of PVs at the winter optimum tilt, compared to PVs at the summer and overall optimum tilts are 31% and 11%, respectively.

Based on the cleaning frequency assumed in Scenario 2, PVs are scheduled to be cleaned once at the middle of the month and a second time at the end on the same month. Accordingly, the cumulative effect of the DF is factored in the daily energy generation rates up to day 15. Then, starts again on day 16 up to the end of the month. The differences in yearly energy production from PVs, by applying the DF based on Scenario 2, are 28%, 19% and 11% corresponding to PVs at tilts 6̊, 29̊ and 52̊ respectively. As in Scenario 1, the winter optimum tilt remains the highest producing tilt. The difference in the total yearly energy production from PVs at the winter optimum tilt, compared to PVs at the summer and overall optimum tilts are 17% and 2%, respectively.

As for Scenario 3, the frequency of cleaning is assumed by the end of every week. This is reflected in the model as a weekly reset to the cumulative effect of the DF. Based on the results from Scenario 3, the order of which tilt can generate more energy has changed from the two previous scenarios. The percentage of yearly energy losses from the optimum values, are 13%, 9% and 5% corresponding to tilts of 6̊, 29̊ and 52̊ respectively. PVs at the overall optimum tilt (29̊) in this scenario has the most yearly energy generation value. The difference in the total yearly energy production from PVs at the overall optimum tilt, compared to PVs at the summer and winter optimum tilts are 9% and 2%, respectively.

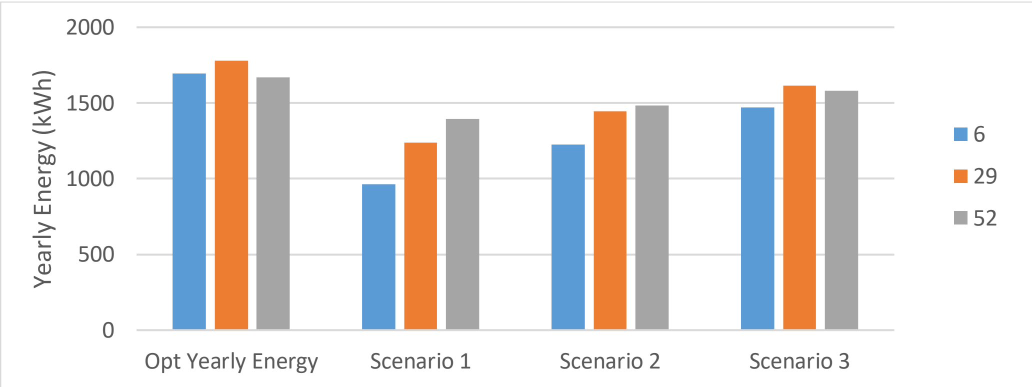


Figure 10 - Yearly Energy Generated (kWh) at Different Cleaning Scenarios

Figure-10 highlights the differences in the yearly energy generation potentials based on the three cleaning scenarios, compared with the rates simulated without the impact of the DF. When the frequency of cleaning is increased, the energy generation potentials get closer to the optimum state of energy production.

The use of this prediction model can be for determining the optimum cleaning schedule for PVs, choosing a tilt based on a trade-off between PVs productivity and losses due to dust, or evaluating the regional efficiency of PV systems in Kuwait. The user gets to decide one or more of those objectives out of this model.

3.3 Simulation of PV potentials on walls

Since the objectives in this research are focused on the energy generation potentials within buildings, PVs' orientation, tilt angles (**Figure-11**), and their quantity are restricted by the different configurations analyzed in the previous chapters. The calculations can consider PV installation at one or multiple sides of the buildings, limited by the available space on each side (excluding windows and doors). The four sides of the buildings vary in geometry, as the aspect ratio varies between 1:1 and 1:2. The buildings energy generation potentials are highly associated with the orientation of each external wall. Based on the buildings' orientation definition, all the building cases would have their four walls positioned in one of two cases (**Figure-12**). Wall-mounted PV's are positioned at angles vertical and close to vertical, for the following reasons:

- Be a part of the building's unutilised wall façade.
- Reduce shading from surrounding panels, being vertical/close to vertical tilts.
- Reduce the cost of panels' structural support, being mounted on walls.
- Ease of access for cleaning and maintenance using pre-existing windows' cleaning systems
- Reduce dust accumulation that would lead to energy generation losses.

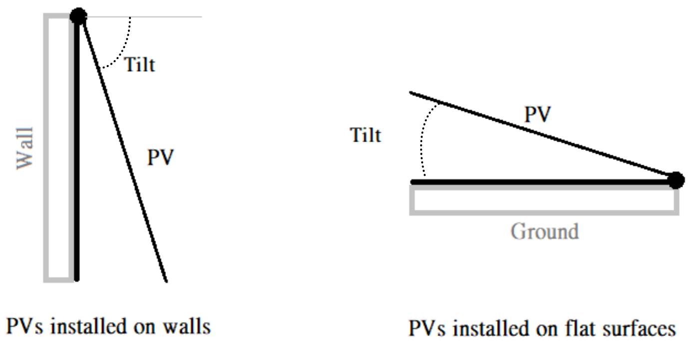


Figure 11 - Tilts of PVs installed on walls vs. PVs installed on flat surfaces

Case (1) highlights the position of buildings with walls facing the true North, East, South and West. Case (2) is for the buildings with walls facing the North-East, -South-East, South-West and North-West.

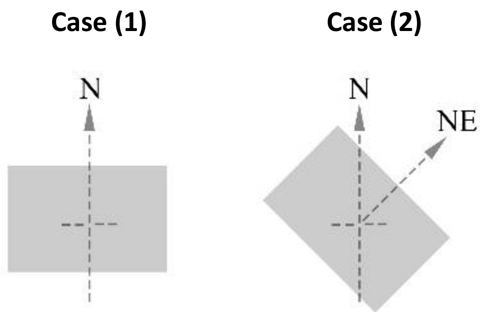


Figure 12 - Potential walls' orientations

As explained in the methodology, the third group of tilts were simulated for PVs potentials at eight different orientations (North, North-East, East, South-East, South, South-West, West and North-West). However, in each building's case, four of the eight orientations are used to calculate the potential energy generation, by simulating the energy generation potential from the four walls/orientations. Accordingly, the daily energy production rates from a 1 kW PV system at 80̊, 85̊, and 90̊ tilts, are simulated based on the regional conditions in Kuwait.

- **Case 1:**

For the buildings with walls facing the true North, East, South and West, the daily energy production rates from a PV system with a 1 kW capacity at 80°, 85°, and 90° tilts are grouped in Figure-12 [A, B, C, & D].

The yearly energy generation from each wall/orientation and the 3 tilts simulated are detailed in **Table-7**. A comparison between the potentials from PVs, at each orientation/tilt, is shown in **Figure-13**. With the availability of such data, the potential energy generation becomes a function of how much area is available to install PVs on each side. This circles back to Chapter-2's definition of building's aspect ratio's and how the building's external surface area is affected by it. It's also affected by the orientation of the aspect ratio, for each building.

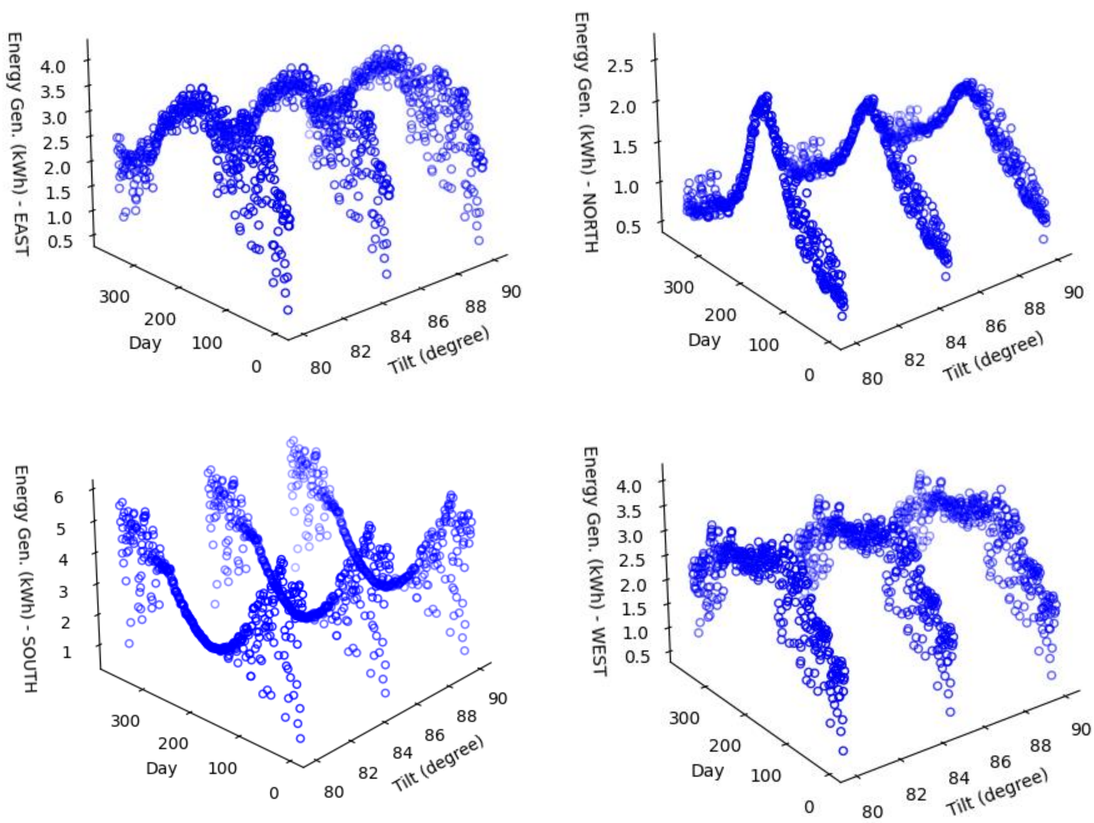


Figure 13 - Energy generation potentials from PVs at 80, 85, & 90 (degree) tilts, and four orientations [A) East, B) North, C) South, & D) West]

Table 7 - Case 1: Energy Generation Potential (S, W, N, & E)

TILT OF PV	90 DEGREES TILT				85 DEGREES TILT				80 DEGREES TILT			
ORIENTATION OF PV	**S**	**W**	**N**	**E**	**S**	**W**	**N**	**E**	**S**	**W**	**N**	**E**
YEARLY ENERGY (KW)	1102	921	462	961	1195	967	473	1013	1284	1019	501	1060

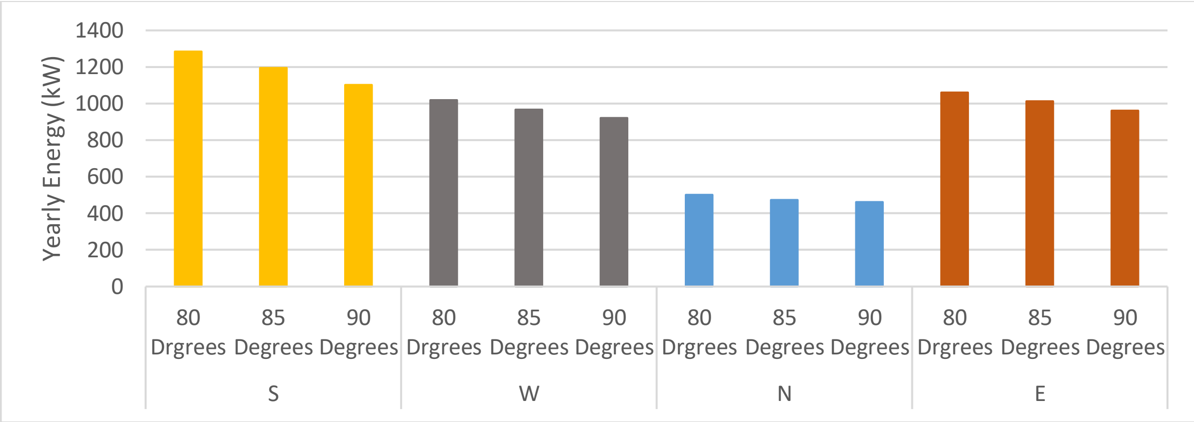


Figure 14 - Yearly Energy from PVs at N, E, S and W orientations

The orientation with the most energy generation potential, from a PV system of the same size, is South, which is consistent with the GIS recommendation about the orientation with the highest energy generation potential, and the least energy producing orientation is North. The difference in energy production from a PV system facing South or North can reach up to 60%.

- **Case 2:**

As for the second case, the orientation of the buildings positions their walls at the North-East, South-East, South-West and North-West directions. The daily energy production rates, from a 1 kWh PV system at 80̊, 85̊, and 90̊ tilts are shown in **Figure-14**. Further, the summary of the yearly energy output from each wall direction is shown in **Table-8**.

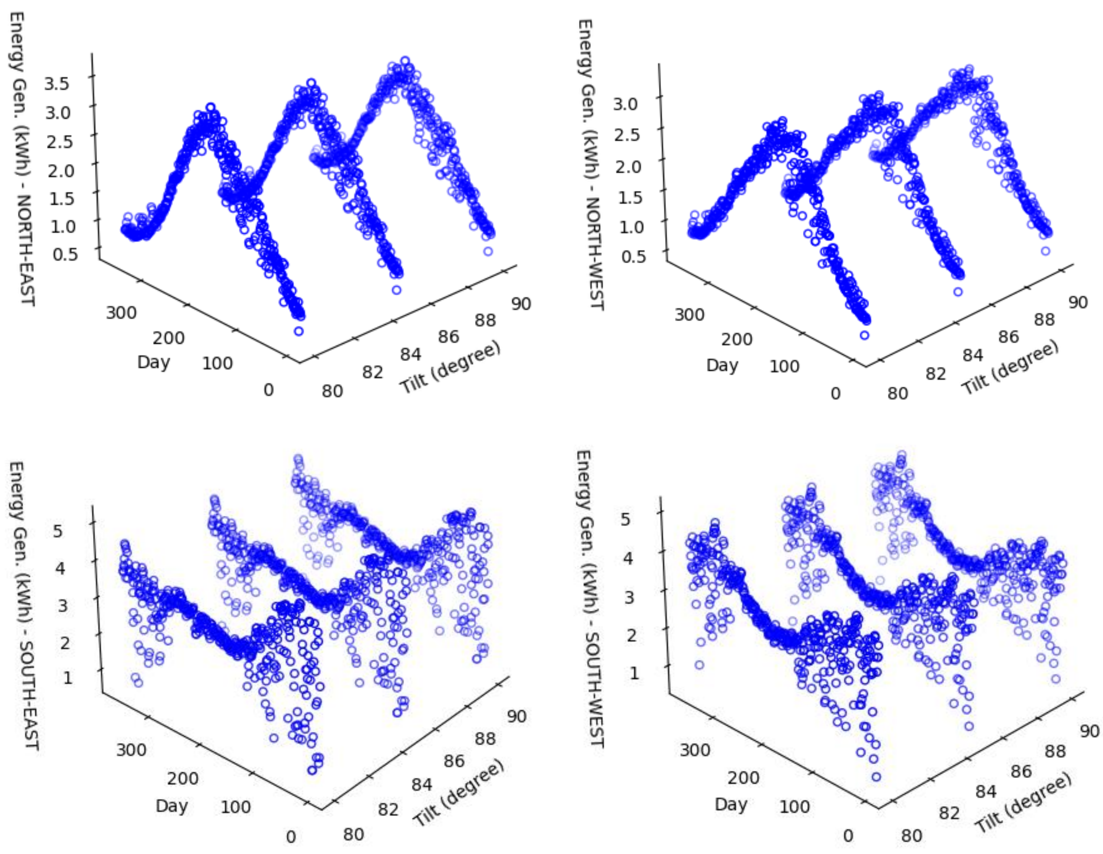


Figure 15 - Energy generation potentials from PVs at 80, 85, & 90 (degree) tilts, and four orientations [A) North-East, B) North-West, C) South-East, & D) South-West]

Table 8 - Case 1: Energy Generation Potential (S, W, N, & E)

TILT OF PV	90 DEGREES TILT				85 DEGREES TILT				80 DEGREES TILT			
ORIENTATION OF PV	**SW**	**NW**	**NE**	**SE**	**SW**	**NW**	**NE**	**SE**	**SW**	**NW**	**NE**	**SE**
YEARLY ENERGY (KW)	1082	633	664	1079	1152	662	695	1151	1220	694	729	1220

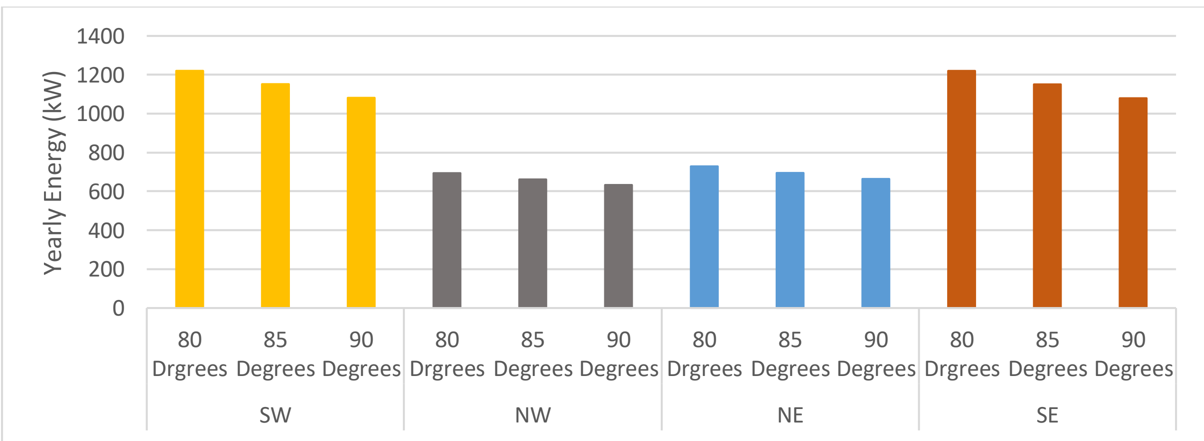


Figure 16 - Yearly Energy at NE, SE, SW and NW orientations

The orientations with the most energy generation potential in the second case are the South-East and the South-West facing walls, while the least energy producing orientations are North-West and North-East facing walls. The maximum difference in in energy production is about 43%.

The effect of the loss in transmittance due to dust is at its lowest when the PVs are at tilts closer to 90̊. The energy generation potentials are factored by the transmittance loss prediction model assuming monthly cleaning of buildings' windows/PVs are summarized in **Table-9**. The maximum yearly loss in energy due to dust is 5.4% when the PVs are at 80̊ tilt, and the minimum yearly loss in energy due to dust is 1.68% when the PVs are at 90̊ tilt. The losses due to the DF are significantly lower when compared with the losses of the optimum tilts, assuming the same exposure period discussed in scenario-1 (3.2 Simulation of PVs potentials).

Table 8 - Energy generation potentials in consideration of the DF

TILT OF PV	**90 DEGREES TILT**				**85 DEGREES TILT**				**80 DEGREES TILT**			
CASE 1	**S**	**W**	**N**	**E**	**S**	**W**	**N**	**E**	**S**	**W**	**N**	**E**
YEARLY ENERGY (KW)	1083	905	454	944	1153	934	457	978	1215	964	474	1003
CASE 2	**SW**	**NW**	**NE**	**SE**	**SW**	**NW**	**NE**	**SE**	**SW**	**NW**	**NE**	**SE**
YEARLY ENERGY (KW)	1064	622	653	1061	1112	639	671	1111	1155	657	690	1155

From Case 1 and 2, it's clear that the energy generation potentials are highly impacted by the orientation of the PVs. The difference in energy generation potentials based on the walls' orientations, 60% in case 1 and 43% in case 2, is significant, and the decision to use all walls or specific walls for PV installation must be evaluated for its environmental and economic benefits. All energy generation potentials discussed in this chapter are based on the simulation of a 1 kWh PV system, with panels occupying approximately eight squared meter area. The physical size of the PV system (in m^2) is a key parameter in quantifying the number of panels that can be installed on each side of the buildings' walls, at the different aspect ratios and window to wall ratios, detailed in Chapter-2. The next chapter is focused on the economic and environmental feasibility of PVs, based on the same building envelop variables, impacting the wall installation of PVs.

4.0 Discussion

Kuwait is a very small country with 17,818 km² area. Most of that land is managed by the government for oil exploration and production. The suggestion of incorporating energy generation systems that require space and access becomes a challenge due to the lack of space. Exploring possible ways of utilising spaces within buildings for energy generation require feasibility and cost benefit analysis. Investments in Renewable Energy Systems can be considered even with no economic profit as long and the environmental impact in lowering emissions is of significance.

For every location/region there are optimum positions (orientation and tilt) for PV's, to generate the maximum energy within the day hours. The maximum daily energy production can be achieved when the PV system is equipped with tracking devices to change it position, following the sun as it rises and sets every day. In some cases, the users change the positioning of their PV's seasonally to maximise the energy production, throughout the year, without the use of a tracking system. However, most commonly, users select a fixed positioning that can yield the maximum yearly energy production, avoiding capital and operation costs associated with changing the PV's position. In Kuwait, the optimum tilt for maximum yearly energy generation is 29°; While the optimum orientation to maximise energy production is South. Wall-mounted PVs would not performed ideally if stacked on top of each other with such tilt due to shading.

The analysis in chapter 2, analysed the impact of the window to wall ratio based on its impact on the buildings' overall energy consumption. Generally, buildings consume less energy with lower windows to wall ratio. Based on the analysis in this chapter, the window to wall ratio also influence the potential energy generation from PVs. The aim form this chapter is to quantify the amount of energy that can be generated utilising the available wall area. The potentials from every wall, in each building configuration are simulated, based on the 5 aspect ratios, 4 window to wall ratios, and 4 buildings orientations analysed in Chapter 2.

One of the objectives of installing the PV's at vertical and semi vertical tilts is minimising the loss in energy generation due to dust accumulation. Using the dust factor (DF) model we built, the daily energy generation rates can be modified to reflect the energy losses due to the weather conditions in Kuwait. The DF model is reset once the PV's are cleaned. The frequency of PV cleaning can be applied in different scenarios such as weekly cleaning, bi-monthly or monthly cleaning. The frequency of cleaning is expected to impact the operational cost, based on the number of staff carrying out the task and the quantity of cleaning supplies such as water and detergents. The economic and environmental feasibility aspects will be examined in the next chapter, breaking down the system's cost/profit and the amount of emission reduction achieved.

5.0 Conclusion

The focus of this chapter is on the energy generation potentials from PV systems based on the regional/climate characteristics of Kuwait. The first section investigates the effect of dust on the productivity of PVs. A prediction model is developed based on regional data, using the Kriging method, to quantify the losses in transmittance, at different PV tilts during 40 days of exposure. The results from the prediction model indicate that the transmittance losses are at their highest when the tilt of PVs are at the horizontal level (0° tilt), and at their lowest when the tilt of PVs are at the vertical level (90° tilt). The difference in transmittance losses between the horizontally and vertically installed PVs after 30 days of exposure is almost 50%.

In the second section, the prediction model is factored in the potentials for energy generation by PVs, at different tilts, using simulation platforms that does not consider the accumulative impact of dust. Yearly energy generation rates are compared for South facing PV, at tilts defined as the optimum overall or seasonal optimum based on Kuwait's location and the sun's radiation. Three cleaning scenarios were discussed, weekly, bi-weekly, and monthly, where the dust factor is reset when a cleaning event is scheduled. The results showed that the optimum tilt would no longer remain the highest energy producing tilt when PVs are cleaned once or twice a month. The overall optimum tilt (29°) is outperformed by higher tilts as the amount of dust impacting the transmittance of their surface is less. With weekly cleaning, the difference in yearly energy production of PVs at 29° and 52° tilts is only 2%.

The third and last section of this chapter considers multiple orientations for energy generation by PVs, to quantify the energy generation potentials when the panels are used on the walls of buildings. PV's energy outputs are Simulated at eight orientations and three tilts (90°, 85° and 80°) to reflect buildings in two cases (Case 1: walls facing N, E, S & W, or Case 2: walls facing NE, SE, SW & NW). The maximum difference in the energy generation potentials of PV between the different orientations in Case 1 is 60%, and in Case 2 is 43%. In those cases, the impact of the dust factor results in energy losses between 5.4% and 1.68% if the panels are cleaned monthly. The model created and the data simulated in this chapter can be used to maximise the energy generation potentials from PVs, used in open areas or mounted on walls. The cost and environmental assessment of such investment are a part of the following chapter, focusing on multiple objectives that can improve buildings' energy performance in consumption and generation potentials through PVs.

Chapter 4

1.0 Introduction and Literature review

1.1 Energy consumption patterns vs. Energy generation potentials

Based on the variables identified in Chapter 2 and Chapter 3, the aim in this chapter is to find optimum envelope design choices that can achieve a balance, considering the energy consumption patterns, and the energy generation potentials from PVs. The Start is with a mathematical formulation, modelled to maximise or minimise the defined objectives; Then an algorithm is used to solve for optimum solution(s). The First objective is based on the energy consumption analysis in Chapter 2, quantifying the impact of envelope design variables to minimise the yearly energy consumed by buildings. The energy simulations specify the amount of energy (in kW) consumed by buildings, from which the associated cost of energy consumed can be calculated. The second objective is to minimise the overall cost impact of the envelope design variables, due to differences in construction materials quantities. The third objective is based on the energy generation potentials, quantified in Chapter 3, maximising the utilisation of PV systems for their emission reduction benefits and fossil-fuel replacement. Meanwhile, the capital cost of the PV system is to be minimise. Figure-1 redefine the work done in the previous chapters in a context of an optimisation problem.

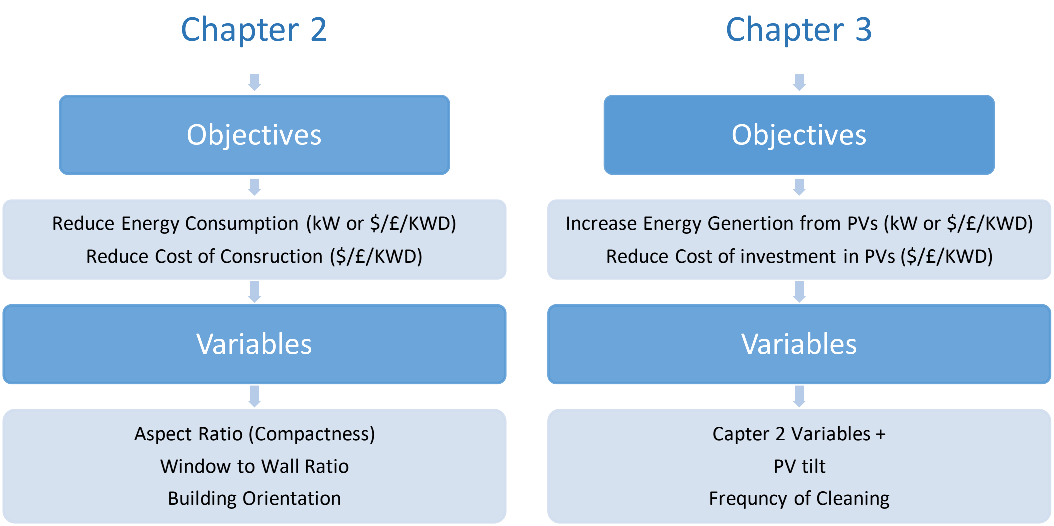


Figure 1 - Objectives and Variables from Chapters 2 and 3

1.2 Optimisation of building envelope design statistics

As in any optimisation problem, the process starts with objective(s) identification, to find a building design(s), installation or operation alternatives that can lead to better performance. by reviewing 36 publications, specific to the improvement of buildings' performance by optimising the design of their envelope [list of the publications used to obtain the statistics in this section are attached as **Appendix-II**], 8% of the publications aimed to improve buildings' performances with a single objective. While 92% of the publications aimed to improve the buildings with multiple objectives, most of which indicate that the complexity of the optimisation process increases when the number of objectives and/or variables increase. Based on the studies reviewed, **Figure-2** highlights the percentages of researches, given the number of objectives considered in their optimisation process.

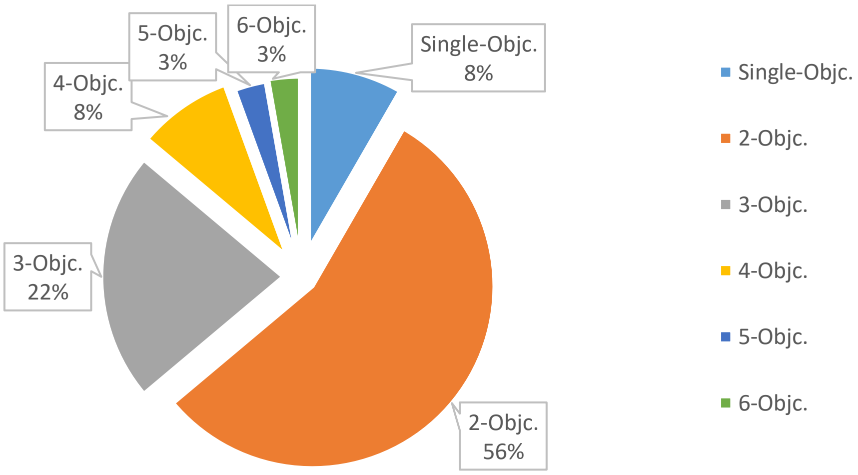


Figure 2 - Breakdown of publications based on the number of objectives used in their optimisation

The most common objective is the reduction of building's yearly energy consumption rates, addressed in 89% of the 36 building envelope optimisation publications. Other common objectives in optimising buildings' designs/performance are the reduction of cost (investment and/or operational costs) at 47%, improving user comfort (visual and/or thermal) at 44%, and the inclusion of Renewable Energy Systems (RES) at 33%. **Figure-3** compares these common objectives and the percentages at which they have been featured in the reviewed publications.

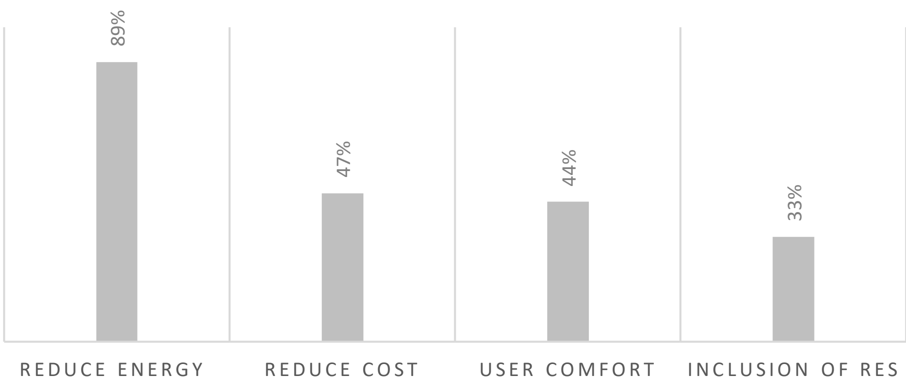


Figure 3 - Distribution of the most common objectives, specific to the optimisation of building envelope design

Next are the variables of interest, as researchers typically choose them based on their impacts on the defined objectives. The most common variables addressed in the building envelop optimisation publications are specific to the thermal qualities of windows at 75%, and the thermal qualities of walls/roof materials/layers at also 75%. Followed by other common variables, specific to geometry aspects of the buildings, the window size at 58%, and the buildings' orientation at 42% (**Figure-4**).

Windows, walls, and roofs specifications are the most considered variables for building performance optimisation, for their significant impact on the overall performance of building. Moreover, some of the studies that evaluate the specifications of windows/walls/roofs has the potential for suggesting improvements for existing buildings as retrofitting solutions (Fan and Xia, 2017; García *et al.*, 2017; Salata *et al.*, 2017), as well as recommending the specifications of new construction projects.

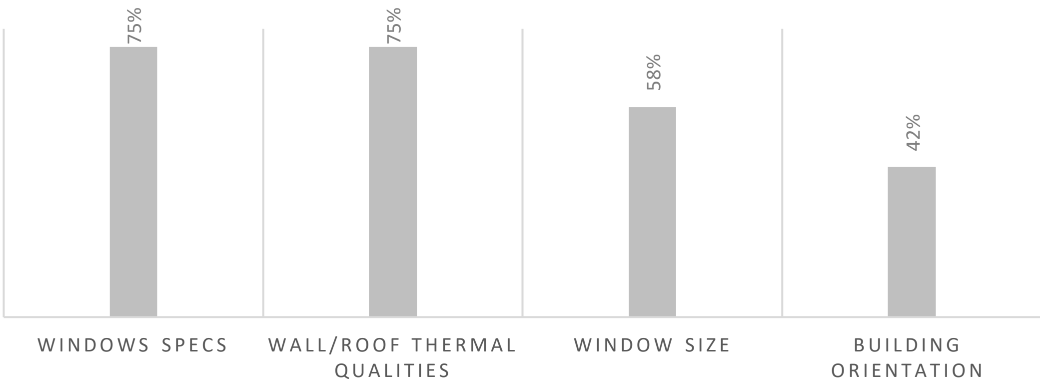


Figure 4 - Distribution of the most common variables, specific to the optimisation of building envelope design

As for the software and algorithms used in reviewed publications, EnergyPlus was used in 61% of the publications reviewed, particularly in the studies that require calculations of the buildings' thermal energy. Radiance and Daysim were mostly used in studies requiring energy calculations specific to building lighting. Some publication had proven that a singular method/algorithm can be used to find optimum solutions (Fan and Xia, 2017; Salata *et al.*, 2017; Yang *et al.*, 2017). Others combined two or more methods/algorithms to solve for optimum solutions (Bre *et al.*, 2016; Hamdy *et al.*, 2016; Peippo *et al.*, 1999). The algorithm(s) selected must be able to produce a well-represented set of trade-off solutions between the objectives. Based on the statistics derived from reviewed studies specific to optimising building envelope variables for better performance, the NSGA-II was the most frequently used method in 34% of the publications.

The NSGA was originally built on Goldberg's notion of nondominated sorting in GAs, to find multiple Pareto-optimal solutions simultaneously (Srinivas and Deb, 1994). The NSGA-II was first introduced in the year 2000, with the aim to improve on three main aspects of the multi-objective evolutionary algorithms (MOEA's) (Deb, K. *et al.*, 2000). First, the MOEA's had high (and expensive) computational complexity of non-dominated sorting when the population size is relatively high. Second, they lacked the ability to preserve good solutions once found, as the preservation of good solution can speed up the performance significantly. As for the third aspect, the MOEA's required the user's definition of a sharing parameter to diversify the solutions. Ideally a parameter-less algorithm that can generate a wide range of optimum solutions more desirable.

1.3 Literature review

To bring some context about the optimisation models used in the statistics presented in **section 1.2**, a detailed review is presented for seven publications that have aimed to optimise a selection of building envelope design variables, using different algorithms, to enhance multiple performance objectives. The selected publications are chosen to represent different objectives, variables, algorithms, and climates, cited in the previous statistics. The details and differences can help in understanding how building optimization models are formulated and the assumptions made in each case.

As multi objective optimisation problems can be solved by studying a trade-off between the different objectives; for a building project, a trade-off was investigated between lowering its energy consumption and lowering the cost of construction (Peippo *et al.*, 1999). The model was created to process the buildings' geometry, thermal insulation type, windows size/characteristics and the building occupancy rates (residential/office building) as variables. Moreover, it considers the use of solar thermal/photovoltaic collectors to lower the dependency on energy from the grid. The algorithm used in that model combined the **method of Hooke and Jeeves** (Bazaraa *et al.*, 1993), using the cyclic coordinate algorithm modified with a pattern search, and one-dimensional minimisation **Golden Section algorithm** (Chang, 2009) to find the univariate minimum. The minimisation of energy consumption, defined as (E_{prim}) as an objective, is evaluated using:

$$E_{prim} = E_{th} + \frac{E_{el} - E_{sp}}{\mu}$$

where, (E_{th}) is the annual energy consumed for thermal processes (space and water thermal control), (E_{el}) is the gross purchased electric energy, (E_{sp}) is the optional surplus PV electricity supplied to the utility grid and (μ) is the conversion factor from primary energy to electricity.

While the minimisation of cost, (C_a) as an objective, is evaluated using:

$$C_a = \sum_i a\, C_i + \lambda(E_{th}c_{th} + E_{el}c_{el} - E_{sp}c_{sp})$$

where, (C_i) is the investment cost of the ith design option based on the building's floor area and the associated cost influencing variables such as windows/walls dimensions and thermal insulation type/quantity. (a) is the uniform capital recovery factor, (c_{th}, c_{el} & c_{sp}) are the respective unit energy costs and (λ) the energy price escalation as a function of time.

The trade-off was illustrated visually, showing the optimum path between the energy savings and the marginal costs. As case studies, three locations (Paris, Helsinki, and Trapani) were used to run the model and report the design guidance changes with respect to the climatic effect at each region.

Some of the key findings reported are the cube shaped residential buildings (considered the most compacted form) perform optimally in all regions. It was suggested though, for office buildings, a larger envelope consuming more energy (due to heat loss) are worth the marginal increases in costs, for the daylight benefits that would increase the users' satisfaction. The model can also solve for zero-energy residential buildings (no dependency on energy from the grid). However, Zero-energy solutions might not necessarily be the optimum, based on the investment cost in renewable energy and their regional productivity, the cost impact Paris was the lowest, with 16% more in Trapani and 40% more in Helsinki.

The concern with such model is in the definition of certain variables and the associated costs and efficiency potentials; In particular, the use of solar collectors (PVs). The model indicates that panels can be installed on vertical facades (walls) or on an inclined rack on the top of the roof. The model aims to solve for tilt angles to be set at optimum solar energy collection tilt. This would not result in maximised energy collection as assumed, due to shading from the building, specifically over panels fixed on the walls, hence no solution found proposing such installation. Moreover, the cost impact of the specific installation requirement for wall-mounted panels, as well as the specific cost to handle the maintenance of such setup are not considered. Lastly, climatic factors affecting solar systems' efficiency are not considered, such as snowfall rates impact on solar systems in Finland.

The way variables are defined, and the limitations on how they can vary impact the optimisation process and the algorithm chosen; In a case of multi-objectives optimisation, the aim was to design free-from buildings, by achieving maximum space efficiency (E_{max}), minimum shape coefficient (S_{min}) and maximum solar radiation gain to contrast the cold weather of the selected region in China (Zhang *et al.*, 2016). The objectives are measured for each iteration of buildings, by varying the free-form of its external surface mathematically, in search of optimum forms. To achieve that, the variables are defined as control-point coordinates, connected to represent the building's curves and surfaces.

The space efficiency is measured by dividing the summation of usable space volume (V_u) at each floor over the total inner volume (V_o) of the building. The usable space volume is defined by the area within the floors of the building that has a minimum clear elevation of 2.2 m.

$$E = \frac{\sum_i^n (V_u)_i}{V_o}$$

where (i) corresponds to the floor and (n) is the total number of floors. As for the shape coefficient, its measured by dividing the building's external surface area (F) by (V_o). This ratio represents how compact the shape is, the higher the value of the shape coefficient, the less compact the building's form is.

$$S = {}^{F}/_{V_o}$$

To calculate the building's heat gain from solar radiation, the region's weather file is selected (from EnergyPlus database). Then the simulation is performed using Rhinoceros/Grasshopper and its plug-in Ladybug. The Climate-Based Daylight Modelling (CBDM) method is used to simulate the daylight solar radiation through the Cumulative Sky approach. The optimisation algorithm used is the **Genetic Algorithm (GA)** developed by Holland in the 1975 and descried as the *"natural selection and survival of the fittest"* (Holland, 1975), as well as a Pareto frontier, generated to plot the optimal solutions. The method was chosen considering the robustness of solutions obtained through the GA, when solving for ten or more variables. The process starts with an initial design of four coordinates, defining the building's corners/dimensions. The results generated include solutions of free-from shapes that satisfy the user conditions and balance the three objectives defined. In their case study, the model found an optimum solution that can maximise the total solar radiation value by 53%, reduce the shape coefficient value by 20% yet decreased the space-efficiency value 5% from the starting cube shape.

Caution is to be taken with this model, as the definition of objectives is customised for cold regions. Within cold regions, users must be aware that the model does not address the performance of the designed buildings during the warmer periods of the year, it does not assess if those derived solutions will impact the design of the building's ventilation or define the requirement of cooling systems. Furthermore, the author states that the model does not take into account the complexity of the free-formed building's construction and the associated cost impact of increase in construction material.

Another multi-objective model was developed to minimise buildings' energy consumption and improve the Indoor thermal performance (Yu *et al.*, 2015). The improvement of the building's thermal performance was evaluated based on the minimum user thermal discomfort hours, not to exceed the standard limitations of acceptable user discomfort hours. The variables were the buildings' orientation, shape coefficient, window to wall ratio, wall heat transfer coefficient, wall heat inertia index, roof heat transfer coefficient, roof heat inertia index, and window's heat transfer coefficient. To solve for optimum solutions, the proposed model uses a three-step process; The first step starts with an improved **Back-Propagation (BP) network** (Lecun *et al.*, 1988), where a genetic algorithm (GA) is used to characterize the building's behaviour, coupled with an **Artificial Neural Network (ANN)** (Krogh, 2008) to establish the multi-objective prediction model, and followed by **GA** to improve the prediction's accuracy. The second step is formulated to establish a GA–BP network model, to rapidly predict the energy consumption and indoor thermal comfort status of buildings. The final step uses the GA–BP network as a fitness function of the **Non-dominated Sorting Genetic Algorithm (NSGA-II)** (Deb *et al.*, 2002). The model is built to interact with EnergyPlus, to calculate the energy consumed in each building design and measure the comfort level for buildings within the defined variables.

When the model was tested in a case study, the user is expected to define the initial values of the variables, within the ranges specified in the model. The model was able to find building design variables with 50% improvement in energy consumption and 1.5% increase in discomfort hours from the initial design. It's up to the designer/user to decide on the compromises between the objectives. However, the model does not consider the cost variance in building materials/quantities, based on the analysed variables. The objective of lowering the building's energy consumption in the model is specific to the energy/operational costs and neglects the cost of building's construction; without which, the solutions found might not be valid if the construction cost is higher than the available funds.

Furthermore, multi-objective optimisation is used to study the trade-off between contradicting objectives, such as finding buildings designs with minimum energy exerted for cooling while minimising the energy consumed for lighting (Delgarm, Sajadi, Delgarm, *et al.*, 2016). The two objectives are selected to improve the overall buildings' energy performance. The variables chosen in that model were the buildings' orientation, windows' sizes and the depth/tilt of the overhang (the structural installation on top of windows designed to provide shade). The nature of these objectives leads to a conflict between the variables defined. With that in mind, the annual cooling and lighting building energy demands are processed through a Mono-criterion as each objective is minimised separately, and a Bi-criteria optimisation analyses achieving a trade-off between the pair of objective functions. This multi-objective problem is solved using the **NSGA-II**, simulated in EnergyPlus for building energy calculations and jEPlus to obtain optimal solutions.

The weighted sum method (WSM) (Hazelrigg, 2019) is used to minimise the two objectives. This simple method sums each normalized objective function ($f_i(x)$), multiplied by their weighting coefficients (w_i) to generate an objectives composite function ($Fws(x)$):

$$Fws(x) = \sum_{i=1}^{k} \frac{w_i \, f_i(x) - f_i(x)^{min}}{f_i(x)^{max} - f_i(x)^{min}} \qquad \& \qquad \sum_{i=1}^{k} w_i = 1$$

where, (k) is the number of objectives, in this model two, and ($f_i(x)^{min}$) and ($f_i(x)^{max}$) are the minimum and the maximum values of the objective functions, respectively. Accordingly, this function is used to find a single optimum solution. With the NSGA-II, the maximum number of cases investigated is the multiplication of the population size by the number of maximum generations.

The model was tested to find the optimum designs of a single room in four locations. The locations are selected for having distinct climatic differences in Iran. The room's size is pre-defined, and the window's placement is restricted to a single wall. The model's output from the four locations indicated that the overhang design specifications are almost similar regardless of the climate variance. Furthermore, the optimum orientation of the rooms is consistent as well, suggest having the wall with the window facing North. As for the window's size, the optimum designs in warmer regions suggested smaller sized window. While within colder regions, larger windows in size are found to be optimum.

The single solution choice through WSM requires a decision-making criteria from the user to define (w_1 & w_2), while the use a Pareto front can offer multiple optimum solutions. The main limitation in this model is the way the building/zones are defined. The suggested model would require redefinition of variables and their ranges, to process multiple zones, zone air mixing, and buildings with internal zones that are not subjected to direct sunlight through windows. The simulation platform (EnergyPlus) has the capabilities to process multi-zone definition, the limitations are the user's definition of the building's characteristics to solve for the selected objectives.

The way the objectives are defined play a major role in the output of optimisation models; In a research with objectives similar to the publication reviewed above (Delgarm, Sajadi, Delgarm, *et al.*, 2016), the model solves for solutions that lower the heating/cooling loads and maximise the daylight penetration into the building through windows rather than lowering lighting energy (Lartigue *et al.*, 2014). Similarly, the lighting objective is controlled by maintaining the luminance level within the standard measures and keeping the visual discomfort hours at minimum. The variables in this research are more specific to the windows design. The module is built to vary the window to wall ratio (between 10% and 60%), as well as the window's visual and solar characteristics, based on their measured visual/solar transmittance and the U-value (13 window types). To solve for the objective of maximum daylight, the annual deficient daylight time (ADDT) is calculated for each case by subtracting the annual sufficient daylight time ($ASDT_{300}$), defined as the hours through the year when the indoor daytime illuminance level is higher 300 lux, from the yearly hours when the daytime illuminance level is higher than zero (4176 hours).

$$\mathrm{ADDT}_i = 4176 \_ \mathrm{ASDT}_{300}$$

where (i) represents the cases calculated for each ($ASDT_{300}$) combination of type of glazing type and at different windows sizes.

The module is written using the software *GenOpt*, linked to *TRNSYS* for energy simulation and *Daysim* for illuminance and daylight calculations (platforms evaluated in Chapter-2). This multi-objective module is built to solve for solutions, satisfying the objectives and within the variables' ranges, using an artificial neural network (ANN), and the Pareto front approach. The Pareto front allows the user to identify their preference toward one of the objectives over the other. The conflict between the objectives comes from the effect of the transmitted solar flux; When it maximised through large windows, while using a glazing material with high transmittance, in winter, the energy required for heating and for artificial lighting are at their lowest. However, that design would lead to higher cooling loads in summer, considering the effect of the transmitted solar flux in raising the indoor temperature of the zone through windows. This conflict is proven with the optimum solutions found in their case study, as an optimum solution found for one window type at a 10% window to wall ratio, leading to energy consumption for cooling/heating of 1,940 (kWh) and ADDT of 2,555 hours. While the other optimum solution suggested the use of another window type at 56% window to wall ratio, leading to energy consumption for cooling/heating of 4,330 (kWh) and ADDT of 341 hours.

While that module aims to lower the building's energy consumption, and consequently lower the building's operating costs, the module does not consider the difference in cost of the 13 glazing materials identified. Furthermore, the costs associated with the walls and windows' dimensions, as variables, are not a part of the optimisation process, proposing optimum solutions that might have significantly higher construction cost than others.

Also with similar objectives, solving for higher daylight availability and lower thermal/electrical energy requirements, the variables selected were specific to the building's geometry and the design of fenestration (windows and skylights) (Fang and Cho, 2019). The user defines the building area, and the module varies the building's width and depth, roof ridge location, windows sizes and locations, skylights sizes and location, and the louver's length. The framework for this model is built using *Rhinoceros/Grasshopper* for building 3D design and parametric modelling. In addition, *Ladybug*, *Honeybee* and *EnergyPlus* plug-ins are used for daylight simulation and for thermal energy calculations. The author acknowledges that their model was built considering previous relevant studies, indicating that a stochastic population-based algorithm such as GA and the Particle swarm are most frequently used for building performance optimisation. Accordingly, GA is used to generate 200 design solutions, randomly selected, as candidate options. Then, with a maximum number of 8 generations, optimum solutions are found among 1000 solutions processed. The optimisation process is run through a Grasshopper plug-in named *Octopus* to find the Pareto front.

The objective of maximum Useful Daylight Illuminance (UDI) is evaluated for each case, measured by dividing the design's yearly hours of useful daylight illuminance (UDI_i) by to the yearly building occupancy hours (YOH), where the usefulness of daylight is considered when the illuminance is between 100 and 2000 lux:

$$UDI = {}^{UDI_i}/_{YOH}$$

For the minimum Energy Use Intensity (EUI) objective, this metric is calculated by summing up the yearly energy loads consumed for heating (E_h), cooling (E_c) and lightings (E_l) divided by the gross floor area (A):

$$EUI = \frac{E_h + E_c + E_l}{A}$$

The model seems most practical when the building design is of standard type (single axis pitched roof) with the essential need for natural light (windows and skylights). In their case study, three locations were selected to find compare the optimum design in the United States, Miami representing a case within a hot climate, Chicago representing a case within a cold climate and Atlanta representing a case within a mixed climate. Three non-dominant solutions found in Miami, five in Chicago, and seven in Atlanta. Comparing three designs from each state/city (2 best solutions and 1 balanced solution), the optimum buildings in Miami found to have larger glazing areas (windows and skylights) than in the buildings in Chicago and Atlanta. The UDI was the highest in Miami and lowest in Chicago, while the EUI was the lowest in Atlanta and highest in Chicago.

Although this model is built to process buildings with a fixed gross area, it does not consider the construction cost variance of different building configurations, significantly varying with the amount of glazing in each case. Also, it seems a wasted opportunity not to consider the orientation of buildings as a variable rather than a user input. Maximised daylighting can improve significantly if the optimum orientation is considered.

In a model created to optimise the selection of 13 building design variables, the objectives were to improve the buildings' energy performance, user comfort, economic feasibility, and its environmental performance (Ascione *et al.*, 2019). The envelop design variables were the building geometry, orientation, window to wall ratio, radiative character of external plasters, thermal conductivity and inertia of materials, thickness of walls, insulation layers, position of the insulation layers, types of windows and shading systems. Other buildings' systems variables were considered, such as a range of energy generation systems using renewable resources and different HVAC systems/operation setups.

The novel approach, named Harlequin, processes the defined variables and objectives in three phases. The first phase starts with using EnergyPlus, as the buildings' energy simulation platform. By processing the buildings' envelope and HVAC operating variables, the GA is deployed to evaluate the solutions and find the Pareto front toward minimum energy consumption and minimum user discomfort hours. The second phase is designed to find the optimal sustainable energy-generating systems (simulated in *PV-GIS* Software) through smart exhaustive sampling of different design scenarios using *MATLAB*. The last phase is concerned with solving for the optimal solutions based on performance indicators, to measure and evaluate the buildings' overall energy sustainability and cost efficiency.

The model is built in multiple phases to handle the large number of variables and lower the computational time. Given the population size of 108 (considering the variables defined) and the set maximum number of generations (50) in the model, the number of cases the GA might run can reach up to 5400 scenarios. The time the model might take to find optimal solution reached 8 days. The first phase in the model does not consider all the objectives, which are processes in the following phases, which may result in missing solutions that can perform better across every objectives, if solved simultaneously. Furthermore, with the phased approach, there's a possibility of overlooking better/optimum solutions. As stated by the author, the model built is not user friendly, for how much processing time it requires and the special expertise the user must have in building simulation optimisation and computer programming.

The outputs of those publications propose methods/models that can improve the performance of buildings through envelope design variations, are operating within specific conditions and limitations. For example, one research would be specific to improving the buildings' performance of underground buildings (Shi *et al.*, 2018); while another is specific to buildings within cold climates (Zhang *et al.*, 2017). Some models are tailored to solve for envelope design variables of defined building shapes (Delgarm, Sajadi, Delgarm, *et al.*, 2016; Foli, 2016); while others are considered less practical for the complexity of their use (with model run-time of 8 days to find optimum solutions) (Ascione *et al.*, 2019), or their disregard to the complexity of execution/construction (Zhang *et al.*, 2016). The model introduce here is the first to consider the climate within the Gulf Cooperation Council (GCC), specifically Kuwait, addressing objectives/variables more relevant to the region. Furthermore, the model accounts for the regional impact of climate on the buildings' performance, as well as the efficiency of RES's within the buildings' envelope. It processes the analysed patterns of energy consumption against envelope design variations (Almufarrej and Erfani, 2021), and the quantified impact of dust on the Photovoltaic (PV) systems (Almufarrej and Erfani, 2022) to maximise their potentials simultaneously.

2.0 Methodology

2.1 Objectives and variables

To find an optimum design, from a combination of selected variables and objectives, the impact of each variable/objective on other variables/objectives must be identified. The analysis reported in Chapter 2 is used as the basis for the objective of minimising the buildings' energy consumption. While the analysis detailed in Chapter 3 is the basis for the objective of maximising energy generation form renewable resources, using the available spaces on the external walls of buildings. The use of renewable resources for generating energy is maximised to minimise the emissions that would have been released, if buildings have been fully dependant on hydrocarbon fuels for energy. Further to those objectives, the cost associated with quantity of construction/installation materials, based on the analysed envelope design variables, is to be minimised. The objectives defined are all measured for their cost impact, given the variables analysed:

1. Minimising the overall cost of yearly energy consumption, considering the effect of the building's envelope design variables detailed in Chapter-2, calculated based on the cost of energy and the source from which it's generated. The variables associated with this objective are:
    a. Building Orientation (BO)
    b. Aspect Ratio (AR)
    c. Window to Wall Ratio (WWR)
2. Minimising the cost of construction and PV installation as capital costs. The negative cost implication of the cost is due to the amount of construction material used and the investment in PVs, processed here only based on the available wall area for PV installation. The variables associated with this objective are:
    a. AR (as the change in the building's aspect ratio results in variance in the building's external surface area (SA), hence, a variance in the quantity of construction materials and the amount of PVs installed)
    b. WWR (with the variance in quantities/area between windows and walls, the cost impact is a result of the variance in the unit price of wall vs. unit price of window, as well as amount of PVs installed, given the available wall area)
3. Maximising the use of PVs for energy generation has two positive impacts, the first is associated with saving the resources used for energy generation (hydrocarbons in Kuwait) that would have been consumed instead of the energy generated by PVs. The second can be quantified based on the equivalent cost of emissions reduction, compared to the CO_2 emitted by hydrocarbon fuels consumed for energy generation. The variables of influence

are the ones that has an impact on the available wall area for PV installation, and the productivity of PVs:

a. AR (as the change in the building's aspect ratio leads to a variance in the building's external surface area (SA), It would impact the quantity of PVs installation accordingly
b. WWR (with the variance in area between windows and walls, the cost impact is associated with the wall area available and the amount of PVs that can be installed
c. BO (as a main deriver of energy generation potentials from PVs at side of the building)
d. PV Tilt (as a main deriver of energy generation potentials from PVs at the selected tilt(s))

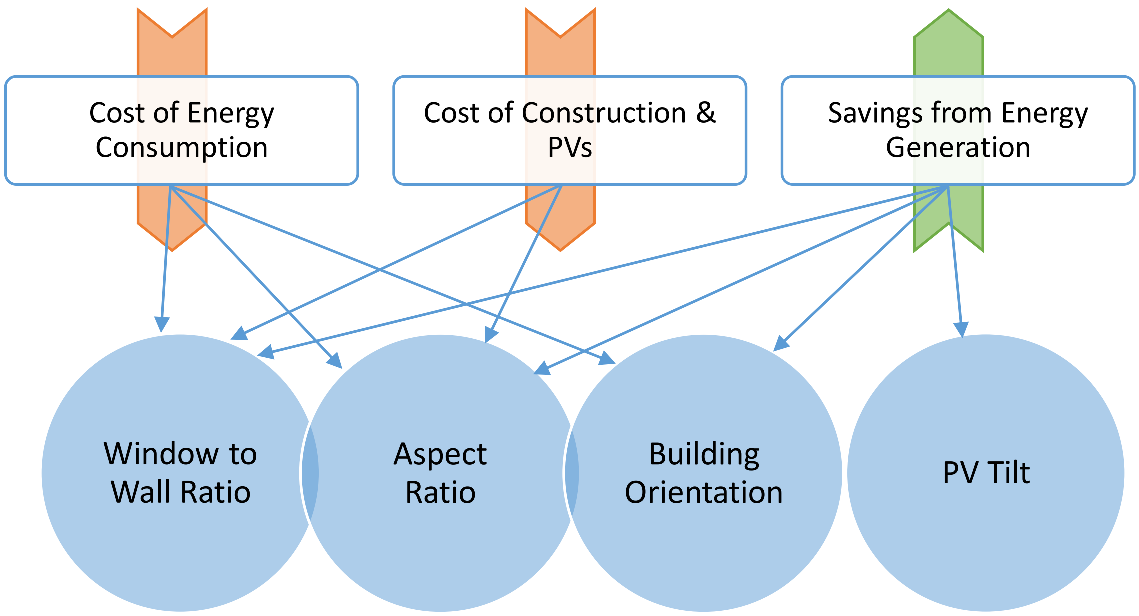


Figure 5 - The connection between the Objectives and the variables

2.2 Objectives and cost calculations

The first objective can be measured by linking the cost of Energy Consumed (CEC) to the cost of a single unit of electricity in $-KD/kW. In Kuwait, the cost of electricity is set by government managed plants, the Unit Price of Energy from the Grid (UPEG) is in $-KD/kW. From Chapter-2, the yearly energy consumption rate can be formulated as a function of the BO, AR and WWR. Those rates can be multiplied by the UPEG to calculate the cost of energy for each building case:

$$CEC = Building\ energy\ consumption\ rate\ \left(BO_i, AR_j, WWR_n\right) \times UPEG \qquad \textbf{(1)}$$

The second objective is measured based on two functions. The first is associated with the cost of construction materials, considering all buildings have similar wall profile (layers) and similar windows' specifications, the difference in cost between the different building cases is a function of the wall and windows area. The Unit Cost for Wall Construction (UCWC) and the Unit Cost for Windows Installed (UCWI) must be obtained based on Kuwait's market values. Also in consideration, when PVs are installed on the external walls, there will be no need for a finish layer underneath the panels. The Unit Cost of the External Finish (UCEF) material can be deducted from the cost of construction, using the same area of PVs (available wall area). The Construction Cost Factor (CCF) for each building case becomes:

$$CCF = [Total\ Wall\ Area\ (AR_j, WWR_n) \times UCWC] + [Total\ Window\ Area\ (AR_j, WWR_n) \times UCWI] - [Area\ available\ for\ PVs(AR_j, WWR_n)\ \times UCEF] \quad \textbf{(2)}$$

In chapter 2, it's explained that the variance in the AR influences the surface area of the building's surface area up to 6%. However, the CCF is not affected by the change in orientation, as the quantities of the construction materials are not impacted by varying the positioning of the buildings.

The second function is specific to the Cost of PV system (CPV) in each building case. The unit price of PV systems can differ based on the System's Specifications and the manufacturers' prices. Moreover, different PV systems, of different Specification, that are designed to produce electricity at similar capacities might not have the same sizes (occupy different space/area). Calculating the CPV should consider the unit price of the PV system (converted to a rate per meter squared), multiplied by the area of installation at each side of the building:

$$CPV\ = Area\ available\ for\ PVs(AR_j, WWR_n) \times Cost\ of\ PV\ unit \quad \textbf{(3)}$$

While the AR and the WWR physically define the available area for PV installation, the effect on the BO can be considered by the user, based on the productivity rates of PVs at the different orientations. The energy production rate for PVs at the different orientations can be analysed for its financial feasibility. Therefore, the model can be run with different scenarios where the user selects if the least energy producing orientations are to be considered for PV installation.

The last element considers the positive impact from PVs. The first function converts the energy generated by PVs from kW to \$-KD/kW. The cost impact based on the energy generated from renewable resources can be equated to the cost of the same amount of energy if supplied from the grid (using hydrocarbon resources). Accordingly, the equivalent cost of energy generated (ECEG) from PVs can be calculated using:

$$ECEG = Energy\ Generated\ from\ PVs\ (BO_i, AR_j, WWR_n, T_m) \times UPEG \quad \textbf{(4)}$$

The second function estimates the cost impact of emission reduction from using PV systems. The reduction assumes that buildings are mostly dependant on the energy supplied from the grid. The electricity produced by desalination plants generate emissions associated with their hydrocarbon fuels (E_H). By deducting the energy produced from the PVs (E_{PV}) at each orientation and for every building scenario, the amount emissions reduced can be calculated as the Emissions Reduction percentage (ER):

$$ER\ (\%) = \frac{P_H - P_{PV}}{P_H} \qquad \textbf{(5)}$$

The calculation of the Equivalent Cost of Emissions (ECE) reduction requires two conversion factors to estimate the amount of emissions, based on the electricity consumed by buildings if PVs where not considered. First, the energy generated from PVs (in kW) is multiplied by an Emissions Factor (EF_{HC}) (in Ton per kW), specific to hydrocarbon fuelled desalination plants, to quantify the amount of Emission Reduction (ER) in Tons:

$$ER = Energy\ Generated\ by\ PVs\ (BO_i, AR_j, WWR_n, T_m) \times\ EF_{HC} \qquad \textbf{(6)}$$

The second conversion factor is the Cost Factor of Emissions Reduction (CFER) (in $-KWD per Ton), estimated based on the negative economic impact of emissions. The equation is specific to the cumulative impact of CO_2 on the environment, emitted from power plants consuming hydrocarbon fuels to generate energy. According to the American Environmental Protection Agency (EPA), the financial impact of CO_2 emissions can be estimated as the Social Cost of Carbon Dioxide (SC-CO_2), measured based on the long-term damage caused by CO_2 emission within a year (EPA, 2016). Alternatively, it can also represent the cost benefit of yearly emissions reduction. The EPA's SC-CO_2 model considers the damages from climate change on the agriculture productivity, human health, the increased risk of flooding and the damages associated with their occurrence, the estimated decrease in the cost of heating and increase in the cost of cooling. The EPA recognises the lack of sufficient information to accurately estimate the scale of damage that the climate change will have, and the spread if its impact. Four estimation models are used, each assume a discount rate to calculate the SC-CO_2 in the future, based on the current climate change patterns and the possible long-term damages. The table below includes portion of the estimated costs from the four models at their individual discounted rates (Table-1).

Table 9 - Cost of emissions estimated by the EPA (per CO_2 Tons)

	MODEL 1	MODEL 2	MODEL 3	MODEL 4
YEAR	5% Average	3% Average	2.5% Average	High Impact (3% 95th percentile)
2015	$11	$36	$56	$105
2020	$12	$42	$62	$123
2025	$14	$46	$68	$138
2030	$16	$50	$73	$152

All the models assume that the damage from climate change will increase with time, estimating an increase of the SC-CO_2 value with time. Furthermore, in general terms, higher discount rates result in lower SC-CO_2 value. However, Model 4 assumes damages of high impact with less risk of occurrence, deriving the SC-CO_2 value higher than the other three modules. Accordingly, the CFER can be estimated based on the average vales in Table-1, and the ECE is calculated using:

$$ECE = ER \times CFER \qquad \textbf{(7)}$$

The economic feasibility of any investment such as PVs can be evaluated in consideration of their initial costs and the fiscal returns from them over time (Mohan *et al.*, 2022). The payback period (PBP) is a duration measurement of when the initial investment value is paid back from the profit/income generated from that investment. In the model, the PBP of the investment in PVs (CPV) can be calculated based on the cumulative revenues from the ECEG and ECE over the years. To simplify the calculation of the PBP value, the potential deterioration in performance of PVs is assumed to cancel out the increasing rate of saving from the potential increase in the cost of hydrocarbon fuels and the equivalent cost of emissions over the years. Accordingly, the PBP is calculated using the following equation:

$$PBP = \frac{CPV}{ECEG+ECE} \qquad \textbf{(8)}$$

It's important to note, while it would be of a great environmental benefit to maximise the use of PVs, it's not necessarily always in line with the fiscal responsibilities of the user. By comparing the PBP's and the initial investment values (CPV), the users can decide on the most suitable scenario that matches their budget and yearly expenditure/returns. Allowing the user to make the early envelope design decisions, based on the trade-off between buildings' optimum energy, their budget, and the potential environmental benefits.

2.3 The optimisation module

Now that the objectives and variables are properly defined, the optimisation module can be built to find design/installation recommendations that can manage a trade-off between the conflicting objectives. The three main objectives are all calculated as cost equivalent elements, allowing the user to directly understand the trade-offs suggested from the module (**Tabel-2**).

Table 2 - Objectives, Variables and Units

OBJECTIVES	OBJECTIVES AS COST EQUATIONS	VARIABLES	UNIT
MINIMUM ENERGY CONSUMPTION	Minimise Cost of Energy Consumption from Buildings **(CEC)**	BO – AR – WWR	$-KWD
MINIMUM COST IMPACT	Minimise Cost of Construction **(CC)**	AR – WWR	
	Minimise Cost of PV as a Capital investment **(CPV)**	AR – WWR	
MAXIMUM ENVIRONMENTAL BENEFITS	Maximise Cost Savings from using PVs instead of Hydrocarbon Fuels **(ECEG)**	BO – AR – WWR – T	
	Maximise Cost Savings of the Fiscal Impact from Emission **(ECE)**	BO – AR – WWR – T	

The NSGA-II is the optimisation algorithm chosen to find the Pareto optimum building's envelop design solutions. There is no novelty in the algorithm development, based on the literature review, it is the most common/suitable algorithm that can achieve trade-offs between the defined objectives and based on the limited variables. The novelty in this model is focused on the defined objectives, formulating the impact of building envelope design to achieve the trade-off; Tailored to deliver regional guidance toward economic and environmental building designs, based on the users' limitations and the specific climate challenges.

3.0 Results and Analysis

3.1 Input Parameters

The model considers the latest market prices as user inputs, based on the regional conditions environmentally and economically. It allows the user to update parameters that are specific to the cost of regional resources, material, and construction costs, based on their latest values and possible inflation in costs. The input data required can be classified in three categories: 1- Cost of energy elements, 2- Cost of construction/installation elements and 3- Cost equivalent of emissions:

A. Cost of Energy Elements

The energy production in Kuwait depends mainly on the local production of hydrocarbon fuels, specifically natural gas, to generate electricity from desalination plants. The cost of electricity, supplied from the governmental grid in Kuwait, is estimated based on local market price of gas.

Accordingly, the electricity prices used in this simulation are based on the regional published prices in June 2021[7] (**Table-3**).

Table 3 – Kuwait's electricity prices

	HOUSEHOLD, KWH	**BUSINESS, KWH**
KUWAITI DINAR	0.009	0.015
U.S. DOLLAR	0.030	0.050

The analysis considers that the buildings are intended for commercial/industrial purposes, consistent with the defined operation specifications used to simulate the buildings' energy consumption in **Chapter-2**. Therefore, the functions that require the value of the UPEG will used the value 0.05 $/kWh.

This rate is used to calculate the cost of the energy consumed by buildings, based on the defined variables in **Chapter-2**. The same rate is also used to estimate the potential cost savings from the energy generated from PVs in **Chapter-3**. This is to calculate the cost of the fuels that would've been consumed to generate the same amount of energy generated from PVs.

B. Cost of construction/installation elements

The model requires the unit prices of walls and windows, per meter square, based on the latest local market prices. The unit prices enlisted in **Table-4** are estimated based on three quotations from local contractors, consistent with the specifications of the materials already used in the simulation of the buildings' energy consumption in **Chapter-2**.

Table 4 -Local unit precise of construction materials

	KD/M²	**$/M²**
UNIT PRICE OF WALL CONSTRUCTION (UPWC)	9	23.4
UNIT PRICE OF WINDOW INSTALLATION (UPWI)	20	59.1
UNIT COST OF THE EXTERNAL FINISH (UCEF) (EXTERNAL PAINT)	6	15.6

Ideally, buildings are designed to have a specific external finish to the walls, complementing the shape and the utilisation of natural sunlight through windows. The user choses the material used for the finish of external walls of buildings can be natural (i.e., stone or marble) or artificial (i.e., paint or panels of manufactured materials). When the assumption is made that wall mounted PVs are considered within the optimization function, the costs associated with the external finish (materials and installation) can be deducted based on the same area that the PVs will occupy. In the analyses, the external finish material is assumed to be paint (15.6 $/m^2$), as it's considered the lowest in value, compared to other finish materials.

[7] www.globalpetrolprices.com

Different PV systems of the same electricity production capacity have different prices and might have different sizes. According to Forbes[8] database (updated on September 2021), monocrystalline solar panels are considered the most energy efficient PV option. The model considers the average international market price of a monocrystalline PV system, provided by Forbes **Table-5**.

Table 5 - International cost of monocrystalline PV system

	SYSTEM COST ($/WATT)	SYSTEM COST ($/M^2)	INSTALLATION COST ($/WATT)
MONOCRYSTALLINE PV	$1 to $1.50	155 to 209	0.27

As the average costs of PV unit of 1.25 $/Watt, 182 $/m^2 and the installation cost of 0.27 $/Watt (39.312 $/ m^2), The calculation of the CPV considers the summation of the average costs of PV unit and the installation cost (221.312($/m^2)).

C. Cost equivalent of emissions

The main source of energy for buildings, supplied by the government in Kuwait through the national desalination plants, is powered by natural gas. The emissions produced from plants powered by hydrocarbon fuels (E_H) in Kuwait are estimated at 827 Kg of CO_2/MWh (Ramadhan and Naseeb, 2011). To calculate the cost equivalent from on the amount of emissions produced in kilograms, the estimation modules suggested by the EPA are used. All the models analysed by the EPA assume that the damage from climate change will increase with time, as they estimate an increase of the SC-CO_2 value with time.

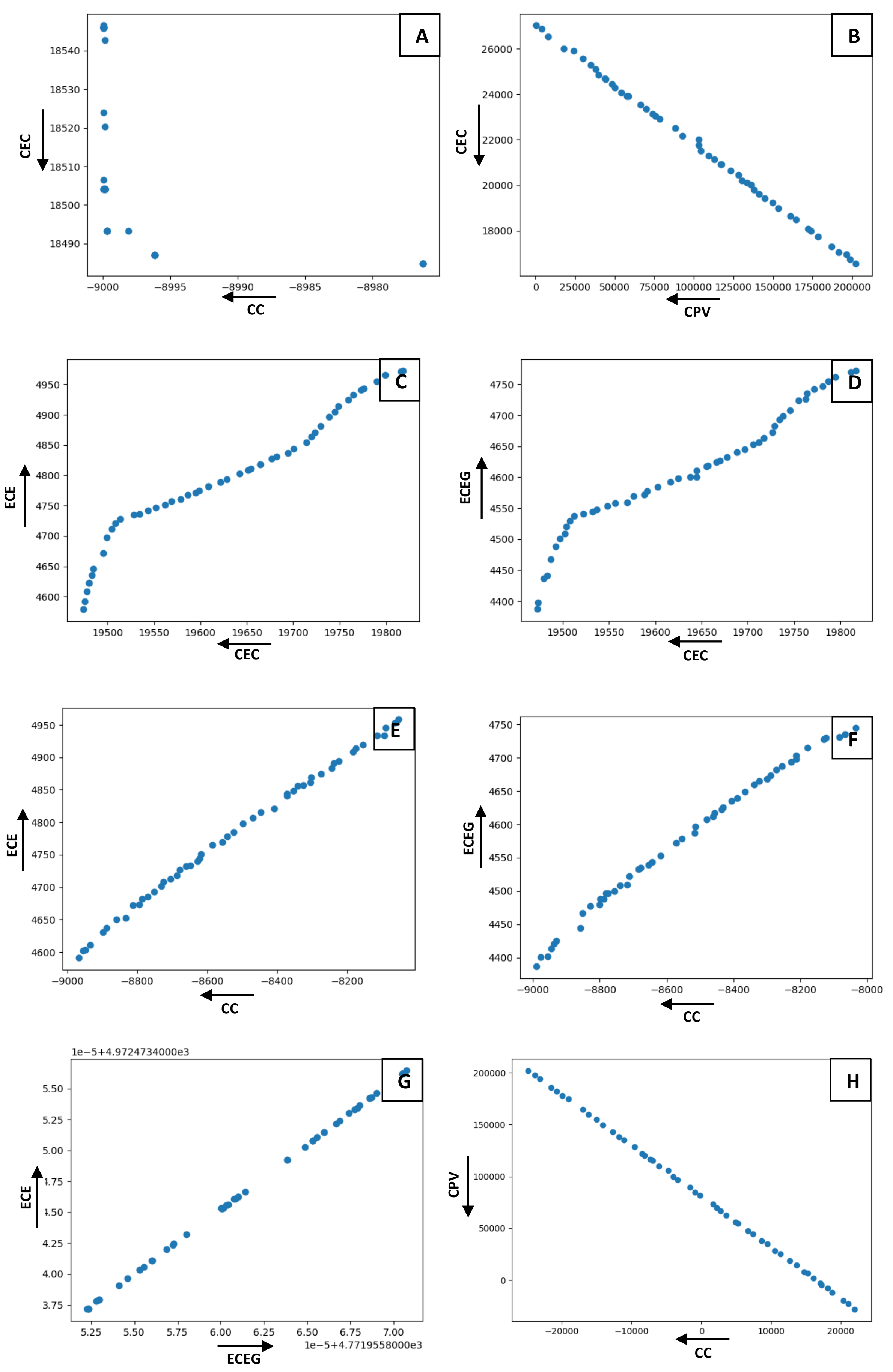
The results in this section are considering the average of the EPA's four modules in the years 2020 and 2025, listed in **Table-1**. Accordingly, the value of the CFER is assumed at $63 per metric Ton.

3.2 Objectives and Trade-offs

3.2.1 Scenario 1: Consideration of PVs on all walls

Each one of the three objectives, defined in **Table-2**, can be evaluated based on the equations explained in the methodology. The first objective is chosen to suggest design variables that would minimise the buildings' cost of energy consumption (CEC), based on the analysis from Chapter-2. The second objective is chosen to suggest design variables that would minimising the cost of construction materials (CC) and minimise the capital cost of the PV system (CPV). The third objective is chosen to suggest design solutions that would maximise equivalent cost of energy generation from PVs (ECEG), replacing the cost of hydrocarbon fuels with free renewable resources and maximise the reduction of emissions and its equivalent costs (ECE). Trade-offs (if any) between different pairs of the five objective functions are shown in **Figure-6**, where each is in ($) unit.

[8] www.forbes.com


A
CEC
CC
18540
18530
18520
18510
18500
18490
−9000
−8995
−8990
−8985
−8980
B
CEC
CPV
26000
24000
22000
20000
18000
0
25000
50000
75000
100000
125000
150000
175000
200000
C
ECE
CEC
4950
4900
4850
4800
4750
4700
4650
4600
19500
19550
19600
19650
19700
19750
19800
D
ECEG
CEC
4750
4700
4650
4600
4550
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4400
19500
19550
19600
19650
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19750
19800
E
ECE
CC
4950
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−8800
−8600
−8400
−8200
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ECEG
CC
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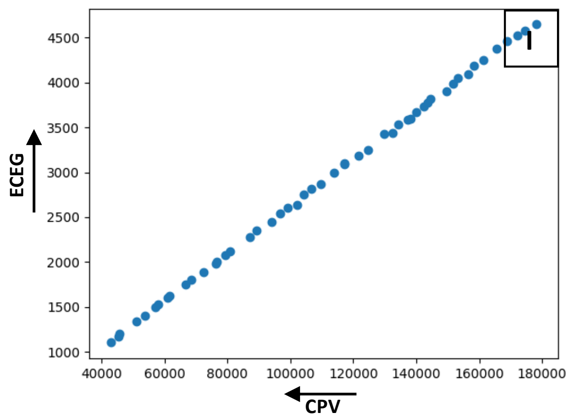
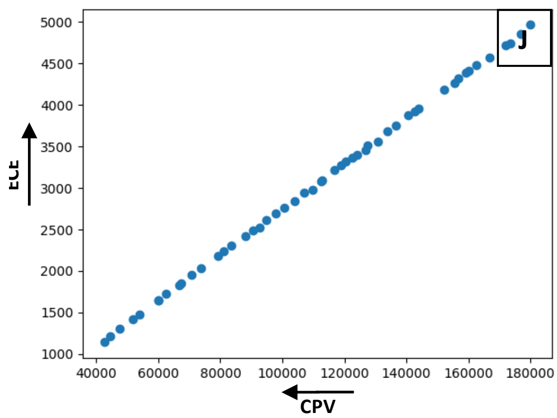
−8800
−8600
−8400
−8200
−8000
G
ECE
ECEG
1e−5+4.9724734000e3
1e−5+4.7719558000e3
5.50
5.25
5.00
3.75
4.00
4.25
5.25
5.50
5.75
6.00
6.25
6.50
6.75
7.00
H
CPV
CC
200000
150000
100000
50000
0
−20000
−10000
0
10000
20000





The plots shown in **Figure-6** are not a representation of the trade-off between the defined five objective functions simultaneously. They represent solutions that target selected pair of objectives to highlight how each function affects the other. **Figure-6/Plot (A)** highlights the optimum solutions limited to the CC and CEC functions, both converging toward their minimum values in a very narrow range with no trade-off. Based on the discussed analysis in Chapter-2 and the construction cost calculations explained in this chapter, **Figure-6/Plot (A)** validates that the CC and CEC are optimum with minimum WWR, being the variable with the dominant impact on the cost of construction materials and influence over the buildings' energy consumption. The other variables (i.e., O and AR) impacting these two functions have significantly less impact and would vary within the lowest margin of the WWR.

The solutions in **Figure-6/Plot (B)** show that when the objective is to minimise the CEC, the CPV is found at its highest rate, indicating a trade-off. This is in line with the analysis, as the buildings were found to consume less energy with minimum WWR, allowing for more wall space to install PVs, leading to higher cost expenditure on PVs (CPV). As for **Figure-6/Plot (C)**, minimising the CEC while maximising the CE, and **Figure-6/Plot (D)** minimising the CEC while maximising the ECEG, the objectives have no significant trade-offs. In both plots the ranges are narrow and the solutions gravitate toward lower WWR, as the CEC is at its lowest, and the ECE and ECEG are at their highest when there are less windows and more wall area. Similarly with the CC in **Figure-6/Plots (E and F)**, the unit price of windows is higher than the unit price of wall construction, when the WWR is low, the CC is low, providing more wall area for PV's, leading to higher ECEG, and ECE.

As the ECE function is calculated based on the ECEG function, **Figure-6/Plot (G)** shows the correlation as linear, with no trade-off. The reason that they are not merged as one objective, is to be able of identifying each for their values independently, allowing the user to adjust the formula based on the latest method for calculating the economic cost equivalent of emissions.

Figure-6/Plot (H) represents the trade-off between minimising the CC and minimising the CPV. Again, the dominant variable is the WWR, and the conflict between the two objectives spread the solutions across the data points. On one hand, the CC is at its minimum when the WWR is at its lowest; However, lower WWR result in more wall space for PV installation and therefore higher CPV. On the other hand, the CC is at its highest when the WWR is at it its highest; Simultaneously, the wall area becomes at its lowest, resulting in minimum CPV.

As for the solutions based on the objective of minimising the CPV against maximising the ECEG and ECE in **Figure-6**/Plots (I and J), the tradeoffs indicate that when the value of the CPV is at its minimum the values of the ECE and ECEG are at their minimum too, conflicting with the objective of achieving maximum ECE and ECEG. On the contrary, Higher CPV is against the set objective, but it would result in maximum ECE and ECEG.

The purpose of the pair-plots **(Figure-6)** is to analyze the interactions between the different objectives and validating the logic in the functions used. The model is built to run the five objective functions simultaneously, using the NSGA-II method, and the output of the module is presented using a Parallel Coordinates Plot (**Figure-7**).

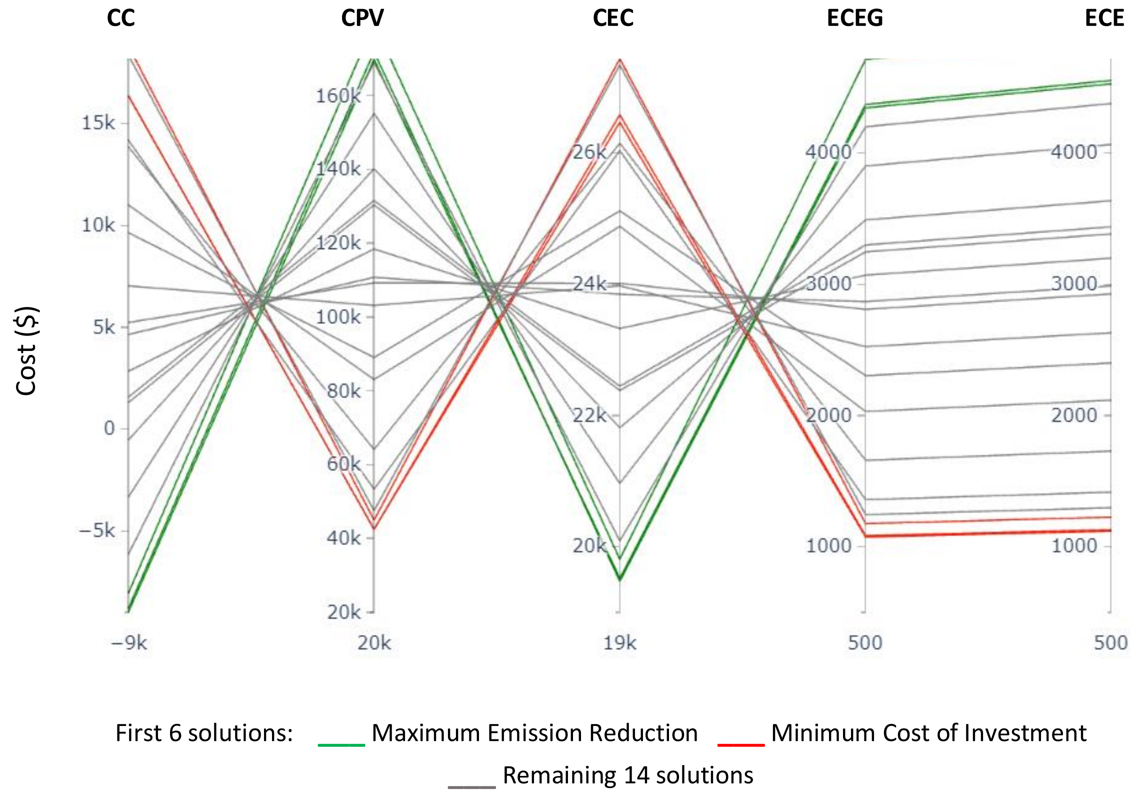


Figure 7 - Parallel coordinates plot of optimised solutions based on the five defined objectives

Each line in **Figure-7** represents a solution with specific BO, WWR, AR and Tilt, marking the corresponding values that minimise the CC, CPV and CEC, while maximising the ECEG and ECE. The CPV objective is clearly a major investment decision for the user, as the solutions are shown to have the widest range, while the cost ranges of the other objectives have less spread. Consistently with the pairs analysis **(Figure-6/Plot (G))**, the ECEG and ECE are shown to be parallel with no trade-offs. The model can generate as many optimal solutions as requested by the user, found using the NSGA-II method. By running the module to find solutions based on a population size of 20, the output design variables and corresponding objectives are presented in **Table-6**.

Table 6 - Variables and objectives of the optimum solutions

	VARIABLES				OBJECTIVES ($)					ENVIRONMENTAL INDICATOR
SOLUTION	**WWR**	**AR**	**BO**	**T**	**CC**	**CPV**	**CEC**	**ECEG**	**ECE**	
1	20%	1/2	90	81	-8068	179694	19808	4714	4912	^
2	80%	1	126	81	16384	42509	26586	1084	1130	v
3	80%	1/2	83	81	18831	44972	27438	1176	1226	v
4	80%	1	1	82	16373	42536	26470	1074	1119	v
5	20%	1	88	81	-8991	169784	19518	4371	4554	^
6	20%	3/4	0	81	-8806	171881	19473	4345	4528	^
7	63%	1/2	0	84	11013	83083	24884	2031	2117	-
8	31%	1/2	5	81	-3341	155218	20966	3902	4066	^
9	60%	1/2	127	80	9656	89058	25119	2304	2401	-
10	71%	4/7	114	81	13869	64138	26151	1659	1729	v
11	46%	3/5	112	81	2836	118475	23326	3070	3199	-
12	54%	1/2	4	84	7034	103170	23977	2525	2631	-
13	51%	5/9	116	82	5236	109301	24016	2809	2927	-
14	37%	1/2	0	82	-537	140213	21814	3491	3637	-
15	24%	1/2	1	82	-6156	168997	20090	4201	4378	^
16	50%	4/7	116	81	4650	110777	23849	2868	2988	-
17	75%	1	114	81	14197	53371	26039	1359	1416	v
18	41%	1/2	4	81	1571	131586	22446	3300	3438	-
19	79%	1/2	83	81	18372	47551	27342	1245	1297	v
20	41%	1/2	0	82	1304	130390	22382	3247	3384	-

The three optimum solutions that maximise the utilisation of PVs, suggest lowering the WWR to a minimum, with an AR of 1:2 or 1:1 while the longer span is facing East/West or and AR of 3:4 while the longer span is facing North/South. If the user's priority is for maximum natural light or is limited financially and wishes to keep the PVs' investment value at a minimum, the WWR is allowed to be at its highest. The three optimum solutions in this case suggest the AR to be either 1:1 while the longer span while facing North/South, 1:1 while the longer span's orientation is at 126°, or 1:2 while the longer span is at 83°. In all those suggested solutions, the tilts of PVs are suggested at approximately 80°. Among the 20 solutions, the model recommends options that are balanced between the environmental benefits and the fiscal investment, such as solutions 6, 8 and 10 in **Table-6**. In those solutions, the five objectives are at the middle of the results range, with sets of different envelop design recommendations. The Environmental indicator signifies which solution has the highest or lowest potentials for environmental benefits (higher or lower ECEG-ECE). While the ideal position is to advocate for higher environmental benefits, the solutions suggested are realistically governed by the available funds, that can be allocated to invest in PVs.

The parallel coordinate plot **(Figure-7)** and tabulated solutions **(Table-6)** are based on the energy calculations of buildings' energy consumption and PVs' energy generation within a year. To analyse the benefits of the CPV as an investment, the ECEG and the ECE can be considered as yearly income/return, from which the Payback Period (PBP) can be calculated. When the model considers the installation of PVs on all walls, the PBP is between 19 and 21 years. The cases where the PVs were installed at 80° resulted in faster return to the investment, as the amount of energy generated, and emissions reduced were higher using the same quantities of PV's. furthermore, buildings with their longer span facing E/W have registered slightly shorter PBP compared to other orientations, for PVs at each tilt.

3.2.2 Scenario 2: Consideration of PVs on selected walls

By investigate further the efficiency of PVs based on their orientation, the economic/environmental feasibility can be a major factor in the renewables' investment decision. As indicated in Chapter-3, the differences in energy production, from PVs of the same size, based on the system's orientation can reach up to 60%. Based on the results from scenario 1, when the CPV decreases, the values of the ECEG and ECE also decrease, but at a lower rate. This is due to the total production from PVs from four different orientations, each having different production potentials, in each building case.

Scenario 2 investigates the exclusion of the least energy producing wall(s) from PVs installation, based on the productivity rates from each orientation. This will also result in an increase in CC, due to the need for external finish on the walls that no longer have PVs as a replacement the external finish. Building on the results in Chapter-3, the buildings can be analyzed based on two positions/cases (**Figure-8**). In Case-1, there is one wall that has significantly low potential to generate energy. While in Case-2, there are two walls that save significantly low potential to generate energy. In the optimisation model, it would be misleading to process the results from the two cases together, as the CPV, CC, ECEG, and ECE are impacted at different rates. Accordingly, the optimisation model is run twice, considering the two cases separately.

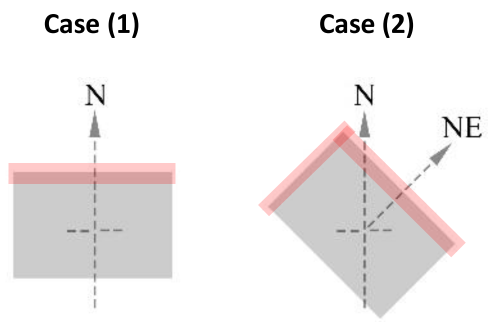
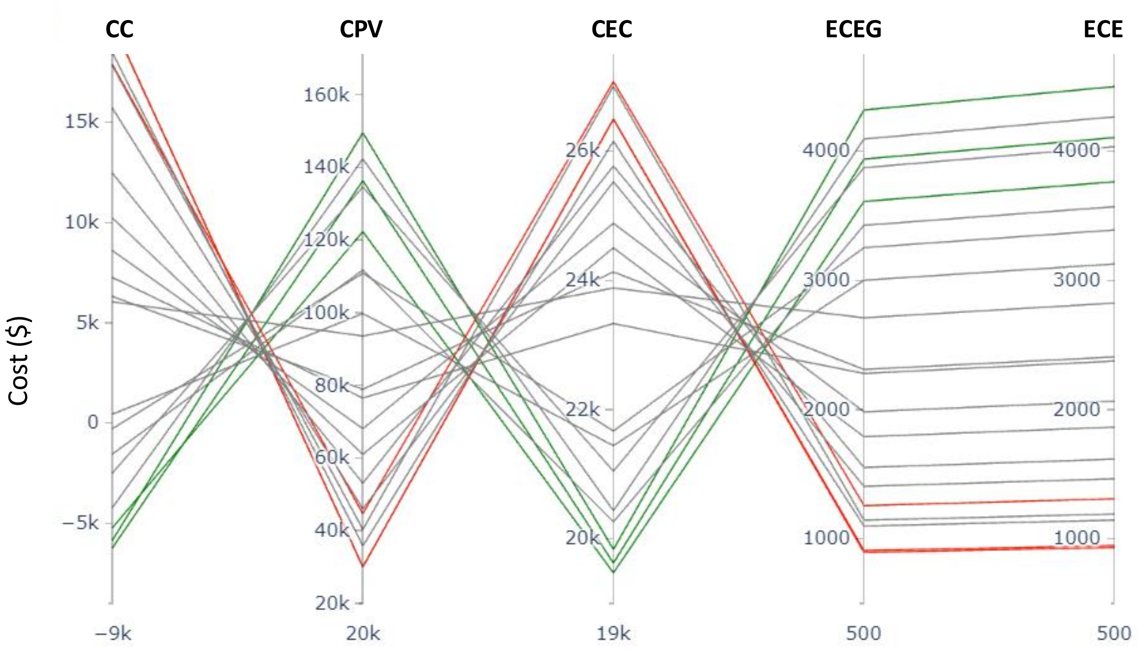


Figure 8 - Excluded wall(s) orientations from PVs

- **Case (1)**

The least energy producing wall-orientation in Case-1 is the North-facing wall. A PV unit (of the same size and capacity) positioned facing the North orientation performs at 40% of what a South-facing the same PV unit can produce. While the East-facing and the West facing PVs can produce almost 80% of the production rate from the South-facing PVs. Based on those production variances, the model is set to exclude the North facing wall from PVs installation. Accordingly, the CPV value, based on the number of PVs installed on the three remaining walls, varies between 67% and 83% from the quantity of PVs in the PVs on all walls case. However, the amount of energy generated/emission-reduced are between 82% and 91% of the energy generated/emission-reduced from the PVs on all walls case. This indicates that the reduction rate in investment value is not the same as the reduction rate in PV's performance. The optimum solutions based on the five objectives for Case-1 are presented in **Figure-9**, and **Table -7** enlists the optimum solutions' design variables and the cost objectives.



First 6 solutions: ____ Maximum Emission Reduction ____ Minimum Cost of Investment

____ Remaining 14 solutions

Figure 9 - Case-1 Parallel coordinates plot of optimised solutions based on the five defined objectives

Table 7- Variables and objectives of the optimum solutions (Case-1)

	VARIABLES				**OBJECTIVES ($)**					**ENVIRONMENTAL INDICATOR**
SOLUTION	**WWR**	**AR**	**BO**	**T**	**CC**	**CPV**	**CEC**	**ECEG**	**ECE**	
1	76%	1/2	E	85	17890	44708	27079	1257	1310	v
2	80%	1/2	N	83	19973	30062	26499	909	948	v
3	20%	3/4	N	84	-5235	122328	19473	3612	3764	^
4	20%	5/7	E	83	-6239	136337	19625	3940	4106	^
5	20%	1/2	E	81	-5861	149540	19836	4320	4501	^
6	80%	1/2	N	85	19964	30048	26498	895	933	v
7	49%	1/2	E	81	6049	93599	23883	2711	2825	-
8	35%	3/4	N	82	437	99790	21442	3002	3128	-
9	35%	3/4	E	81	-285	110863	21670	3254	3391	-
10	69%	5/7	E	81	12470	53099	25772	1552	1617	-
11	60%	5/7	N	85	10231	61022	24506	1790	1865	-
12	69%	1/2	N	82	15718	46059	25529	1406	1465	v
13	24%	1/2	E	82	-4228	142336	20435	4095	4267	^
14	28%	1/2	E	82	-2499	134619	21047	3873	4036	^
15	60%	5/7	E	82	8605	68090	24885	1983	2066	-
16	76%	1/2	N	81	18476	35841	26156	1099	1145	v
17	49%	1/2	N	84	7262	76548	23333	2280	2376	-
18	78%	5/9	E	84	17838	40351	27005	1144	1192	v
19	54%	3/4	E	81	6318	78919	24132	2311	2408	-
20	26%	1/2	N	82	-1552	111779	20262	3427	3571	^

The three optimum solutions that suggest maximum investment in PVs recommend a WWR at the minimum value. The AR is either 1:2 or 5:7 while the longer span is facing East, or an AR of 3:4 while the longer span is facing North. The Tilts of PVs are 81°, 83° and 84° respectively. The top three optimum solutions that maximises the utilisation of natural light and lower the investment in PVs suggest the AR to be 1:2, two of which recommend the longer span to face North with PVs tilt either at 83° or 85°, and one solution suggesting the longer span to face East with PVs tilted at 85°. Among the 20 solutions in Case-1, the model also generated options that are balanced between the environmental benefits and the fiscal investment, such as solutions 6, 7 and 8 in **Table-7**, marking the corresponding envelop design variables.

Clearly the optimum solutions in Case-1 suggest different building envelop variables than those of the initial case where all the walls were used to install PVs. Furthermore, based on the CPV, CEG and CE calculations in Case 1, the PBP is calculated between 16 and 18 years. This is consistent with the understanding that the reduction in the value of the CPV does not lead to a reduction of the CEG/CE at the same rate.

- **Case (2)**

A PV unit facing the North-East or North-West walls produces almost 60% of the production from PVs installed at South-East and South-West walls. The exclusion of two wall orientations from PVs installation in Case-2 results in a reduction in the investment value (CPV) of 50% in all building cases due to the buildings' symmetry. However, when the North-East and the North-West orientations are excluded from PV installation, the amount of energy generated/emission-reduced is about 62% of the PVs on all walls case. The same observation here about the reduction rate in investment value not being the same as the reduction rate in PV's performance. The optimum solutions based on the five objectives for Case-2 are presented in **Figure-10**, and **Table-8** enlists the optimum solutions' design variables and the cost objectives.

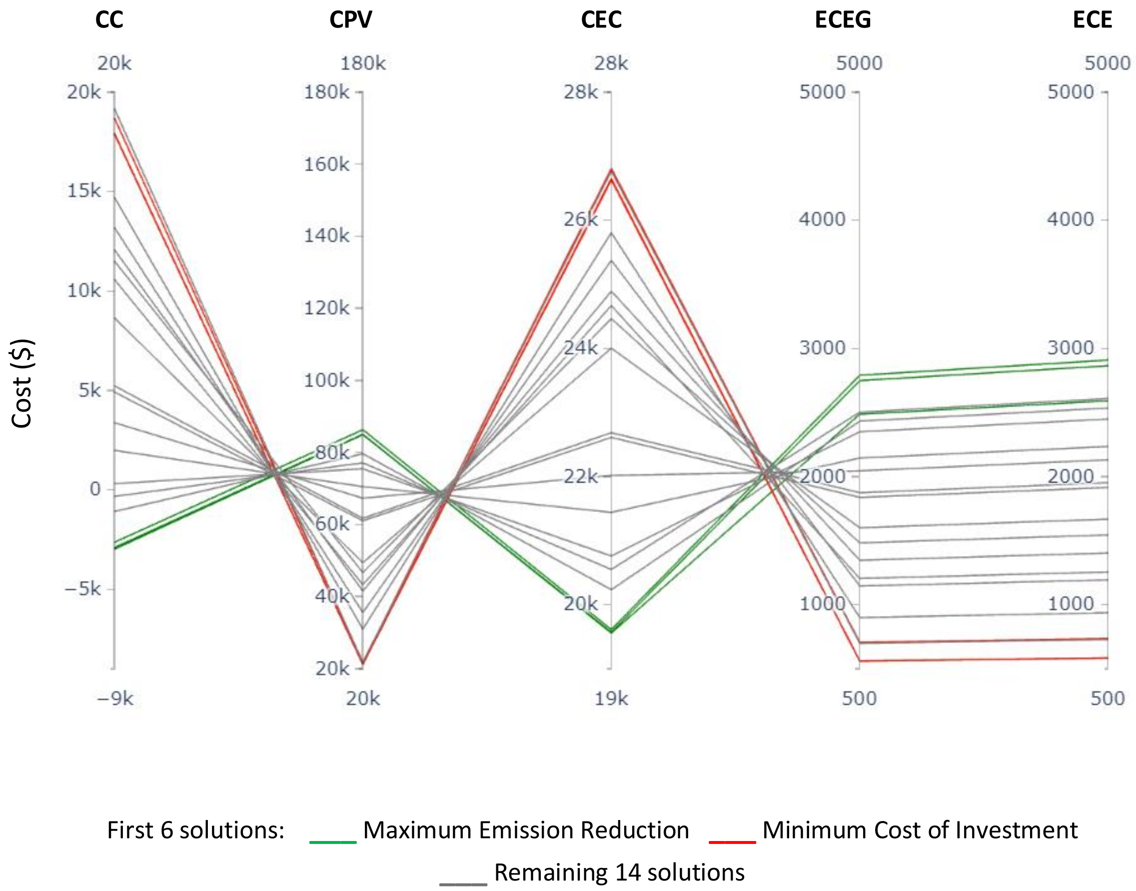


Figure 10 - Case-2 Parallel coordinates plot of optimised solutions based on the five defined objectives

Table 8 - Variables and objectives of the optimum solutions (Case-2)

	VARIABLES				OBJECTIVES ($)					ENVIRONMENTAL INDICATOR FIG-10
SOLUTION	**WWR**	**AR**	**BO**	**T**	**CC**	**CPV**	**CEC**	**ECEG**	**ECE**	
1	80%	1	SE	90	17937	21258	26631	560	584	v
2	80%	1	SE	90	17913	21248	26652	561	585	v
3	20%	1	NE	81	-2983	84974	19572	2749	2865	^
4	80%	2/3	NE	81	18701	21806	26810	706	736	v
5	20%	7/8	SE	86	-2903	85051	19558	2487	2592	^
6	20%	5/7	NE	81	-2638	86343	19613	2791	2909	^
7	80%	5/7	NE	81	19179	21695	26770	699	729	v
8	53%	1	NE	81	8653	49443	24004	1601	1668	-
9	42%	1	NE	90	4921	61085	22612	1838	1915	-
10	29%	7/8	NE	86	312	75501	20760	2350	2449	^
11	34%	5/6	NE	89	1986	70564	21442	2145	2235	-
12	42%	3/4	NE	89	5231	61766	22685	1874	1953	-
13	57%	5/7	NE	83	11508	46710	24465	1483	1545	-
14	27%	1	NE	81	-331	77161	20550	2503	2609	^
15	25%	7/8	SE	80	-1089	79673	20235	2433	2535	^
16	59%	1	SE	89	10584	43350	24668	1205	1256	-
17	66%	1	NE	81	13199	35635	25374	1146	1194	-
18	37%	5/7	NE	89	3379	67356	22018	2045	2131	-
19	71%	1	SE	81	14717	31006	25806	900	938	v
20	61%	7/9	NE	81	12076	41578	24893	1347	1404	-

The three optimum solutions that suggest maximum investment in PVs recommend a WWR at the minimum value, and an AR of 1:1 with PVs at 81° tilt, an AR of 7:8 while the longer span is facing South-East and PVs tilt at 86°, or an AR of 5:7 while the longer span is facing North-East and PVs tilt of 81°. The three optimum solutions that maximise the natural light and lower the investment value in PVs, suggested by the model, two of which were almost identical with AR of 1:1 and PVs at 90° tilt. While the third is with an AR of 2:3, while the longer span is facing North-East, and PVs at an 81° tilt. Also, some of the optimum 20 solutions in Case-2, are balanced between the environmental benefits and the fiscal investment, such as solutions 7, 8 and 11 in **Table-8** alongside their corresponding envelop design variables.

It is noticed that the envelope design recommendations in Case-2 differ from both previous cases, especially with the suggested optimum AR and the PVs tilt. Almost half of the solutions recommend an AR of 1:1, and almost 30% of the solutions suggested PVs at or close to 90° tilt. This can be attributed to the fact that the walls with PVs are facing the South-East and the South-West, with potentials for energy generation optimally during the sunrise and sunset. In addition, based on the CPV, ECEG and ECE calculations in Case-2, the PBP is calculated between 15 and 16 years.

3.3 Design selection by the user

Based on the two scenarios, analysed in sections 3.1 and 3.2, the model's user can compare the results of multiple options, guided by their design limitations and financial obligations. **Figure-11** highlights the top six solutions from the three cases discussed, solving for the same five functions (Cost of Energy Consumption (CEC) - Cost of Construction (CC) - Cost of PVs (CPV) - Equivalent Cost of Energy Generation (ECEG) and Equivalent Cost of Emissions (ECE).

The comparison shows that a selective approach where specific walls are used for PVs installation (Case-1 and Case-2) can perform environmentally (Based on the ECEG and ECE values) as good as some of the optimum PVs on all walls option. In one specific solution, Case-1 [Solution:4], the ECEG and ECE are on the higher margin and close in performance to the optimum solutions in the PVs on all walls case (only $500 difference). However, the CPV investment in that solution is less by almost $20k-30k from the solutions requiring PVs on all walls. While comparing the different results, the user must distinguish between the CC and CPV as capital costs, and the CEC, ECEG, and ECE as yearly cost/revenues. Comparing the PBP can also be factored in when deciding which solution is to be considered.

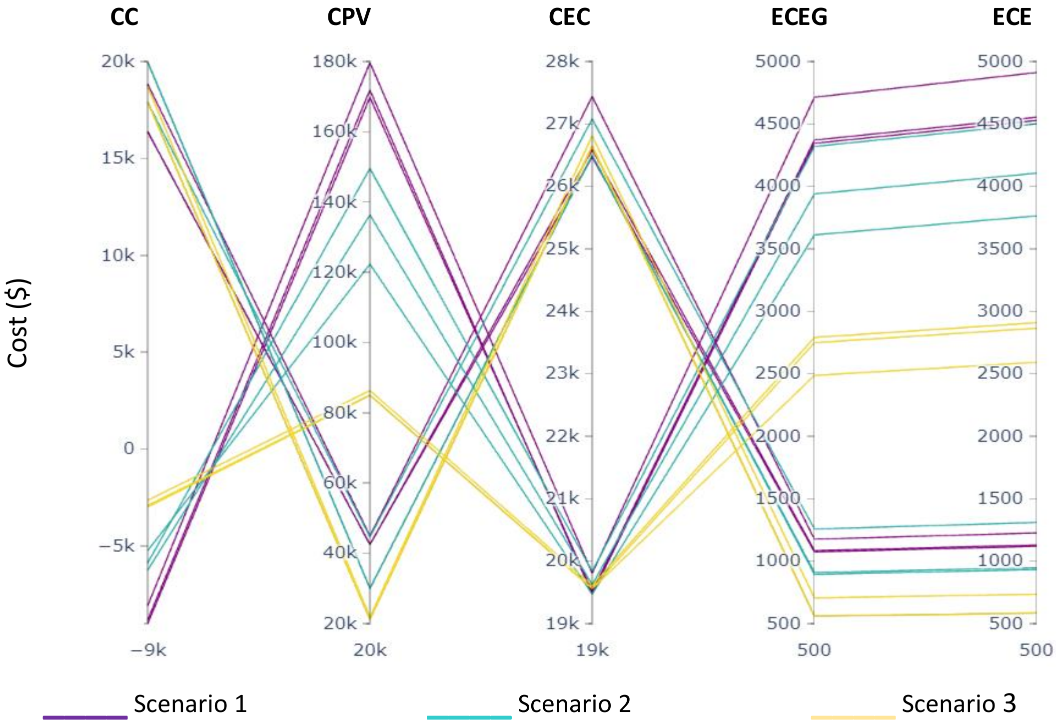


Figure 11 - Comparison between the optimum solutions in each case

Some solutions can be excluded by the user due to land restrictions. While other solutions can be excluded for specific design requirements, such as the desired amount of natural sunlight, set by the user. Accordingly, the list of optimum solution can be evaluated, shortened, and ranked based on the user's priorities.

The solutions proposed based on Case-1 and Case-2 assume that the user has no plans to further invest in the installation of PVs on the excluded walls in the years to come. If the user wishes to plan the investment of PVs to take place over different years, based on the available funds, the building's envelope design decision can be made based on the maximum potentials from the chosen solution. Then, the PBP can be calculated based on the CPV, ECEG and ECE accounting for the years of installation and operation. For Example, if the user decides to choose a building design from the results in scenario 1 (PVs on all walls), but only has 50% of the funds needed to install the PVs suggested in that solution (budget for 50% of the CPV); The user can make the decision to strategically select the walls to install the PVs (based on Case-1 and Case-2 analysis), at which maximum energy generation can be achieved from the selected walls/orientations. That means the 50% of the CPV (quantity of PVs) would not result in 50% reduction in the ECEG and ECE. Then when the funds are available, the user can plan the installation of the remaining 50% of PVs on the walls that produce lower energy.

The user can also update the CEC, ECEG and ECE values throughout the years of operations, by a simple adjustment to the rates used in in the model to calculate the cost equivalent of those objective functions. To user can also adjust the costs/rates of energy supplied from the grid, based on the most recent local market prices.

4.0 Conclusion

The work presented in this chapter helps the decision makers during the early planning stages of building construction projects to explore trade-offs between economic and environmental designs. The model created can recommend key envelope design variables, performing optimally toward economic and environmental objectives. The model uses the NSGA-II algorithm to solve for a set of Pareto optimum solutions, recommending the values of the Aspect Ratio (AR), the Window to Wall Ratio (WWR), the Building Orientation (BO) and the Tilt of PVs, to be installed on the available external wall areas of the buildings. The solutions are recommended based on five objective functions, the Cost of Construction (CC), the Cost of Energy Consumption (CEC), the Cost of PVs (CPV), the Equivalent Cost of Energy Generation (ECEG) and the Equivalent Cost of Emissions (ECE). Each objective function is derived from regional simulation and data, specific to the climate and buildings' energy consumption/ generation rates in Kuwait.

When the aim is to maximise the environmental opportunities within building projects, the model recommends several solutions where the PVs are recommended on every available wall area. The first six Pareto optimum solutions suggest that both extreme points of the WWR range would perform optimally, leading to either maximum or minimum investment in PVs. In scenario 1, the buildings are suggested to perform optimally with an AR of 1:2 in more than 50% of the solutions. Most of the solutions suggest AR's of 1:1 or 1:2 ratios, and positioning the buildings with the longer span facing either North to minimise the building's energy consumption or East to maximise energy generation potentials from PVs. The tilt of PVs was consistently recommended at the lower tilt (80̊), maximising the energy generation potentials from all walls/orientations.

The differences in the productivity rates of PVs at different orientations can be a factor in deciding which walls can be utilised to maximise the use of such expensive investment. In scenario 2, two cases, defined based on the BO, are explored where the least energy producing wall(s) are excluded from PVs installation. In the first case, the buildings are positioned limiting the walls to face North-East-South-West. In this position, the least producing wall is the one facing North. The first six Pareto optimum solutions in the first case suggest buildings with WWR at both extremes of the margin (20% or 80%), either maximising the energy generating potentials or minimising the investment value in PVs. However, the AR of all optimum buildings in Case-1 is suggested to be less than 1:1.5, recommending an elongated building form in all cases. It can also be noticed in the Tilt variable that

25% of the optimum cases recommended positioning the PVs at an approximately 85° tilt, as the rest of the recommended tilts are in the lower range.

As for the second case, the buildings are positioned in an orientation that the walls are facing the North-East, South-East, South-West and North-West. In this position, the least energy producing walls to be excluded from PVs installation are the North-East and the North-West facing walls. The first six Pareto optimum solutions in Case-2 also recommend buildings with WWR at both extremes of the margin (20% or 80%), to either maximise the energy generating potentials or minimise the investment value in PVs. However, form the top 20 optimum solutions, 50% of them recommend the AR at its highest value (1:1), suggesting that the buildings with a more compact form would perform optimally across all objectives. 30% of the solutions recommend the tilt of PVs at almost 90°, while 50% of the solutions recommended the tilt of PVs at approximately 80°.

Future work

There are gaps in literature, specific to certain climates and their impact on energy and buildings. The opportunities to improve buildings' energy consumption while maximising the potentials from renewables to generate energy in the middle east are not thoroughly researched. Better understanding of climate factors in the GCC, such as the high temperatures during summer months, the high humidity levels, dust, and pollution from hydrocarbon-fuelled plants, is needed, while considering the use of renewable energy systems. This research achieves a trade-off between buildings' energy consumption for thermal balance and the use of renewable energy systems (RES) within the building's envelope design, in consideration of the impact of dust in Kuwait. Further work can address the specific impact of other climate factors on buildings' designs and energy.

The model can be used to investigate the opportunities in regions at similar/close latitudes to Kuwait, that would mostly be subject to similar climate challenges. At regions with the opposite latitude of Kuwait (from the equator), the same parameters can be useful. However, the productivity rates of PVs correlating their orientation has to be inverted. For example, the energy data from PVs in Kuwait facing South are assumed to be similar to PVs facing North in Namibia. Furthermore, the model can be adapted for other regions, such as regions with high rate of rainfall and/or snowfall. However, the parameters and assumptions must be based on that region's studies and data, to quantify the impact of each factor.

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Appendix – I

The details in this appendix explain some of the main concepts modelled in EnergyPlus, used to process buildings' input data for energy calculation purposes. It summarises the equations and algorithms used to process the following 20 functions:

1- Basis for the Zone and Air System Integration
2- Air System Control
3- Summary of Time Marching Solution
4- Conduction Through the Walls
5- Conduction Finite Difference Solution Algorithm
6- Combined Heat and Moisture Transfer (HAMT) Model
7- Outside Surface Heat Balance
8- Inside Heat Balance
9- Climate Calculations
10- Sky Radiance Model
11- Daylighting Calculations
12- Time-Step Daylighting Calculation
13- Window Calculation Module
14- Window Heat Balance Calculation
15- Infiltration
16- Ventilation
17- Air Exchange
18- Zone Internal Gains
19- Set-point Managers
20- Occupant Thermal Comfort

Appendix – II

The references used in the detailed statistics presented in Chapter 4