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DESIGNING AND ASSESSING THE ECONOMIC FEASIBILITY OF A SMALL HYBRID NEGAWATT POWER PLANT

by
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ABSTRACT
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The world is witnessing an increasing trend in energy consumption due to several reasons of which the most important ones are the increase in population size, technology developments, and country social and economic development. Such increasing trends lead to more rapid resources depletion and more harmful gaseous emissions and greenhouse gases being emitted to the atmosphere from the combustion of various energy resources especially fossil fuels.

Several research studies have been conducted to understand this increasing energy trend, specifically from office and residential buildings, and its negative consequences on the economy and heath. These studies seek to find solutions for better energy sustainability measures and resource allocations management through modifying the user's energy consumption trends without affecting the personal comfort, in addition to further developments of renewable energy resources.

This Thesis aims at studying different building energy conservation measures and provides economic feasibility. In addition, it will examine the deployment of renewable energy resources, namely PV cells, to aid in the transition to clean energy. The Thesis work will make use of the Negawatt concept which is based on assessing the feasibility of establishing more efficient technologies to lower energy consumption rather than expanding the power supply to meet increased demand.

The feasibility study of a small Hybrid Negawatt power plant for a recently constructed office building at the American University of Beirut (AUB) is assessed. Various conservation measures are assessed mainly focusing on reducing energy consumption during unoccupancy periods, in addition to addressing alternative technologies, such as more efficient lighting and upgrading the double-glazed windows. A rooftop PV canopy design system is proposed, while maintaining the unique roof terrace and its wonderful sea view. The feasibility study carried out compares the cost of implementing these measures and alternative technologies to the cost of expanding the supplied thermal power from conventional fossil fuels. The results show that the hybrid Negawatt solution is more economically feasible, especially where certain mitigation measures require only managerial and behavioral adjustments at no additional costs.

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ABBREVIATIONS

KTOE	Kilo-ton Oil Equivalent
GHG	Green House Gases
DOE	US Department of Energy
LED	Light Emitting Diode
PV	Photovoltaic
EDL	Electricité du Liban
NPV	Net Present Value
kWh	Kilowatt-hour

CHAPTER 1

INTRODUCTION

The total global energy consumption was estimated to be 7,032,033 ktoe for the year 2000 of which 1,804,114 ktoe was for the residential sector and 1,962,766 ktoe was for the transport sector. For the year 2018, the total figure reached 9,937,702 ktoe of which 2,109,205 ktoe was accounted for the residential sector and 2,890,900 ktoe was for the transport sector [1]. Growth rates percentages are calculated to be respectively 16% for the residential sectors and 37% for the transport sector which highlight the important trend increase in global energy consumption and specifically for these two sectors in the past two decades.

As for the power sector, there is also a high and ever-increasing demand for energy and electricity especially in developed countries. The electricity consumption in the world as depicted in Figure 1 from 1990 to 2018 [1] shows an increasing trend of 110%, i.e., the demand has almost doubled during this period.

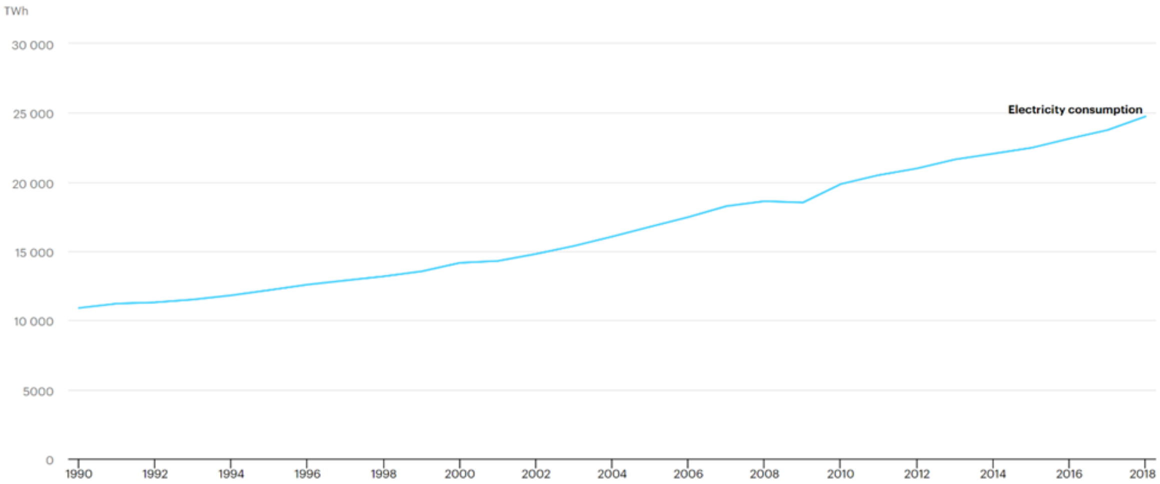


Figure 1: Electricity consumption in the world

One impact of energy conversion processes is the emission of several local toxic gases such as NO_x, SO_2 and others, in addition to emissions of CO_2, the main greenhouse gas (GHG). There is also scientific evidence that GHG buildup in the atmosphere increases global temperature, and this has detrimental impacts on all economic sectors. With the limited supply and increasing costs of fossil fuels, several governments such as the United States and European Union, have mandated incentives to reduce emissions and conserve energy waste.

1.1. Definition of the NegaWatt concept:

The Negawatt is a term that was first introduced by Amory Lovins; an American, environmental scientist, chairman and chief scientist of the Rocky Mountain Institute. He defined the Negawatt in 1989 as the amount of energy (watt) that has not been used through energy conservation because of using energy efficient products [2]. It is each Watt saved in the process of energy saving while keeping the necessary usage/living standards and comfort.

It is generally easier to save energy than to consume it, in turn protecting the environment and reducing pollution not on a cost perspective but as a profit. Lovins claimed the creation of the Negawatt market (a theoretical energy market) in which the traded commodity is Negawatt-hour that is a unit of energy saved as a direct result of energy conservation methods. Examples of institutions and associations working on energy conservation is the Rocky Mountain Institute in the USA and the “The Negawatt Association” in France [3]. The latter main interests are to recommend solutions for energy demand and supply thereby implementing a successful energy transition.

1.2. Deployment of Negawatt power plants:

In Germany, Siegrun Appelt’s light installation 64 kW served as a visual exclamation point for a more conscious handling of energy resources in 2008 [4]. The work called on visitors to save energy and then symbolically donate that energy to the 64 kW Negawatt Power Plant. The plant was inspired by the scientist Amory Lovins’ term Negawatt. The first energy donator for the 64 kW Negawatt Power Plant was the city of Berlin. Once the exhibition began, the illumination at the Brandenburg Gate was turned on and off over the course of several days according to a strategy that was designed by Appelt herself. The light-update of Berlin’s most prominent emblem served as a prime example of the fact that saving energy would not only mean abnegation, but also the creation of a surplus.

Also, in Germany, there was an objective to build a "Negawatt power plant" at a local authority school in Freiburg, using private capital [5]. An organization (ECO-Watt GmbH) was created in May 1998 to implement the project. Besides retrofitting the lighting system, efficiency improvements were made to the ventilation and heating system. In addition, two solar plants (thermal and photovoltaic) were installed. The investment for the project totaled 250,000 EUR. The final investment measures were implemented in the summer holidays of 1999, and the Negawatt power plant has been running for the benefit of investors and the school together. The school receives a sum of between 2500 EUR and 10,000 EUR per year to spend as it likes, depending on the extent of the savings made. A contractual period of eight years was placed and after it has ended, the savings went to the City of Freiburg. Over the service life of the technologies, the City of Freiburg realized savings of more than 500,000 EUR through this project. More than 200,000 kWh of electricity were saved over the first year and apart from the direct reductions in emissions achieved through the reduced use of fossil energy sources (approximately 350 tons CO_2 per year), the project also had further environmental impacts. By using more efficient luminaires and lamps, it has proved possible to reduce the amount of mercury used in the lighting by more than 90 percent. After the successful startup of the Negawatt plant, students were encouraged to recognize energy savings in their homes and a lot were able to achieve interesting results. They found hidden electricity gluttons at home in the form of televisions, printers, video recorders, and halogen lamps. The stand-by losses were generally readily avoided using switchable sockets. The students also frequently established a need for changes in the lighting.

In Japan, Kansai Electric Power (KEPCO) issued a press release on June 21, 2012 with the title “Negawatt Trading for Large Customers Outside Kansai Electric Power’s Service Area.” [6]. The announcement was related to the expansion of Negawatt trading, which KEPCO called the “Negawatt Plan” within its service area, to the part of the 60Hz power grid in Japan comprising the service areas of Chubu Electric Power, Hokuriku Electric Power, and Chugoku Electric Power. The initiative was a power conservation scheme based on economic rationality theory in which electricity conserved during times of peak power demand is purchased as if it were generated electricity (Negawatt power generation). The scheme worked under Demand Response (DR) which is an important method of Demand-Side Management (DSM). Customers, including residential users, were requested to conserve electricity in the spirit of sacrifice or voluntarism without any enforcement. DR is a mechanism of purchasing power conserved during peak demand, as if that power were generated (referred to as “Negawatt generation”).

A large U.S. utility designed, built, and is monitoring two single family homes to test the hypothesis that substantial energy savings as high as 75% can be achieved in residential buildings, at economically acceptable costs, using integrated energy efficient end-use technologies and systems [7]. These energy savings can be conceived as "Negawatt" Power Plants which suggest investing in energy efficiency rather than producing more energy to compensate the increased growth in demand. The goal of the "Advanced Customer Technology Test for Maximum Energy Efficiency" (ACT Project) was to provide scientific information on the maximum energy savings possible, at or below projected competitive supply costs, by using modern high-efficiency end-use technologies. ACT's residential efforts started with the designing and constructing of two new single-family homes located in California's Central Valley and a DOE2.lE model was created for each site using construction drawings of the base case houses. Each design maximizes energy efficiency by installing energy efficiency measures (EEMs) that improve the efficiency of appliance and lighting, in addition to reducing or eliminating the need for mechanical cooling in certain climate temperature. Both homes produced projected savings of 62% and 64% in total energy consumption at market costs competitive with new supply. The construction of the two homes was completed in December 1993 and April 1994 and ACT is now monitoring actual energy use and EEM performance.

In the UK, there are risks for having to pay for at least eight new power stations because it is failing to harness its huge potential for saving electricity. The UK electricity market would save over £2 billion by 2025 if power stations were made to compete against electricity saving, which is disadvantaged by current rules and financial incentives [8]. Negawatts delivered through permanent electricity demand reduction measures, are available at £30 per MWh, and can compete with new power stations, which cost a minimum of £76 per MWh. A new strategy is proposed for electricity markets that responds to technology changes. The core of this strategy is the creation of incentives, enabling companies to aggregate energy efficiency measures and compete to deliver them on the most cost-effective basis. It requires two changes to the electricity market: A Negawatts feed-in tariff which is paid based on energy consumption and opening the capacity market to competition from demand-side response and energy demand reduction with equal basis for electricity generation. The following brief three case studies examples illustrate how much energy efficiency can help at peak times and how much these projects could receive if they were to participate in the capacity market [9]. Together, the electricity savings from just these three case studies achieve a peak load reduction of over 1,800 kW, equal to the peak power demand of around 2,900 UK households:

BASF, an American/German company creating chemistry for a sustainable future, has taken electricity efficiency measures from upgrading the cooling towers and converting to LED to reach upgrades in air filtration systems. Saving measures resulted in a peak load reduction of 884 kW. These electricity load reductions are equal to the typical power required by 1,427 homes in the UK.

A leader in the field of environmental sustainability, **The Guy's, and St Thomas' NHS Foundation Trust,** has taken saving projects that include switching to LED lighting, putting frequency inverters on fixed speed motors, and installing a high specification chiller. These measures resulted in a peak load reduction of 674 kW and are equal to the typical power required by 1,086 households in the UK.

Oxford Brookes University has implemented numerous electricity saving measurements over the past few years. Electricity saving projects since November 2010, together with planned projects, reduced loads at peak time by a total of 273 kW. These electricity load reductions are equal to the typical peak power required by 440 homes in the UK.

In South Korea, in January 2014 when the government established the 2nd Korea National Energy Master Plan, 15% electricity demand reduction by 2035 has been set through demand management. In addition, the Ministry of Trade, Industry and Energy announced ‘The Six New Energy Businesses’ with private sectors in the same year where one of them aimed at obtaining electricity of 1.9 million kW by 2017, equivalent of the amount of power generating from two nuclear power plants through the electricity demand management (Negawatt) [10]. The reason that the Korean government started engaging actively in demand management is based on realistic judgments that the availability of power facilities is deteriorating. An energy expert mentioned that the energy sustainability can only be secured by a series of technologies that improve energy efficiency, save energy, and alternative energy. Out of them, energy efficiency and energy saving are thought to be attainable by energy demand management. Korea with 80GW peak demand and a 90GW generation capacity in 2014, is one of the large-scale demand management markets in the world. But its lower reserve, compared to the electricity demand, is a stressful problem. The electricity demand management includes traditional demand management handling with load only and broader demand management covering generation support. It is divided into three categories of Energy Efficiency (EE), Demand Response (DR) and Self Generation. Negawatt represents an energy-saving activity in terms of demand response and considering the feature that Korea’s power demand is skyrocketed during summer and winter, the demand response programs are now applied only to reducing such seasonal peak load.

In Malaysia, the Ministry of Education has urged all education centers to conserve energy [11]. They proposed the concept of a sustainable university with a view of some steps to conserve energy and achieve sustainability. Energy conservation methods can be classified into two categories: structural and non-structural. Within the context of these two categories, five high-impact energy conservation methods are suggested, including renewable energy, improvement of energy efficiency, energy usage management and monitoring, promotion and integration of energy concept, improvement on energy-saving awareness and energy-use behavior. Based on the recommendations in the concerned paper, Malaysian universities can adopt energy conservation methods that can be in harmony with their policies and strategies. Many universities have taken initiatives to create sustainable environment through various projects and research activities. Sustainable University should include three aspects, namely environment performance, social performance, and economic performance. Behavioral approach and technology approach are two common ways in energy management known also as structural and non-structural conservation methods. Structural energy conservation method refers to technology fixation whereby instrument, tools or technology are used to conserve energy. These include the introduction of new process, change to automation systems, or installation of large energy-saving devices, such as heat recovery systems and others. The structural energy conservation methods can be divided into three types: renewable energy generating technology, energy efficiency improvement technology, and technology for managing and monitoring energy usage. Non-structural energy conservation includes integrating energy conservation concept in the management and co-curriculum of universities, in addition to improving energy awareness and energy use-behavior among users. It is suggested that universities begin with low budget energy conservation methods which can be achieved through the non-structural energy conservation method that can be used after an appropriate feasibility study is conducted.

1.3. Integration of renewable energy:

The effects of climate change and the impact that GHG emissions have on the atmosphere are pushing for a reassessment of energy supply sources and their sustainability. Countries are considering gradual overall transition to alternative energy resources mainly renewable energy because of what they provide in better energy security with less dependence on fossil fuels and a road to energy sustainability. The future stands in the light of environmentally compliant power generation systems that can be interconnected to respond to electricity demands and remain commercially viable. Alternative energy sources in buildings make use of renewable energy technologies that can be incorporated with building energy such as solar electric photovoltaic (PV systems), solar thermal (SWH for domestic water heating or space heating), and solar ventilation air preheating.

The ECO-Watt GmbH project previously mentioned [5], implemented energy-saving measures that were supplemented by the construction of a thermal solar plant with a collector surface of 42 m^2. This covered most of the hot water requirements for the two gymnasiums. In addition, plans were made for the construction of a 2-kW solar plant, which was to be financed through subsidies and sponsorship money. Since these plants do not pay for themselves within the eight-year term of the contract concluded with the City of Freiburg, they had to be financed through the savings made on energy costs. The results obtained indicated that a considerable increase can be expected in the share of renewable energy supplies, given the savings that have been made. Instead of the 2-kW solar power plant that was planned to be installed, a 4-kW was already installed.

In the same study for Malaysia [11], a structural energy conservation method is renewable energy generating technology mainly from biomass and solar, where the latter is more convenient to be utilized for Malaysian universities.

The U.S. Department of Energy’s National Renewable Energy Laboratory, introduces technical opportunities, means, and methods for incorporating renewable energy technologies into building designs and operations [12]. They provide an overview of renewable energy resources and available technologies used successfully to offset building electrical and thermal energy loads. Methods for applying these technologies in buildings and the role of building energy efficiency in successful renewable energy projects are addressed. **Solar electric PV**, building-integrated photovoltaic (BIPV) products may be appropriately suited for applications on existing buildings during major renovations. These technologies can double as rooftop shingles (single-ply membrane, standing seam metal roofs, and others) and tiles, building facades, or the glazing for skylights. These systems can be designed to provide power simultaneously with the utility (grid-connected), independent of the utility (stand-alone) or to do both (dual mode). They can be designed to power any percent of an electric load, from a very small percentage to above 100% of the load, depending on available area for the panels, sun availability, and allowances provided by utility policy to sell the energy back to the utility. **Solar thermal**, such as solar water systems are reliable and low maintenance because they have few moving parts. Also, solar ventilation preheating systems heat ventilation air for applications needing high volumes of ventilation air. **Geothermal,** building applications for geothermal technologies include geothermal heat pumps and direct use of the geothermal resource. **Wind turbines** require land area, so on-site wind power generation usually occurs for projects having space for installing the turbines. Roof-mounted wind systems are beginning to be used in some building projects. There are many types of **Biomass** organic matter such as plants, residue from agriculture and forestry, and others that can be used to produce fuels, chemicals, and power.

Significant amount of heat and electricity needs of buildings can be effectively covered by using solar thermal collectors and photovoltaic [13]. Other renewable energy sources (RES) such as wind turbines, biomass, and hydrogen (produced only from RES) can be applied, minimizing the use of the conventional energy sources. The exploitation of solar energy systems toward sustainable development applications could take the form of the creation of innovative buildings aiming at the saving of energy. Some of the building integrated solar energy systems adopted worldwide are: Flat plate thermosyphon units (FPTU) and integrated collector storage (ICS) that are small size solar water heater, solar collectors with colored absorbers, solar collectors with booster reflectors, unglazed solar collectors, hybrid photovoltaic/thermal (PV/T) systems which provide solar and heat simultaneously, Fresnel lenses for building atria (optical devices for solar radiation concentration, and building integration of solar/wind systems. The authors also discuss the economics of these renewable energy projects in buildings where several values are considered to estimate the unit cost of electricity from the renewable energy source generation. A feasible alternative would be the focus on the promotion of renewable energy technology in meeting building energy requirements. When the building energy is completely met by renewable energy system, then it is known as a highly energy efficient or zero emission green building. The economics that the authors present of various renewable energy systems indicate the acceptance of these technologies as compared to the conventional energy sources. For example, the wind electricity cost can be reduced by reduction in capital cost, increased energy output because of improved airfoil, larger turbines, and the introduction of more efficient operating strategies. The capital cost will be reduced because of innovations which may include the use of lighter weight materials and designs leading to lower manufacturing costs.

1.4. The Lebanese case:

Lebanon relies on fuel imports to satisfy its energy demand. Consumption is met through Liquid Petroleum Gas (LPG), gasolines, gas oil, kerosene, fuel oil, and bitumen with some sources of clean energy produced mainly including Solar Water Heaters and Hydro power plants. The Lebanese electricity sector has suffered since the mid-1990s mainly due to the lack of investment which led to the deterioration of the electric power infrastructure. Lebanon’s electricity supply and demand balance as shown in Figure 2 reveals how the electricity demand unmet by EDL increased from 22% in 2008 to 37% in 2018 [14].

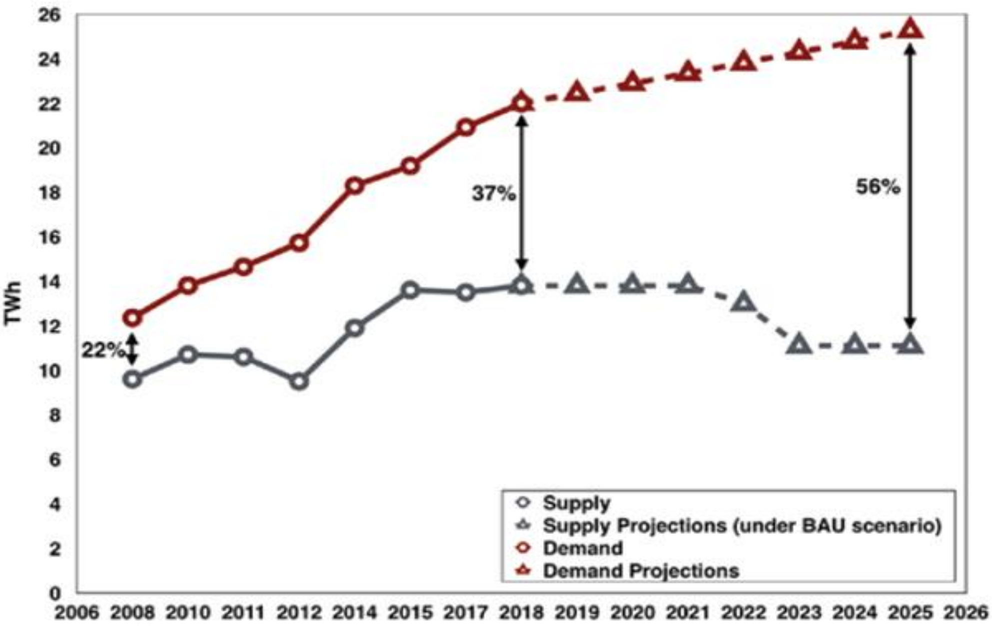
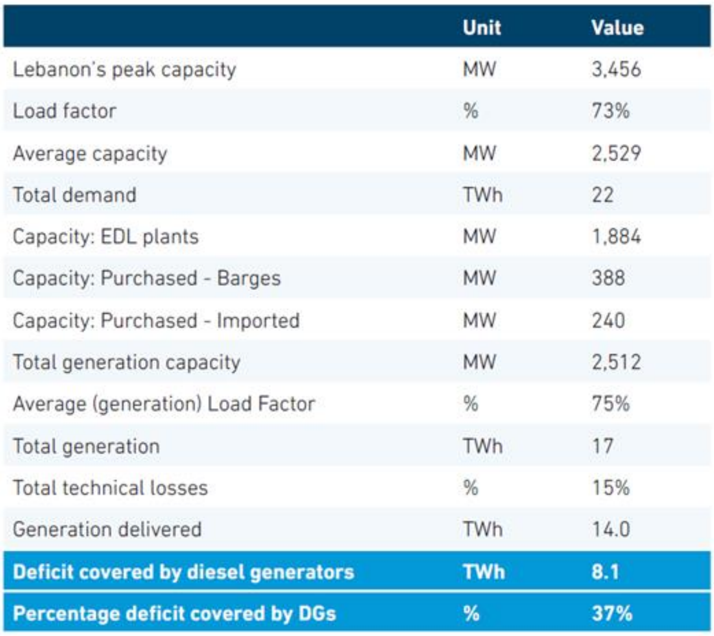


Figure 2: Lebanon's electricity supply and demand balance

A projection scenario where demand would continue to grow and no generation capacity would be added and in addition, the Jiyeh and Zouk power generation units would be retired in 2022, indicates a deficit growth up to 56% in 2025. In addition, installed capacity of solar PV grew from almost 0 in 2011 to around 47 MWp in 2018. Subtracting the capacities of the Beirut River Solar Snake and the Zahrani Oil Installations projects, which account for 1.08 and 1.09 MWp, respectively, the remaining 44.8 MWp are all installed as decentralized systems. In terms of electricity generation, solar PV projects generated around 53 GWh, which is equivalent to 0.25% of Lebanon’s total demand and 0.4% of EDL’s total production.

The gap between the power supplied by EDL and the demand is covered by private diesel generators that are dispersed all over the country. In 2018, the power deficit covered by diesel generators totaled around 8.1 terawatt hours (TWh). As shown in table 1 for 2018 data, about 37% of the unmet demand is covered by private generators.

Table 1: Back-up diesel generators electricity portion share in Lebanon (2018)



	Unit	Value
Lebanon's peak capacity	MW	3,456
Load factor	%	73%
Average capacity	MW	2,529
Total demand	TWh	22
Capacity: EDL plants	MW	1,884
Capacity: Purchased - Barges	MW	388
Capacity: Purchased - Imported	MW	240
Total generation capacity	MW	2,512
Average (generation) Load Factor	%	75%
Total generation	TWh	17
Total technical losses	%	15%
Generation delivered	TWh	14.0
Deficit covered by diesel generators	**TWh**	**8.1**
Percentage deficit covered by DGs	**%**	**37%**

Therefore, the increasing electricity demand in Lebanon faced by the limited generation supply capability, imposes on taking alternative methods of energy efficiency measures to reduce the current consumption. It is therefore essential for Lebanon to benefit from the advanced knowledge of the Negawatt power plants and to push for further transition to renewable energy.

1.5. The AUB case:

Like any other institution or economic sector in Lebanon, AUB has installed standby generators to compensate for the electricity outages from the Lebanese power utility. Demand for power in AUB is increasing due to the growth of staff, facilities, students, and employees. The university has buildings that go back to the 19th century. It mainly has 55 buildings including the AUB medical center with a total power demand in 2008 of around 11.6 MW [15]. A recent figure from the power plant indicates a total power demand in 2018 of around 17.8 MW.

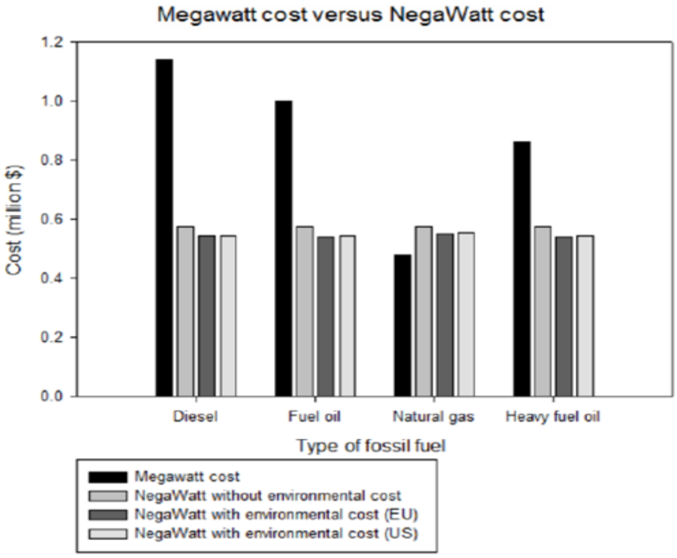


Figure 3: Megawatt cost vs Negawatt cost

A previous Negawatt power plant project was executed over three stages, the first by collecting data for the energy consumption and the second by building the base case model using visual DOE software and the third for developing the Negawatt power plant and estimating its cost [16].

The goal of the project was to utilize the developments in clean and efficient technologies by modifying the usage of electricity without affecting comfort. It was shown that building a Negawatt power plant is more-cost effective than building a new thermal power plant or to install standby generators. The plant is a combustion- free plant that ensures reduction in GHG emissions because less fuel is burnt to supply the necessary demand. A summary of the Megawatt costs vs. the Negawatt costs is shown in Figure 3.

In 2016, AUB has installed a photovoltaic system with a total capacity of 150 KW_p, consisting of 474 panels that cover the roofs of Bechtel Engineering building (BEB) and the Scientific Research Building (SRB) over an area of 1,500 m^2. This promises a production of around 209 MWh per year with potential savings of 40,000 $, in turn mitigating high environmental and economic cost of electricity generation from the combustion of diesel.

In the case of thermal power plants driven by fuel oil for example, the price of a Negawatt is 42% lower than the actual cost of a megawatt without considering the environmental cost (1 million $ compared to 0.58 million $) and that with the environmental cost gives further reduction of around 5.8% in the price of the Negawatt.

According to the discussion with the AUB power plant engineers, AUB has 16 MW generator sets installed and rents additional generators in peak seasons in the summer. It is anticipated that up to 2 MW are needed to match the campus activities expansion, leading to more fuel consumption and GHG emissions. The university's total emissions are estimated at 54,990 tons of CO_2 per year equivalent in 2018-2019 [17]. Electricity consumption from EDL accounts for most emissions (30.53%), followed by student commuting (25.89%), steam generation (14.12%), electricity from on-site generators (13.88%), staff business air travel (6.64%), staff commuting (4.03%), faculty commuting (2.82%), solid waste disposal (1.32%), paper consumption (0.47%), and AUB owned vehicles (0.3%) [17].

The increase in growth demand can be tackled either by expanding the power plants generation capacities with new generators that will lead to capital and operating costs and fuel consumption, or through taking renewable energy and energy efficiency measures to reduce the current consumption up to 2 MW. This study will focus on taking energy efficiency measures at AUB highlighting the design and economic feasibility of a hybrid Negawatt power plant to decrease energy demand and to bridge the transition to renewable energy. Applying such measures will reduce consumption, save fuel costs, and reduce the GHG emissions which in turn lead to less negative effects on the environment.

CHAPTER 2

METHODOLOGY

2.1. Addressing the problem:

Due to the power demand growth at AUB, it is anticipated that up to 2 MW are additionally needed to match the expansion in the campus infrastructure and operations. This increase in growth can be solved by either adding more generating supply units or through energy efficiency measures to reduce the current consumption by up to 2 MW.

The increase in growth demand is better off being tackled through taking energy efficiency measures and at the same time, working on bridging the transition to renewable energy. Applying such measures will reduce negative impacts on the environment, save fuel costs and consumption, and reduce the GHG emissions. It will help AUB to maintain the increase in demand in a sustainable manner and in labelling the campus as green or eco-campus.

Accordingly, this thesis research will try to better understand and assess the power demand and its anticipated growth at AUB and afterwards apply energy conservation with the Negawatt principle. In addition, it will also focus on switching to clean renewable energy through hybrid Negawatt concepts. If adopted properly, electricity consumption will be reduced, and this will increase efficiency without affecting the comfort. With less consumption and more reliance on clean energy, these measures will reduce the impacts on the environment with less CO_2 and other toxic emissions and save fuel costs. Therefore, the main issue(s) that this research will address are assessing the AUB power demand and its anticipated growth, applying energy conservation with the Negawatt principle, assessing the possible integration of renewable energy alternatives into the power system (Hybrid), identifying the possible environmental and economic implications, and a feasibility study of the hybrid Negawatt plant implementation.

2.2. Project execution:

The Negawatt power plant will be built over four stages and each stage involves certain tasks or stages as per the below:

The first stage consists of data collection and monitoring to calculate the amount of energy consumed. This data will include the total energy consumption (kWh) of the campus buildings, the HVAC system, and the lighting system. In addition, the research will focus on the construction material used in the buildings, type of glass (Single or double glazing), and occupancy rate and schedule. Such data will enable to identify the energy consumption percentages to each area of interest and try to limit the loss thus increase the efficiency as much as possible.

The second stage is building the base case models of the base model building(s) using the US department of energy (DOE) Buildings Technologies Office (BTO) software “Energy Plus” through the graphical user interface “Open studio”. After building the model, energy conservation measures (lightning replacements, lighting sensors, window glass replacement, roof insulation, ...) will be applied. The total reduced energy consumption will be the basis of the Negawatt power plant to be produced.

The third stage involves the integration of renewable energy alternatives into the existing campus power system. Applications will involve the capability to install systems such as separate PV cells. For this stage, the software “PVsyst” is used for panels analysis and integration, for best possible output and load coverage.

The fourth and last stage involves forming and developing the Negawatt mitigation measures. Environmental and economic studies will be carried out to compare the costs of the two concepts of the ordinary Megawatt power plant and the clean hybrid Negawatt power plant taking into consideration the capital costs, operation and maintenance costs, fuel costs, purchasing costs, and CO_2 emissions. The analysis will reflect the market prices of the mentioned systems and calculating the payback period. The results will be compared with the Megawatt power generation accordingly to conclude its feasibility.

2.3. The base model and simulation:

For this work, AUB “Munib & Angela MASRI Building” referred here after as “MASRI building” is chosen for the base model for implementing energy conservation measures and the integration of renewable energy. It is a modern building fitted with a building management system (BMS) intended to provide control and monitoring for different mechanical and electrical equipment installed, to provide energy management and optimize energy efficiency. Some of the features installed are advanced Air Handling Units (AHUs), Fan Coil Units (FCUs), variable speed pumps and many others.

The MASRI building is drawn in “Sketchup”, a well-known 3D drawing software. Afterwards, the drawing is imported to the “Energy Plus” graphical user interface, “Open studio” software. The simulation results include the energy consumption of the building (kWh), peak power demand (KW), and energy resources such as diesel and steam consumption (kWh). The results are plotted on a full year interval to understand the power fluctuations during the year and where conservation measures can be best addressed. After the full building understanding, the measures are implemented in “Open studio” and the simulation is done for each measure with its consequent results. The plotting of results for each method generally gives a better visualization to best reduced energy consumption and demand, thus giving estimates on the feasibility and output of deployment scenarios.

The design of the PV panels is also executed in “Sketchup” for the same 3D model previously done. The panels arrangements and specifications are then entered in “PVsyst” to analyze the production. The results are plotted on a full year interval which mainly include the production output.

Generation costs, both capital costs and operational costs, of different technologies are then calculated and compared to estimate the optimal generation mix for the Negawatt power plant. After building the base model, combing both conservation measures and renewable energy integration leads to less consumption and load demand for the building (reduced kWh), which means savings in the long run and reduced environmental impact, that constitute the Hybrid Negawatt power plant.

CHAPTER 3

TECHNOLOGY OVERVIEW

Before studying the hybrid deployment of energy efficiency and renewable energy methods, it is essential to begin with a technological overview of the renewable energy aspect especially for solar photovoltaics, focusing on the development, operation, and cost estimates.

3.1. Solar photovoltaics (PV) cells:

More energy from the sun falls on the earth in one hour than is used by the whole world in one year [18]. The most used solar technologies for homes and businesses are solar photovoltaic (PV) units for direct conversion of solar beams into electricity, passive solar design for space heating and cooling, and solar water heating. Businesses and industry use solar technologies to diversify their energy sources, improve efficiency, and save money.

PVs get its name from the process of converting light (photons) to electricity (voltage), which is called the photovoltaic effect. Today, electricity from solar cells has become cost competitive and PV systems are being deployed at large scales to help power the electric grid. There are different PV technologies commercially available mainly those based on:

- *Silicon:* Solar cells made from silicon offer both reasonable prices and good efficiency. These cells are usually assembled into larger modules that can be installed on the roofs of residential or commercial buildings or deployed on ground-mounted racks to create huge, utility-scale systems.

- *Thin Film:* Another commonly used photovoltaic technology are made from very thin layers of semiconductor material, such as cadmium telluride or copper indium gallium selenide. The thickness of these cell layers is only a few micrometers. Thin-film solar cells can be flexible and lightweight, making them ideal for portable applications or for use in other products like windows that generate electricity from the sun.
- *III-V* solar cells: are mainly constructed from elements in Group III—e.g., gallium and indium—and Group V—e.g., arsenic and antimony—of the periodic table. These solar cells are generally much more expensive to manufacture than other technologies, but they convert sunlight into electricity at much higher efficiencies.

The three major types of solar panels are: monocrystalline, polycrystalline, and thin film, see Figure 4. Each type has its own unique advantages and disadvantages, shown in Table 2, and the solar panel type best suited for installation will depend on factors specific to own property and desired system characteristics [19]:

Table 2: Advantages and disadvantages of different solar panels

Solar panel type	Advantages	Disadvantages
Monocrystalline	• High efficiency/performance • Aesthetics	• Higher costs
Polycrystalline	• Low cost	• Lower efficiency/performance
Thin-film	• Portable and flexible • Lightweight • Aesthetics	• Lowest efficiency/performance

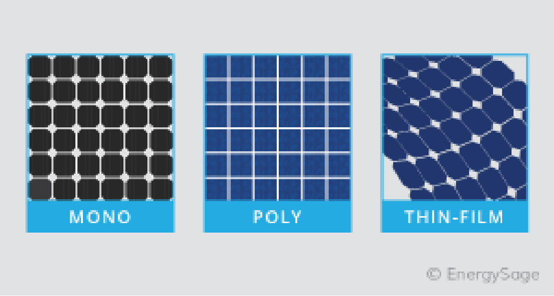


Figure 4: Types of PV

3.2. Off-grid vs On-grid:

An off-grid solar energy system is not connected to the utility grid, whereas an on-grid (aka grid-tied) solar energy system is connected to the utility grid. The choice of an off-grid system or on-grid system will determine the access to electricity, what equipment is needed for excess production, what happens when the grid goes down, and how one is billed for electricity.

Table 3: Off-grid vs On-grid

Measure	Off Grid	On Grid
Access to Electricity	No access to extra electricity if you need it. What you are producing and what you have stored is all that is there to power your equipment.	Always have access to electricity (unless the grid goes down), whether your solar system is producing or if you have batteries. You can pull energy from the utility grid to supplement it. This ensures you always have enough electricity for what you need.
Excess Production	Most off-grid solar systems are designed to produce a certain amount of “extra” electricity in the daytime, which is sent to batteries for storage. The energy stored in those batteries can then be accessed when the system is	Just like off-grid solar systems, many who choose to install an on-grid solar system want to cover 100% or nearly 100% of their energy usage. Instead of sending it to

	not producing, like at night or during cloudy weather.	batteries as you would in an off-grid system, you can send it to the grid, and you will be compensated for that electricity.
If grid goes down	Your solar system is working independently from the power grid. You can continue operating, you will not notice changes in your service or access to electricity.	You will not have electricity unless you opt for a grid-tied solar system with battery backup.
Method of billing	You will not receive an electric bill at all.	Few bills such as service fee, demand charges, depending in which country and the usage pattern.

3.3. Azimuth and tilt:

The “tilt angle” or “elevation angle” describes the vertical angle of the solar panels. The “Azimuth angle” is their horizontal facing in relation to the Equator. Solar panels should face directly into the sun to optimize their output, as shown in Figure 5. If one lives in the Northern Hemisphere, they should be faced south. Whereas for Southern Hemisphere, they should face north. A zero-tilt angle means that the face of the panel is aimed directly overhead. A positive tilt angle means that the panel faces more towards the equator.

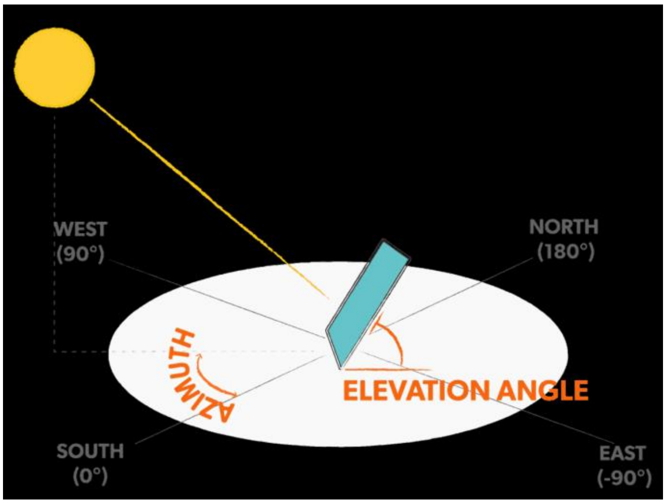


Figure 5: Azimuth and tilt angles

To get the best out of the solar radiation for Lebanon, the solar panels should be installed at an angle around 35 degrees from the flat surface and should be facing south in an un-shaded area. Any shift of around 15 degrees in tilt or orientation would lead to a 23% drop in system performance [24]. Shading has significant negative effects on the performance of the PV system because solar panels are made up of several connected solar cells and little shading as 2.5% could reduce the electricity output of the PV significantly.

3.4. Inverters and maximum power point tracking (MPPT):

Solar inverters may be classified into four broad types:

Stand-alone inverters: used in isolated systems where the inverter draws its DC energy from batteries charged by photovoltaic arrays. Many stand-alone inverters also incorporate integral battery chargers to replenish the battery from an AC source, when available. Normally these do not interface in any way with the utility grid, and as such, are not required to have anti-islanding protection.

Grid-tie inverters: which are designed to shut down automatically upon loss of utility supply, for safety reasons. They do not provide backup power during utility outages.

Battery backup inverters: are special inverters which are designed to draw energy from a battery, manage the battery charge via an onboard charger, and export excess energy to the utility grid. These inverters are capable of supplying AC energy to selected loads during a utility outage and are required to have anti-islanding protection.

Intelligent hybrid inverters: manage photovoltaic array, battery storage and utility grid, which are all coupled directly to the unit. These modern all-in-one systems are usually highly versatile and can be used for grid-tie, stand-alone or backup applications but their primary function is self-consumption with the use of storage.

Solar inverters use maximum power point tracking (MPPT) to get the maximum possible power from the PV array. Solar cells have a complex relationship between solar irradiation, temperature and total resistance that produces a non-linear output efficiency known as the I-V curve. It is the purpose of the MPPT system to sample the output of the cells and determine a resistance (load) to obtain maximum power for any given environmental conditions.

3.5. Efficiency of solar panels:

Solar panel efficiency is a measurement of a solar panel's ability to convert sunlight into usable electricity. Given the same amount of sunlight shining for the same duration of time on two solar panels with different efficiency ratings, the more efficient panel will produce more electricity than the less efficient panel. Solar panel efficiency is determined by the production of electricity by solar cells, which is in turn influenced by the cells’ composition, electrical configuration, surrounding components, and more. Solar panel efficiency relates to the ability of the panel to convert energy at a low cost and high supply rate. Most solar PV panels are between 15% and 20% efficient, with outliers on either side of the range. High-quality solar panels can exceed 22% efficiency in some cases (and almost reach 23%!), but most photovoltaic panels available in the market are not above 20% efficiency. The top five best solar panel manufacturers in 2019 ranked based on the highest efficiency are: SunPower (22.8%), LG (22.0%), REC Solar (21.7%), CSUN (21.2%), and Panasonic (21.2%).

There are several items that solar cell researchers and manufacturers consider when designing and producing efficient solar panels such as the material (type of material like monocrystalline silicon, polycrystalline silicon, cadmium telluride, etc.) which impacts how light converts to electricity, wiring and busing which determine the organization of wires and “busbars” on a solar panel that capture and transfer electricity impacts efficiency and the reflection of light away from a solar panel.

Additionally, factors like being able to absorb light on both sides of a cell (bifacial solar panels) and being able to absorb variable wavelengths of light (multijunction solar panels) change the efficiency equation for solar panels.

3.6. Battery depth of discharge and life cycle:

DOD, or depth of discharge, is one of the concepts that needs to be understood when dealing with solar batteries. Solar batteries, also known as deep cycle batteries, use solar panels to store energy from the sun. They are commonly used to store energy for standalone solar and wind and other renewable energy systems. DOD is the amount or degree of depletion of a battery. This means that if the battery is drained fully, the depth of discharge is 100%. On the other hand, if the battery is fully charged, the DOD is 0%. DOD has a connection to the cycle life of batteries. Cycle life is the number of discharge cycles that a battery can support before it reaches 80% of its capacity. Cycle life is one of the two factors that affect battery degradation, the other one being the maximum depth of discharge.

Because DOD and the cycle life of batteries are closely linked, it is important to know that the more you fully discharge your battery, the more chances that it will degrade quickly. Similarly, the more discharge cycles that a battery undergoes, the faster it will degrade. Therefore, the maximum DOD for the cycle life of a battery matters in its overall value. It is highly advised to keep the maximum DOD of the battery at the allowable depth which is 80% to maintain the life of your deep cycle batteries.

3.7. Building-integrated photovoltaics (BIPV):

BIPV are dual-purpose as they serve both the outer layer of a structure and generate electricity. BIPV systems can provide savings in materials and electricity costs, reduce pollution, and add to the architectural appeal of a building. Though they can be added to a structure as a retrofit, the greatest value for BIPV systems is realized by including them in the initial building design. By substituting PV for standard materials during the initial construction, builders can reduce the incremental cost of PV systems and eliminate costs and design issues for separate mounting systems.

Semi-transparent thin-film PV can allow for natural day lighting and solar thermal systems can capture heat energy to generate hot water or provide space heating and cooling capacity. *Façade* PV can be integrated into the sides of buildings, replacing traditional glass windows with semi-transparent thin-film or crystalline solar panels. These surfaces have less access to direct sunlight than rooftop systems, but typically offer a larger available area. *Rooftops* PV replaces roofing material or, in some cases, the roof itself. They can be single-piece solar rooftop made with laminated glass or solar “shingles” which can be mounted in place of regular roof shingles. *Glazing* PV are ultra-thin solar cells which may be used to create semi-transparent surfaces that allow daylight to penetrate while simultaneously generating electricity. These are often used to create PV skylights or greenhouses.

3.8. Temperature impact on solar PV:

Solar panel efficiency is affected negatively with temperature increase. The panels are usually tested at 25 ℃ (STC) and depending on their location, heat can reduce the panel’s efficiency by 10-20%. There are several ways to minimize the negative effects of high temperatures:

- Install panels a few inches above the roof so that convective air flow can cool the panels.
- Ensure that the panels are constructed with light-colored materials, to reduce heat absorption.
- Move components like inverters and combiners into the shaded areas behind the panel array.

In an assessment report for the Lebanese Beirut River Solar Snake, a first medium voltage grid-integrated solar photovoltaic farm in Lebanon [20], a detailed analysis was performed to visualize the correlation between the project performance and the module temperature. A performance ratio and module temperature correlation for the project is shown in Figure 6.

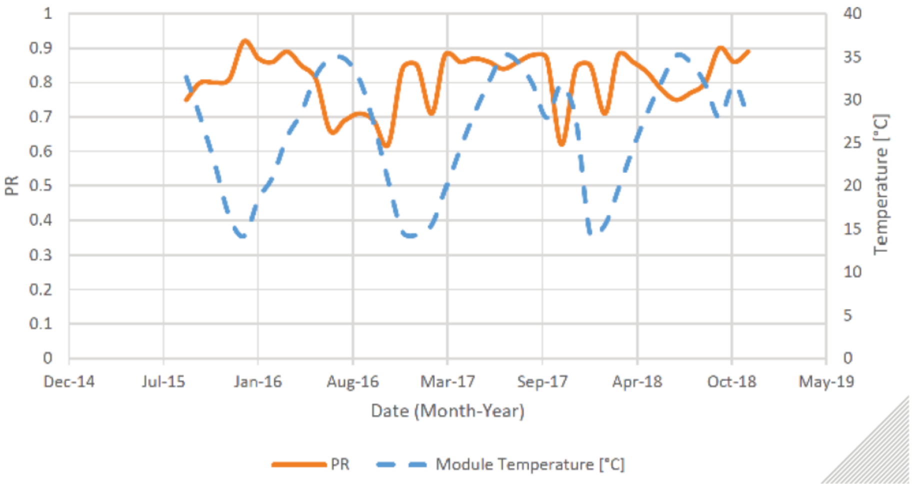


Figure 6: Performance ratio and module temperature correlation for the BRSS project

It was verified that the PR is inversely proportional to the module temperature. Assuming similar irradiation levels, thus the higher the module temperature, the lower the PR. The results aligned with the conduction bandgap theory of semiconductors, which suggests that a higher module temperature reduces the conduction bandgap and hence reduces the PV cell voltage build-up. On another hand, it was also verified in additional interpolations that the capacity factor is directly proportional to the module temperature and that the module temperature is directly proportional to the ambient temperature.

3.9. Solar PV manufacturing costs and performance:

Over the past decade, the crystalline-silicon (c-Si) photovoltaic (PV) industries have grown rapidly and developed a global supply chain driven from one hand by the increasing consumer demand and from another hand by the technical advancements in the field, thus enabling more efficient manufacturing at reduced costs [21].

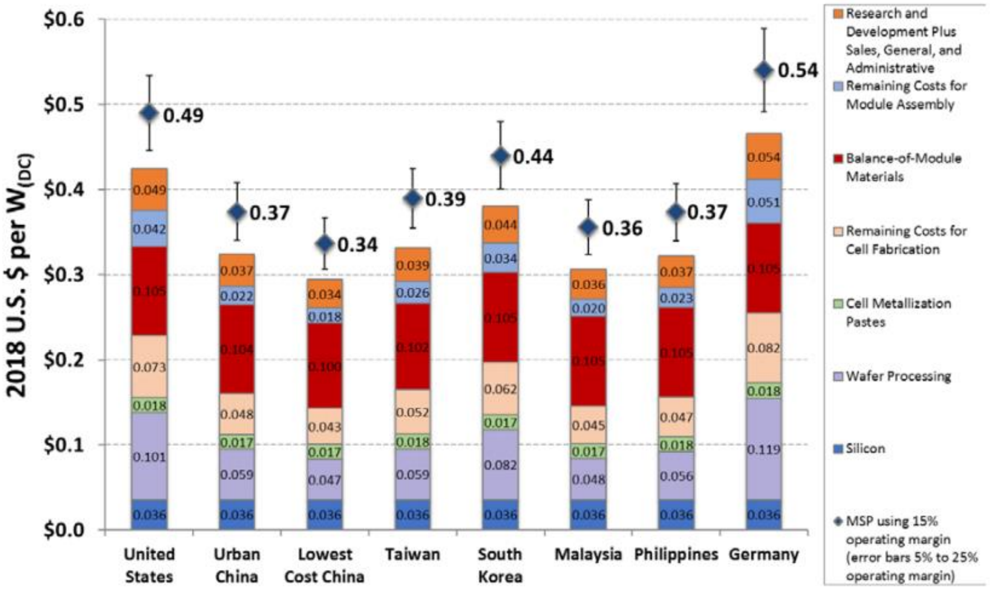


Figure 7: Benchmark 1H 2018 MSPs 60-cell monocrystalline PV in 2018 US$/W

Figure 7 depicts costs and minimum sustainable prices (MSPs) for each step in the supply chain. It can be noted how the numbers are narrowing to each other as the supply chain matures, with manufacturing in rural China resulting in the lowest MSP wafers, cells, and modules. This can be mostly attributed to the technological advancements in the manufacturing processes thus reducing labor requirements and increasing production.

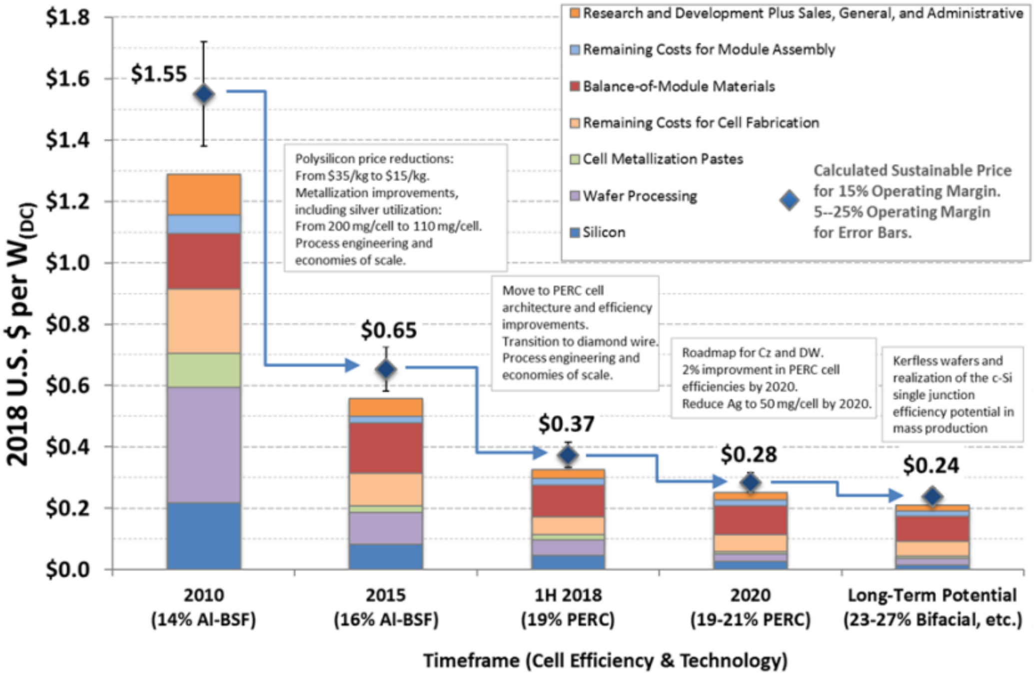


Figure 8: Benchmark and projected module pricing for long term in 2018 US$/W

Figure 8 is a cost reduction road map which illustrates how the module pricing costs are declining since 2010, yielding 0.28$/W in 2020 and projecting a 0.24$/W in the long term (2030-2040). This decline is due to thinner wafers, reduced silicon and silver utilization, and improved cell efficiencies.

3.10. Solar PV operational costs and performance:

Over the last years, the balance of system (BOS) costs has become the crucial factor for the overall system costs of photovoltaic (PV) electricity production. For PV to continue competing with other energy sources such as fossil and nuclear, electricity generation by photovoltaics is no longer preferentially limited by the PV module costs, but by the requirement for substantial further reduction of BOS costs. The PV module costs are lower than half the total investment costs for the system except for very large

PV plants. BOS costs together with the operation and maintenance costs (O&M) lead to the total plant lifetime costs, with only roughly one-third belonging to PV modules at the end [22].

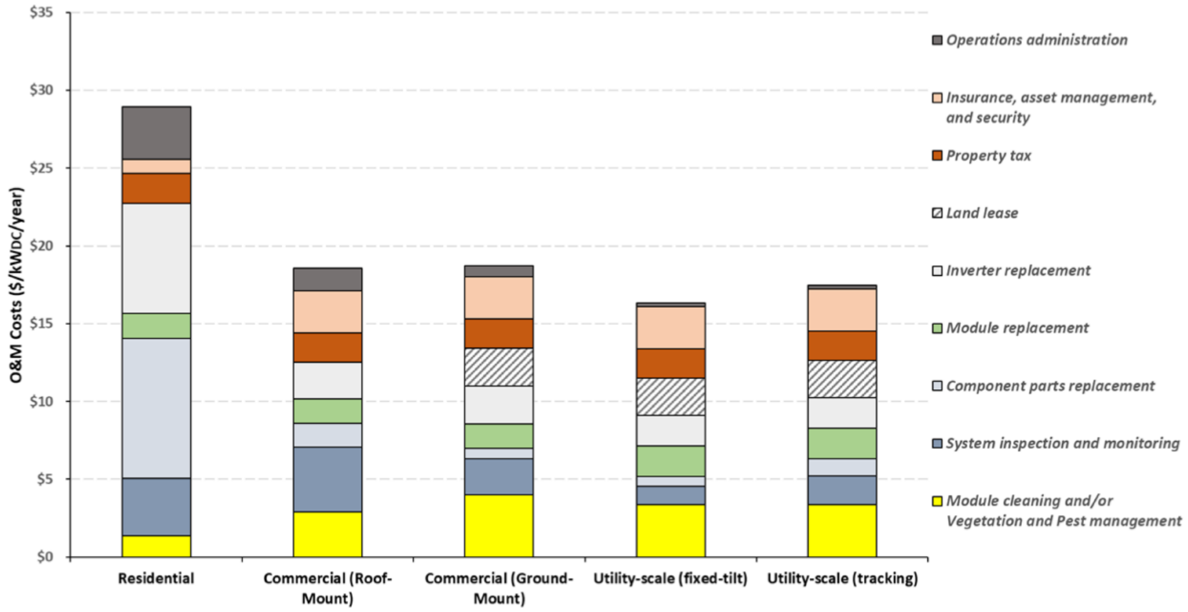


Figure 9: PV BOS structure

Figure 9 above represents the cost drives for the operation and maintenance sorted into nine O&M cost categories: inverter replacement, operations administration, module replacement, components parts replacement, system inspection and monitoring, module cleaning and/or vegetation and pest management, land lease, property tax, and insurance, asset management, and security. The current benchmarks are $28.94/kWDC/yr (residential), $18.55/kWDC/yr (commercial; roof mount), $18.71/kWDC/yr (commercial; ground mount), $16.32/kWDC/yr (utility-scale, fixed-tilt), and $17.46/kWDC/yr (utility-scale, single-axis tracking) [23]. A rough breakdown of O&M costs can be summarized by:

- Scheduled Maintenance/Cleaning.
- Unscheduled Maintenance.
- Inverter Replacement Reserve.
- Insurance, Property Taxes, Owner's Cost

The price of a system varies depending on its size, type, and capacity, as well as the grid requirements. On average, a complete 2-kW peak system installed at one's premises in Lebanon would cost between $10,000 and $12,000 [24]. Savings from installing a PV system depend on the actual size and type of the system installed, as well as what the PV system is replacing. For this same 2 kW peak system in Lebanon, if properly designed and if the peak demand loads are reduced by energy efficiency measures concurrently, then the diesel generator rent will be removed which is equal to at least $100 per month and Electricité du Liban (EDL) bills can be cut. Therefore, a saving of around $120 - $150 per month is achievable. With the weather in Lebanon, a typical 16 square meters PV system would be enough for a 2-kW peak system capacity and would produce around 8 kWh per day [24].

A complete 2-kW peak system would be able to contribute to daily savings of 5 kg of CO_2 reaching up to 47,000 kg of CO_2 over the lifetime of the PV system. The average lifetime is 25 years, but the system could live up to 30 years. The expected pay-back period for a PV system is between 5 and 8 years, depending on what is being displaced, household behavior, location, and other parameters.

3.11. FIT and net metering:

Usually, selling electricity generated through renewable energy such as solar PV is accepted under the feed-in tariff (FIT) scheme, but this is still not possible in

Lebanon. FIT sets different tariffs for renewable energy technologies at which the electricity utility would buy power from homeowners.

Net metering on another hand, only allows a quantity exchange of electricity without transfer of money. Net metering is a renewable energy incentive through which consumers can offset the cost of power drawn from the utility. This is achieved by installing a meter that records the bidirectional energy flow, allowing the excess power to be transmitted to the grid. The exported energy from the system is subtracted from the imported energy, and only the net output is calculated and priced. In Lebanon, Net Metering was launched by the Ministry of Energy and Water and adopted by EDL in 2011. A consumer can set up the operation through an agreement with EDL.

CHAPTER 4

AUB MASRI BUILDING

4.1. Description:

"Munib and Angela MASRI" building, referred here after as "MASRI" building, is located on the lower campus of AUB with an area of about 3,000 m^2. MASRI building is on the west side of Bechtel building overlooking the green field and is connected to Bechtel on various levels. The building is made up of 2 basements, 5 floors, and a roof.

The facility is mostly for offices, conference spaces and other common spaces needed by the expanding MASRI institute, in addition to other office spaces, seminar rooms, computer labs and an Engineering lecture Hall for the Faculty of Engineering and Architecture. The facility design chosen is thus an Offices building located in climate zone 1-3 (Satisfying Beirut, Lebanon location).

The 2D AutoCAD files were obtained from the Facilities Planning and Design Unit (FPDU) at the university and were used for the sketching of each floor in "Sketchup". Each floor was divided with its respective rooms and the 3D building model was then obtained with each floor on top of the other. The model was imported to "Open studio" (Software powered by the Energy Plus engine) in which all input data was identified for the energy simulation. Where applicable, built-in library of space types (loads and their associated schedules) for DOE reference buildings ASHRAE 189.1-2009, ASHRAE 90.1-2007, and ASHRAE 90.1-2010 are defined and attributed.

Figures 10-12 show the 3D building sketch and a sample section view for the inner spaces:

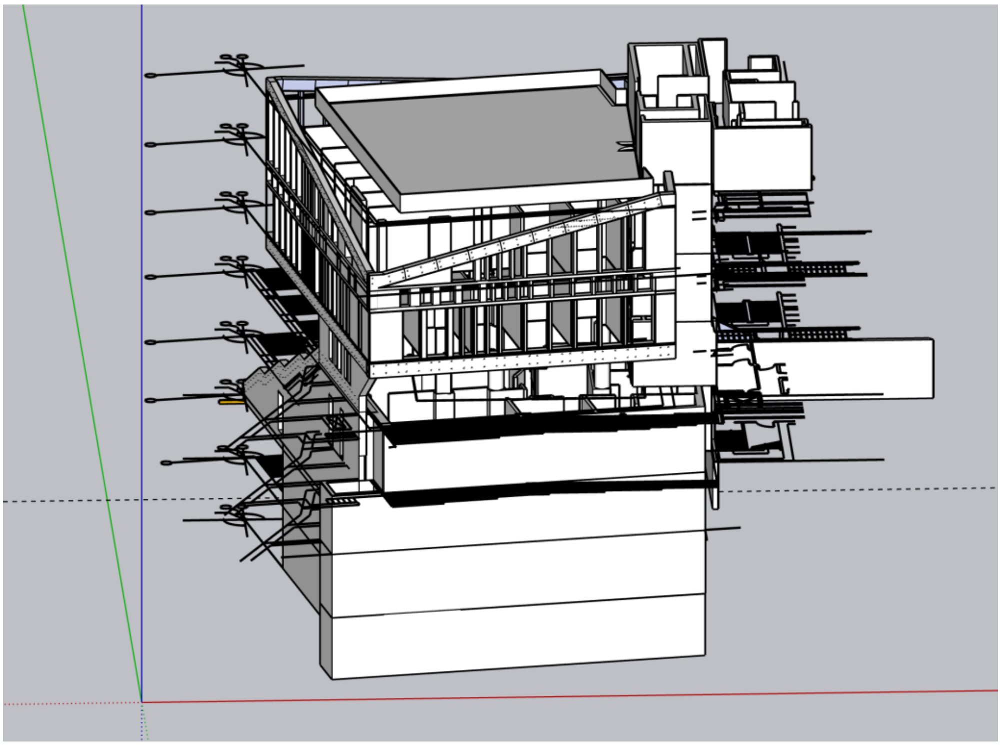


Figure 10: 3D Drawing of MASRI building (Green: North, Red: East)

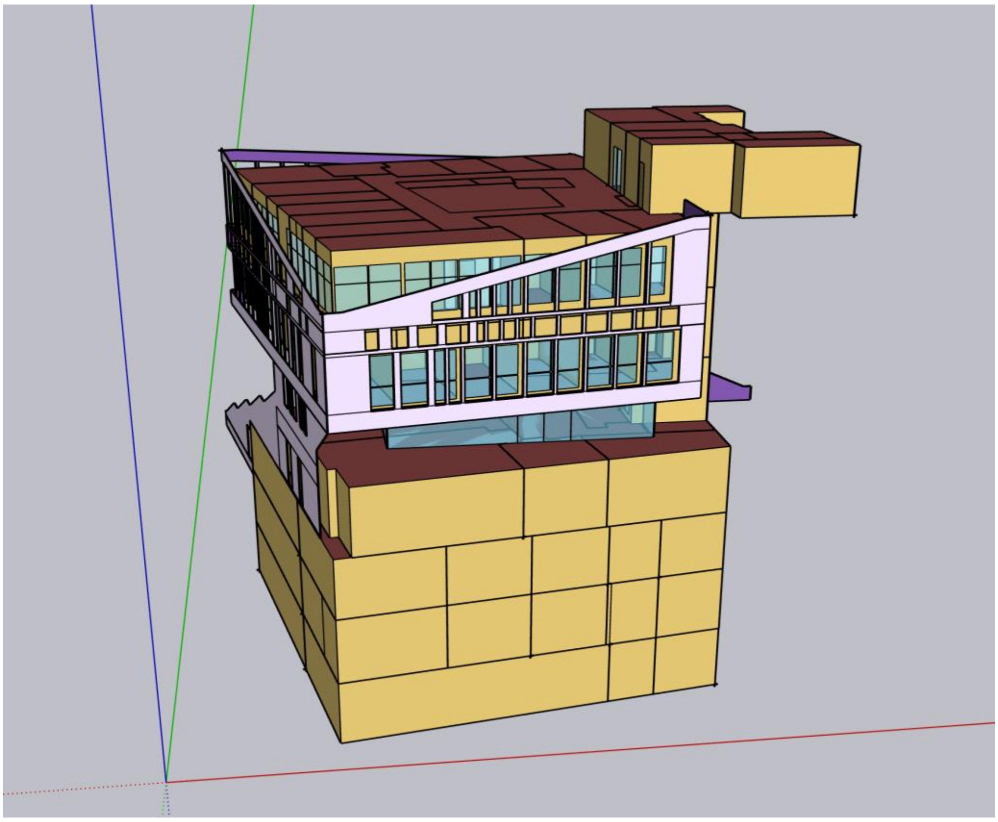


Figure 11: 3D Energy model of MASRI building (Green: North, Red: East)

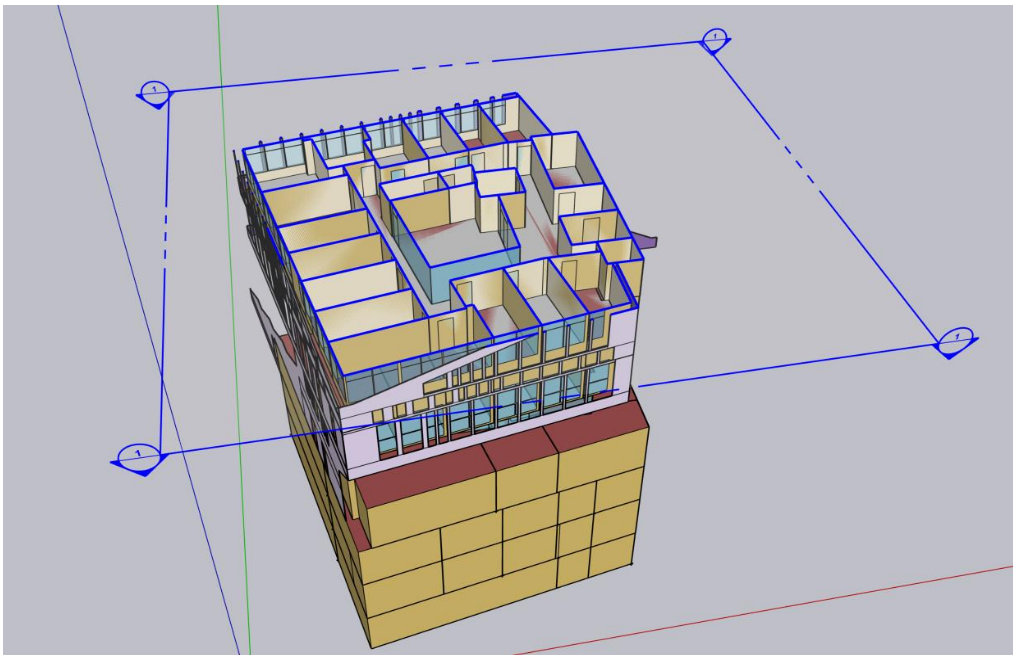


Figure 12: Sample section view for a floor (Green: North, Red: East)

4.2. Input data:

4.2.1. Weather:

Weather files for Beirut International Airport are used to simulate the best results for the location of the MASRI AUB campus building. The extension weather files used are:

- .epw: Energy Plus Weather format data during the year.
- .ddy: Design Days files for the summer and winter representing hottest and coldest days respectively during the year

4.2.2. Building Construction:

Construction sets are defined based on various material used in the construction of the building. The sets chosen are based on the provided building drawings:

- Exterior surface walls: Gypsum, insulation, and hard concrete.

- Exterior surface roof: Hard concrete, insulation, light concrete, roof membrane, and light concrete tiles.
- Interior surface walls: Light concrete cement and masonry.
- Interior surface floors: Light concrete, air space, and acoustic tiles.
- Interior surface ceilings: Gypsum, air space, and light concrete.
- Ground contact surfaces: Light concrete, air space, and gypsum.
- Fixed and Operable windows: Double glazing (Clear 6mm, air 13 mm, and clear 6 mm) with low emissivity (e2 = 0.2) with an overall rate of heat transfer (U-factor) of 1.932. The windows total area is about 400 m^2.
- Metal Glass Doors and Wood Glass Doors. The Doors total area is about 120 m^2.

4.2.3. Building Loads:

People definitions were entered as per the different rooms in which on average each office contains 1 person. In addition, for other spaces defined such as corridor, lobby, auditorium, the built-in definitions of "Openstudio" were defined as applicable ranging from 0.010764 people/m^2 for corridor to 0.538196 people/m^2 for conference rooms.

The lighting system in the building is mostly LED lights mounted mainly ceiling and recessed mounted. The lights were defined in "Openstudio" as per the electrical drawings obtained from the FPDU and they were attributed to the spaces accordingly. The lighting wattages vary between 6 W and 50 W.

Electric Equipment definitions for the spaces used are those built-in definitions of "Openstudio" were defined as applicable. The values vary between 0.753474 W/m^2 for the lobby and 30.031310 W/m^2 for the print rooms. The elevator uses around 2080 W according to its respective specifications.

4.2.4. Thermal zones:

Thermal zones are defined in Table 4 based on the types of spaces and their location.

Table 4: Defined thermal zones and associated spaces

Building Story	No. of Thermal Zones	Associated Spaces for the Thermal Zones
Basement 2	1	ELH storage
	1	Remaining rooms in story
Basement 1	1	Computer Lab
	1	Electrical
	1	Storage
	1	Mechanical
	1	Main DER
	1	3 WC
	1	Corridor, Elevator, Lobby, Stairs
Floor 1	1	Electrical, Janitor
	1	ELH Auditorium
	1	Remaining rooms in story
Floor 2	7	Offices
	1	Storage
	2	Seminar
	1	3 WC
	1	Electrical
	1	Corridor, Elevator, Lobby, Stairs
Floor 3	8	Offices
	1	Electrical
	1	WC
	1	Corridor, Elevator, Lobby, Stairs
Floor 4	16	Offices
	1	Meeting
	1	Photocopy
	1	Storage
	1	Electrical
	1	WC
	1	Corridor, Elevator, Lobby, Stairs
Floor 5	15	Offices
	1	Meeting
	1	Photocopy
	1	Storage
	1	Electrical
	1	WC
	1	Corridor, Elevator, Lobby, Stairs
Roof	1	Preparation Area
	1	Electrical
	1	WC
	1	Corridor, Elevator, Lobby, Stairs
Total No. of defined thermal zones	**83**	

4.2.5. HVAC:

The following loops are defined based on the built mechanical drawings of the building. Sizing parameters are entered according to the available data drawings and auto-sizing (Which bases parameters based on their performance for the design days) is selected for unreachable data:

- Air Handling Units (AHUs): In total, 11 AHUs are defined. Each AHU has an outdoor air system, cooling water coil, heating water coil, and a variable volume fan. The coils are linked to the chiller water loop and hot water loop. The loop has outlet diffusers to simulate the outlet air provided to each concerned zone.
- Fan Coil Units (FCUs): In total, 69 FCUs are deployed. The FCUs are added as Zone Equipment in which one can attribute this component to the associated zone. The FCU has a fan, a cooling water coil, and a heating water coil. The coils are linked to the chiller water loop and hot water loop.
- Chilled water and condenser water loops: In total, 1 chilled water loop and 1 condenser water loop are defined. The loop has an absorption chiller and 1 variable speed pump. The absorption chiller is connected to a condenser water loop. The chiller is powered by steam. AUB uses a central steam powered chiller located at Hostler center which provided cold water for more than 5 buildings in the campus. The parameters for the chiller and condenser (Such as nominal capacity, nominal power, ...) are chosen to be auto sized by the software.
- Hot water loop: In total, 1 hot water loop is defined. The loop has a boiler and 1 variable speed pump. All water-heating coils are then connected to the loop. The boiler uses Diesel fuel. AUB has 3 steam boilers with 15 tons/hour each

maximum capacity. The boilers provide steam for several buildings in the campus. The parameters for the boiler (Such as nominal capacity, …) are then chosen to be auto sized by the software.

- Roof Split Units: In total, 2 split units are defined. Each split unit has an outdoor air system, single speed cooling coil, single speed heating coil, and a cycling fan. The loop also has an outlet diffuser to simulate the outlet air provided to the concerned zone.

4.3. Schedule inputs and consumption:

The schedule operation input is based on the understanding of the building actual schedule operation during different days of the year, also considering that the building is an office building with one conference room.

- For the Conference Room: 2 days per week are selected with a usage of around 2 hours in the morning and 3 hours in the afternoon.
- For the elevator: An operation during the day from 8 am till 8 pm during weekdays and 8 am till 2 pm during Saturdays.
- For the offices: Operation schedule from 8 am till 6 pm during weekdays, 8 am till 2 pm during Saturdays, and 8 am till 12 pm during Sundays. Saturdays and Sundays are portioned due to less office's usage during the weekends.
- For the roof: An operation of about 4 hours during weekdays in the Summer only.
- The HVAC cooling and heating setpoints are selected as:

  For the storage, electrical, and mechanical rooms, and basements: Average of 24 ℃ for cooling and 19 ℃ for heating during all times.

For the offices, corridors, and lobbies: Average of 22 ℃ for cooling and 21 ℃ for heating during all times.

Inputting the above data in the software and simulating for a period of 1 year yields the following results:

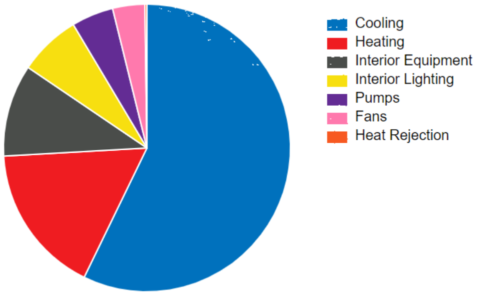


Figure 13: Energy consumption end use pie chart (Illustration only with no figures)

We can see from Figure 13 that about 75% of the energy consumption is attributed to the HVAC system specifically a large portion of steam consumption for cooling and diesel consumption for heating. The rest of the energy is attributed to the electricity consumption in the building which is divided between electrical equipment, lights, fans, and pumps. The simulation numerical data for each month are indicated in the following table:

Table 5: Consumption (kWh) and peak demand (kW) per month

MONTH	**Electricity Peak Demand (kW)**	**CONSUMPTION (KWH)**			
		Electricity	**Diesel for Boiler**	**Steam for Chiller**	**TOTAL**
JANUARY	55	14890	36162	Cooling turned Off	**51051**
FEBRUARY	54	13653	28592		**42245**
MARCH	55	15778	25272		**41050**
APRIL	60	17748	Heating turned Off	19187	**36935**
MAY	62	20340		41030	**61370**

JUNE	65	20384		73203	**93587**
JULY	67	21163		119025	**140187**
AUGUST	66	22086		114210	**136296**
SEPTEMBER	65	20523		92480	**113003**
OCTOBER	55	16787	3869	Cooling turned Off	**20657**
NOVEMBER	56	15857	16483		**32340**
DECEMBER	55	14685	26408		**41094**
TOTAL		**213894**	**136786**	**459135**	**809815**

The monthly variations for the concerned data are shown in Figures 14-16:

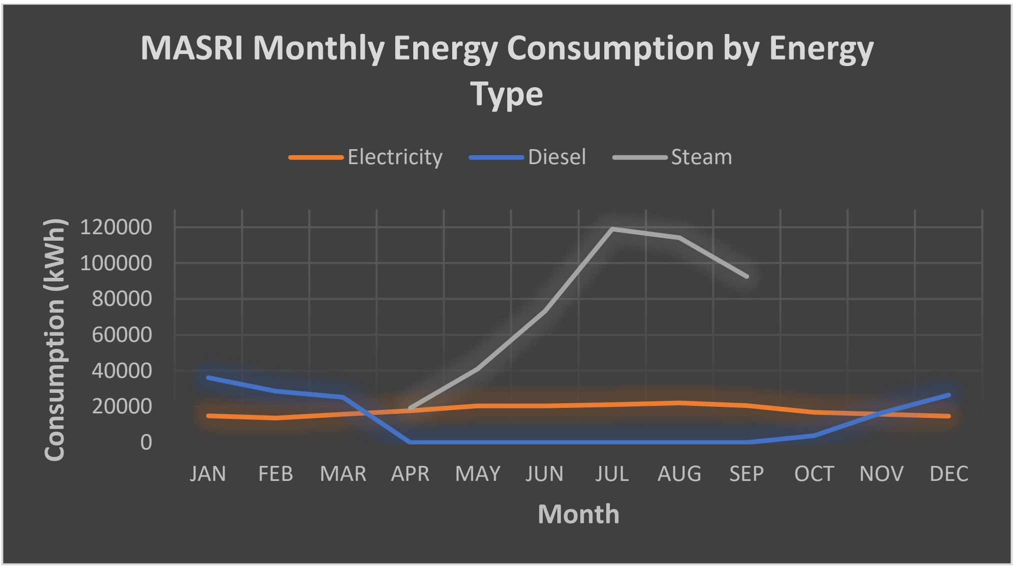


Figure 14: Monthly consumption (kWh)

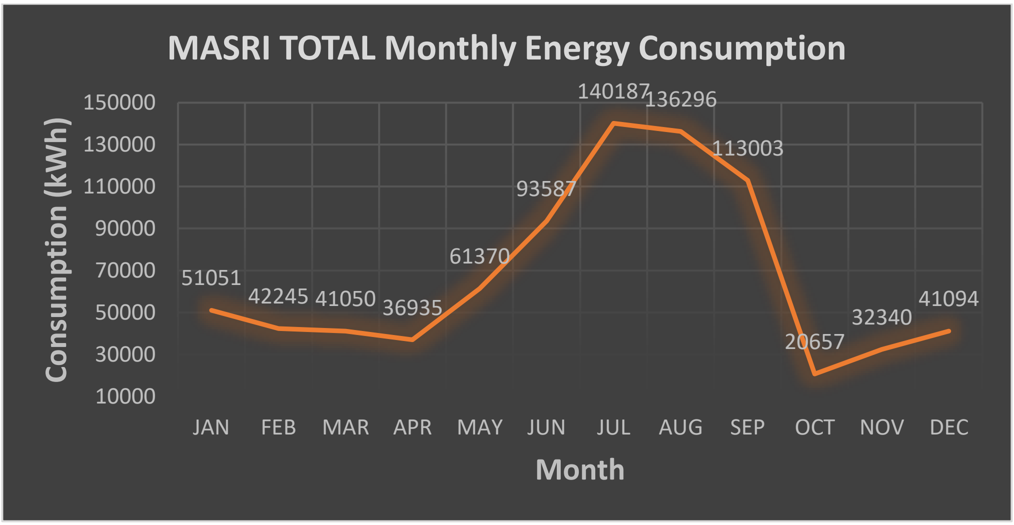


Figure 15: Monthly total consumption (kWh)

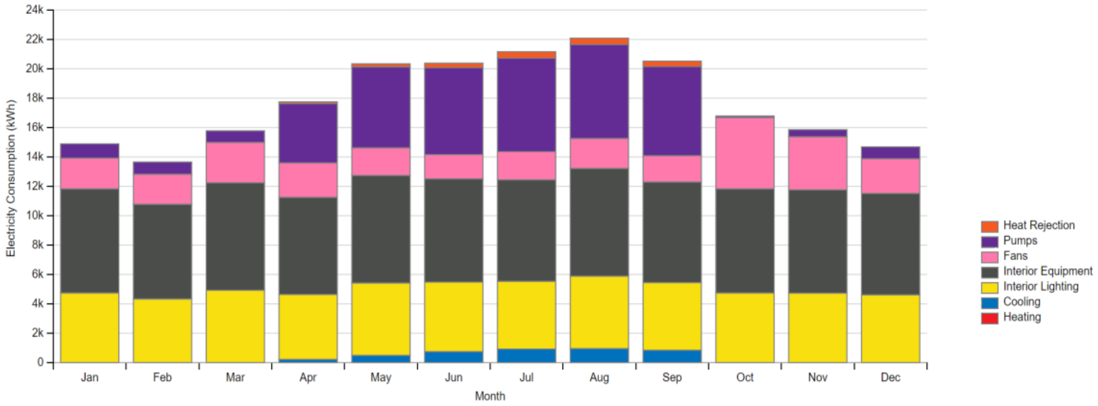


Figure 16: Electricity consumption distribution (kWh) per month for the full year

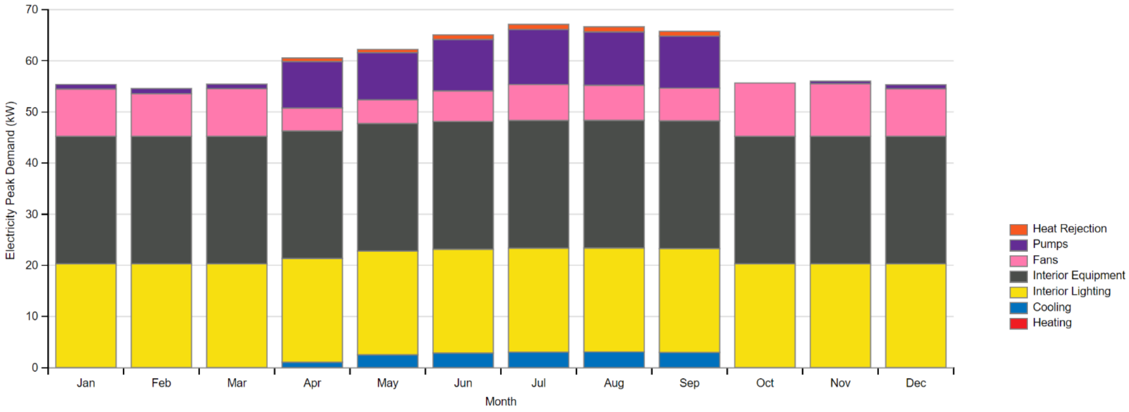


Figure 17: Electricity peak demand distribution (kW) per month for the full year

4.4. Comparing with actual benchmark:

The available actual consumption report provided consists of the consumption by hour in (kWh) from July 2, 2019, till December 31, 2019. It was preferrable to obtain data prior to 2020 considering the COVID-19 outbreak and its implications on the building usage parameters. The report contains 6 columns defined to be the Total consumption (kWh), Occupied consumption (kWh), Unoccupied consumption (kWh), Max Demand (kW), Min Demand (kW), and Average Demand (kW). All data are reported per hour of the day. Summing the data per hour for the consumption to calculate the consumption per month, the following table and its attributed variation are obtained:

Table 6: Actual consumption data (July-December 2019 in kWh)

Month	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
Occupied	9,779	9,593	10,090	10,256	8,977	8,453	57,148
Unoccupied	10,093	9,909	9,570	10,440	8,721	8,160	56,893
Total	19,872	19,502	19,660	20,696	17,698	16,613	**114,041**

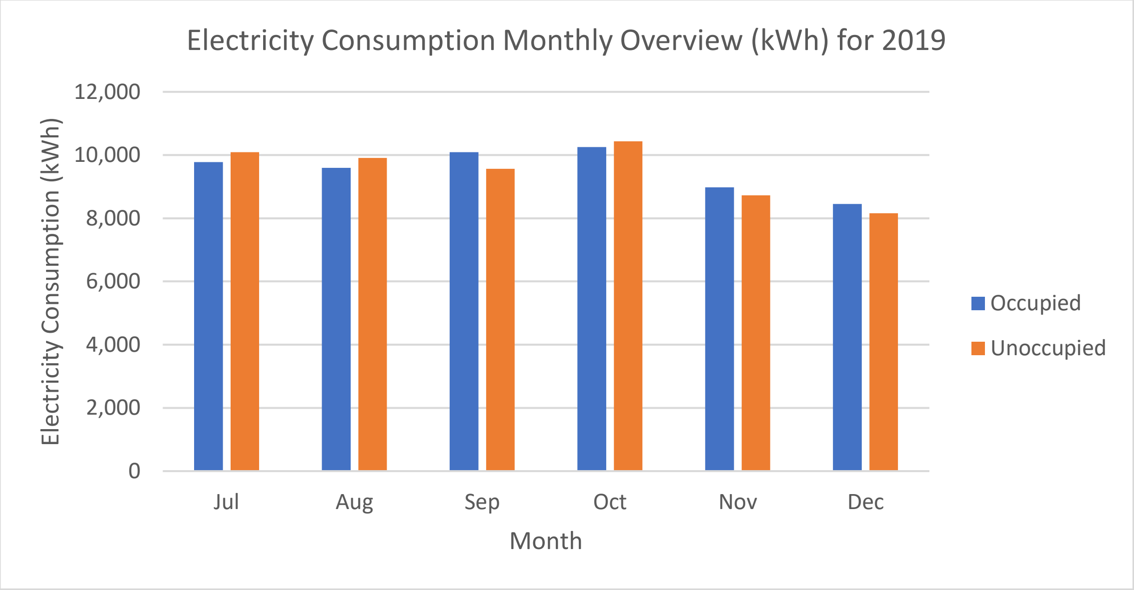


Figure 18: Actual consumption data (July-December 2019 in kWh)

Occupancy hours of the building range between 8 am till 6 pm during weekdays and some morning hours during the weekends. Actual data indicates that energy consumption is almost the same during occupied hours and unoccupied hours. It is therefore vital to consider application of energy conservation measures to reduce consumption during unoccupied hours of the building.

The total actual consumption from July till December 2019 is: **114,041 kWh (114 MWh).**

For a full year estimation, the data becomes: 2 * 114,041 = **228,082 kWh/year (228 MWh).**

The simulated data for the full year in section 4.3 is: **213,894 kWh/year (214 MWh).**

Thus, the simulated data shows values close to the estimated actual ones with a small deviation of: $\frac{|213894-228082|}{228082} * 100 = \mathbf{6.22}\ \%$

The actual demand from July till December 2019 ranges between **52 kW and 57 kW.**

The simulated data demand for the full year (Specifically taking July to December) in section 4.3 ranges between **55 kW and 67 kW,** which also indicates acceptable values and data range.

The simulation is considered acceptable and will be used for base mark for the implementation of energy conservation measures.

4.5. Applied energy conservation measures to the base simulation:

4.5.1. Reducing electric equipment load at night:

This measure proposes the reduction of the electric equipment load at night by about 10% of its normal value through disconnecting the electric equipment from the supply. Electric equipment includes PCs, screens, printers, machines, … Through simulation, such reduction reduces the energy consumption by _8.085_MWh per year, thus from _809.815_MWh to _801.730_MWh, around **_1_%** of total energy consumption during the year.

4.5.2. Personal desk fans and cooling HVAC setpoints modification:

This measure proposes providing small personal desk fans. The fans are hands free personal ventilation system, offering an array of options such as battery operated and running as a USB. These fans are to be used in all offices and will thus serve to reduce the cooling energy consumption by modifying the HVAC setpoint. These desk fans are portable, quiet, and can be chosen on different speed levels. Through simulation for using the fans for 5 hours per day during summer and simultaneously modifying (increasing) the HVAC setpoints by 1.5 ℃, the energy consumption is reduced by _9.073_MWh per year, thus from _809.815_MWh to _800.742_MWh, around **_1.12_%** of total energy consumption.

4.5.3. Upgrading the lighting system:

All the lighting system installed in the building are of modern LED type which are known for their low energy consumption. This measure details the substitution of the installed 50W LED lights only with 37W LED lights providing the same luminaire brightness and comfort color. Through simulation, replacing the lighting with current efficient and high technology lighting reduces the energy consumption by _15.497_MWh per year, thus from _809.815_MWh to _794.318_MWh, around **_1.9_%** of total energy consumption during the year.

4.5.4. Triple glazed windows:

This measure encounters replacing the currently installed double glazed windows by Triple glazed ones (Clear 3mm, air 13 mm, clear 3 mm, air 13 mm, clear 3 mm) with low emissivity (e2 = 0.1) with an overall rate of heat transfer (U-factor) of

1.265. The analysis is done for all installed windows on the three directions (South, West, and North). Through simulation, replacing the windows reduces the energy consumption by _20.396_MWh per year, thus from _809.815_MWh to _789.419_MWh, around **_2.5_%** of total energy consumption during the year.

4.5.5. Modifying HVAC setpoints:

One of the two cases below can be chosen:

Case 1: This measure encounters modifying the HVAC setpoints by 0.5 ℃ each without introducing table fans. Thus, increasing cooling setpoints by 0.5 ℃ and decreasing heating setpoints by 0.5 ℃. The analysis is done for all AHUs and FCUs installed. Through simulation, this measure reduces the energy consumption by _27.051_MWh per year, thus from _809.815_MWh to _782.764_MWh, around **_3.3_%** of total energy consumption during the year.

Case 2: This measure encounters modifying the HVAC setpoints by 1 ℃ each without introducing table fans. Thus, increasing cooling setpoints by 1 ℃ and decreasing heating setpoints by 1 ℃. The analysis is done for all AHUs and FCUs installed. Through simulation, this measure reduces the energy consumption by _45.260_MWh per year, thus from _809.815_MWh to _764.555_MWh, around **_5.5_%** of total energy consumption during the year.

4.5.6. Turing the HVAC off during unoccupancy:

This measure aims at switching off the HVAC system during the majority time of the unoccupied hours, modeled to be from 8:30 pm till 6:30 am for the whole building. For the cooling period (April till September), windows can be open for natural ventilation of the building during this time where the HVAC is switched off. This is because the space is not occupied, and comfort and air quality are of no importance. Through simulation, this measure reduces the energy consumption by _126.241_MWh per year, thus from _809.815_MWh to _683.574_MWh, around **_15.5_%** of total energy consumption during the year.

4.6. Summary of results:

Figures 19 and 20 show the total simulated building energy consumption for the base case model (First column) and the remaining six samples after implementing the conservation measures previously mentioned on separate basis. Measure 5 for the HVAC setpoints modification is considered in both cases (Case 1: 0.5 ℃ in Figure 19 and Case 2: 1 ℃ in Figure 20).

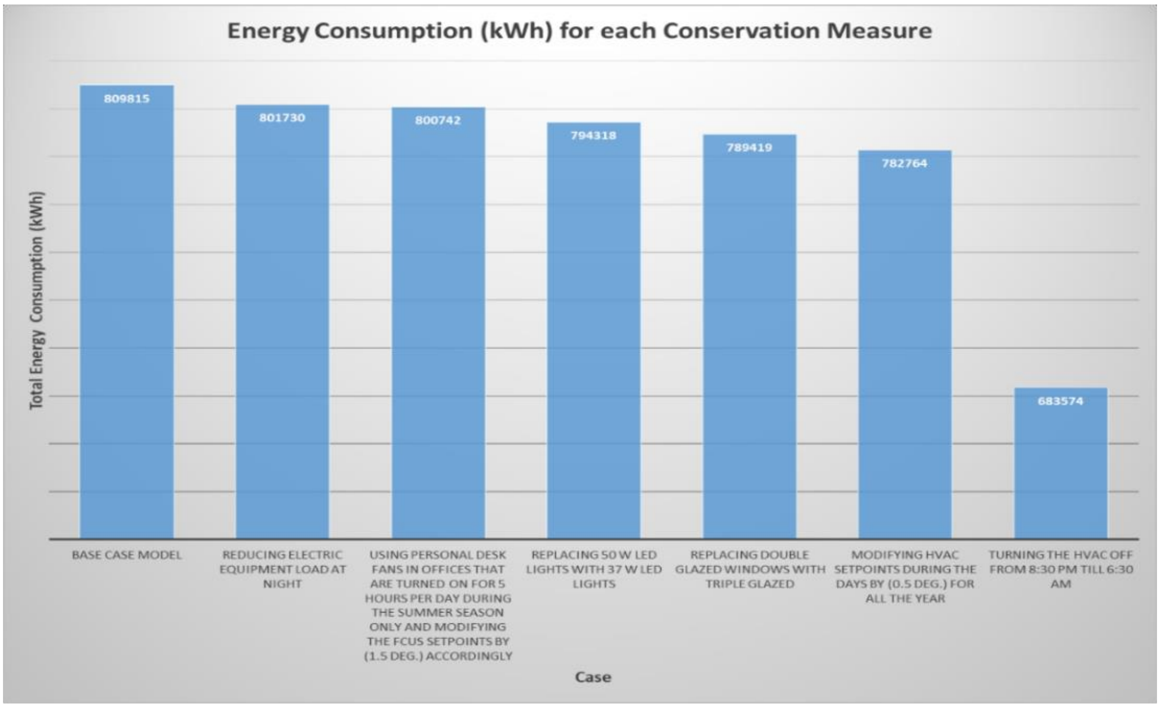


Figure 19: Energy consumption for each conservation measure (Case 1)

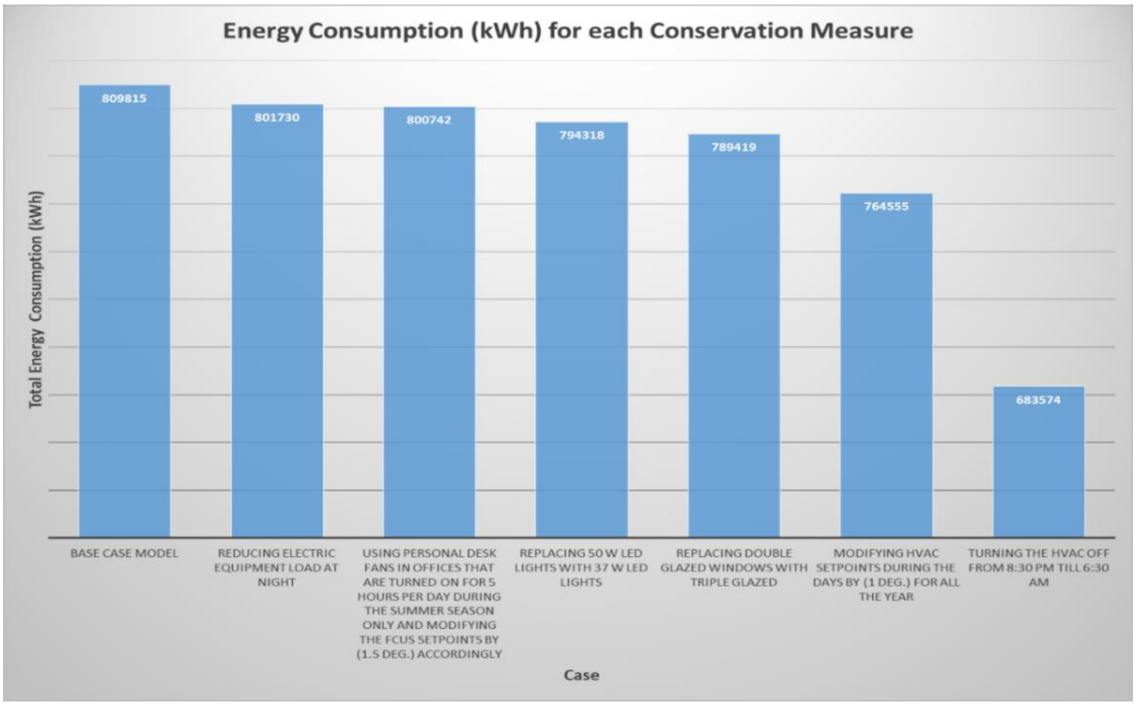


Figure 20: Energy consumption for each conservation measure (Case 2)

A similar study was done on an existing eight-story building located in Beirut, Lebanon in which zero and low-cost energy saving measures were assessed [25]. The first measure in the reference study concerned raising temperature comfort settings (23 ℃ to 24 ℃) with applied conditions which resulted in an overall energy consumption savings of 3.4%. This Thesis applied a measure of HVAC setpoints modification (Measure no. 5 with case 1 of 0.5 ℃ and case 2 of 1 ℃). The overall energy consumption savings ranged between 3.3%-5.5%. Comparing both results, the results of this Thesis study are reasonably similar to those of the reference study.

4.6.1. Feasibility of the measures:

According to the ministry of Energy and Water, the levelized cost of production for combined cycle gas turbine for diesel is about 21 Cents/kWh and the electricity is sold from Electricity of Lebanon (EDL) at an average of 11 Cents/kWh. These values will be used to compare the feasibility of the measures. The dollar rate of LL1500/1USD is considered in the analysis.

No cost is attributed for disconnecting the electric equipment at night, turning off the HVAC system, and modifying the cooling/heating setpoints. Thus, the cost of the kWh saved is zero and requires only behavioral and equipment parameters adjustments.

For the Personal desk fans, the cost of a single fan is through online sellers is about 15 $. Considering buying a fan for each office, we will need around 56 fans, thus a cost of around 840 $. The fan is rated at around 35 W and for using the fans for 5 hours per day during summer, thus an average daily consumption of _9.8_ kWh is estimated. Simultaneously modifying the HVAC setpoints by 1.5 ℃ and adding the fans consumption data in the simulation, the net energy consumption saved is around 9073 kWh (9 MWh). The cost of the kWh saved for this measure is thus:

$$Cost\ of\ kWh\ saved_{fans} = \frac{ReplacementCost}{kWh\ saved} = \frac{840\ \$}{9073\ kWh} = \mathbf{0.09}\ \$/\boldsymbol{kWh}$$

For the lighting system replacements, a local supplier “Debbas” was contacted to understand the market cost and quote different installed lightings in the building. The cost of a 37 W LED recessed panel lamp assembly to replace the current 50 W LED assembly is 68.5 $ per set. The cost of the currently installed 50 W LED assembly lighting in new condition is about 178 $ per set, we can then estimate the cost of the assembly in its current condition in the building to be almost 25% of the new cost so about 44.5 \$ per set. For a total quantity of 350 of these installed lighting in the building, the attributed replacement cost will thus be: (68.5-44.5) \$ * 350 = 8,400 \$. The cost of the kWh saved for this measure is thus:

$$Cost\ of\ kWh\ saved = \frac{ReplacementCost}{kWh\ saved} = \frac{8{,}400\ \$}{15497\ kWh} = \mathbf{0.54}\ \$/\boldsymbol{kWh}$$

This measure has a high cost and therefore will be ranked very low or even rejected.

The market cost of a triple glazed window for an area of 1 m^2 with its aluminum chassis is about 300 \$. The building has an area of 423 m^2 of fenestration, an estimate cost of the new equipment is thus: 300 \$/m^2 X 423 m^2 = 126,900 \$. The market cost of the current installed double-glazed window for an area of 1 m^2 with its aluminum chassis is about 100 \$ in new condition. The cost of the assembly in its current condition in the building is then around half this price, so 50 \$ per m^2. The total cost of the double-glazed windows in their current condition is 50 \$ * 423 = 21,150 \$. The replacement cost will thus be: 126,900 – 21150 = 105,750 \$.

The cost of the kWh saved for this measure is thus:

$$Cost\ of\ kWh\ saved = \frac{ReplacementCost}{kWh\ saved} = \frac{105{,}750\ \$}{20396\ kWh} = \mathbf{5.18}\ \$/\boldsymbol{kWh}$$

This measure will also be ranked very low or even rejected.

4.6.2. Weighted average costs:

Four scenarios will be considered for the approach as per the following summary table. The weight of each cost is interpolated based on its percentage energy reduction and is converted to a total sum of 100.

Table 7: Summary table for the four different scenarios

Scenario	**Low ranked measures**		**Modifying HVAC setpoint measure by**	
	With	**Without**	**0.5 ℃**	**1 ℃**
1	X		X	
2		X	X	
3	X			X
4		X		X

<u>Scenario 1 (With low ranked measures and considering 0.5 ℃ for the HVAC setpoint measure):</u>

$$Total\ \%\ Energy\ Reduction = \%Reduction_{Windows} + \%Reduction_{lighting} + \%Reduction_{Fans} + \%Reduction_{ElectricEquipment} + \%Reduction_{HVAC(0.5℃)} + \%Reduction_{HVAC\ Off} = 2.5 + 1.9 + 1.12 + 1 + 3.3 + 15.58 = 25.48\%$$

For the windows:

$$Weight_{Windows} = \%\ Energy\ Redution_{Windows} * \frac{100}{\%\ Energy\ Reduction_{Total}}$$

$$= 2.5 * \frac{100}{25.48} = 9.9$$

For the lighting:

$$Weight_{Lighting} = \%\ Energy\ Redution_{Lighting} * \frac{100}{\%\ Energy\ Reduction_{Total}}$$

$$= 1.9 * \frac{100}{25.48} = 7.5$$

For the personal desk fans-cooling setpoint modification:

$$Weight_{fans} = \%\ Energy\ Redution_{fans} * \frac{100}{\%\ Energy\ Reduction_{Total}}$$

$$= 1.12 * \frac{100}{25.48} = 4.4$$

For reducing electric equipment:

$$Weight_{EE} = \%\ Energy\ Redution_{EE} * \frac{100}{\%\ Energy\ Reduction_{Total}} = 1 * \frac{100}{25.48} = 3.9$$

For modifying HVAC setpoints:

$$Weight_{Setpoints} = \%\ Energy\ Redution_{Setpoints} * \frac{100}{\%\ Energy\ Reduction_{Total}}$$

$$= 3.3 * \frac{100}{25.48} = 13.1$$

For turning the HVAC off:

$$Weight_{Off} = \%\ Energy\ Redution_{Off} * \frac{100}{\%\ Energy\ Reduction_{Total}}$$

$$= 15.58 * \frac{100}{25.48} = 61.2$$

Sum of weight and costs is:

$$\begin{aligned} Sum = {} & (Weight_{Windows} * Cost\ of\ kWh\ saved_{Windows}) \\ & + \left(Weight_{Lighting} * Cost\ of\ kWh\ saved_{Lighting}\right) \\ & + \left(Weight_{fans} * \ Cost\ of\ kWh\ saved_{fans}\right) + (Weight_{EE} * 0) \\ & + \left(Weight_{Setpoints} * 0\right) + \left(Weight_{Off} * 0\right) = \ 55.73\ \$ \end{aligned}$$

The weighted average cost per kWh saved becomes:

$$\boldsymbol{Cost_{WA}\ of\ KWh\ saved = \frac{Sum}{100} = \frac{55.73\ \$}{100} = 0.557\ \$/kWh}$$

<u>Scenario 2 (Without low ranked measures and considering 0.5 ℃ for the HVAC setpoint measure):</u>

$$\begin{aligned}
&Total\ \%\ Energy\ Reduction \\
&\quad = \%Reduction_{Fans} + \%Reduction_{ElectricEquipment} \\
&\quad + \%Reduction_{HVAC(0.5℃)} + \%Reduction_{HVAC\ Off} \\
&\quad = 1.12 + 1 + 3.3 + 15.58 = 21.05\%
\end{aligned}$$

For the personal desk fans-cooling setpoint modification:

$$Weight_{fans} = \%\ Energy\ Redution_{fans} * \frac{100}{\%\ Energy\ Reduction_{Total}}$$

$$= 1.12 * \frac{100}{21.05} = 5.32$$

For reducing electric equipment:

$$Weight_{EE} = \%\ Energy\ Redution_{EE} * \frac{100}{\%\ Energy\ Reduction_{Total}} = 1 * \frac{100}{21.05}$$

$$= 4.74$$

For modifying HVAC setpoints:

$$Weight_{Setpoints} = \%\ Energy\ Redution_{Setpoints} * \frac{100}{\%\ Energy\ Reduction_{Total}}$$

$$= 3.3 * \frac{100}{21.05} = 15.87$$

For turning the HVAC off:

$$Weight_{Off} = \%\ Energy\ Redution_{Off} * \frac{100}{\%\ Energy\ Reduction_{Total}}$$

$$= 15.58 * \frac{100}{21.05} = 74.06$$

Sum of weight and costs is:

$$Sum = \left(Weight_{fans} *\ Cost\ of\ kWh\ saved_{fans}\right) + (Weight_{EE} * 0)$$
$$+ \left(Weight_{Setpoints} * 0\right) + \left(Weight_{Off} * 0\right) = \ 0.49\ \$$$

The weighted average cost per kWh saved becomes:

$$\boldsymbol{Cost_{WA}\ of\ KWh\ saved = \frac{Sum}{100} = \frac{0.49\ \$}{100} = 0.0049\ \$/kWh}$$

<u>Scenario 3 (With low ranked measures and considering 1 °C for the HVAC setpoint measure):</u>

$$Total\ \%\ Energy\ Reduction$$
$$= \%Reduction_{Windows} + \%Reduction_{lighting} + \%Reduction_{Fans}$$
$$+ \%Reduction_{ElectricEquipment} + \%Reduction_{HVAC(1°C)}$$
$$+ \%Reduction_{HVAC\ Off} = 2.5 + 1.9 + 1.12 + 1 + 5.5 + 15.58$$
$$= 27.73\%$$

For the windows:

$$Weight_{Windows} = \%\ Energy\ Redution_{Windows} * \frac{100}{\%\ Energy\ Reduction_{Total}}$$

$$= 2.5 * \frac{100}{27.73} = 9.1$$

For the lighting:

$$Weight_{Lighting} = \%\ Energy\ Redution_{Lighting} * \frac{100}{\%\ Energy\ Reduction_{Total}}$$

$$= 1.9 * \frac{100}{27.73} = 6.9$$

For the personal desk fans-cooling setpoint modification:

$$Weight_{fans} = \%\ Energy\ Redution_{fans} * \frac{100}{\%\ Energy\ Reduction_{Total}}$$

$$= 1.12 * \frac{100}{27.73} = 4$$

For reducing electric equipment:

$$Weight_{EE} = \%\ Energy\ Redution_{EE} * \frac{100}{\%\ Energy\ Reduction_{Total}} = 1 * \frac{100}{27.73} = 3.6$$

For modifying HVAC setpoints:

$$Weight_{Setpoints} = \%\ Energy\ Redution_{Setpoints} * \frac{100}{\%\ Energy\ Reduction_{Total}}$$

$$= 5.5 * \frac{100}{27.73} = 20.2$$

For turning the HVAC off:

$$Weight_{Off} = \%\ Energy\ Redution_{Off} * \frac{100}{\%\ Energy\ Reduction_{Total}}$$

$$= 15.58 * \frac{100}{27.73} = 56.2$$

Sum of weight and costs is:

$$\begin{aligned} Sum = {} & (Weight_{Windows} * Cost\ of\ kWh\ saved_{Windows}) \\ & + \left(Weight_{Lighting} * Cost\ of\ kWh\ saved_{Lighting}\right) \\ & + \left(Weight_{fans} *\ Cost\ of\ kWh\ saved_{fans}\right) + (Weight_{EE} * 0) \\ & + \left(Weight_{Setpoints} * 0\right) + \left(Weight_{Off} * 0\right) =\ 51.21\ \$/kWh \end{aligned}$$

The weighted average cost per kWh saved becomes:

$$\boldsymbol{Cost_{WA}\ of\ KWh\ saved = \frac{Sum}{100} = \frac{51.21\ \$}{100} = 0.512\ \$/kWh}$$

<u>Scenario 4 (Without low ranked measures and considering 1 ℃ for the HVAC setpoint measure):</u>

$$\begin{aligned} & Total\ \%\ Energy\ Reduction \\ & \quad = \%Reduction_{Fans} + \%Reduction_{ElectricEquipment} \\ & \quad + \%Reduction_{HVAC(0.5℃)} + \%Reduction_{HVAC\ Off} \\ & \quad = 1.12 + 1 + 5.5 + 15.58 = 23.29\% \end{aligned}$$

For the personal desk fans-cooling setpoint modification:

$$Weight_{fans} = \%\ Energy\ Redution_{fans} * \frac{100}{\%\ Energy\ Reduction_{Total}}$$

$$= 1.12 * \frac{100}{23.29} = 4.8$$

For reducing electric equipment:

$$Weight_{EE} = \%\ Energy\ Redution_{EE} * \frac{100}{\%\ Energy\ Reduction_{Total}} = 1 * \frac{100}{23.29}$$

$$= 4.28$$

For modifying HVAC setpoints:

$$Weight_{Setpoints} = \%\ Energy\ Redution_{Setpoints} * \frac{100}{\%\ Energy\ Reduction_{Total}}$$

$$= 5.5 * \frac{100}{23.29} = 23.99$$

For turning the HVAC off:

$$Weight_{Off} = \%\ Energy\ Redution_{Off} * \frac{100}{\%\ Energy\ Reduction_{Total}}$$

$$= 15.58 * \frac{100}{23.29} = 66.91$$

Sum of weight and costs is:

$$Sum = \left(Weight_{fans} *\ Cost\ of\ kWh\ saved_{fans}\right) + (Weight_{EE} * 0)$$

$$+ \left(Weight_{Setpoints} * 0\right) + \left(Weight_{Off} * 0\right) = 0.45\ \$/kWh$$

The weighted average cost per kWh saved becomes:

$$\boldsymbol{Cost_{WA}\ of\ KWh\ saved = \frac{Sum}{100} = \frac{0.45\ \$}{100} = 0.0045\ \$/kWh}$$

4.7. Analysis of results:

4.7.1. Savings:

For the Windows, the annual saved energy costs are:

$$SavedCost_{Windows} = 0.11\frac{\$}{kWh} * \left(kWh_{Electricity\ saved}\right) + 0.21\frac{\$}{kWh} * (\mathrm{kWh}_{\mathrm{Diesel\ saved}} + kWh_{Steam\ saved}) = 0.11 * (-991) + 0.21 * (303 + 21084) = 4{,}382\ \$$$

For the lighting, the annual saved costs are:

$$SavedCost_{Lighting} = 0.11\frac{\$}{kWh} * \left(kWh_{Electricity\ saved}\right) + 0.21\frac{\$}{kWh} * (\mathrm{kWh}_{\mathrm{Diesel\ saved}} + kWh_{Steam\ saved}) = 0.11 * (9299) + 0.21 * (-1282 + 7480) = 2{,}324\ \$$$

For the personal desk fans and cooling HVAC setpoints modification, the annual saved costs are:

$$
\begin{aligned}
&SavedCost_{fans} \\
&\quad = 0.11\frac{\$}{kWh} * \left(kWh_{Electricity\ saved}\right) + 0.21\frac{\$}{kWh} \\
&\quad * (\mathrm{kWh}_{\mathrm{Diesel\ saved}} + kWh_{Steam\ saved}) \\
&\quad = 0.11 * (58) + 0.21 * (9060 - 45) = 1{,}899\ \$
\end{aligned}
$$

For disconnecting electric equipment from the supply at night, the annual saved costs are:

$$
\begin{aligned}
SavedCost_{EE} &= 0.11\frac{\$}{kWh} * \left(kWh_{Electricity\ saved}\right) + 0.21\frac{\$}{kWh} \\
&* (\mathrm{kWh}_{\mathrm{Diesel\ saved}} + kWh_{Steam\ saved}) \\
&= 0.11 * (5931) + 0.21 * (-1310 + 3464) = 1{,}104\ \$
\end{aligned}
$$

For modifying HVAC setpoints, the annual saved costs are:

$$
\begin{aligned}
&SavedCost_{HVAC\ 0.5\ ^{\circ}\mathrm{C}} \\
&\quad = 0.11\frac{\$}{kWh} * \left(kWh_{Electricity\ saved}\right) + 0.21\frac{\$}{kWh} \\
&\quad * (\mathrm{kWh}_{\mathrm{Diesel\ saved}} + kWh_{Steam\ saved}) \\
&\quad = 0.11 * (3100) + 0.21 * (4431 + 19520) = 5{,}370\ \$
\end{aligned}
$$

$$
\begin{aligned}
&SavedCost_{HVAC\ 1\ ^{\circ}\mathrm{C}} \\
&\quad = 0.11\frac{\$}{kWh} * \left(kWh_{Electricity\ saved}\right) + 0.21\frac{\$}{kWh} \\
&\quad * (\mathrm{kWh}_{\mathrm{Diesel\ saved}} + kWh_{Steam\ saved}) \\
&\quad = 0.11 * (4599) + 0.21 * (3824 + 36837) = 9{,}044\ \$
\end{aligned}
$$

For turning the HVAC off, the annual saved costs are:

$$SavedCost_{HVAC\ Off}$$

$$= 0.11\frac{\$}{kWh} * \left(kWh_{Electricity\ saved}\right) + 0.21\frac{\$}{kWh}$$

$$* (\mathrm{kWh}_{\mathrm{Diesel\ saved}} + kWh_{Steam\ saved})$$

$$= 0.11 * (5944) + 0.21 * (43539 + 76758) = 25{,}916\ \$$$

Thus, total Savings is the sum of all measure savings which is equal to:

- Scenario 1 (With low ranked measures and considering 0.5 °C for the HVAC setpoint measure): **40,997 $**
- Scenario 2 (Without low ranked measures and considering 0.5 °C for the HVAC setpoint measure): **34,290 $**
- Scenario 3 (With low ranked measures and considering 1 °C for the HVAC setpoint measure): **44,671 $**
- Scenario 4 (Without low ranked measures and considering 1 °C for the HVAC setpoint measure): **37,964 $**

4.7.2. Payback periods:

For the windows:

$$Payback\ Period = \frac{ReplacementCost}{SavedCost} = \frac{105750}{4382.17} = 24.13\ years$$

For the lighting:

$$Payback\ Period = \frac{ReplacementCost}{SavedCost} = \frac{8400}{2324.38} = 3.61\ years$$

For the personal desk fans and cooling HVAC setpoints modification:

$$Payback\ Period = \frac{ReplacementCost}{SavedCost} = \frac{840}{1899.44} = 0.44\ years$$

For the other measures, payback period is 0.

$$Total\ Payback\ Period = \frac{Total\ ReplacementCost}{Total\ SavedCost}$$

Thus, the total Payback Period for the four scenarios is:

- Scenario 1 (With low ranked measures and considering 0.5 ℃ for the HVAC setpoint measure): **2.80 years**
- Scenario 2 (Without low ranked measures and considering 0.5 ℃ for the HVAC setpoint measure): **0.02 years**
- Scenario 3 (With low ranked measures and considering 1 ℃ for the HVAC setpoint measure): **2.57 years**
- Scenario 4 (Without low ranked measures and considering 1 ℃ for the HVAC setpoint measure): **0.02 years**

4.7.3. Ranking the measures:

- No.1 would be the measure with best savings and least payback period: The measure to turn the HVAC system off.
- No. 2 would be the second-best savings and near payback period: The measure to modify the HVAC setpoints.

- No. 3 would be reducing electric equipment usage at night by disconnecting electric equipment supply.
- No .4 would be the measure to implement personal desk fans and modify the cooling HVAC setpoints by 1.5 ℃ accordingly.
- No. 5 would be the measure of replacing the lighting. It is considered a low ranked measure and will even be rejected due to its high associated cost per kWh saved.
- No. 6 would be the measure of replacing the windows. It is also considered a very low ranked measure and will even be rejected due to its very high associated cost per kWh saved.

4.7.4. Environmental factors:

$$1\ \text{kWh} = 3412.97\ \text{Btu}$$

CO_2 Emission Coefficients (Reference to Energy Information Administration) [26]:

Fuel Oil	74.54	kgCO_2 / Million BTU
Diesel	73.16	kgCO_2 / Million BTU

Converting to kgCO_2/kWh:

Fuel Oil	0.25	kgCO_2 / kWh
Diesel	0.25	kgCO_2 / kWh

The saved CO_2 emissions are:

For Scenario 1 (With low ranked measures and considering 0.5 ℃ for the HVAC setpoint measure):

Fuel Oil $0.25 * (23341) = 5{,}937.92$ $kgCO_2$

Diesel $0.25 * (45636 + 137364) = 45{,}693.68$ $kgCO_2$

To Tons:

Fuel Oil 5.94 tons CO_2

Diesel 45.69 tons CO_2

For Scenario 2 (Without low ranked measures and considering 0.5 ℃ for the HVAC setpoint measure):

Fuel Oil $0.25 * (15033) = 3{,}824.38$ $kgCO_2$

Diesel $0.25 * (46615 + 108801) = 38{,}806.11$ $kgCO_2$

To Tons:

Fuel Oil 3.82 tons CO_2

Diesel 38.81 tons CO_2

For Scenario 3 (With low ranked measures and considering 1 ℃ for the HVAC setpoint measure):

Fuel Oil $0.25 * (24840) = 6{,}319.27$ $kgCO_2$

Diesel $0.25 * (45029 + 154681) = 49{,}866.05$ $kgCO_2$

To Tons:

Fuel Oil 6.32 tons CO_2

Diesel 49.87 tons CO_2

For Scenario 4 (Without low ranked measures and considering 1 °C for the HVAC setpoint measure):

Fuel Oil $0.25 * (16532) = 4{,}205.73$ $kgCO_2$

Diesel $0.25 * (46008 + 126118) = 42{,}978.47$ $kgCO_2$

To Tons:

Fuel Oil 4.21 tons CO_2

Diesel 42.98 tons CO_2

4.7.5. *Megawatt vs Negawatt cost:*

$$KW\ saved \coloneqq \frac{Total_{kWhSaved}}{Yearly\ Operation\ Period} =$$

$$\frac{Total_{kWhSaved}}{\left(261\frac{working\ days}{year}*10\frac{hours}{day}\right)+\left(52\frac{Saturdays}{year}*6\frac{hours}{day}\right)+\left(52\frac{Sundays}{year}*4\frac{hours}{day}\right)} = \frac{Total_{kWhSaved}}{3130}$$

The operation schedule from 8 am till 6 pm during weekdays, from 8 am till 2 pm during Saturdays, and from 8 am till 12 pm during Sundays.

$$\mathbf{Megawatt\ cost} = \mathbf{Capital\ Costs}\ (\mathbf{CAPEX}) + \mathbf{Operational\ Costs}\ (\mathbf{OPEX})$$

For AUB’s case, diesel is used for the power plants, and thus the Megawatt will be based on the plant powered by diesel.

Capital Costs: Considering an approximate 1,560 $ per kW production for diesel plants [27].

Operational and Maintenance Costs: The fixed O&M costs are 19.46 $ per kW and variable O&M costs are 0.00865 $ per kWh [27].

$$\textbf{Negawatt cost} = \textbf{Capital Costs (CAPEX)} + \textbf{Operational Costs (OPEX)}$$

Capital Costs: Is the replacement costs of the measures.

Operational and Maintenance Costs:

- Negligible for the 3 measures that require no replacement costs and for the windows replacement measure.
- For the lighting, the lamp life rating is 50,000 hours (Datasheet). Running the lamp for 3,130 hours per year, so 3,130/50,000 = 0.06 times a LED lamp is changed per year. The O&M costs of lamps:

  Price of lamp x No. of lamps x 0.06 = 68.5 $ x 350 x 0.06 = 1,439 $ per year.
- For the personal desk fans, considering a replacement of all the fans for 1 time per year for better performance, the operational costs per year can be assumed to be the price of the fans per year.

Table 8 is a summary for the 4 scenarios:

1 - (With low ranked measures and considering 0.5 ℃ for the HVAC setpoint measure)

2 - (Without low ranked measures and considering 0.5 ℃ for the HVAC setpoint measure)

3 - (With low ranked measures and considering 1 ℃ for the HVAC setpoint measure)

4 - (Without low ranked measures and considering 1 ℃ for the HVAC setpoint measure)

Table 8: Megawatt vs Negawatt costs

Scenario	**KWh (MWh) saved**	**KW (MW) saved**	**Megawatt cost ($)**			**Negawatt cost ($)**		
			CAPEX	OPEX	**TOTAL**	CAPEX	OPEX	**TOTAL**
1	206,340 (206.340)	66 (0.066)	102,960	3,069	**106,029**	114,990	2,279	**117,269**
2	170,448 (170.448)	54 (0.054)	84,240	2,525	**86,765**	840	840	**1,680**
3	224,549 (224.549)	72 (0.072)	112,320	3,343	**115,663**	114,990	2,279	**117,269**
4	188,657 (188.657)	60 (0.060)	93,600	2,799	**96,399**	840	840	**1,680**

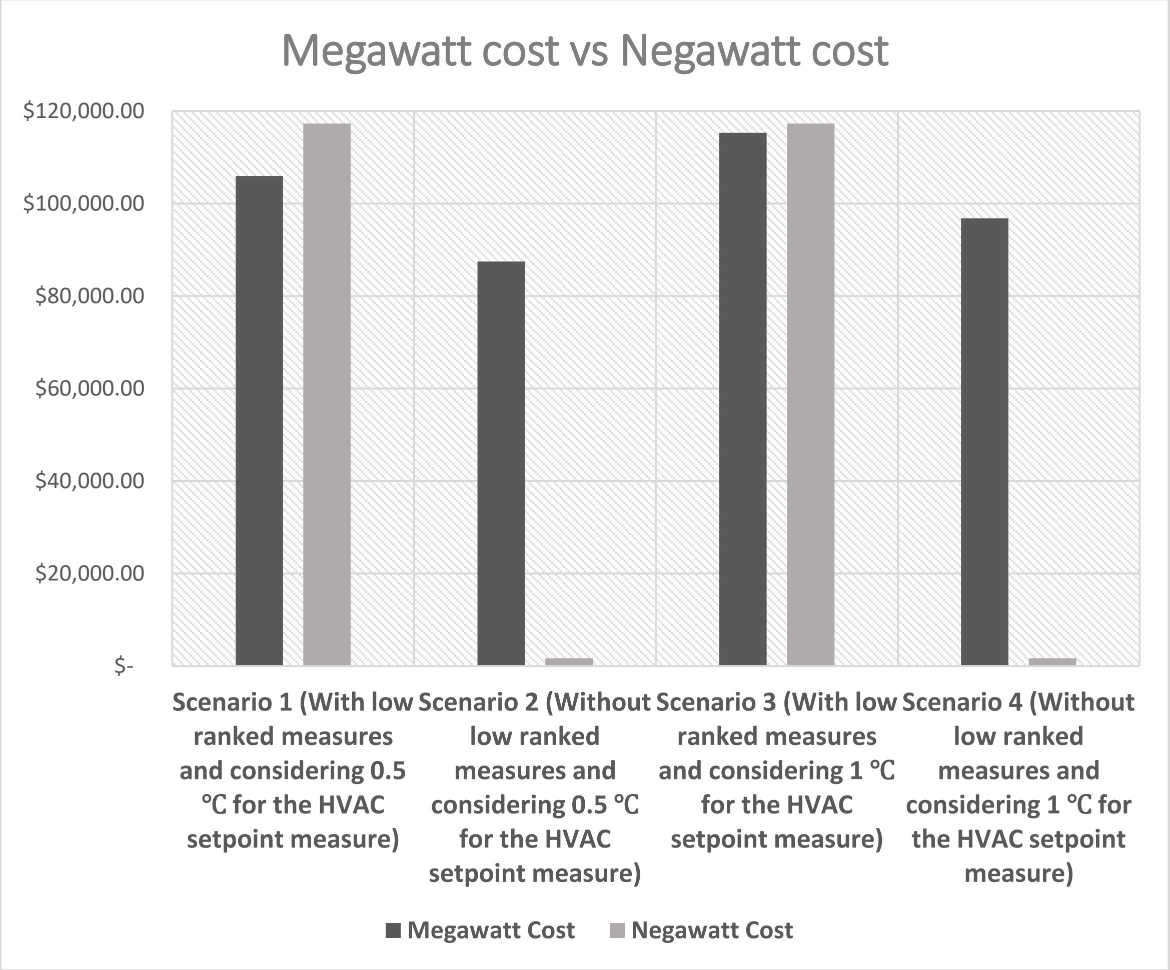


Figure 21: Megawatt cost vs Negawatt cost

In reference to Figure 21, both scenarios 1 and 3 include the low ranked measures and their associated Negawatt cost is more than that of the Megawatt, which shows that these options are not feasible and will be rejected.

Both scenarios 2 and 4 do not include the low ranked measures and their associated Negawatt cost is less than that of the Megawatt, which shows that these options are feasible options to proceed with.

4.8. Applying PV technology:

AUB MASRI building has a complex architecture, especially when considering the outside concrete beams along the building envelope. The building also has several windows from the three directions south, north, and west which also contributes to the overall appearance and design. The building was drawn in “Sketchup” and the location was entered from the geographical mapping, thus allowing for real weather data to be simulated. The basic weather data needed is the sun radiation on the building from the different directions to understand the shadowing effects from the architecture and nearby objects (See figure 11).

It was thus encouraging at the beginning to think of possible ways to install PV panels especially Façade panels for the windows, but it was concluded that such Façade panels will not be as productive since the concrete architecture poses shading all over the available windows and pace and will thus reduce any generated power. In addition, any design on the concrete beams themselves was also studied but was then overlooked due to the appearance of the building, in addition to the complex mounting structure associated with such design.

Thus, the best location for the installation of the panels was chosen to be the roof. The building roof is known to be used as a terrace for events and occasions and it is thus not advisable to do any ground roof mounting. The proposed design is based on a canopy structure mounting where people will still be able to walk under the panels while not altering their terrace experience and the elegant sea view. The proposed design takes into consideration the maximum possible available space while preserving the roof angle from the south and taking into consideration the necessary elevations to allow people to be accommodated under it.

The **mounting structure** will be made of galvanized steel or aluminum taking considering the near sea location of the building in Beirut and the adverse effects of corrosion on the structure. The structure will also be designed to maintain the high wind loads in the winter and be waterproof for better lodging. To choose the best possible design, three different designs listed in Table 9 and shown in Figures 22-24, were done and the most efficient was selected.

Table 9: Summary table for chosen PV design

Category	Criteria	Design 1	Design 2	Design 3	Remark(s)
Type	Facing	South	South	East-West	-
Structure	Canopy Height	2 meters to 3.6 meters slope	2 meters to 5.3 meters slope	2.5 meters flat	-
PV Panels	Azimuth	-7 degrees	-7 degrees	-90.7 degrees / 83 degrees	Like the roof angle to preserve the nice appearance
	Tilt	5 degrees	10 degrees	5 degrees / 5 degrees	To not go up so high in the mounting structure and an acceptable production value for Beirut location
	Model	LONGI Hi-MO LR5-72HPH			-
	Nominal Power	550 Wp/module			New available market panels for 2021. The system is rated at **39.6 kWp**.
	Fitted Number	72			Max. that can be fit
	Panel Dimensions	2256x1133x35 mm			-
Inverter	Model	HUAWEI PV Controller SUN2000-36KTL			-
	Fitted Number	1			-
	Nominal Power	36 KW			-

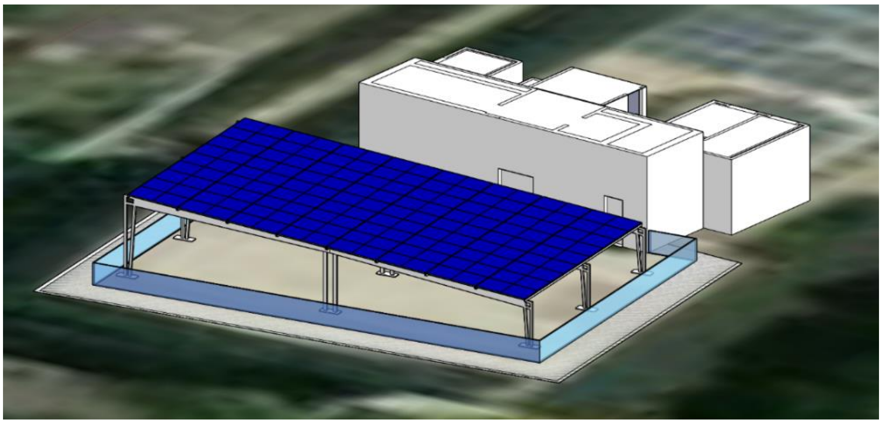


Figure 22: Design 1

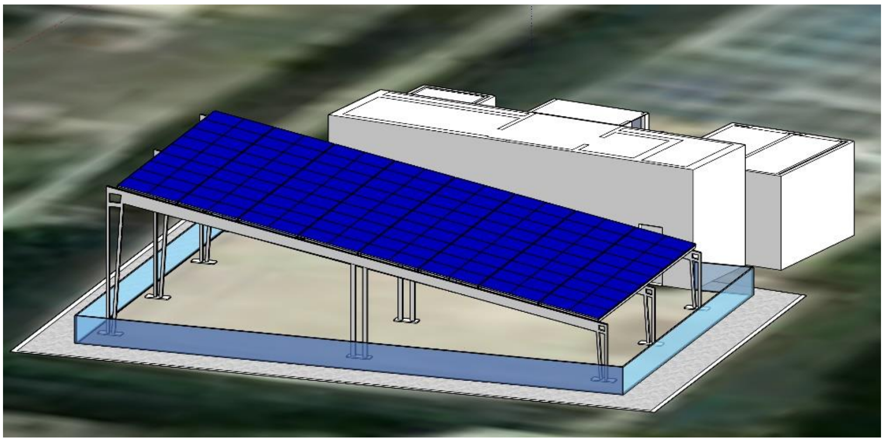


Figure 23: Design 2

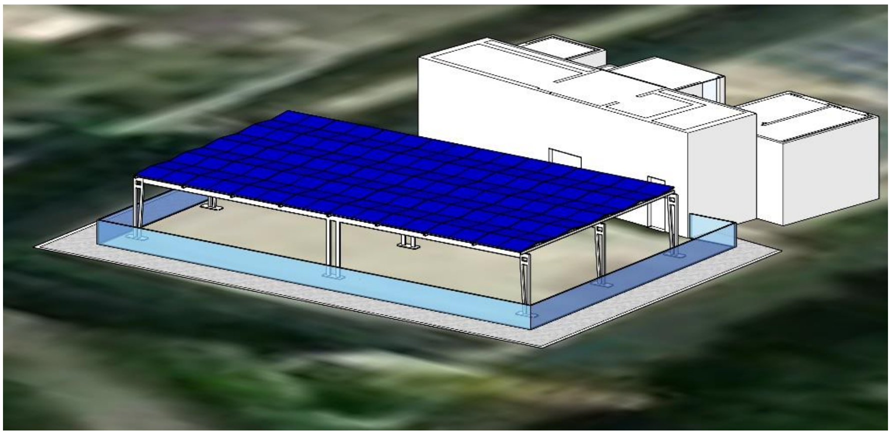


Figure 24: Design 3

Table 10: Design outputs comparison

Design	**Energy to Grid (MWh) per year**	**Payback Period**		**Internal Rate of Return (IRR %)**	**Levelized Cost of Electricity (LCOE $/kWh)**
		Static	**Dynamic**		
1	**65.79**	**4.85**	**6.87**	**10**	**0.07**
2	67.64	5.35	7.91	8	0.08
3	63.40	4.76	6.7	10	0.07

The payback period is calculated based on the initial investment costs and operation and maintenance costs for a project life of 20 years for all designs. Refer to section 4.9 for a detailed cost estimate analysis.

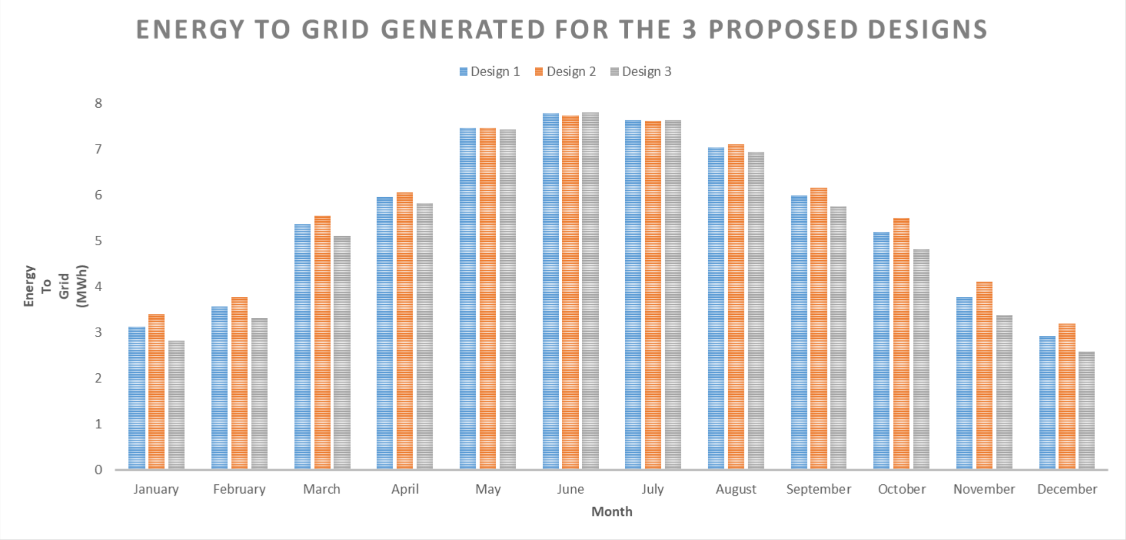


Figure 25: Monthly energy to grid (MWh) comparison

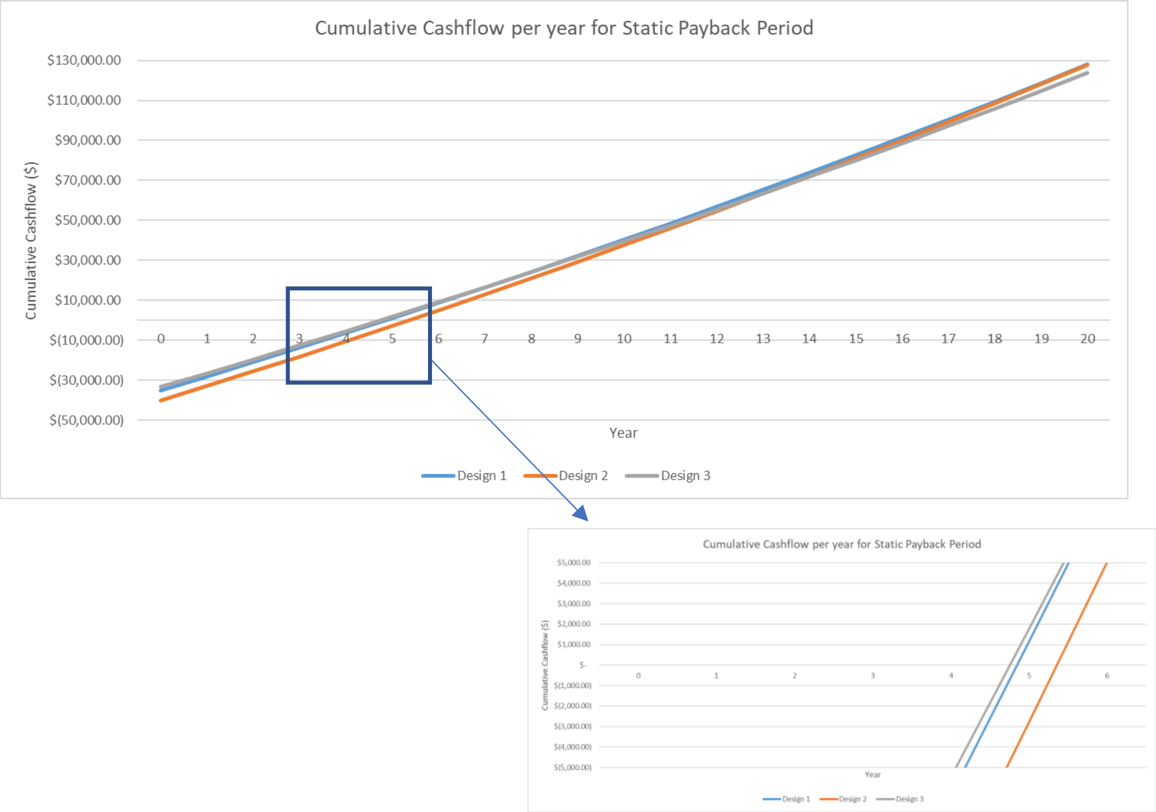


Figure 26: Cumulative cashflow ($) vs lifetime of the project (Years) for static payback period

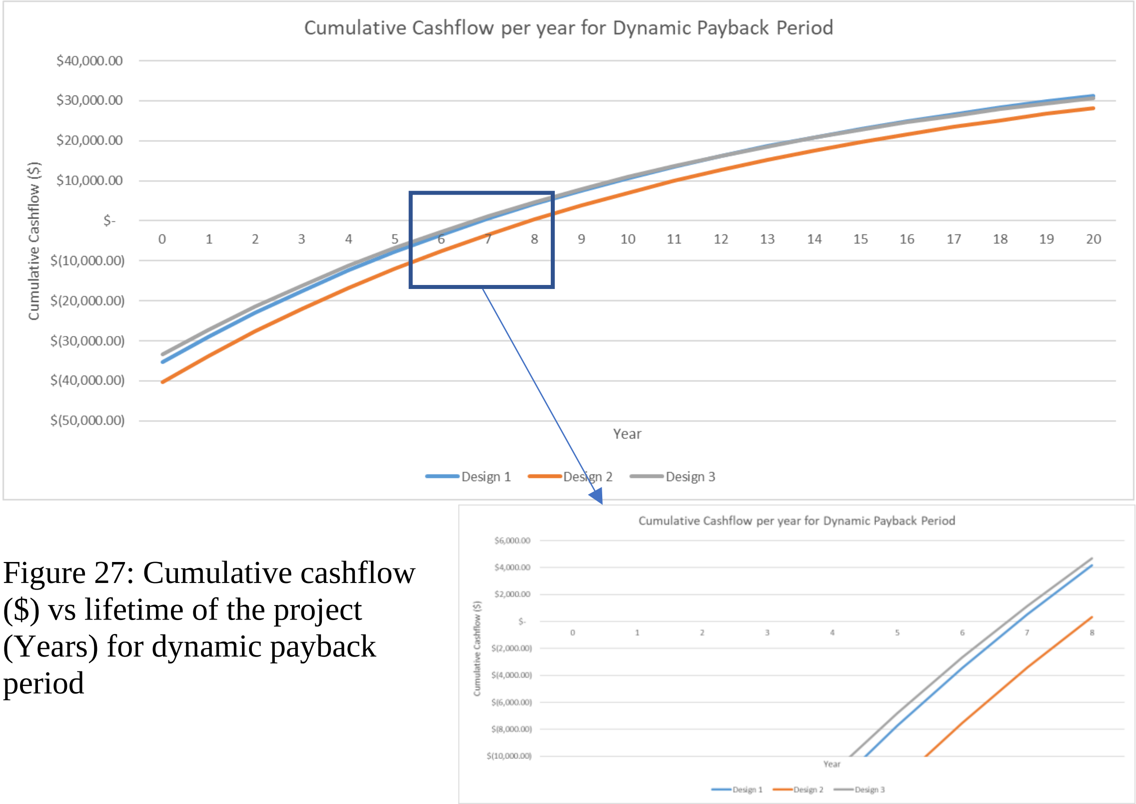


Figure 27: Cumulative cashflow ($) vs lifetime of the project (Years) for dynamic payback period

Figure 26 indicates the static payback period calculated from the cumulative cashflow per year for the three designs. The period would be the intersection of the curves with the 0 cashflow which indicates the breakeven point. Design 3 has the least payback period (4.76 years) followed by Design 1 (4.85 years) followed by Design 2 (5.35 years). Similarly, Figure 27 indicates the dynamic payback period calculated from the cumulative cashflow per year for the three designs. The period would be the intersection of the curves with the 0 cashflow which indicates the breakeven point. Design 3 has the least payback period (6.7 years) followed by Design 1 (6.87 years) followed by Design 2 (7.91 years).

Design 3 has the least energy output but the lowest payback periods. Design 2 on the other hand has the highest energy output and the highest payback periods, but design 2 canopy slopes from 2 meters to 5.3 meters high where 5.3 meters is considered too high for a roof installation that is exposed to different weather conditions and wind speeds during the year. Design 1 has an energy output better than Design 3 with slightly higher payback periods and its installation is acceptable, sloping from 2 meters to 3.6 meters. **Thus, Design 1 is seen to be the best design.**

Shading analysis was done in “Sketchup” and the design was confirmed to be far from nay nearby surfaces, walls, and any outside objects such as trees that can cause shading and affect the entire output.

“LONGI SOLAR” and “HUAWEI” are from the top 5 manufacturers in their industries for the panels and inverters respectively and were thus chosen due to their high quality and competitive pricing in the market. After drawing the design and choosing the criteria, the solar simulation software “PVsyst” was used for the simulation to obtain the produced energy throughout the year. The plan was chosen to be a **39.6 kWp** as designed with the associated panels and inverter. The exact location of the building was specified, and weather data was imported from "Meteonorm" through the software.

When deciding for the system grid type, the main factors are the availability of power from the grid and the building usage. The building is an office building used mostly during the day and is connected to both utility and internal generator sets installed. The chosen design is thus an On-Grid (Grid Connected) solar energy system without the need for any batteries.

4.9. Summary of results:

PVsyst simulates for the best possible array design and the result obtained was 18 modules in series and 4 strings design. The total produced energy is **65.79 MWh/year**, the specific production is 1661 kWh/kWp/year, and the Performance Ratio is 86.47 %. The system us rated at 53 Amperes.

4.10. Economic analysis:

To estimate the savings, it is necessary to concur the fixed and operational costs of the project and calculate the assumed savings from the production accordingly. The costs are the initial investment costs for the PV modules, Inverter, Mounting, Wiring, Combining, Monitoring, and Installation. The yearly costs are the maintenance routine and non-routine costs.

Table 11: PV initial and O&M costs

Type	**Criteria**	**Price**	**Total Price**	**Reference**
Initial Investment – One Time	PV Modules	72 Modules x 230$/Module	16,560 $	Estimate value available online
	Inverter	1 Inverter x 4,000$/Inverter	4,000 $	Estimate value available online
	Mounting Structure	10,000 $		Quoted through a specialized company located in China
	Wiring	2,500 $		Estimate value available online
	Combiner Box	800$		Estimate value available online
	Monitoring System	600$		Estimate value available online
	Installation Fees	15 Hrs. x 50$/Hr.	750 $	Estimate Value
	Transport	100$	100$	Estimate Value
	TOTAL:		**35,310 $**	
Yearly	O&M	About 300$/year + inflation		Estimate Value [28]
	TOTAL:		**300 $**	

Considering a project lifetime of 20 years, a discount rate of 10%, an inflation rate of 2% per year, solar panel degradation of 0.5% per year [28], and an electricity cost in Lebanon of 0.11$/kWh, the IRR and static and dynamic payback periods of the project are calculated.

The following calculations are used for the 20-year lifetime [29] costs analysis of the project ("i" being a chosen year out of the lifetime):

$$\boxed{N = 20}$$

$$\boxed{\text{Initial Investment Cost: } IV_{cost} = 35{,}310\ \$}$$

$$\text{Discount Factor (DF): } DF_i = \frac{1}{1+\frac{10}{100}} * i$$

$$\text{O\&M Cost: } O\&M_i = O\&M_{i-1} * (1 + 0.02)$$

$$\text{NPV of yearly Costs: } NPV_{cost} = O\&M_i * DF_i$$

Calculating:

$$\boxed{Total\ NPV_{cost} = 38{,}231\ \$}$$

$$\text{Energy production: } Eoutput_i = Eoutput_{i-1} * 99.5\%$$

$$\text{NPV of yearly Production: } NPV_{production} = Eoutput_i * DF_i$$

$$\text{Electricity Cost with inflation: } Ecost_i = Ecost_{i-1} * (1 + 0.02)$$

For static payback period: Annual Cashflow: $CF_{Si} = (Eoutput_i * Ecost_i) - O\&M_i$

Calculating:

$$\boxed{PaybackPeriod_{Static} = 4.85\ years}$$

For dynamic payback period: Annual Cashflow: $CF_{Di} = \frac{CF_{Si}}{\left(1+\frac{10}{100}\right)^i}$

Calculating:

$$\boxed{PaybackPeriod_{Dynamic} = 6.87\ years}$$

$$\boxed{\text{LCOE: } LCOE = \frac{\sum_{i=0}^{N} NPV_{cost}}{\sum_{i=0}^{N} NPV_{production}} = 0.07\ \$/kWh}$$

$$\boxed{\text{IRR: } 0 = \sum_{i=1}^{N} \frac{CF_{Di}}{(1+IRR)^{i}} - IV_{cost} = 10\%}$$

4.11. Environmental analysis:

The life cycle emissions (LCE) for Lebanon are: 714 gCO_2/kWh (In reference to "PVsyst" global emissions data per country). Using grey energy conversion factors, thus:

LCE per kWp = 714 gCO_2/kWh * 2168 kWh/kWp = **1,548 $KgCO_2$/KWp**

LCE per kg weight of aluminum = 714 gCO_2/kWh * 6.67 kWh/Kg = **4.8 $kgCO_2$/kg**

LCE per unit manufacturing = 714 gCO_2/kWh * 660.8 kWh/unit = **472 $kgCO_2$/unit**

Table 12: Total LCE for the project

Item	Description	Value	Total LCE ($kgCO_2$)
PV Modules	Power (kWp)	39.6	61298.8992
Aluminum Support	Weight (kg)	720	3428.9136
Inverter	No. (Unit)	1	471.8112
TOTAL			**65,199.624**

Estimating the carbon balance:

$$((\sum_{i=1}^{N} Eoutput_i) * LCE_{Lebanon}) - Total\ LCE_{project}$$

(Total energy output is calculated separately for the 20-year lifetime and added to obtain the total sum which is 1255135 kWh)

Thus, substituting in the equation, we obtain:

= (1255135*0.714) – 65200

= 830967 kgCO_2 **which are the saved CO_2 emissions**

= 831 tCO_2

= 42 tCO_2/year

= 21 tCO_2/kWp

= 1 tCO_2/kWp/year

CHAPTER 5

FINAL RESULTS

The **Hybrid Negawatt** power plant is designed based on the four acceptable conservation measures and the rooftop PV system. Tables 13 and 14 are summary tables for the end results obtained for scenarios 2 and 4, now with PV:

Scenario 2 with PV: Without low ranked measures and considering 0.5 ℃ for the HVAC setpoint measure + integrated PV.

Scenario 4 with PV: Without low ranked measures and considering 1 ℃ for the HVAC setpoint measure + integrated PV.

Table 13: The Hybrid Negawatt economic and environmental results

Scenario	**Total consumption reduction (kWh per year)**	**Saved Energy (KW)**	**Replacement cost ($)**	**Weighted average cost of kWh saved ($/kWh)**	**Savings per year ($)**	**Payback period (years)**	**Reduced CO_2 emissions (tCO_2 per year)**
2 with PV	233,205	75	36,150	0.023	41,194	0.88	19.79 (Fuel Oil) 38.81 (Diesel)
4 with PV	251,414	80	36,150	0.021	44,868	0.81	20.17 (Fuel Oil) 42.98 (Diesel)

Table 14: Megawatt vs Hybrid Negawatt costs

Scenario	**Thermal diesel Megawatt cost ($)**			**Energy efficiency Hybrid Negawatt cost ($)**		
	CAPEX	OPEX	**TOTAL**	CAPEX	OPEX	**TOTAL**
2 with PV	117,000	3,476	**120,476**	36,150	1202	**37,352**
4 with PV	124,800	3,732	**128,532**	36,150	1202	**37,352**

The generated PV system production power is considered as saved electrical power from fossil fuels and is added to the reduction noting that operations costs, mainly maintenance costs, are typically around 1 percent of the capital cost [28].

The cost of the Hybrid Negawatt is about 30% of the cost of the Megawatt. Therefore, it is cheaper to go with the Hybrid Negawatt concept than to expand the thermal power plant for the concerned demand. In addition to the positive impact on the environment by reducing CO_2 emissions by nearly 63 tons per year.

CHAPTER 6

CONCLUSION

This Thesis studied different building energy conservation measures and examined the deployment of renewable energy resources, namely PV cells. The work used the Negawatt concept which is based on assessing the feasibility of establishing more efficient technologies and behavioral changes to lower energy consumption rather than expanding the power supply to meet increased demand.

The feasibility study of a small Hybrid Negawatt power plant for a recently constructed office building at the American University of Beirut (AUB), the Munib and Angela MASRI building, was assessed. Various conservation measures are addressed mainly focusing on reducing energy consumption during unoccupancy periods, in addition to addressing alternative technologies, such as more efficient lighting and upgrading the double-glazed windows. A rooftop PV canopy design system is proposed, while maintaining the unique roof terrace and its wonderful sea view.

The building model was imported to “Open studio” (interface powered by the Energy-Plus engine) in which all input data was identified for the energy simulation. Where applicable, built-in library of space types (loads and their associated schedules) for DOE reference buildings ASHRAE 189.1-2009, ASHRAE 90.1-2007, and ASHRAE 90.1-2010 were defined and attributed. The available actual consumption report provided by the university building management division included energy consumption by hour in (kWh) from July 2, 2019, till December 31, 2019. The simulated data was compared with the actual benchmark and was found acceptable.

The accepted conservation measures are disconnecting electric equipment at night, using personal desk fans with increasing cooling setpoints, modifying the HVAC setpoints by 0.5 or 1 ℃, turning the HVAC system off at night, and installing a solar PV rooftop. The assessed measures fall into three categories:

- More efficient technology.
- Integrating PV cells.
- Introducing behavioral changes that has big benefit (cost-free).

The study carried out compared the cost of implementing these measures and alternative technologies to the cost of expanding the supplied thermal power from conventional fossil fuels. The simulations showed that the hybrid Negawatt solution with the chosen measures reduced energy consumption from 809815 kWh per year to 233205 kWh per year (For the 0.5 ℃ setpoint modified measure) and to 251414 kWh per year (For the 1 ℃ setpoint modified measure), thus a reduction of 28.79 % and 31.04 % respectively and the consumption dropped by up to 80 kW.

The cost of the Negawatt was calculated by considering the costs of the measures and the payback period was calculated by taking into consideration the cost of the new equipment as investment costs and the reduced energy consumption costs as savings. The calculations proved that the price of the Hybrid Negawatt is much lower than that of the thermal Megawatt especially where certain mitigation measures require only managerial and behavioral adjustments at no additional costs. The Hybrid Negawatt plant is a green plant that reduces CO_2 emissions by up to 62 tons of CO_2 per year combined for different fossil fuels.

Future work could use the concept of the Hybrid Negawatt on the Lebanese electric sector. Appling such measures on large commercial and industrial scales ought to provide best economical and feasible solutions for the shortages in electricity in Lebanon in which these shortages will be tackled from the concept of reducing consumption and going green rather than expanding current power plants. It will also lead to substantial savings in Lebanon’s energy bill and aid in solving the Lebanese economy shortfalls.

REFERENCES

[1] IEA Data and Statistics, [Online]. Available: https://www.iea.org/data-and-statistics?country=WORLD&fuel=Energy%20consumption&indicator=TotElecCons

[2] L.B. Amory, "THE NEGAWATT REVOLUTION", Across the Board, vol. XXVII, no. 9, Sept. 1990. [Online]. Available: https://rmi.org/wp-content/uploads/2017/04/E90-20_NegawattRevolution.pdf

[3] The Negawatt Association [Online]. Available: https://negawatt.org/en

[4] Raumtaktik/Urbanegestalt, “A LIGHT INSTALLATION AT THE GERMAN PAVILION”, Venice, Italy, 2008. [Online]. Available: https://www.raumtaktik.de/en/projects/64-kw

[5] Dieter Seifried, “THE "ECO-WATT PROJECT": BUILDING A NEGAWATT POWER PLANT IN A SCHOOL”, ECEEE, 2001. [Online]. Available: https://www.eceee.org/static/media/uploads/site-2/library/conference_proceedings/eceee_Summer_Studies/2001/Panel_5/p5_12/paper.pdf

[6] Norio Murakami, “EXPECTATIONS FOR NEGAWATT TRADING”, July 2012. [Online]. Available: http://www.gepr.org/en/contents/20120702-01/

[7] Lance E. Elberling & Richard C. Bourne, “ACT PROJECT: MAXIMIZING RESIDENTIAL NEW CONSTRUCTION ENERGY EFFICIENCY”, ACEEE, 1994. [Online]. Available: https://www.aceee.org/files/proceedings/1994/data/papers/SS94_Panel3_Paper07.pdf

[8] Amy Mount & Dustin Benton, “GETTING MORE FROM LESS REALISING THE POTENTIAL OF NEGAWATTS IN THE UK ELECTRICITY MARKET”, Green

Alliance policy insight, Oct. 2015. [Online]. Available: https://www.green-alliance.org.uk/getting_more_from_less.php

[9] Katherine Watts & Friederike Metternich, “KICKSTARTING THE NEGAWATTS MARKET: HOW TO MAKE SURE THE ELECTRICITY DEMAND REDUCTION PILOT SUCCEEDS”, Green Alliance, 2014. [Online]. Available: http://www.green-alliance.org.uk/resources/Kickstarting_negawatts.pdf

[10] Lee, ChungHwan, “THE NEGAWATT ERA IS COMING”, Green Focus, vol. 07, Sept. 2015. [Online]. Available: https://www.gtck.re.kr/frt/center/en/tech/green_focus.do?pageMode=View&nttId=22279

[11] Ng Sock Yen, Elia Syarafina Abdul Shakur & Choong Weng Wai, “ENERGY CONSERVATION OPPORTUNITIES IN MALAYSIAN UNIVERSITIES”, Malaysian Journal of Real Estate, vol. 5, no. 1, 2010. [Online]. Available: https://core.ac.uk/download/pdf/11793209.pdf

[12] Sheila J. Hayter & Alicen Kandt, “RENEWABLE ENERGY APPLICATIONS FOR EXISTING BUILDINGS”, Conference Paper NREL/CP-7A40-52172, August 2011. [Online]. Available: https://www.nrel.gov/docs/fy11osti/52172.pdf

[13] Arvind Chel & Geetanjali Kaushik, “RENEWABLE ENERGY TECHNOLOGIES FOR SUSTAINABLE DEVELOPMENT OF ENERGY EFFICIENT BUILDING”, Alexandria Engineering Journal, vol. 57, pages 655–669, 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1110016817300911

[14] Ahmad A., “DISTRIBUTED POWER GENERATION FOR LEBANON MARKET ASSESSMENT AND POLICY PATHWAYS”, World Bank Group and ESMAP, May 2020. [Online]. Available:

http://documents1.worldbank.org/curated/en/353531589865018948/pdf/Distributed-Power-Generation-for-Lebanon-Market-Assessment-and-Policy-Pathways.pdf

[15] S. Karaki, N. Ghaddar, F. Moukalled, F.B. Chaaban, “ENERGY ANALYSIS OF AUB BUILDINGS”, pp. 1-39, 2008.

[16] D. Sbeity, F. B. Chaaban, “DESIGN AND FEASIBILITY OF A SMALL NEGAWATT POWER PLANT”, Energy power sources, vol. 2, no. 4, 2015.

[17] AUB Environmental Health, Safety, and Risk Management, “AUB’s CARBON FOOTPRINT REPORT 2019”, 2019. [Online]. Available: https://www.aub.edu.lb/facilities/ehsrm/Documents/Carbon%20footprint%20report%202019.pdf

[18] NREL, “RESEARCH SOLAR ENERGY BASICS” Available from: https://www.nrel.gov/research/re-solar.html Internet; accessed in April 2021.

[19] Energy Usage, “TYPES OF SOLAR PANELS” Available from: https://www.energysage.com/solar/101/types-solar-panels/ Internet; accessed in April 2021.

[20] LCEC & MEW, “BEIRUT RIVER SOLAR SNAKE; THE DAWN OF THE SOLAR MARKET IN LEBANON MAY 2020”, Available from: https://lcec.org.lb/sites/default/files/2021-02/BRSS%20Report.pdf Internet; accessed in May 2021.

[21] NREL, “CRYSTALLINE SILICON PHOTOVOLTAIC MODULE MANUFACTURING COSTS AND SUSTAINABLE PRICING: 1H 2018 BENCHMARK AND COST REDUCTION ROAD MAP”, 2020. [Online]. Available: https://www.nrel.gov/solar/solar-cost-analysis.html

[22] Pearsall, Nicola, “THE PERFORMANCE OF PHOTOVOLTAIC (PV) SYSTEMS - MODELLING, MEASUREMENT AND ASSESSMENT”, Woodhead Publishing Series in Energy Number 105, 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9781782423362099870

[23] NREL, “U.S. SOLAR PHOTOVOLTAIC SYSTEM AND ENERGY STORAGE COST BENCHMARK: Q1 2020”, Available from: https://www.nrel.gov/docs/fy21osti/77324.pdf Internet; accessed in April 2021.

[24] LCEC & UNDP, “SOLAR PHOTOVOLTAIC ELECTRICITY FOR YOUR HOUSE”, Available from: http://www.cedro-undp.org/content/uploads/Publication/141010120115339~PV-booklet-EN.pdf Internet; accessed in May 2021.

[25] T. Itani, N. Ghaddar & K. Ghali (2013), “Strategies for reducing energy consumption in existing office buildings”, International Journal of Sustainable Energy, 32:4, 259-275, DOI: 10.1080/14786451.2011.622765. [Online]. Available: https://doi.org/10.1080/14786451.2011.622765

[26] US Environmental Protection Agency, “EMISSION FACTORS FOR GREENHOUSE GAS INVENTORIES”, 2021. [Online]. Available: https://www.epa.gov/sites/default/files/2021-04/documents/emission-factors_apr2021.pdf

[27] US Energy Information Administration, “COST AND PERFORMANCE CHARACTERISTICS OF NEW GENERATING TECHNOLOGIES, ANNUAL ENERGY OUTLOOK 2021”, 2021. [Online]. Available: https://www.eia.gov/outlooks/aeo/assumptions/pdf/table_8.2.pdf

[28] CNRS/Aub Policy Institute, “ASSESSING SOLAR PV’S POTENTIAL IN LEBANON”, 2021. [Online]. Available: https://www.aub.edu.lb/ifi/Documents/publications/working_papers/2016-2017/20170808_solar_pvs.pdf

[29] NREL, “LIFETIME OF PV PANELS”, 2018. [Online]. Available: https://www.nrel.gov/state-local-tribal/blog/posts/stat-faqs-part2-lifetime-of-pv-panels.html