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HYBRID PV BATTERY SYSTEM FOR A TYPICAL HOUSE IN LEBANON INLAND REGION

by
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AN ABSTRACT OF THE THESIS OF

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Power shortages are forcing the residential sector to rely on backup diesel generators (DG). Using photovoltaic (PV) technology can be one of the clean solutions to this problem; however its adoption is challenged by its relative high capital cost. To overcome this challenge, we propose reducing the initial construction cost through the use of local low-embodied energy construction materials and use the savings resulting from envelop replacement costs to offset the PV cost. A typical house in the dry desert climate of inland Lebanon is thermally modeled using commercial software for the base case and when using local low-embodied energy construction materials, mainly hemp and straw. The savings resulting from reduced electrical demand and from the initial cost change between the base case model and the local material model were found to be $41/m^2. The savings are used to assess the investment in installing a solar water heater (SWH) and a hybrid PV battery system while reducing operating cost of the diesel generator.

HOMER software is used in the assessment hybrid PV battery system while considering two scenarios. In Scenario 1, we used the savings from the initial cost of envelope material and downsized DG which resulted in net energy savings up to 47% with payback period of 3 years. In Scenario 2, the DG replacement by PV is based on life cycle assessment in which further investment in the PV system is evaluated and optimized. This resulted in a system able to operate without need for the DG, to decrease the electricity purchased form the grid, and to increase the electricity sold to the grid with net energy savings reaching 130% with a payback period of 6 years. In addition to these economic benefits to home owners, the system resulted in environmental benefit, where the reduction of CO_2 emissions reached 200% in Scenario 2.

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CHAPTER I

INTRODUCTION

Challenges to the electricity sector faced in several countries in the Middle East are increasing day after day due to the increase in energy consumption, lack of new projects to cover this increase, and the rapid increase of fossil fuel prices. Diesel generators are being used to cover any power shortages and serve as a backup during cut-off hours. But diesel generators not only impact the environment negatively but also pose a high financial burden on the individuals. Since the energy sector has a significant role in the overall development of countries, we should look for other alternatives to cover and decrease the energy consumption. Efficient building design has proven to be the first step in decreasing the energy consumption (1). In addition, renewable energy is another possible solution where investments in renewable energy systems will not only help in covering the electricity supply shortage and decreasing the CO_2 emissions, but will also help in reducing the dependence on fossil fuels which are all imported. This can result in some security to those countries in addition to the economic growth and the overall sustainable development.

Since the residential sector accounts for a high percentage of the energy consumption, for instance it reaches 47% in Lebanon, any possible consumption savings in this sector would result in improvement in the environmental conditions (2). In this study we aim to replace conventional envelop material of a typical Lebanese house by local construction material to assess reduction in the initial cost of the building and investigate the soundness of investing the savings in a renewable energy system such as photovoltaic (PV) for power generation and solar water heating (SWH), thus decreasing the energy consumption while maintaining initial cost at its conventional level. Further investment in PV systems is also evaluated as potential replacement of the backup diesel generator and the associated payback period is determined.

CHAPTER II

LITERATURE REVIEW

The key issue is to use local material to decrease the first cost of the building. The use of local material will not only decrease the first cost but also the embodied energy. Building materials and their embodied energy constitute an integral part of any sustainable construction. The term initial Embodied Energy is used to refer to the energy consumed in manufacturing, processing and transporting the building construction materials to the construction site (3). The embodied energy constitutes approximately 5% to 15% of the total energy consumption of a residential building throughout its lifetime (4). So the more the amount of embodied energy in buildings is minimized, the more the environmental impact of the construction is reduced (4). One way of achieving reduction in embodied energy is by using local construction material such as rammed earth and straw as Morel et al. (5) concluded in their study that resulted in an energy consumption reduction of 215% in a small residential unit in southern France. This significance of using local material such as hemp is also verified by Awwad et al. (6) who surveyed the major coarse aggregate resources in Lebanon and found that the Bekaa area has a supply of this local material that exceeded its demand. Most of the studies were directed towards life cycle assessments considering the both the embodied and operational energy of the building from cradle to grave. The literature studies were mainly targeting carbon emissions; however lowering the embodied could lower also the first cost of the building which can be beneficial for financing renewable energy systems.

The selection of local material and the selection of the proper renewable system are specific to the building and its geographic location. For countries with good solar insolation, which is the total energy per unit area received from the sun on one day, solar renewable energy systems such as PV and SWH are the most attractive. Guilherme et al. (1) studied the feasibility of implementing solar net zero energy building systems for a typical house in the mild southern European climate zone. The solar thermal and PV systems were sized to meet all annual needs, and it was found that having such system in this climate is feasible but with an increase in the initial cost that can reach 22% (1). Soufi et al. (7) also studied the feasibility of having a stand-alone photovoltaic system in remote livestock shelters located in a village in Algeria. To cover the daily electric load of 5.5kWh, it was found that they need a system composed of a 4kW PV modules, 6 batteries (200 Ah and 12 V), and a 5-kW inverter (7). Al-Hasan et al. evaluated the usage of grid connected PV systems to cover part of the electric load in Kuwait. They found that the daily peak load and the maximum solar radiation are attained at the time; this increased the role of the PV system in minimizing the electric load demand (8). Rehman et al. evaluated the energy production of a 5MW grid connected PV system power plant in different sites in Saudi Arabia. The best site was shown according to the economic indicators they got such as the net present cost, payback period and the internal rate of return (9).

These systems relatively high initial cost restrains house owners from adopting them. But savings from initial construction cost can offset the PV and SWH cost and make them more desirable. For example, in the rural area of Lebanon where the local material are available and will be cheaper due to less transportation cost as compared to imported material, investments in these systems can be applied. In addition, Lebanon is suffering from frequent cuts in the electric power supply. The building is usually supplied by a diesel generator to provide electricity during cut-off-hours. So, Having the PV system installed can also result in decreasing the size of the backup diesel generator and thus more savings can be invested to increase the size of the PV system. In addition to these finance resources, official's policies and decrease in these technologies prices will also encourage home owners to invest in PV and SWH.

Although the use of PV systems is still minimal in some countries such as Lebanon, the use of SWH is increasing (10). This is due to increase in diesel prices and the special financing facilities supported by banks which is encouraging more reliance on the solar water heating systems (11). These same reasons can encourage home owners to invest in PV if they can afford to.

PV module prices are dramatically going down as per Swanson (12) who predicted that the module price will reach 1.44$/kW in 2013 which is in accordance with what we see currently in the market (13). The decrease in prices as well as bank incentives provided to individuals will encourage home owners to install PV systems. Investing in PV systems will also help reducing the CO_2 emission per capita especially if these systems are to replace the backup diesel generators.

For the investment in PV system to succeed, its components should be chosen and sized accurately. The PV system requires PV modules, inverter, controller, batteries, and mounting structure (14). PV modules power rating is based on Standard Testing Conditions (STC) of 1 kW/m^2 of sunlight and a PV cell temperature of 25 °C (15).

Predicting accurate output of renewable energy sources is not attainable due to these sources random behavior. The PV output might exceed the batteries charging limit during sunny days, and the batteries might go beyond its discharge limit during winter cloudy days. That being so, sizing the PV should be studied carefully starting from the number of PV modules and both number and capacity of batteries. To consider all extreme weather conditions without increasing the cost of the system is a real challenge. Optimization and tradeoffs between the system cost and its reliability level are the best procedure to design such systems with minimizing the possibility of both over sizing and under sizing the system (16). According to Carrilho da Graca (1), low energy needs, efficient energy systems, properly sized renewable energy systems, and exchange prepared electrical grid can lead us to net zero energy house. The low energy needs depend on the optimal building design of the house; from using as much as possible natural lighting and ventilation to the best heating and cooling. Oversizing or under-sizing renewable energy systems can have negative effect on the overall outcome; so it’s always important to study and size the systems adequately. An equipped grid ready to exchange energy is a very important factor that would allow successful investments in such systems.

Since reliability and cost are the two main aspects of choosing renewable energy sources, and it is confirmed that hybrid systems are more reliable and less costly than single systems (17), a hybrid PV-diesel battery system for electricity generation and SWH for domestic hot water use will be considered.

Optimization of renewable energy systems design has been studied by many researches so far. Minimizing the net present cost (NPC) or levelized cost of electricity (LCE) without losing reliability is the essential of reaching the optimum design (17). To analyze the proposed renewable energy system, simulations and optimization of different scenarios using a planning model is needed.

Such feasibility and optimization studies have been done extensively in the last 10 years for many applications all over the world. Building houses with cheap local material while enhancing the house energy performance and then using these construction savings to invest in PV without increasing the house initial cost is the main contribution of the study. In both the locality and the cost constraint relies the importance of this study.

CHAPTER III

METHODOLOGY

In this study, cheap local construction materials are used as a method to decrease the initial construction cost of a typical house. The typical house will serve as a base case model to which the integration of PV system and SWH will be examined. As presented in Figure 1 the PV system will be grid connected but with the use of battery storage. The three main components that home owners are concerned include the decrease in the initial capital cost, the increase the lifetime benefits, and minimizing of the payback period.

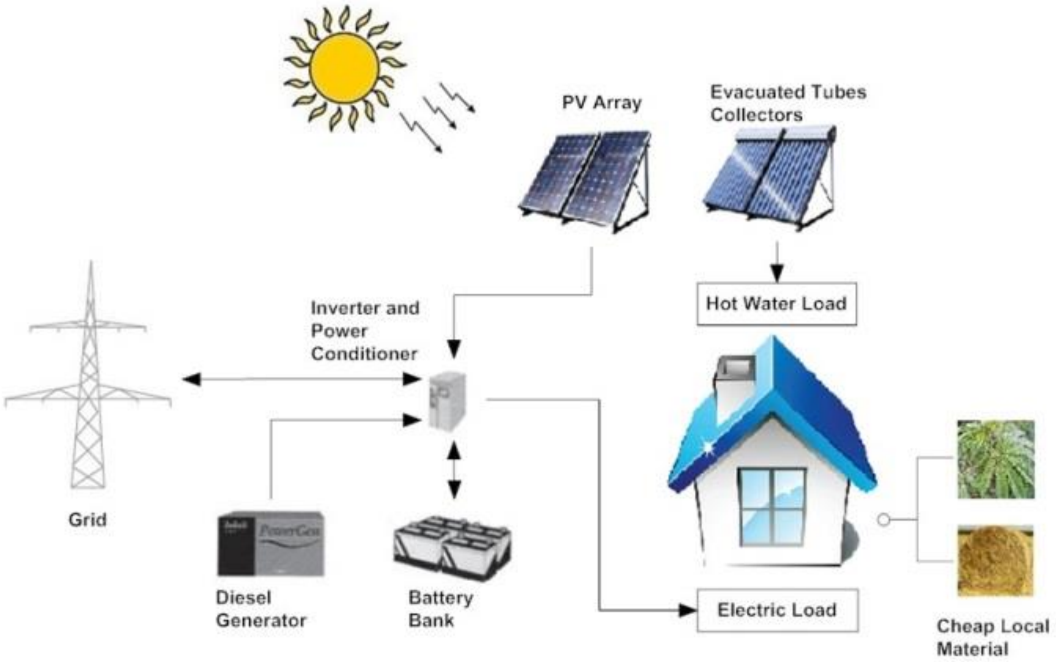


Figure 1: System Schematic

The methodology provided in Figure 2 is followed in the study. The typical house is selected such that it meets the thermal standard guidelines to which local material will be applied to replace conventional material and reduce initial construction cost. Having this house model characteristics, eQUEST (18) simulation is done to get the average energy consumption, daily load profile for all months, peak demand, and CO_2 emissions. The SWH size is calculated based on the water consumption of a typical family. Applicable different PV sizes with the needed number of batteries and inverter size will be estimated based on the chosen type of PV modules to be installed, the percentage of roof area available for installation of the PV modules, and the maximum electric load. Solar data, results of eQUEST, PV modules sizes, number of batteries, and inverter size are then served as input to HOMER software (19) to study and optimize the best system based on life cycle assessment. Energy savings, initial cost, payback period, and CO_2 emissions reduction are the main indicators to evaluate the studied system.

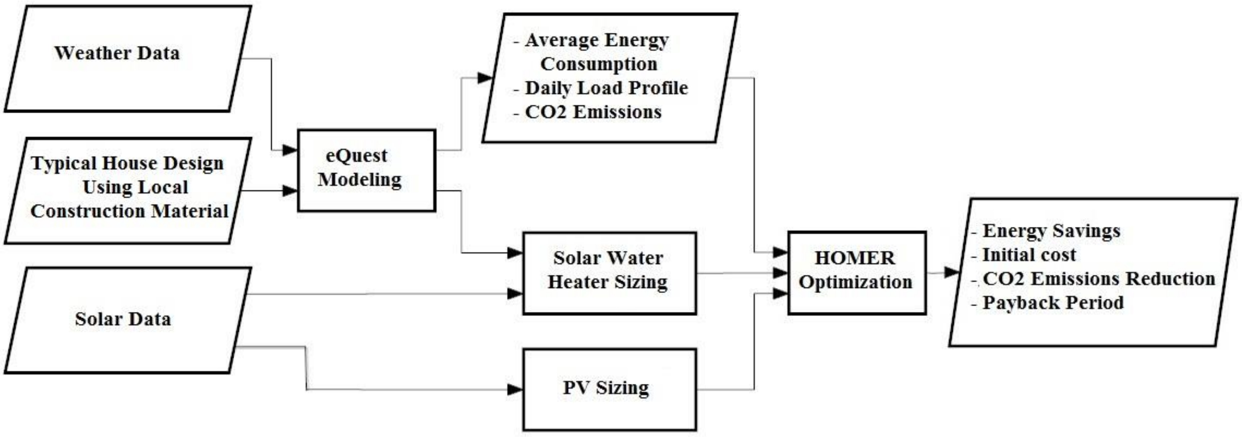


Figure 2: Methodology Flow Chart

This methodology is followed to evaluate two scenarios; the first is designing a system constrained by investing only the savings attained from decreasing the initial cost of envelope construction material and the savings from decreasing the required backup diesel generator. The second scenario designs a PV system to replace the backup diesel generator based on life cycle assessment and not just initial cost. Both scenarios have to cover the needed electric energy demand.

A. Typical House Description

The above-mentioned methodology is applied to the typical single-family duplex house located in the Lebanese inland region, Bekaa area studied by Tibi (20).The house has typical rectangular floor plans, as shown in Figure 3, with a footprint of 120 m^2, and a total built area of 240m^2. The number of family members is 7.

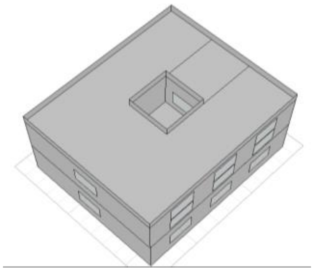


Figure 3: House Model Geometry

Such typical houses usually use conventional building materials such as hollow blocks, steel reinforced concrete, and single glazed window which have an overall envelope U-value above what is allowed by the Lebanese thermal standard (21). The overall envelope U-value for our case study using such material is equal to 3.31 W/m^2K which is much higher than the maximum allowed value of 0.88$W/m^2.K$ as set by the standard for the inland regions. In order to decrease this U-value to meet the standard, insulation material such polystyrene is used. This conventional material has a high embodied energy that causes the overall cost of the initial construction to increase by around 127$/m^2 as compared to the conventional non-insulating envelope according to market prices.

However, the standard and the same overall U-value from using conventional material can also be met if local materials with low embodied energy and relatively high thermal storage capacity such as rammed earth, straw, and natural stone are used for the building envelope. The rammed earth construction is a method of building walls using a balanced mixture of clay, sand and aggregate. This method has a promising potential for future construction for it is abundant, recyclable and has a minimal environmental impact (22); also, the use of natural fibers such as Hemp to enhance the tensile strength of rammed earth construction proved to be effective (23). In our proposed envelop replacement case, the roof and slabs are made up of steel reinforced concrete of 15 cm thickness that is insulated using straw boards of 5 cm thickness decreasing the U-value to 0.82 W/m^2.K. The walls are made of hemp-reinforced rammed earth blocks of 20 cm thickness on the interior, insulated using straw boards of 5 cm thickness sealed with cement board on the exterior making the U-value reach 0.51 W/m^2.K. The windows are double glazed with a low-e film and aluminum frame decreasing the U-Value to 2.41 W/m^2.K. The windows facing south have operable horizontal shading elements to be used during summer. The overall U-value for this replacement envelope is 0.77W/m^2.K which complies with the Lebanese standard guideline for the inland regions.

Comparing the conventional material envelope case with the local material replacement envelop case, it was found that the annual embodied energy is equal to 62.1 kWh/m^2 for the conventional case but it decreased to 12.4 kWh/m^2 for the proposed case. Also to meet the thermal standard, the conventional case increased the envelope construction cost by 127\$/m^2 whereas the proposed local material case increased this cost by only 86\$/m^2.

Thus, using local material for the house envelope construction, enabled us to have savings of around 41\$/m^2.These savings will be used to invest in SWH and PV. A total of 9840$ savings will be the first constraint for the first scenario; the sizing of the system will depend mainly on this constraint.

The eQUEST (18) software was used to get the hourly energy consumption of the typical house. All data was entered for the building envelop, HVAC systems, lighting, and equipment. By using ASHRAE IWEC2 Weather Files for International Locations and EnergyPlus Energy Simulation Software weather data, the weather files for Damascus were used since the weather for Bekaa area is the same as that for Damascus (24). After simulating the house, the total energy consumption per month as well as the average daily profile through the year is predicted as shown in Figure 4 and 5. The peak demand is noticeable at around 6 p.m. when the house is almost fully occupied. The peak demand reached 6.6 kW during summer season due to the cooling load. The daily average consumption reached 32 kWh, and the total energy consumption for one year was found to be equal to 11,826 kWh.

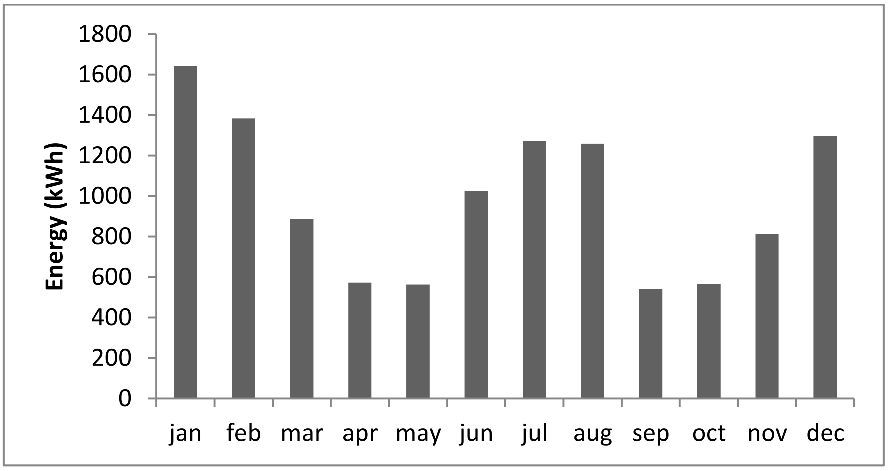


Figure 4: Energy Consumption for each month

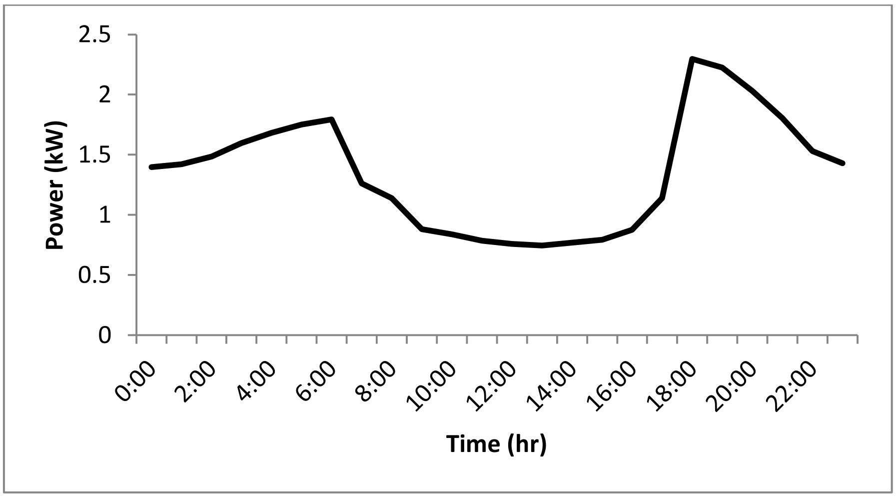


Figure 5: Average Hourly Electric Consumption Profile

Another data that was extracted from eQUEST was the annual hot water load. The domestic hot water system used in this study is considered to use gas. It was found that around 4500 kWh is consumed yearly to heat the water. Based on 40 L/day/occupant (25), the average daily usage of hot water was estimated to be around 280 L. This value will be used to size the solar hot water system to replace the gas heaters whenever possible.

B. Designing the Alternative system

1. Domestic Hot water Sizing

The SWH sizing depends on the solar radiation available at the site, the type and efficiency of the collectors, the house hot water demand or the number of occupants, and the desired hot water temperature (26). RETScreen (27) software is used to size the SHW. By using the number of occupant of 7 with an average of 65% occupancy rate, RETsreen estimated the average daily usage of around 273 L which in accordance of the estimated value in eQUEST with an error of only 2.5%. The base case was modeled as per the results of eQUEST, and the proposed case consisted of two SWH collectors of 2.8kW capacity with a total storage capacity of 400 L at a cost of 2000$ as per current market prices. The area required to install these solar collectors is around 7 m^2. The proposed system resulted in savings of 80% and the financial analysis estimated around 6.5 years to payback the invested amount in the SWH system. This was based on the current market rate of 1.2 $/Kg of propane gas (28) which is usually used in gas heaters.

2. PV Sizing

To predict the maximum size of PV modules that can be used to cover the available roof area, the following equation is used;

$$P_{dc} = A * \eta_{PVCells} * \frac{1kW}{m^2} \quad \text{of insolation} \qquad (1)$$

Where P_{dc} is the DC rating power of the PV modules, A is the total area of these modules, and $1kW/m^2$ is the maximum solar insolation that can be reached at the peak sun hours.

If considering one third of the roof area to be partially filled with cooling systems or electrical and mechanical rooms, SWHs, and the remaining to be the space lost between the PV modules, the area left that can be filled with PV modules is equal to 80 m^2. Since the efficiency of the PV cells available in the market ranges between 7 to 18% as mentioned earlier, a 15% efficient module under standard test conditions (STC) is considered for this study. Due to the fact that PV efficiency drops by 0.5% for each one degree Celsius increase above STC temperature of 25^0C (29), this considered 15% efficiency will slightly decrease during summer time, in July and August specifically, where it might decrease to around 14.5% if considering an average temperature of 30^0C during this period of the year. According to Wakim (30) the PV efficiency in Kuwait decreased by 17% due to sand and dust after 6 days, but this is not a problem in the Lebanon, Bekaa area specifically, as we do not face sand storms as in Kuwait. This does not cancel the fact that regular cleaning of the modules is necessary to remove all dust and thus preserve the same efficiency. Thus, the maximum possible size of the PV modules to be considered is 12 kW. However, to reach the best optimized system, a range of PV sizes from 0 kW to 12kW is considered. The selected size will depend on the initial construction cost savings in scenario 1 and on DG elimination for Scenario 2.

Batteries and inverter are also needed for the PV system. The batteries are sized in a way to cover the intermittent nature of solar energy. For this study, batteries of 12V rated capacity with a maximum storage capacity of 200 Ah will be considered. To estimate the battery capacity needed to cover the electrical demand, equation 2 is used. (14)

$$C = \frac{TD}{LU\eta_b} \tag{2}$$

Where C is the total capacity needed in Ah, T is the Autonomy time in days, D is the Daily need in Wh, L is the Deep discharge limit (between 60 and 80%) (14), U in the nominal voltage of the battery pack in V, and η_b is the battery efficiency that represents all losses.

To get rid of the diesel generator, the maximum capacity required to cover the demand needs is predicted to be around 24 batteries. However, to have the best optimized system for both scenarios, a range of batteries number from 0 to 28 is considered. To size the inverter, the total Watt of all appliances operating at the same times should be considered. For safety, the inverter should be considered at least of 30% bigger size (14). Since our peak demand reaches 6.6 kW, the maximum inverter size needed is predicted to be around 8.5 kW if the diesel generator will be eliminated. However, to have the best optimized system for both scenarios, a range of inverter sizes from 0 to 10 kW is considered.

3. Size of the Generator

In a typical house in Lebanon, people are relying either on personal small home diesel generators or on monthly subscription to private companies that sell electricity being generated from large diesel generators. Based on the highest demand of 6.6 kW, 8 kVA (6.8kW) rated generator is assumed to be used to cover the utility cut off hours. So, the base case study is a 6.8 kW diesel generator used with the utility grid to cover the electricity demand. A range of diesel generators with lower capacities are then considered to get the best size, if still needed, to assist the PV panels to cover the electricity shortage based on cost optimization results.

CHAPTER IV

HYBRID PV SYSTEM SIZING AND SELECTION MODEL

To study the feasibility of installing a hybrid PV-battery system in a typical house, HOMER (19) software was used. Its sensitivity and optimization analysis algorithms help in evaluating the economic and technical feasibility of different technology options while accounting for variations in technology costs and energy resource availability. HOMER's optimization algorithm is an enhanced grid search; it is the most robust since the problem is very non-linear and non-convex (19). It enables the user to optimize a simulation rather than an analytic function and gives him plenty of flexibility about the decision variables. It is enhanced relative to a simple grid search in that it disregards systems that are smaller than any system it has already found to be infeasible and it re-uses results when possible. Since it was validated by Bekle and Palm (31), Bludszuweit et al. (32), Jamil et al. (33), Shaahid and Elhadidy (34), and many others as a good tool to access and analyze the importance of using different renewable energy sources, HOMER was used in this study to access the importance of PV.

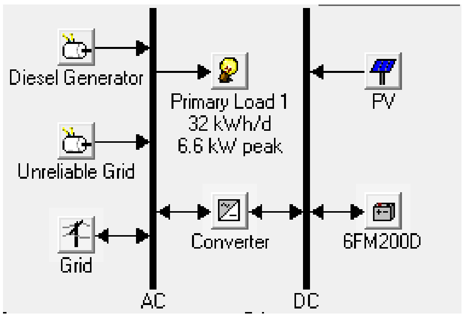


Figure 6: HOMER Model

By using the hourly solar radiation data for the whole year, hourly load profile as resulted in eQUEST, PV, diesel generator (DG), batteries, converter, and unreliable grid, the model for the hybrid PV-grid system for the house is as shown in Figure 6. The optimization parameters are the PV size, the generator size, the number of batteries, and the converter size. 0 to 12 kW PV sizes, 4 to 6.8 kW DG, 0 to 24 batteries of 12V 200Ah, 0 to 10 kW converter are the variable ranges used for each of these parameters. Three different schedules of operation for the unreliable grid will be considered to convey how the size and the savings of the PV system will be affected especially if the cut-off hours are during the time of peak PV production. For schedule 1 (SCH1), the grid is cut only at night for only 4 consecutive hours randomly alternating through months. For Schedule 2 (SCH2), in addition for the 4 night hours, the grid is always cut from 10a.m to 2p.m for all months. However, schedule 3 (SCH3) has both the 4 night hours and the 4 day hours randomly alternating through months. All component costs used in the model are based on current market prices. Also the case of having 100% grid supply; that is no shortages at all, will also be considered to see the effect on the system size and its feasibility. The cost of 1kW of PV is assumed 1500$, and the cost of 6.8 kW, 5kW, & 4 kW DG are assumed 4000$, 3200, and 3000$ respectively.

HOMER simulated these different configurations and scaled them according to their total lifetime installation and operational cost which is also known as net present cost (NPC). First it estimated if the proposed system can serve the electrical load, then it estimated the system’s NPC. The model was done over one operational year based on an hourly time-step simulations. The full year hourly load data obtained from eQUEST served as the input to HOMER. One of the main calculations that are hourly performed is the PV-battery supply which was compared to the required electrical load. If this supply satisfies the load, the excess will be sold to the grid. If the supply does not satisfy the load, the shortage will be covered by either the unreliable grid or the diesel generator.

The NPC used to represent the Life cycle cost of the system will be calculated according to equations 3, 4, & 5. (35)

$$NPC = \frac{TAC}{CRF} \tag{3}$$

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{4}$$

$$Salvage(\$) = C_{rep} \frac{R_{rem}}{R_{comp}} \tag{5}$$

The total annualized cost (TAC) is the sum of the annualized costs of PV modules, batteries, generator, grid… The capital recovery factor (CRF) depends on the lifetime of the project (N) the annual real interest rate (i). The lifetime of the project is considered to be 50 years with an interest rate of 6%. The value that remains from any component at the end of the project lifetime is the salvage value that will also be calculated in NPC. C_{rep} , R_{rep}, & R_{comp} are replacement cost, remaining lifetime, and component lifetime respectively. The following sections presents the two scenarios studied with their simulation and optimization results.

A. Scenario 1: PV-Battery-DG System

Choosing a system by only using the savings attained from decreasing the initial cost of envelope construction material plus the savings of decreasing the required backup diesel generator is the first scenario studied and optimized. The cost function is represented by:

$$C_{PV,capital} + C_{b,capital} + C_{I,capital} = Sav_E - C_{SWH,capital} + Sav_{DG,capital} \qquad (6)$$

Where $C_{PV,capital}$, $C_{b,capital}$, $C_{I,capital}$, $C_{SWH,capital}$, $C_{DG,capital}$ are the PV, batteries, invertor, SWH, and diesel generator capital cost respectively. Sav_E is the total savings in envelop material, $Sav_{DG,capital}$ is the savings in decreasing the generator capital cost.

So the most feasible combination between the backup generator, size of the PV, batteries, and converter for scenario 1 is constrained by the initial cost. The best optimized case should have a capital cost not exceeding the cost of the DG plus the savings of building material (9840$) minus the cost of the SWH system (2000$) plus the savings due to decreasing the generator size. This capital cost should not be much less than the constraint to benefit as much as possible from the savings attained. So, the initial capital cost should be less than or equal to 11840$ but not less than or equal to 11400$. After meeting the initial cost constraint, the best optimized case should also cover the needed electric consumption at the lower possible NPC. This would be based on life cycle assessment; that is decreasing the total life cycle cost of the system components. The cost functions are represented by equations 7 to 12 as follows;

$$LCC = C_{PV} + C_b + C_I + C_{DG} + C_{grid} \qquad (7)$$

$$C_{PV} = C_{PV,capital} + C_{O\&M} + C_{PV,rep} \qquad (8)$$

$$C_b = C_{b,capital} + C_{b,O\&M} + C_{b,rep} \qquad (9)$$

$$C_I = C_{I,capital} + C_{I,O\&M} + C_{I,rep} \qquad (10)$$

$$C_{DG} = C_{DG,capital} + C_{DG,O\&M} + C_{DG,rep} + C_{fuel} \qquad (11)$$

$$C_{grid} = E_{purchased} * C_{1kWh,purchasing} - E_{sold} * C_{1kWh,sold} \qquad (12)$$

Where $C_{PV,capital}$, $C_{b,capital}$, $C_{I,capital}$, $C_{SWH,capital}$, $C_{DG,capital}$ are the PV, batteries, invertor, SWH, and diesel generator capital cost respectively. Sav_E is the total savings in envelop material, $Sav_{DG,\ capital}$ is the savings in decreasing the generator capital cost. $C_{PV,O\&M}$, $C_{b,O\&M}$, $C_{I,O\&M}$, and $C_{DG,O\&M}$ are the operational and maintenance cost for the PV, battery, invertor, and diesel generator respectively. $C_{b,rep}$, $C_{I,rep}$, and $C_{DG,rep}$ are the replacement cost for the battery, invertor, and diesel generator respectively. $E_{purshaces}$ and E_{sold} are the electric energy grid purchases and sales respectively. $C_{1kWh,\ purchasing}$ and $C_{1kWh,sold}$ are the cost of each 1kWh being purchased from the grid and sold to the grid respectively which are equal to 0.1$.

B. Scenario 2: DG Free System

The second scenario will evaluate and optimize further investment in the PV system to replace the backup diesel generator based on life cycle assessment; that is its main objective is to decrease the total life cycle cost of the DG free system. The cost functions for scenario two are equations 7 till 12 as well but with excluding the DG component as follows;

$$C_{DG} = C_{DG,capital} + C_{DG,O\&M} + C_{DG,rep} + C_{fuel} = 0 \qquad (13)$$

$$C_{DG,capital} = 0 \,;\; C_{DG,O\&M} = 0 \,;\; C_{DG,rep} = 0 \,;\; C_{fuel} = 0 \qquad (14)$$

So the most feasible combination between the backup generator, size of the PV, batteries, and converter for Scenario 2 is constrained by the DG elimination. The best optimized case should have the lowest NPC, cover the needed electric load, and be DG free.

CHAPTER V

RESULTS AND DISCUSSION

For Scenario 1, the best optimized case meeting the cost constraint for the three schedules had an initial capital of 11400$ and consisted of a 2kW PV, a 4kW DG, 12 batteries, and a 2 kW converter in addition to the unreliable grid.

Table 1: Scenario 2 Best Case Component Sizes and Important indicators

	SCH1	**SCH2**	**SCH3**
	SIZE/NUMBER/VALUE		
PV (kW)	12	3	12
Batteries: 6FM200D	24	24	28
Converter (kW)	9	6	9
Initial capital ($)	29000	15100	30600
Renewable fraction	0.673	0.172	0.59
Annual Electric Load covered by PV (kWh)	5711	5063	6100

For scenario 2, the best optimized case is the DG free case with the lower NPC. In addition to the unreliable grid, the best case components for the three schedules are provided in Table 1. The differences among the three schedules are mainly due to the ability to have grid sales. It is obvious from SCH2 results that a 3 kW PV with 24 batteries is enough to get rid of the DG if the grid is cut during the peak PV production and the lowest energy consumption duration; however, the more we increase the size of the PV, the more grid sales are possible. Since the potential of selling to the grid is mainly possible during the PV peak production between 10 a.m. and 2 p.m., increasing the size of the PV to 12 kW is only attractive in SCH1 where the selling is always possible and to SCH3 where the selling is still possible but with less occurrence then SCH1; however not to SCH2 since the grid is always off for this duration of time. More batteries and a bigger convertor are needed for SCH3 since for some months the grid might be off during the peak load. The renewable fraction depends not only on the size of the PV but also on how much the PV electricity generation could offset the conventional generation. This explains the differences of this fraction for the three schedules where it exceeded 0.6 for the SCH1.

Figure 7 shows the load covered by each of the PV system, DG, and the unreliable grid for the three schedules in base case, Scenario1 and Scenario 2. The yearly energy production of both systems exceeded the needed electric load of 11826 kWh and thus could have some grid sales ranging between 2% to 8% of the total consumption in Scenario 1 and between 6% and 143% in Scenario 2.

In Scenario 1, the PV system energy production reached yearly 3,842 kWh covering between 3,173 kWh and 3,491 kWh of the total electric load as shown in Figure 7. In Scenario 2, the PV system energy reached yearly 23052 kWh for SCH1 and SCH3, and it only reached 5763 kWh for SCH2. The production difference among the schedules in Scenario 2 affected mainly the grid sales where the electric load covered by this system reached 5711kWh, 5036kWh, 6100 kWh for SCH1, SCH2, and SCH3 respectively as shown in Figure 7.

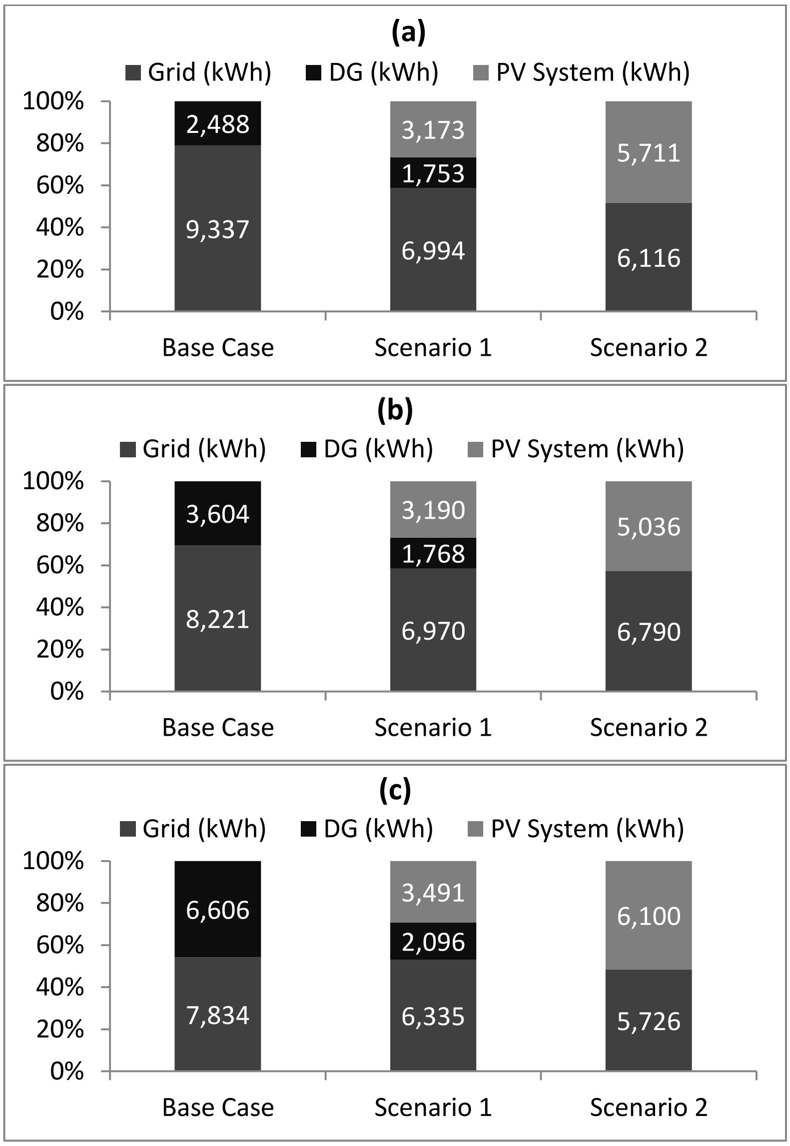


Figure 7: Electric Load Percentages covered by the Grid, DG, and PV system for the Base case, Scenario 1, and Scenario 2 in SCH1 (a), SCH2 (b), SCH3 (c)

The grid sales reached yearly a total of 942kWh, 205kWh, and 474kWh for SCH1, SCH2, and SCH respectively in Scenario 1 as shown in Figure 8. Much higher kWh sales are noticed in Scenario 2 as shown in Figure 9 which shows the variation of these sales throughout the year. SCH 1 had the highest sales since the grid was considered to be always on between 10 a.m. and 2 p.m. during which the PV output is at its maximum; thus selling the excess production was doable. However, SCH 2 had the lowest sales as during this same duration the grid was off for both Scenarios, and since it had a smaller size as in Scenario 1.

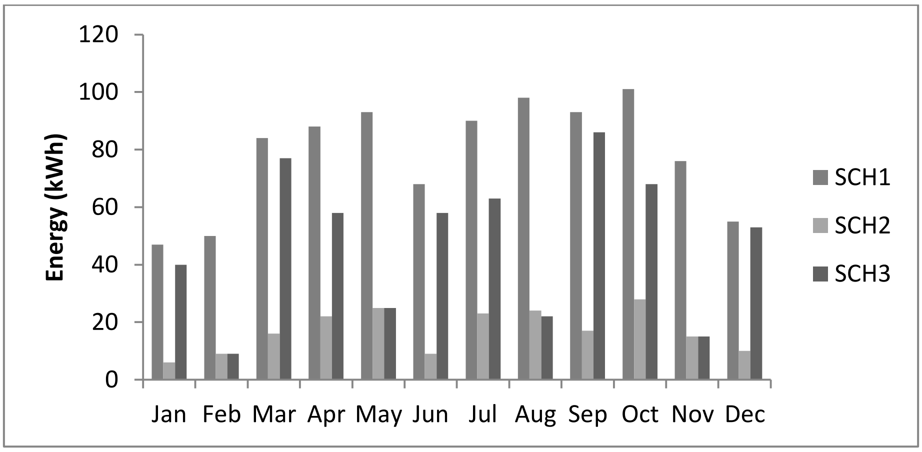


Figure 8: Scenario 1 Monthly Grid Sales for the three schedules

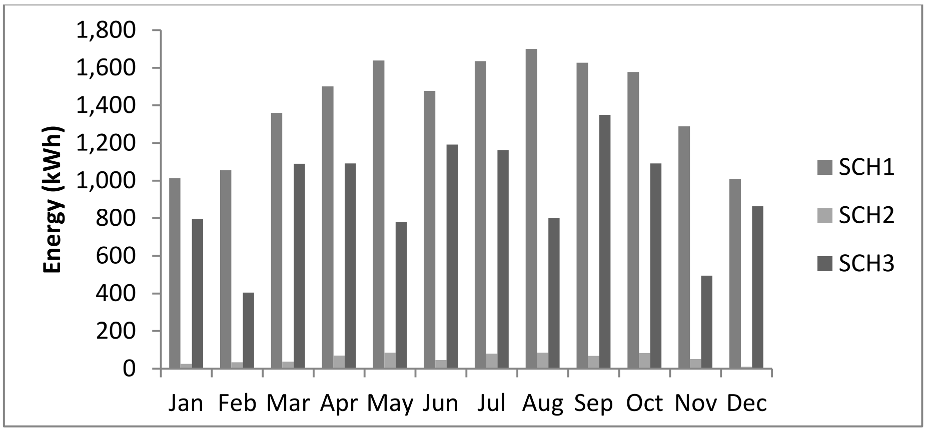


Figure 9: Scenario 2 Monthly Grid Sales for the three schedules

So, the load covered by the PV system along with grid sales allowed for net energy savings ranging between 30% and 35% in Scenario 1, and between 48% and 190% in Scenario 2.

However, if the grid is on all the time; that is there no need for a DG; the results for Scenario 1 is a 4kW PV and a 9kW converter, and that of Scenario 2, which in this case is only constrained by the roof area, is a 12kW PV with a 9kW converter. These results clearly show that no batteries are required since we have 24 hours grid supply. Figure 10 presents the annual grid purchases, load covered by the PV system, and grid sales for base case, Scenario 1, and Scenario 2. By using only the savings in construction cost, we can a PV system that can cover up to 25% of the electric load and around 34% of grid sales. However, these percentages will increase in Scenario 2 to 29% and 140% of the electric load and of grid sales respectively. So the load covered by the PV system in Scenario 2 will not increase much even if the size of the PV system is tripled, however the grid sales will be significantly affected by an increase of more than 100% as compared to Scenario1.

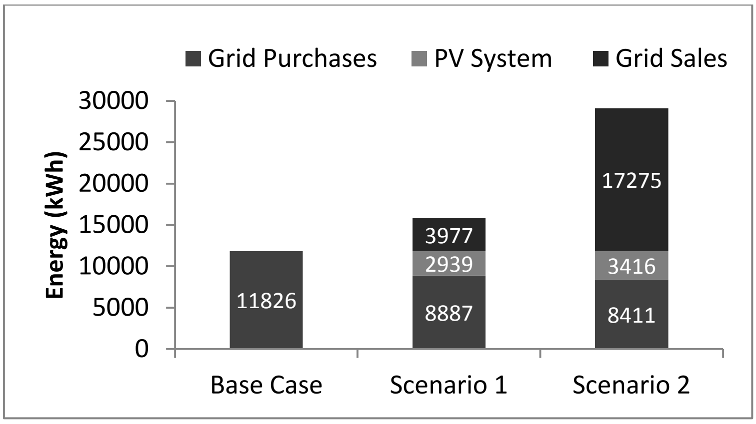


Figure 10: Grid purchases, electric load covered by the PV system, and grid sales for the Base case, Scenario 1, and Scenario 2

A. System Performance

This section will provide more detailed illustration of the system performance throughout the year. Eliminating both schedules extremes, SCH3 results will only be presented as it is the most possible schedule to occur and its related results reflected the actual situation the most. To study this performance, four months are chosen to represent the four seasons.

During January and July, and due to heating and cooling load respectively, the dependence on the DG during the cutoff hours in Scenario 1 is still high. However, during April and October, the PV output with the batteries storage almost eliminated the need to use the DG. In Scenario 1, the percentage of the daily load covered by the PV and battery storage reached 11% during January, 57% during April, 27% during July, and 58% during October. In Scenario 2, this percentage reached 45% during January, 66% during April, 62% during July, and 64% during October.

In addition to these load energy savings, during the PV production hours, between 10 a.m. and 4 p.m., and when the AC load is less than this production, the excess in energy is sold to the grid if the latter was on otherwise it will only charge the batteries. The maximum attained PV power reached 1.8 kW in Scenario 1 during October but with so close values for April and July. The daily PV output profile for the four seasons does not differ much, thus the reliability of the PV system can be considered similar all year round; it is not seasonal based. However, the penetration of the PV and the ability to cover the required load in all months depend on the required load itself. Here rises the need to have larger PV system to accommodate for the peak load and thus get rid of the DG.

In Scenario 2, most of the PV energy output is sold to the grid where these sales reached 82% of the PV output during the peak hours due to the fact that during this time the house load is minimal. The grid sales are not only important to home owners but also to the grid itself where it will be able to cover more of the needed load for other houses or non-residential sector. For instance; the grid is also supplying companies that have their peak load mainly between 10 a.m. and 4 p.m., so the excess in energy generated by the house with the PV can be used to assist the grid in covering the peak load for this company. If more houses invest is this system, they will make the grid stronger and increase its ability to cover more demand especially during the day. This will affect the Lebanese energy sector by having more reliable electric supply.

B. Comparison with Base Case

To check how profitable both investing the envelope savings in the PV system and then having a system that eliminates the DG, the comparison with the base case is done. The base case is the 6.8kW DG with the unreliable grid. Its levelized cost of electricity (COE), which reflects the unit cost of electricity generation over the life of the project, is 0.257$/kWh, 0.403$/kWh, and 0.402$/kWh for SCH1, SCH2, and SCH3 respectively. The higher the consumption of the DG, the higher the levelized COE due to high cost of diesel as compared to price of 1kWh paid to the grid.

Table 2 presents some of the economic indicators that reflect how much the investment is worth having it. SCH 1 had the worst indicators' figures since the daily grid cut-off hours are only four and during night; the DG needed contribution is minimal as compared to the grid contribution. The highest the contribution needed from the DG in the base case especially during the day, the more the PV system can have a better contribution.

Table 2: Scenarios 1 & 2 Economic indicators Results for the three schedules cases and the no shortage case

	Scenario 1				**Scenario 2**			
Grid Schedules	SCH1	SCH2	SCH3	NO Shortage	SCH1	SCH2	SCH3	NO Shortage
Levelized COE ($/kWh)	0.176	0.193	0.2	0.064	0.063	0.211	0.113	0.013
Annual Savings ($)	1290	2609	2556	692	3295	2976	4095	2069
Return on investment (%)	16.9	39.2	36.9	8.71	11.2	25.3	14.3	10.4
Simple payback (years)	5.73	2.93	2.95	10.7	9.41	3.73	5.71	9.38

In Scenario 1, as compared to SCH1, SCH2 and SCH3 had much higher return on investment of 39% and 37% respectively since they have 8 total cut-off hours out which 4 hours are during the day. The levelized COE decreased by around 50% in SCH2 and SCH3 and had a simple payback period for less than three years. The total savings from covering 27% to 30% of the total electric load and from selling to the grid in Scenario 1 reached around 2609$ as in SCH2.

In Scenario 2, even though the return of investment and payback period of SCH2 look better than SCH3, but this just because of the lower initial cost associated with the lower PV size. A levelized COE of 0.211 $/kWh with a payback period of around 6 years is an important indicator that can encourage home owners to cover their roofs with PV panels.

To clarify how the PV system in case of no shortages can also be considered a feasible investment; the economic indicators presented in Table 2 reflect this. The annual savings reached 692$ as in the case of Scenario 1 and 2069$ for Scenario 2. The simple payback period is around 9.5 years for Scenario 1 and increased to 10.5 years in Scenario 2.

C. Environmental Analysis

In addition to the benefits the above system will have in terms of having less costly electricity backup system, it will also have a positive impact on the environment. Minimizing or canceling the need for the DG generator will decrease the level of CO_2 emissions. To calculate these emissions the rate of CO_2 emission per kWh in Lebanon of around 700g/kWh as provided by the International Energy Agency (IEA) is used. This calculation is not important to home owners from economical view of point as they are not paying penalty for this. However, it is very important to look into these emissions from environmental perspective and thus this should be governmental concern.

A total of 9452 kg of CO_2 is yearly emitted to cover both the electric and heating load for the studied house. Having both SWH and the PV system will decrease these emissions by 87%, 82%, and 81% for SCH1, SCH2, and SCH3 respectively if only applying Scenario 1. As for Scenario 2, these percentages will reach 212%, 104%, and 173% for SCH1, SCH2, and SCH3 respectively. If the cost of one ton of CO2 emissions of 30$ (36) to be forced on governments as a penalty for each country's emissions, then the Lebanese government can have savings that can go up to 600$ as in

Scenario 2, SCH1 case. Figure 11 presents the savings that can be attained for each scenario for the three schedules.

If the PV system and the SWH were to be installed and integrated by similar houses in the Bekaa area, 10,000 houses for example, the government can have around five million dollars of savings from CO2 emissions only for Scenario 2, SCH3. These huge savings can then be used by the government to invest in more sustainable projects that will be reflected back on the house occupants themselves as well as on the whole society.

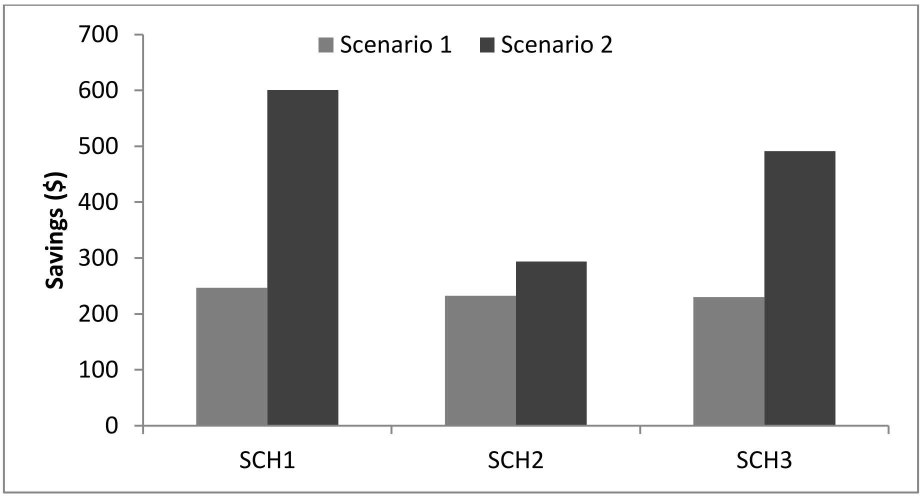


Figure 11: CO2 emissions Savings

This is again conveys the importance of encouraging people to start investing is such systems for the good benefits reflected in terms of economic growth and sustainable development.

CHAPTER VI

CONCLUSION

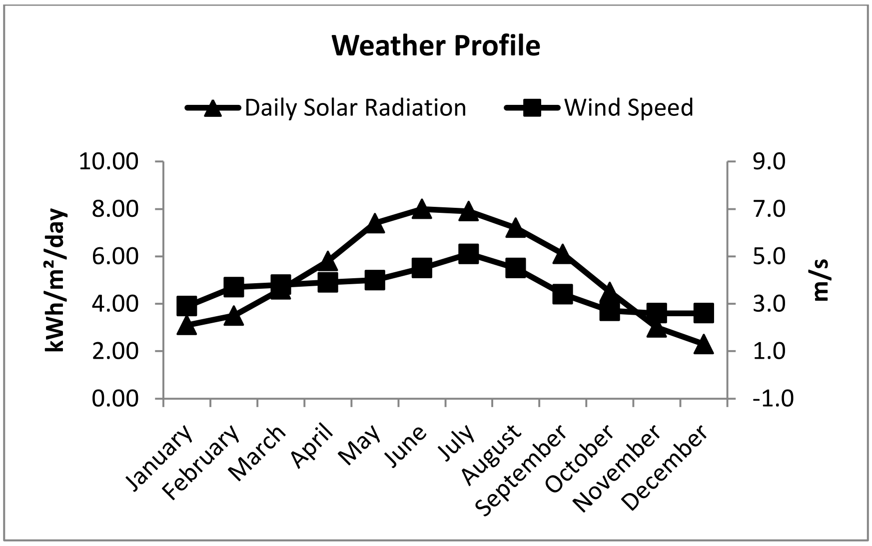
In the view of the above, the crucial role the solar energy can have in solving the electricity problem in Lebanon and countries with similar climate is proved. Integrating a hybrid PV system and a SWH heater in houses will generate not only direct profit to house owners but also to the whole society and energy sector. By using savings attained from integrating cheap local material for a typical house design of 41 $\$/m^2$ to invest in these renewable systems will result in further savings that can each up to 2933$ each year from both covering part of the electric load, hot water, and selling to the grid. However, if increasing the size of this system to eliminate the DG, the total savings can reach around 4472$ for each year. The being so, the government should stress more in this area and provide further incentives to both the end users and suppliers. The end users will be driven by low interest loans, low prices for PV and SWH, experienced suppliers and installers, and high prices of each 1 kWh being sold by them to the grid.

APPENDIX I

WEATHER PROFILE

This section includes the solar radiation and wind profile for the Bekaa area. The weather file used to simulate the weather of the Lebanese inland region is that of Damascus city since it is very similar to the Lebanese inland weather. The below figure shows the daily average solar insolation for each month as per NASA. The average annual insolation is found to be 5.29 kWh/m^2/day. The variation of this insolation throughout the year is also shown in the figure, where it reaches its maximum values during summer season. In June, the solar insolation can reach 8 kWh/m^2/day.

The average wind speed for this area is 3.6m/s, so it belongs to wind speed class 1. The wind turbine option will be eliminated from our study since class 1 is considered not suitable for installing a wind turbine; it is below the minimum requirement to have successful investment in wind turbines. Also the maximum reached speed is 5 m/s during July which also reflects that non-feasibility for installing a wind turbine even before investigating this using our optimization software.



APPENDIX II

COMPONENTS COST

Cost Table	Size / Quantity	Cost
PV, 1kW	1kW	$1,500
Battery	1	$400
DG	4kW	$3,000
	5kW	$3,200
	6.8kW	$4,000
Converter	1kW	$500
	2kW	$600
	3kW	$700
	4kW	$800
	5kW	$900
Grid (sales and purchase)	1kWh	$0.10

APPENDIX III

GRID SCHEDULES

Sch1 Best case Scenario (4 hours only at night)

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:00	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON
1:00	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON
2:00	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF
3:00	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF
4:00	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF
5:00	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF
6:00	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
7:00	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
8:00	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
9:00	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
10:00	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
11:00	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
12:00	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
13:00	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
14:00	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
15:00	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
16:00	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
17:00	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
18:00	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON
19:00	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON
20:00	OFF	OFF	ON	OFF	OFF	ON	OFF	ON	ON	OFF	ON	ON
21:00	OFF	OFF	ON	OFF	OFF	ON	OFF	ON	ON	OFF	ON	ON
22:00	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON
23:00	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON

Sch2 Worst Case Scenario (4 hours at night alternating, 4 hours during the day at maximum PV output)

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:00	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON
1:00	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON
2:00	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF
3:00	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF
4:00	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF
5:00	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF
6:00	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
7:00	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON

8:00	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
9:00	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
10:00	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
11:00	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
12:00	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
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20:00	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON
21:00	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON
22:00	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON
23:00	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON

Sch3 8 hours every day (4 day 4 night alternating)

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:00	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON
1:00	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON
2:00	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF
3:00	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF
4:00	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF
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7:00	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON
8:00	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON
9:00	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON
10:00	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON
11:00	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON
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16:00	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF
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18:00	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON
19:00	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON
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21:00	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON
22:00	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON
23:00	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON

APPENDIX IV

SIMULATION GRAPHS

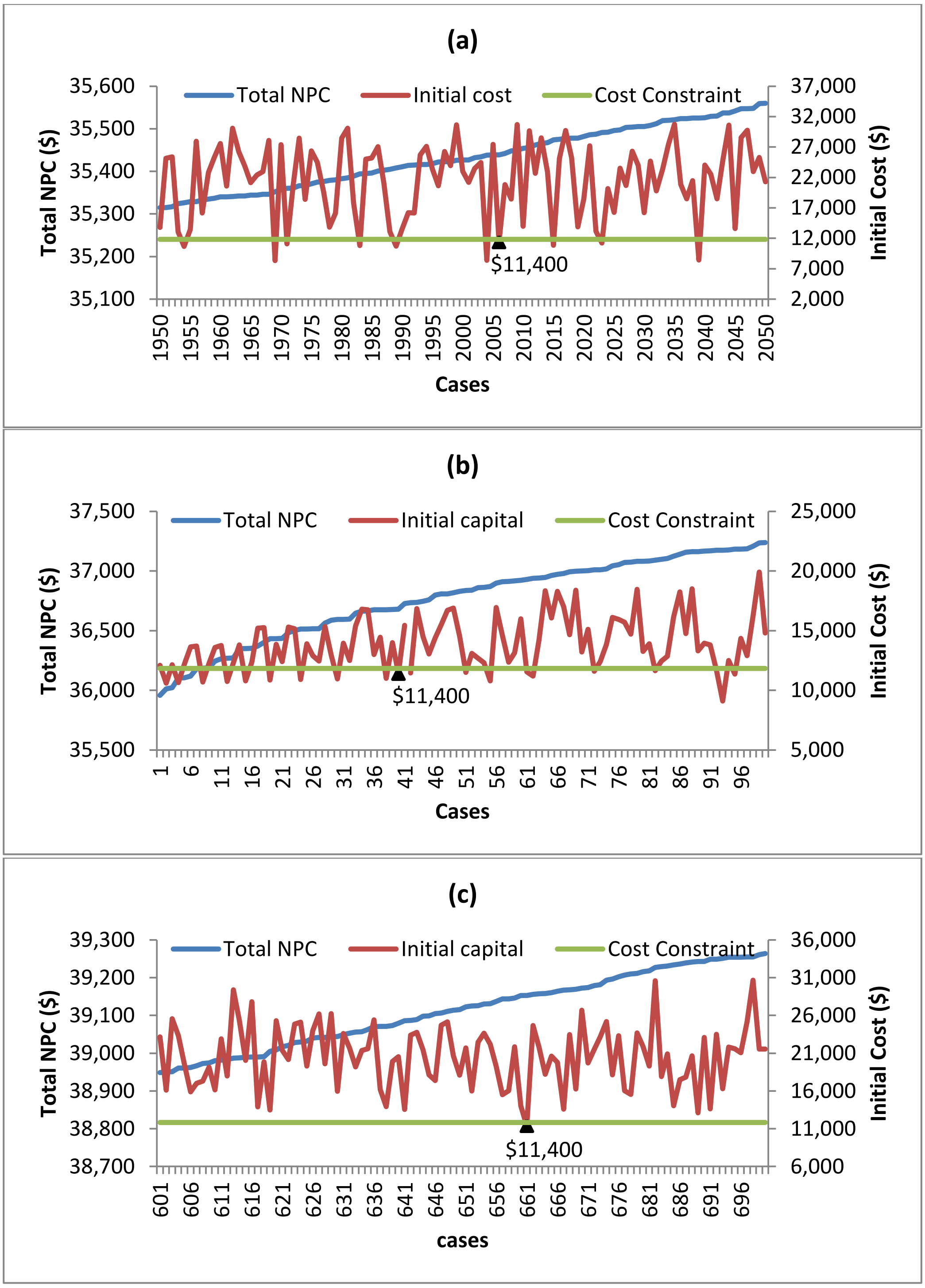

Figure 12: Total NPC and Initial Cost of a selected simulation results that included the best case for scenario 1 for the three schedules: (a) SCH1, (b) SCH2, and (c) SCH3

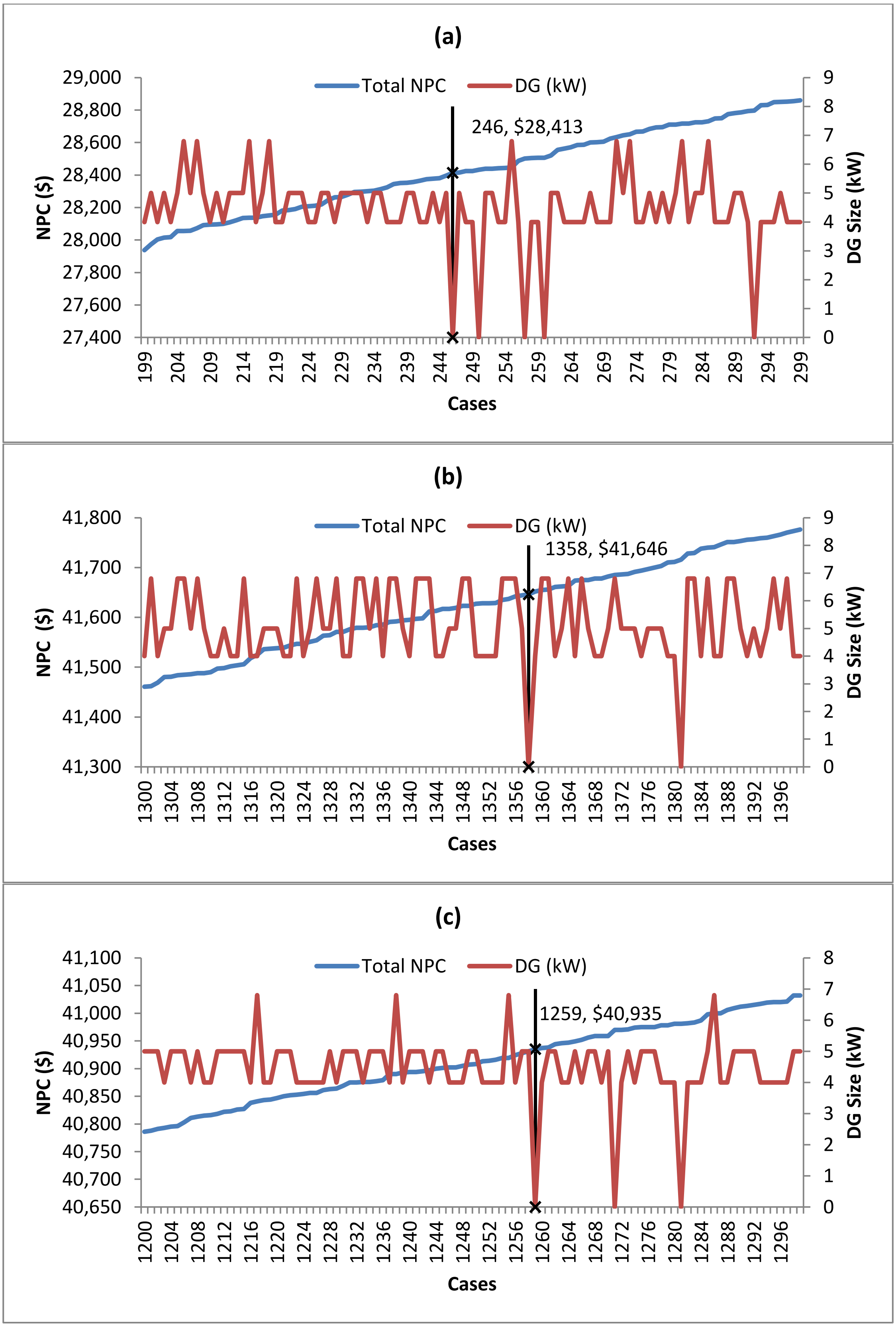

Figure 13: Total NPC and size of the generator for 100 simulation results cases which includes the first case where no DG is required for the three schedules: (a) SCH1, (b) SCH2, and (c) SCH3

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