KTH Industrial Engineering and Management

Development of an Optimization Method/A Tool for RE application in Intermittent Grids with focus on Lebanon

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Master of Science Thesis

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KTH Industrial Engineering and Management	**Master of Science ThesisEGI 2012:81MSC EKV910** **Development of an Optimization Method/A Tool for RE application in Intermittent Grids with focus on Lebanon** Elie Abou Jaoudeh

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Abstract

Renewable energy applications require sound design and optimization of life cycle costs because they need upfront investments and as long as possible operating lifetimes are expected. Using modern tools for optimizing designs of grid-tied and autonomous plants allows investors to deploy these technologies while keeping risks within acceptable limits.

Nevertheless in Lebanon, the grid is intermittent and the most adapted solutions are dual-mode plants that can operate autonomously and with grid-tie. There are no existent simulation models particularly adapted to optimize these applications for such a situation. The objective of this research is to suggest and test a model adapted from commercially available software that can simulate the particular conditions of Lebanon. The studied solution has a PV generator associated with a PV charge controller, lead acid battery, a dual mode inverter, and transfer switchgear and protections. The research successfully met the objective of finding a setup in HOMER 2.68beta for simulating and optimizing a PV-Battery AC plant for an intermittent grid with scheduled blackouts.

The setup and adaptation in HOMER is made to replicate an existing reference PV-Battery plant at a public school. The measured datafrom this public school is used to validate the results obtained from the adapted HOMER simulation. The grid is supplied for an average of 12 hours per day at the reference site with a tariff of USD 0.1/kWh.

After the validation process, a sensitivity analysis is performed to simulate this plant under

a. Different grid supply hours, 12 and 18 hours of supply daily
b. Different grid electricity prices, USD 0.1 and 0.1375 /kWh
c. Simulation of PV plants to meet other load profiles typical of community and municipality building centers

All the simulations cross matched 20 different PV generator sizes to 7 different battery sizes for 5 different total setups.

The levelized cost of electricity, COE, is the main parameter used to find the optimum setups, whereas options that shortened the battery life to less than 12 years or couldn't meet at least 90% of the required

yearly load were filtered out. The COE is calculated manually since several corrections related to grid and net-metering limitations are not obtained directly from HOMER.

The simulated results can serve as a good indicator on how the systems would perform for typical public institutions in Lebanon, given the current conditions, and knowing that the range of this study is limited to small scale institutions with consumption levels less than 30 kWh/day. Storage capacity should also be limited to 100 kWh/day of useful storage, since batteries are not the best option to use for storage capacities higher than the mentioned limit.

The setup has a great potential for advancement and acts as a first step for Lebanon to have a specialized tool for simulating the performance of PV-battery AC plants optimized for the conditions existing in the country. Future steps could be made to improve and diversify the software to include:

- irradiation data that come from actual data logging data from other PV sites which are installed around the whole country, almost a 100
- financial analysis for offsetting private generation with fossil fueled gensets, which is the main backupfor electricity blackouts
- wind turbine simulations, several installations are provisioned to be completed by the end of 2012, and it would be possible to carry out a similar validation process for small wind turbines
- pollution and other environmental costs
- value of lost load, “VOLL”, to compare different options in parallel with COE.

P R E F A C E

This publication is in partial fulfillment of my M.Sc in Sustainable Energy Engineering at KTH University. I am from Lebanon and work there in an UNDP project dedicated to promoting renewable energies on all levels including the implementation of around 100 projects using several renewable energy resources. My idea was to create a research that can fill a missing gap in the Lebanese renewable energy market, a software that can simulate and optimize renewable source electricity for Lebanon. This is due to the current electrical grid situation which is intermittent in supply, with scheduled blackouts, among other factors that you will discover in this publication. The research had an added benefit of being able to use data, collected from an existing PV plant installed at a public school, to validate the software results and setup.

I would like to thank the people who contributed to the writing of this dissertation to my advisors Dr. Amir Vadiie, from KTH, and Mr. Xavier Vallve, from TTA for their continuous support. I am very grateful to my mentor Zghank Lein who always taught me how to move forwardand was always there for me. I am also thankful to Mrs Jihan Seoud and Dr. Hassan Harajli from UNDP and CEDRO respectively for their support throughout this degree. And last but not least to my friends Elie and Elsi Hakmeh, who helped me perfect and review this work for long hours.

I would like to end this note with the hope that you, the reader, find this work enjoyable and beneficial as much as I did.

Elie Abou Jaoudeh

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Introduction

The overall objective of this thesis is to design a method to be able tosimulate and optimize renewable energy (RE) power production for small scale applications in an intermittent grid, with focus on Lebanon. Due to the intermittent grid, the RE applications installed in Lebanon are dual mode plants able to operate autonomously or with grid-tie. Even though modern software are able to give good results for simulations of RE applications, but existing simulation models cannot replicate dual-mode operation. The novelty in this research is to take an existing RE simulation software, HOMER2.68beta, and create a model in it that is able to simulate and optimize performance of RE applications in an intermittent grid with scheduled blackouts. The scope of this study is for small scale RE applications with loads less than 30kWh/day and with battery storage not exceeding 100 kWh of usable energy.

The idea is to create a setup on HOMER2.68beta which is able to replicate the conditions in Lebanon, and then validate this setup with data obtained from an actual reference renewable energy installation. The setup parameters are the national grid and its schedule of electricity supply, the consumption of the reference site, and a replication of the renewable energy system, a PV plant for this case, that was installed on this site. The simulation results will be cross-matched and validated with results of the reference site obtained from an extensive data logging setup already installed with the PV plant. One of the biggest challenges is to re-create the schedule of the Lebanese grid, which has an average daily hourly supply of 12 to 21 hours, depending on the region. The capital city of Beirut generally receives 21 hours of daily supply, and the amount diminishes with increased distance from the capital until it reaches the 12 hours daily supply mark for rural areas such as the area considered in this research. The reference site chosen is Meniara Public School in the village of Meniara in the north of Lebanon and has a PV plant of 1.8kW_{STC}withbattery backup.

The intermittency of the grid in Lebanon has created several problems for the residential and commercial sectors, which turned to privately owned diesel generators in order to cover their electricity needs. A method which is not cost efficient since the approximate cost of self-generation with diesel fueledgensetscosts around 0.4 USD/kWh compared to the 0.1 USD/kWh supplied by the national grid. With the emerging awareness about renewable power production in Lebanon several private investors, ESCO's, among others are seeking to create RE projects for power production. Having the ability to be able to simulate and optimize the performance of such systems will lower the investment risks and consequently increase the number of RE projects.

The reference site chosen is an installation done by the CEDRO-UNDP project, in which I work. Part of the mandate of this project is to install renewable energy systems, such as photovoltaic electricity generators with battery backup for public owned sites, such as schools, community centers, and municipal buildings. All those installations have data loggers installed in them to collect hourly data to assess their performance. Most of those installations are either 1.125 or 1.8 kW (STC), with a few of them that can cover up to 2.7 kW (STC), and they can all operate in dual mode. The PV plants are not optimized for each implemented site, but are optimized to be able to accommodate for the consumption of all the implemented sites as much as possible as with using the least possible different designs. Since CEDRO project or the UNDP do not implement the projects directly, a bidding process is undertaken to choose contractors for implementing the installations. The need for standardizing the systems is justified by the complicated bidding process.Recently, a governmental bill approving net metering has been passed, and the installations have been programmed to be able to back-feed to the grid when certain conditions are met, such as battery state of charge and availability of PV power and consumption loads.

In HOMER, conditions of the Lebanese grid were implemented, but with certain differences related to the limitations of programming parameters in the software. One of those differences is the grid blackout schedule in HOMER which was set as a monthly rotation while in fact on site it is a daily rotation that exists in the grid. Also, most of the beneficiaries from the systems have implemented several energy efficiency measures, which cause the data to differ than what was expected from the design. Those measures are mostly related to saving on the PV system for critical operations and using the grid for heavy duties.

This study focuses special attention on battery sizing, optimization, and lengthening total life, as well as electricity cost per kWh for various sized systems. Once the model is validated, sensitivity and optimization analysis of the PV plant were carried out. Also simulations for similar PV plants installed in different types of institutions were performed.

1- COUNTRY PROFILEANDPV PLANT DESCRIPTION

1.1 Country Profile and Energy Situation

a. Lebanon's geographical data

Lebanon, officially the Republic of Lebanon, is a small country in the Middle East with a large eastern coast on the Mediterranean Sea, bordered by Syria from the East and North, and Israel-Palestine from the South. The total surface area is 10,452 square kilometers and located between latitudes 33° and 35° N, and longitudes 35° and 37° E.

Figure 1. Geographic Location of Lebanon

Lebanon has a moderate Mediterranean climate. In coastal areas winters are generally cool and rainy whilst summers are hot and humid. Elevated areas have lower temperatures and high mountains are characterized with a large amount of snowfall which generally remains until early summer. It should be noted that mountains rise steeply in from the coast.

b. Energy Situation

The country imports more than 97.5%, 5400 kToe, of its energy from neighboring oil producing countries through its sea ports. Most of these imports are Heavy Fuel Oil (23.9%), Gasoline (27.2%), and Gasoil (35.4%) for electricity production and transportation. The rest of the energy is produced by hydroelectric dams and some use of biomass for heating and cooking in few regions. In 2009, the IEA Energy Statistics showed that Lebanon imported 6.63 MToe of energy but only produced 0.17 MToe.

c. Energy Security

Given that most of the energy used in Lebanon comes from imports from neighboring Middle Eastern countries, the energy security is very low and this goes for several reasons:

- Dependency on political and security stability in foreign countries, and this dependency can be felt now when most of the oil exporting countries are facing interior problems whether in the form of political unrest or security breaches. Notably, Lebanon was supposed to import natural gas from pipelines from Syria and Egypt, both of which are in political instability, and in the case of Syria the conditions are sometimes labeled as civil war.
- Dependency on political and security stability in countries in the path of energy import, similar to the case above.
- Repetitive clashes between Lebanon and neighboring countries which, most often, leads to blockades to fossil fuel import routes. Though in the foreseen future, the situation seems to have calmed on that front.
- Increasing prices and low economic power to subsidize costs by the government. In the past, the government used to subsidize several fossil fuel energy products, such as diesel used for heating during the winter season. But with the increasing prices, the Lebanese government is not subsidizing these costs anymore, and is only subsidizing electricity production.

The factors counted above, and several others which are not as urgent, are driving forces towards finding more localized sources for energy production, the state of which will be discussed further in this section.

d. Electricity Sector

Electricity is provided to the country through a public utility company, Electricite Du Liban (EDL). The country is characterized by 99% electrification but with a supply deficiency which leads to scheduled blackouts amounting between 3 to 12 hours per day, depending on the region. The grid is old and lacking in maintenance on several fronts and this leads to technical losses higher than 15% of the electricity generation value. It should also be noted that several power plants have surpassed their normal operating lifetime and are now being operated at very low efficiency.

To compensate for the deficiency in electricity supply, most Lebanese households have access to neighborhood generators which operate on diesel fuel and pay around 0.4 USD/kWh which is not affordable for everyone. The cost of private generation is approximated in the policy paper of the

Lebanese Ministry of Energy and Water; several neighborhood generators are selling the electricity slightly more expensive than the mentioned value.

The major fuels used for electricity generation are Heavy Fuel Oils and Diesel, with plans to move towards the use of Natural Gas coming through pipelines from neighboring countries.

Below are descriptive tables summarizing some key factors in the Lebanese electricity sector taken from the Policy Paper published by the Ministry of Energy and Water in 2010.

Table 1. Summary of key parameters for Lebanese Electricity Sector

Average Available Capacity (MW)	1500	Power Purchase (% of Total)	7.5	Cost of Production (USc/kWh)	17.14
Average Demand (MW)	2100	Thermal Power plant Production (% of Total)	88	Selling Cost (USc/kWh)	9.85
Annual Demand Growth (%)	7	Hydroelectric Production (% of Total)	4.5	Electricity Demand (Thousand GWh)	15
Energy Not Supplied (GWh)	3478	Financial Deficit (Billion USD)	1.5	Electricity Supplied (Thousand GWh)	11.5

e. Net Metering

In the middle of year 2012 a net metering bill has been approved, and it is now possible for every subscriber to the grid to trade electricity with the grid operator under certain conditions:

- The electricity traded should have renewable origin.
- The grid operator is not required to pay any fees to the customer if the latter has more electricity sold to the grid than used from it. The zeroing of the meter is scheduled at the end of the fiscal year of EDL, which is around December.

f. Renewable Energy Potential

Several natural exploitable renewable energy resources exist in the country. A small list with respective information is given below:

- Hydropower: A large amount of rivers exist due to the nature of the mountainous landscape which slopes steeply towards the coast. Rivers are seasonal and largely affected by the snow cover of the mountain peaks. Hydro dams constitute the major potential from this resource.
- Solar energy: Horizontal irradiation of 5000Wh/m^2 depending with the maximum in summer, according to PVGIS of the Join Research Center of the European Commission. The exploitation of this resource should take into account limited land availability for large centralized projects.
- Wind Energy: The CEDRO project recently completed the wind atlas for Lebanon with an identified potential exceeding 1.5GW.
- Bioenergy: Several resources exist, mainly municipal waste and olive plantation residues, the full bioenergy assessment study was also completed by the CEDRO project.

1.2 Renewable Energy System Description

a. CEDRO-UNDP Project

A project funded by the Spanish Government through the Lebanese Recovery Fund, which was initiated after a destructive war with Israel in 2006. The CEDRO project and the funds, totaling USD 9.75 Million, are run by the UNDP office in Lebanon. The project has many goals related to the dissemination of renewable energy (RE) and energy efficiency (EE) projects distributed on several levels:

- Level 1: Implementation of end use EE and RE demonstration projects in around 100 public sites mostly public schools, governmental hospitals, community centers, and municipalities.
- Level 2: Using CEDRO knowledge and experience towards alleviating barriers to increased penetration of RE and EE applications, such as the net-metering concept for distributed RE generation which was pushed through by CEDRO.
- Level 3: Targeting public awareness issues on climate change, energy consumption, RE and EE applications through workshops, seminars, and the implementations themselves.
- Level 4: Increasing the availability of data related to RE and EE performance parameters and benefits and on consumption patterns, via the data loggers installed on all the sites implemented so far.

- Level 5: Supporting the formulation of a national sustainable energy strategy and action plan through a research and development program, this produced so far the "National Bioenergy Assessment of Lebanon" and the "Lebanese Wind Atlas", and an ongoing study on the potentials of micro-hydro.

b. Site Selection For Public Schools and PV Plant Sizing

An extensive process is followed to select each site, depending on a grading system linked to site ownership, consumption (should be in the level that can be displaced by small PV systems), beneficiary interest, impact, etc. The PV power systems' designs were standardized to ease the CEDRO bidding process for selecting the contractors that are to supply and install the systems. It has been initiated with two standardized designs of 1.125 kW and 1.8 kW (STC) PV generation, and later on two other capacities were added for larger sites of 2 kW and 2.7 kW (STC). To preserve the longevity of the installations and to protect them from over-consumption in case the beneficiaries didn't implement energy efficiency measures, it was decided to include, as part of the project, a priority line to be fed directly by the PV backup system. In the case of surplus energy generation, the PV system will back feed into the main electrical line, and eventually if no consumption exists on that line as well, it will feed back to the utility grid with the concept of net-metering. An example of site selection and respective system sizing is given in Table 2 below.A count of all equipment found on a certain side was made with their respective power consumption, and then an assumption was made to assess how many hours per day each of these equipment was needed. The result is the approximation of the daily consumption expected on the priority line in the school.

Figure 2. Meniara Public School PV panels

Table 2. Priority Line Consumption Approximation for Meniara Public School. The colored items are connected to the priority line

	Number	Watts/Unit	Watts	Time (hrs)	Wh/day
TC-Lamps	3	36	108	5	540
CFL	41	50	2050	5	10250
Computers	2	200	400	3	1200
Printers	1	30	30	0.5	15
Laser Printer	1	570	570	0.1	57
Photocopier (standby)	2	10	20	5	100
Photocopier (operation)	2	800	1600	0.5	800
TV	1	200	200	3	600
Electrical Space Heater	2	1000	2000	0	0
Fridge	1	150	150	6	900
			Total Consumption		14462
			Priority Line Loads		13505

Table 3. Energy and autonomy that can be expected from the PV power systems - 1.125 kWp and 1.8 kWp respectively as a function of load during the autonomous operation

Intensity of secured load	Output Inverter Voltage	Power Design	Energy Battery (75%)	Energy Photovoltaic	Autonomy
10 A	220 Vac	2,000 W	7,560 Wh	0 Wh/day	3,43 hours
				1,500 Wh/day	4,11 hours
				3,000 Wh/day	4,8 hours
7.5 A	220 Vac	1,650 W	7,560 Wh	0 Wh/day	4,58 hours
				1,500 Wh/day	5,49 hours
				3,000 Wh/day	6,4 hours
6 A	220 Vac	1,320 W	7,560 Wh	0 Wh/day	5,72 hours
				1,500 Wh/day	6,86 hours
				3,000 Wh/day	8 hours
5 A	220 Vac	1,100 W	7,560 Wh	0 Wh/day	6,87 hours
				1,500 Wh/day	8,23 hours
				3,000 Wh/day	9,6 hours

Intensity of secured load	Output Inverter Voltage	Power Design	Energy Battery (75%)	Energy Photovoltaic	Autonomy
15 A	220 Vac	3,300 W	10,080 Wh	0 Wh/day	3,05 hours
				2,500 Wh/day	3,81 hours
				5,000 Wh/day	4,57 hours
11.25 A	220 Vac	2,475 W	10,080 Wh	0 Wh/day	4,07 hours
				2,500 Wh/day	5,08 hours
				5,000 Wh/day	6,09 hours
9 A	220 Vac	1,980 W	10,080 Wh	0 Wh/day	5,09 hours
				2,500 Wh/day	6,35 hours
				5,000 Wh/day	7,61 hours
7.5 A	220 Vac	1,650 W	10,080 Wh	0 Wh/day	6,11 hours
				2,500 Wh/day	7,62 hours
				5,000 Wh/day	9,14 hours

The combination of Tables 2 and 3 lead to assigning a PV 1.8 kWp(ref. PVB-15) power system for the Meniara Public School.

c. System Description and Control Strategy

For this study, the main focus will be on the larger system; the control strategies are similar for all systems, and only differ depending on special conditions related to some of the public sites that received a PV system.

Table 4. Technical description of the PV back up plant as published in the competitive bidding documents for the selection of contractors to supply and install the system

		PVB-10	**PVB-15**
PV GENERATOR	Installed Capacity (STC)	1.125 kWp	1.8 kWp
	Type of Module	Crystalline 75 W	Crystalline 75 W
	Inclination and Orientation	45° - 20° E oriented	45° - 20° E oriented
Dual Inverter	Nominal Power	4000 W Dual Mode	4000 W Dual Mode
Battery	Rated Capacity (C100)	10,080 Wh	13,440 Wh
	Voltage	48 V	48 V
	Max depth of discharge	75%	75%
	Type	Lead Acid vented	Lead Acid vented
	Quantity	4x12Vx210 Ah	4x12Vx280 Ah
Charge Controller MPPT		60 A/ 48V	60 A/ 48V

Several parameters define the method of operation of the plant and are mainly controlled by the supervisory controller and the inverter. The main energy dispatch strategy is:

- PV generation available, grid available: Priority for solar energy, whenever there is solar energy the load/battery is supplied from the PV generator. The PV panels first supply the priority load, and in case the battery is full and the priority load is small, the electricity is also back fed to the main electrical line.
- PV generation, no grid available: Priority line is fed by PV panels first and batteries if the generation of the PV cannot meet the load. The inverter breaks the connection with the main electrical line (secondary line) of the school when it detects loss of grid power.
- No PV, Grid Available: Grid supplies all loads and charges the battery until a preset value, namely 85% SOC. The battery is not charged to the maximum so that there would be room to charge from PV power in case it existed after the charging period.
- No PV and No Grid: The system goes to back-up mode and the priority loads are supplied by the batteries.

It should be noted that the batteries installed are 8x12Vx150 Ah instead of the requested 4x12Vx280 Ah, due to higher market availability. The total storage power of the batteries is 14.4kWh, but taking into account the maximum depth of discharge of 75%, the total power available for use is 10.8 kWh.

Appendix A contains the installation and electrical drawings of the system.

d. Data Logging

The data loggers provide extensive and complete hourly data of most important parameters related to the PV systems, such as irradiance, PV electricity generation, site consumption, battery state of charge, etc.

A complete set of sensors measure data which is collected hourly in a data logger, then the information is processed using a user built software. Several parameters are collected, and to name some: electricity consumption from the grid, electricity back-feed to the grid, priority and main line consumptions, Battery Relative Availabilty"$(SOC - SOC_{\min})/(100 - SOC_{min})$", irradiance, PV generation, etc. SOC stands for state of charge and SOC_{min} is the minimum allowed state of charge, in this case 25%. The data is normalized with respect to the PV capacity and then graphed and tabulated for daily, monthly, and yearly analysis as can be seen in the figures 3 to 5. The graphs are shown with the horizontal axis unit of h/d, or hours per day. The irradiance is normalized for STC at an irradiance of 1000W/m^2, thus a "2" value for irradiance on the graph is actually 2000Wh/m^2. The PV generated is also normalized and the h/d term signifies the amount of time which the PV plant has to operate with nominal solar generator power (Peak Watts of the PV generator) to generate the energy produced. Appendix B contains the equations as explained by the producer of the data logging software.

Significance of Parameters:

Table 5. Explanation of parameters in the data logging software - (Figures 3, 4, and 5)

Parameter	Description
Average Irradiance	Solar irradiance in plane over a given time interval
PV gen	Yield (normalized energy from the photovoltaic generator
NRS1 gen	Yield (normalized energy) from non-renewable energy source used to charge the battery
ORE2 Gen	2nd non-renewable energy source used – Not applicable for this system
AC Cons	Normalized total electrical consumption of priority line – includes electricity diverted from priority line excess to main line and/or back-feeding to the grid
DC Cons	Normalized DC loads consumption. In this case only data logger and controller self-consumption
AC 1	Input electricity from the grid, takes into account all electricity consumption from the grid including NRS1
AC 2	Back-feeding to the grid. Electricity exported to the grid via net metering
Battery	Battery State of Availability in % and in days of autonomy at the rated load
ED	Available Energy – Not applicable for this system

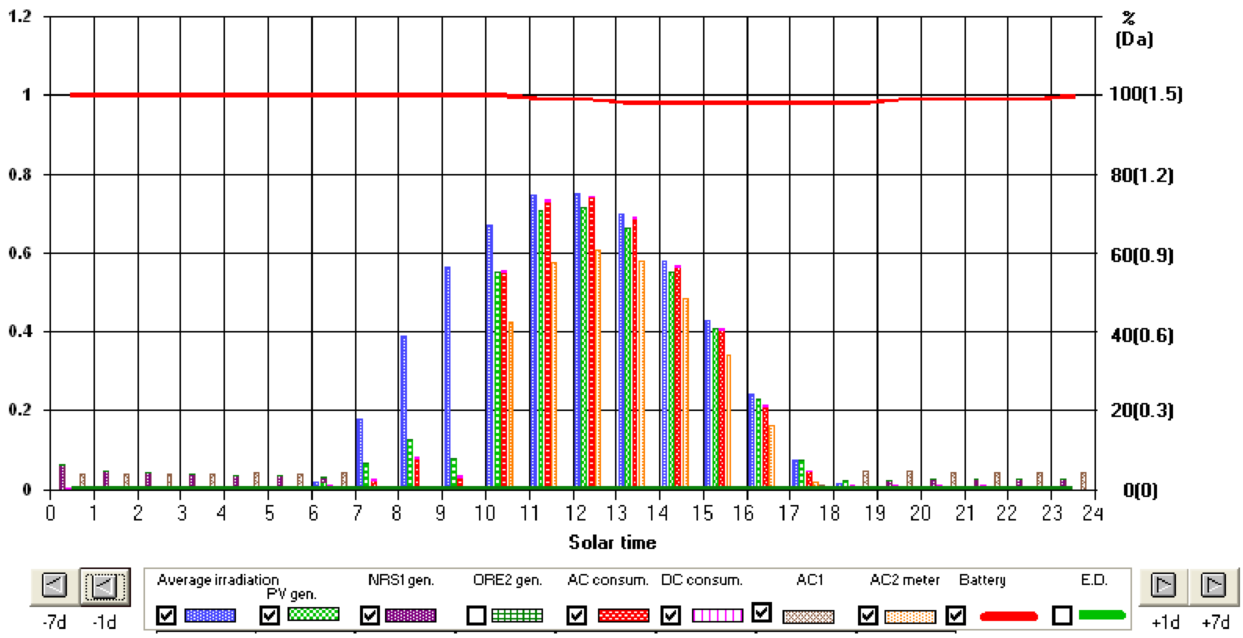

Figure3. Daily readings analysis for Meniara Public School obtained from the data logger software, normalized in terms of hours per day (Horizontal Axis)

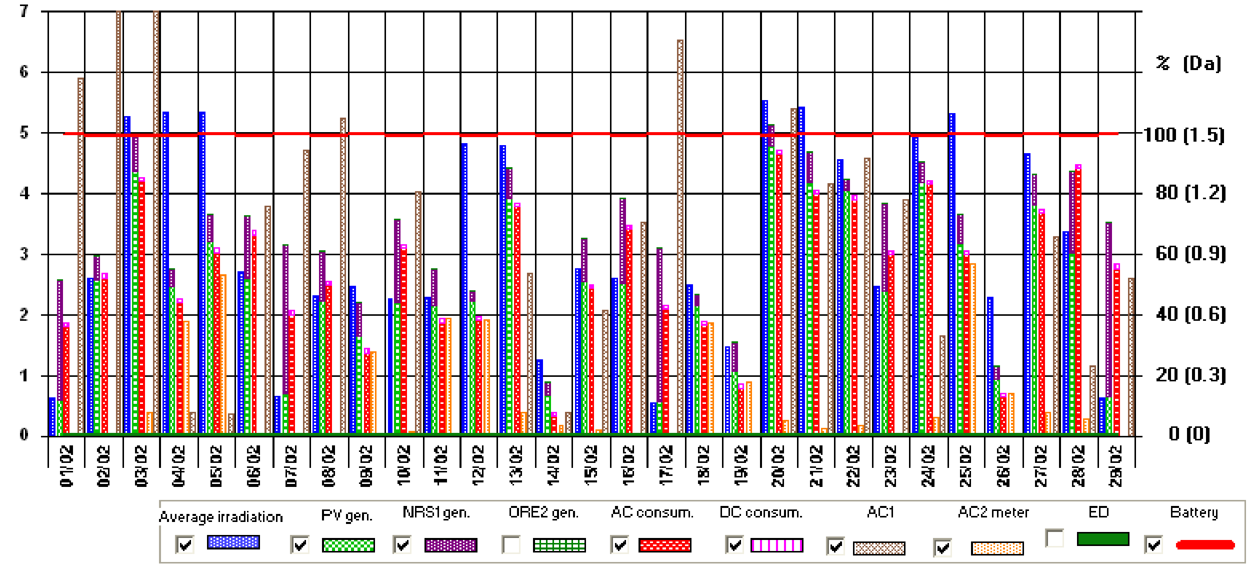

Figure 4. Monthly Data Logging Example for Meniara Public School, normalized in terms of hours per day (Horizontal Axis)

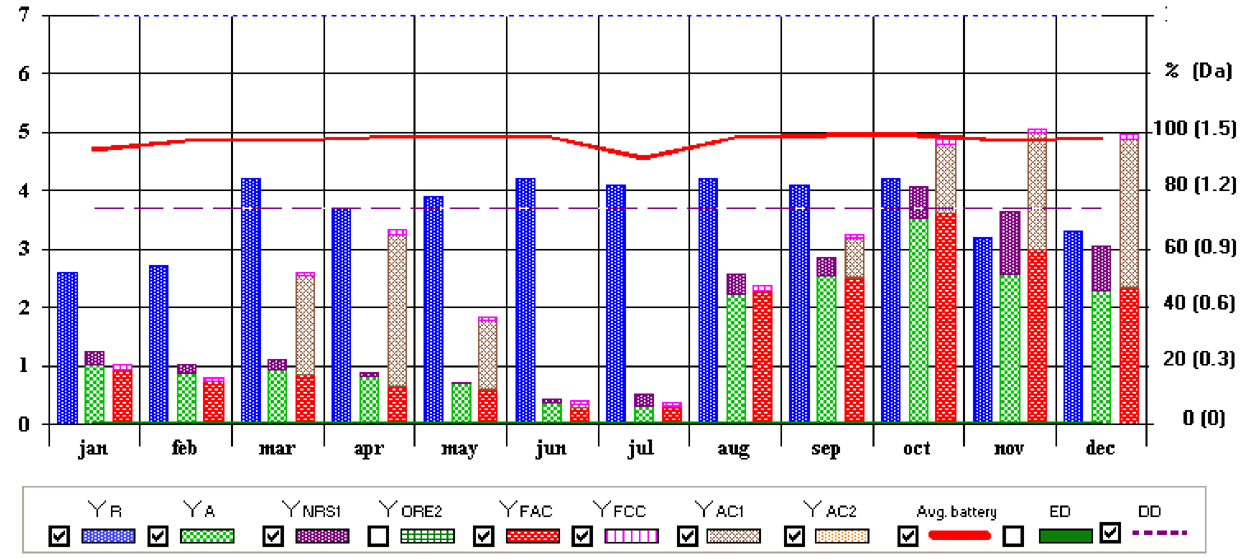

Figure 5. Yearly Data Logging example for Meniara Public School, normalized in terms of hours per day (Horizontal Axis)

2- Methodology and Software Setup

2.1 Methodology

Given the difficult nature of the Lebanese grid and the introduction of a priority in the sites which is different from the already existent main line,optimization software will not be able to reproduce the exact conditions present on the real site. However,for this study HOMER2.68beta is chosen as the optimization software and was setup in a way to make it as similar as possible to the exact grid condition.

The method of analysis is split into four steps as given below:

Step 1: Recreation of a PV installation, the grid, and its governing parameters in HOMER

Step 2: Overlaying the results from HOMER to the data logging results obtained from the considered reference site and validating the HOMER model

Step 3: After validation, varying several parameters to find optimum components sizing and setup in a sensitivity analysis. The main parameters being the electricity cost per kWh for each model, the percentage of the load that cannot be met, and the battery life

Step 4: Using validated model to compare options for other public institutions such as community centers with healthcare units

2.2 Homer Setup

The goal of the setup is to mimic as closely as possible the real conditions in the simulated school based on data logging equipment installed in the school itself, and on the knowledge of the intermittency of the Lebanese grid and the conditions surrounding it. All the costs associated with the Renewable Energy System equipment, the grid parameters, the school consumption parameters, among others are values collected from the bidding process or from the site itself and can be used as is, or are a derivationfrom the collected values. The generator modeled below is to replace the grid because only a generator can accommodate for intermittent supply condition in HOMER.

a. Grid Modeling

Since an intermittent grid is not an option in the HOMER version 2.68beta, an alternative solution had to be produced. For import from the grid, a generator was modeled to produce the same cost and conditions as the existent grid in Lebanon. The Lebanese grid varies in supply schedule as shown in Table 6 below. The situation is such that the supply hours today are similar to the supply schedule of the day after.

Table 6. Real Time Schedule of Grid supply hours for public schools

00:00 → 6:00	Grid ON	00:00 → 6:00	GRID OFF
6:00 → 10:00	Grid OFF	6:00 → 10:00	Grid ON
10:00 → 14:00	GRID ON	10:00 → 14:00	GRID OFF
14:00 → 18:00	GRID OFF	14:00 → 18:00	GRID ON
18:00 → 24:00	GRID ON	18:00 → 24:00	GRID OFF

The generator (grid in this case) was modeled with a schedule that can approximate the schedules of blackouts in the country, but the HOMER model can only vary schedule times per month relative to the grid supply strategy that is scheduled per day. For exporting to the grid, the configuration is discussed in part ii that follows.

i. Grid Electricity Import – Modeled as Generator

Table 7. Generator Parameters to replicate Lebanese grid conditions and price

Name	Grid_Input		Abberviation	GridI
Size (kW)	1000		Capital (USD)	0
Replacement($)	0		O&M (USD/hr)	0
Lifetime (hrs)	150000		Min. Load Ratio (%)	0.001

Table 8. Fuel for Grid_Input generator

Fuel Name	Grid		Intercept Coeff (kg/hr/kW rated)	0
Slope (Kg/hr/kW output)	0		Fuel Price ($/Kg)	0.1
Replacement($)	0		O&M (USD/hr)	0
Lifetime (hrs)	150000		Min. Load Ratio (%)	0.001

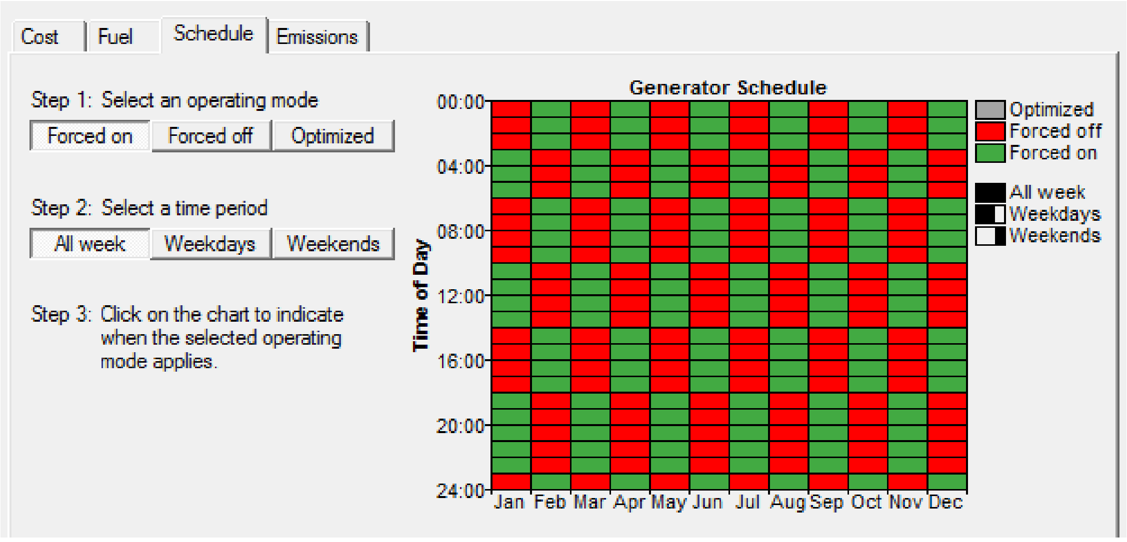

Figure 6. Schedule for Grid_Input ON and OFF hours

The above input parameters will produce a generator whose efficiency is not affected by percentage loading and which produces electricity with a price of USD 0.1 per kWh, which is equal to the kWh retail price sold by the national grid provider, EDL.

The above schedule replicates the Lebanese grid schedule of supply differing in the fact that the schedule has daily changes in Lebanon, while in HOMER those changes are considered monthly.On a two day analysis the electrical grid is ON for 24 hours, which is half of the time. Since in HOMER this kind of schedule is not possible, an alternative solution was configured. Since the schools are fully operational from 8:00 till 14:00, the HOMER simulation schedule was different from that of the grid, but in a way that can supply the electricity to the school half of the hours of the functioning times of the school.

ii. Grid Electricity Export – Net Metering

A grid parameter is introduced in HOMER, but this grid does not supply electricity to the loads, it only buys electricity surplus supplied from the site. This grid was modeled with two different tariffs as explained below:

- Tariff 1 is USD 0.1/kWh, which is the same price that the subscriber pays for importing electricity from the grid, since the electricity trade is done with net-metering.
- Part 2 is set at zero, and scheduled at the same time when the Grid_Input generator is OFF. Since when the generator is OFF the grid is considered to be OFF as well. The system will still sell all electricity to the grid in the HOMER simulation, and that will be apparent in the kWh numbers, but the income from the selling will only be descriptive to the real electricity sold when the GRID_INPUT generator is ON, or when tariff 1 is in place. This is achieved by the fact that at the zero tariff the electricity sold to the grid does not account for any revenue. Thus when the revenue simulated by HOMER is read it will show the amount of electricity sold to the grid when the grid is ON.

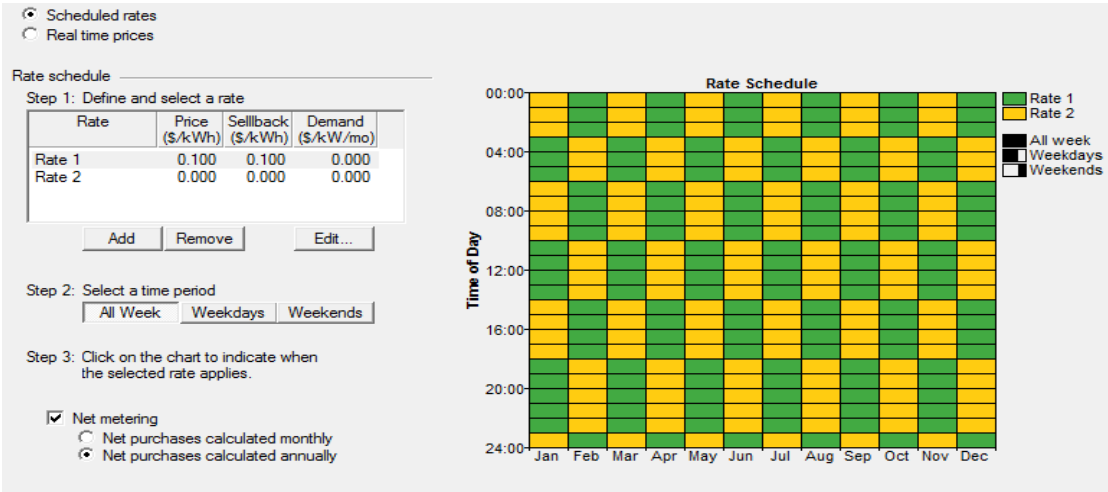

Figure 7. Scheduled selling prices for electricity from the public school to the national grid

To be able to compare the values of electricity sold to the grid obtained from HOMER with the data obtained from the data logging equipment on site, the electricity sold at tariff 2 in the HOMER simulation should be subtracted from the total electricity sold to the grid. Since, the electricity sold at tariff 2 is the electricity sold when there is no grid available according to the schedule.

Equation 1

$$\text{El. Sold}_{\text{actual}} = \text{El. Sold}_{\text{total}} - \text{El Sold to Grid}_{@\text{ zero tariff}}$$

b. PV Generator Modeling

The 1.8kWp PV generator described in section 1.2c is used as input for HOMER. In the sensitivity analysis, that follows the model validation, the PV generator size is varied in increments of 0.18 kW (10% of original design size of 1.8 kW). The different generator sizes covered are between 0 and 200%. The cost of the panels is the same as the one supplied in response to the competitive bidding process and includes supply and installation costs and profit for the contracted company. The cost curve is considered to be linear, and this is further validated by the fact that PV manufacturing companies tend to sell panels as a fixed cost per kWp. The most recent tender for the supply and installation of PV-Battery plant had prices ranging from USD 1.8-2.5/Wp depending on the supplier and the size of the system, with the lower values being for the larger projects. For this research a USD2.1/Wp was used for the 1.8 kWp system.

Table 9. Initial PV setup parameters

Size (kWp)	1.8	Capital (USD)	3780
Replacement Cost (USD)	4000	Lifetime (yrs)	25
Derating Factor (%)	90	Slope (Degrees)	45
Azimuth	0 – South	Ground Reflectance (%)	20

Given the explanation given for equation 1, a similar equation needs to deduct the electricity generated and sold to the grid at tariff 2 from the total generated electricity. This electricity would have not been produced by the PV generator if the grid was off and no electrical loads existed.

Equation 2

$$\text{HOMER}: PV_{actual} = PV_{total} - ElSoldtoGrid_{@\,zerotariff}$$

c. Battery Modeling

The same logic is followed for the battery as for the PV generator. The batteries simulated have the same capacity and setup as the ones installed on the reference site. For the optimization process the sizes of the batteries were varied in values between0 to 200% from the original design size in the optimization process. The cost of the battery is priced at USD 3250; the price is taken from the same bids as the PV generator. To increase the significance of the battery size variations, the results will be graphed in terms of days of autonomy provided by the batteries using equation 3 to convert from total power to the needed value. From section 1.2, the depth of discharge for all the simulations is 75%.

Equation 3

$$Storage\ Capacity\ (Days) = \frac{Total\ Battery\ Power\ (kWh) x\ Depth\ of\ Discharge\ (\%)}{Institution\ Consumption\ (\frac{kWh}{day})}$$

Table 10. Initial setup parameters for the battery bank

Manufacturer	Sunlight – Greece	Type	OPzS – Lead Acid
Technical Nomenclature	12V 3 OPzS 150	Capacity (C10) (A.h)	150
Voltage (V)	12	Total Voltage (V)	48
Number of Strings	2	Batteries per String	4
Floating Lifetime (yrs)	12	Roundtrip Efficiency (%)	85

The battery lifetime is calculated by HOMER using data supplied by the manufacturer about the effect of the depth of discharge and the number of cycles on the battery life. The battery life is a parameter calculated with every simulation, and is used in the selection criteria of the optimization process.

d. Converter Modeling

The converter in HOMER, or inverter in several references, is a dual mode inverter capable of operating as grid connected or as stand-alone. Because of the nature of operation of the system and the fact that varying the size of the inverter doesn't produce major savings in cost of the system, the same inverter is used for all plant sizes in the range of the study.

Table 11. Inverter input parameters

Manufacturer	Studer-Innotec	Nomenclature	XTM 4000 – 48
Power (kW)	4	Voltage (V)	48
Lifetime (yrs)	15	Efficiency (%)	90
Rectifier capacity (kW)	4	Rectifier Efficiency (%)	90
Unit Price (USD)	3000	Replacement Cost (USD)	3000

e. Primary Load Modeling

The load modeling of the MeniaraSchool was based on the information obtained from the data logging. The consumption in the school is split into two parts:

- Part 1: The consumption from the priority line connected directly to the inverter
- Part 2: The consumption from the main line which already existed in the school prior to the PV installation. This line is only fed from the PV power system with the excess PV generation when the batteries are full and when the grid is available.

After the installation of the PV system and the performing of a small lecture about energy saving and about using the PV system wisely, the school implemented several EE strategies which considerably lowered their consumption from what was initially foreseen by the initial design sizing calculation. They also reverted on usinglarge electricity consumers, such as photocopying machines, when the PV plant is on stand-alone mode to save the PV system for the necessary loads. The data logging shows that the school has an average consumption of 7.65 kWh instead of the 13.505 kWh/day that was calculated during the design phaseTable 2.

By analyzing the consumption patterns from the data logging, an approximation for the school's consumption is obtained as in Table 12.

Table 12. Consumption pattern for Meniara Public School

Time of Day	Consumption (kW)
6:00 - 7:00	0.05
7:00 - 8:00	0.05
8:00 - 9:00	0.8
9:00 - 10:00	1.1
10:00 - 11:00	1.2
11:00 - 12:00	1.7
12:00 - 13:00	1.3
13:00 - 14:00	1.4
14:00 - 15:00	0.05
TOTAL (kWh)	**7.65**

Some comments on the consumption patterns from the data logging tables:

- In the winter months, mainly from December to February, the PV yield is lower than average, and the battery is used more frequently.
- Consequently, peaks are reached in the consumption from grid electricity due to the fact that when the grid is ON, it will provide electricity for the school usage and for recharging the battery.
- Saturdays and Sundays the school is closed and thus the consumption is zero. But in the data logging, consumption is not always zero in the weekends because the consumption counter on the inverter counts electricity back-fed to the grid as well as the consumption of the priority line.
- Similarly for the months of July and August, the school is closed for the summer break.

f. General conditions and constraints

a. Economic Constraints
   - Interest rate is taken at 6%
   - Lifetime of the project is 25 years

b. System Controls
   - Time Steps: 60 minutes
   - Set point of charge above which battery charging is not allowed from the grid: 85%

c. Constraints
   - Operating reserve as part of load: 5%

g. Levelized Cost of Electricity (COE)

As a merit indicator to be able to compare the effect of component size variations, the levelized cost of electricity for each option is considered. The levelized cost of electricity is, by definition, the cost of producing every 1kWh of electricity under a certain setup during the total project horizon. The unit of the COE is USD/kWh, and is calculated by equation 4.

Equation 4

$$COE = \frac{C, annual}{El_{cons} + El_{sold}}$$

Where,

$C, annual$ is the annual investment cost of the PV system including maintenance, fuel consumed for generator if any, and cost of grid electricity purchased or sold. Where the electricity exported to the grid has a negative value sign. The interest rate is also considered to convert the initial investment which is paid in today's money value to future worth.

El_{cons} , is the electricity consumed on the site

El_{sold} , is the electricity sold to the grid

HOMER is not setup for the exact application analyzed herein and thus to correct the COE result obtained from HOMER, two steps were taken:

- In the net metering agreement of Lebanon, any negative value on the net meter is zeroed yearly, thus the grid operator is not required to pay for any additional yearly electricity produced by the consumer that surpasses his yearly consumption. Thus a comparison was required between the electricity sold to the grid and the electricity provided by the grid_input generator discussed in section2.2i, for every simulation.
  The comparison could have two different outcomes:
  1. Electricity Exported to grid <Electricity Import from Grid, then the value of the electricity exported is used for El_{sold} in the calculations. The cost of the value of electricity sold used in the calculation of the annual cost of the system.
  2. Electricity Exported to grid >Electricity Import from Grid, then the value of electricity imported from the grid is used for El_{sold} to calculate the electrical production of the plant. The respective cost for the electricity import from the grid is also used to calculate the income from selling electricity to the grid in the calculation for $C, annual$.
- The electricity sold to the grid under tariff 2, discussed in the grid modeling section, is subtracted from the total electricity back fed to the grid. As discussed previously, this electricity is actually never produced and is also subtracted from El_{sold} .

3- Results and Analysis

This chapter contains the validation process of the HOMER simulation by comparison to actual data from the PV plant installed in Meniara Public School. After the validation, a sensitivity analysis of the RE system is carried out and the results are used torecommend sizing options that can be used in future designs to optimize their electrical and financial performance. Furthermore, the model will be projected to model a PV back up plant for other types of buildings like, in this case a community center and a municipal building.

Four main steps define this chapter:

a. Validation step by comparing the results of the HOMER simulation with the results of the data logging from the Meniara Public School.
b. For the sensitivity analysis and optimization of the school system, 3 different scenarios were considered with variations in blackout schedules and grid tariffs in line with the Policy Paper of the Lebanese Ministry of Energy and Water. Through all 3 scenarios, 20 PV generator sizes and 7 battery sizes were cross matched. The comparison will be based on the levelized cost of electricity (COE) given that the capacity shortage doesn't fall below 10% and the battery life stays maximized at 12 years lifetime.The annual capacity shortage percentage is the percent of the total annual load in kWh that couldn't be met by using the simulated renewable energy generator.
c. A similar analysis will be carried out on a community center, but using only 1 scenario, which is the condition that the policy paper plans to reach in the year 2015, with tariffs increasing to USD 0.1375/kWh and grid supply hours also increasing in parallel.
d. Similarly the model will be used to simulate a municipal building using the same conditions of case b.

3.1 Validation

a. HOMER Simulation Result

Putting in the data as discussed in the previous Chapter, with an inflation rate of 6%, the results for the simulation of the Meniara Public School PV power system would give the below results:

i. **Cash flow summary**

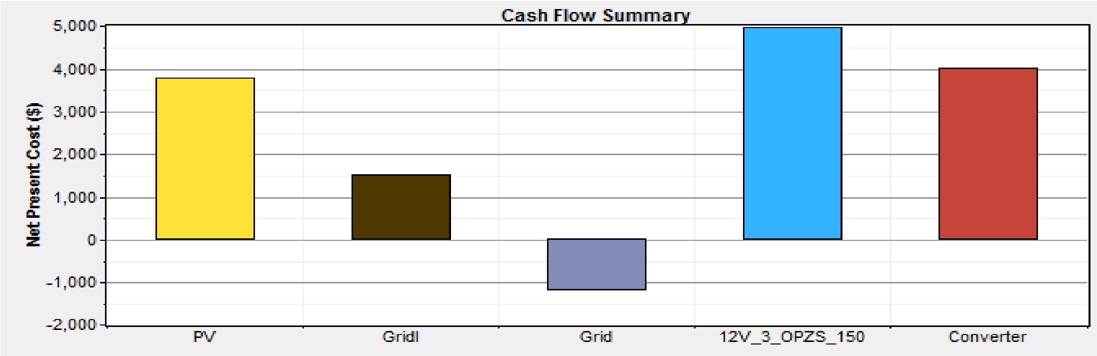

Figure 8. Result of Cash flow in HOMER for the Meniara PV Plant

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	3,780	0	0	0	0	3,780
Grid_input	0	0	0	1,520	0	1,520
Grid	0	0	-1,184	0	0	-1,184
12V_3_OPZS_150	3,250	2,418	0	0	-694	4,974
Converter	3,000	1,252	0	0	-233	4,019
System	10,030	3,670	-1,184	1,520	-927	13,109

Figure 9. HOMER simulation results for the Meniara Public School System in terms of Net Present Value

Component	Capital ($/yr)	Replacement ($/yr	O&M ($/yr)	Fuel ($/yr)	Salvage ($/yr)	Total ($/yr)
PV	296	0	0	0	0	296
Grid_input	0	0	0	119	0	119
Grid	0	0	-93	0	0	-93
12V_3_OPZS_150	254	189	0	0	-54	389
Converter	235	98	0	0	-18	314
System	785	287	-93	119	-73	1,025

Figure 10. HOMER simulation results for the Meniara Public School System in terms of Annual Values

Financial comparison will not be used to validate the model since all the inputs are based on actual installation costs. The capital values, replacement values, and salvage value are all set by the initial cost estimates and the interest rate.

The O&M income in the example above is due to the net-metering of excess electricity with the grid at tariff 1. Figure 9 shows the electricity sold along the 25 years lifetime of the PV plant, while in figure 10 it signifies the electricity sold per year from it. The fuel cost is the price of fuel used to run the generator, but as explained in section 2.1 part b, this is the actual cost of purchasing electricity from the grid when it is available.

According to the simulation, the electricity exported to the grid amounts to 1920 kWh which is worth USD 192 if net-metering to the grid is always available. But since the grid is intermittent the actual amount of electricity sold to the grid is 926 kWh, and the rest of the capacity is actually lost, or sold for free in HOMER terms.

ii. Electrical parameter Simulation results

Tables 13 to 16 are the simulation results obtained from HOMER for the inputs discussed previously. The values are for the electrical performance of the 1.8 kW(STC) reference PV Plant which is installed in the Meniara Public School.

Table 13. Electrical production values of the site

Electricity Production	kWh/yr	Percentage (%)
PV System	3,331	74
Grid_Input	1,189	26

Table 14. Electrical consumption values of the site

Load Consumption	kWh/yr	Percentage (%)
AC Primary Loads	2,086	52
Grid Sales	1,920	48

Table 15. Electrical consumption values of the site

Quantity	kWh/yr	Percentage (%)
Excess Electricity	0.00564	0
Unmet Electrical Load	64.1	2.98
Capacity Shortage	77.4	3.60

Table 16. Renewable Energy Fraction

Renewable Energy Fraction	0.737

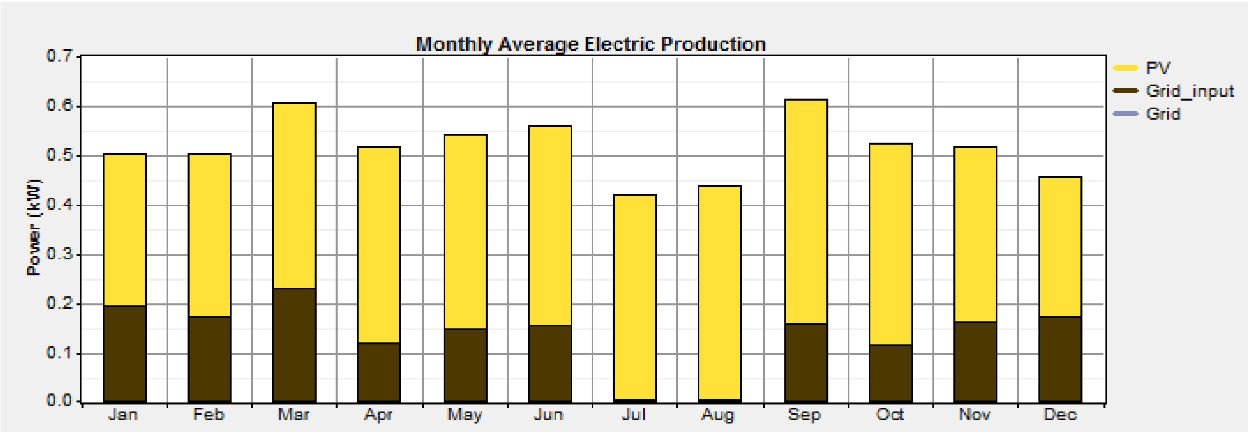

Figure 11. Electrical production per month according to source

iii. Battery Parameter Simulation Results

Table 17 shows the energy values obtained from HOMER for the battery performance. The parameter of highest concern is the expected life of the battery in the simulated scenario. Given the high cost of replacing batteries, obtaining a system that preserves the battery life is of high importance. The number of cycles and the depth of discharge at every cycle are the main impact on the survival rate of the battery.

Table 17. Battery Parameters in Meniara Public School System Simulation

Quantity	Value	Units
Energy In	769	kWh/yr
Energy Out	655	kWh/yr
Storage Depletion	1	kWh/yr
Losses	114	kWh/yr
Annual Throughput	710	kWh/yr
Expected Life	12	yrs.

Figures 12 and 13show the distribution in percentage frequency of the battery state of charge and the State of Charge (SOC) limits of the battery respectively. It can be seen that the battery is not heavily used in the system, and this is mostly due to the high concurrence between the hours with available of PV generation and the consumption hours, where most of the loads would be met directly with the PV generation without having to pass by the battery.

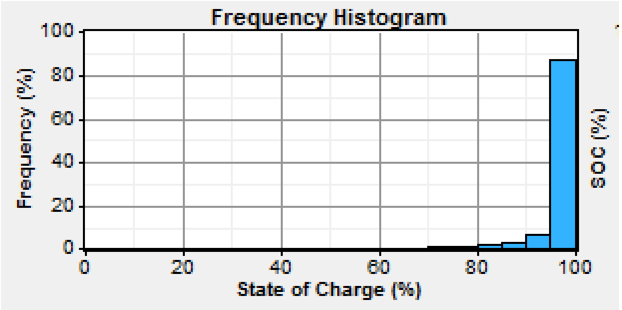

Figure 12. Battery state of charge (SOC) frequency

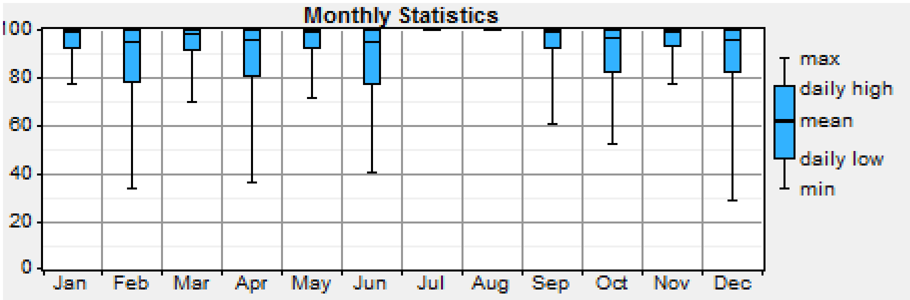

Figure 13. Battery Cycling per month as percentage of State of Charge

The battery does not cycle in July and August since the school is not operational in those 2 months, and the battery capacity is not used to sell to the grid. And this is for two main reasons; the focus on increasing the battery life by using it as seldom as possible, furthermore the levelized cost of electricity (COE) of battery power is higher than the gain from selling the electricity to the grid. There's also the importance of keeping the battery charge level high to be available for the school when needed.

A minor discrepancy between HOMER and the installed PV Plant, installed at the school, is the battery control. While HOMER takes the decision whether to export to the grid from the battery or not according to COE, the installed system allows back-feeding to the grid from the battery as long as its SOC is above 85%. This allows selling to the grid in nighttime the energy generated by the PV in daytime when no grid was available. To further explain this,Table 18 provides a comparison between two scenarios, one which allows back-feeding from the battery (Scenario 1) and one does not allow it (Scenario 2).

Table 18. Comparison between Battery SOC if selling to the grid was allowed from the battery when it has an SOC higher than 85%

	Time of Day	Grid	Battery SOC Change Scenario 1	Battery SOC Change Scenario 2
DAY 1	Daytime	OFF	100 %	100 % - 100 %
	Nighttime	ON	100 % → 85 %	100 % - 100 %
DAY 2	Daytime	OFF	85 % → 100%	100 % - 100 %
	Nighttime	ON	100 % → 85 %	100 % - 100 %

- Scenario 1 allows a financial gain worth 15% of the storage capacity of the battery in times when the grid is off during the day and on during the night.
- It is beneficial for the lifetime of the battery to use it lightly from time to time.

Another observation from the analysis is the fact that the battery is used more in the months where the grid is not available in the morning as set in section 2.1. As set in HOMER, the months of January has grid availability in the morning hours and grid blacks out at noon. So the system in January would draw from the grid in the morning and from the PV system directly backed by the battery in the afternoons. The month of February sees the opposite pattern in grid availability, which causes the school to depend on battery coverage in the mornings, which explains the higher use of the battery in February. The months with electricity during the morning have an average SOC of 71.2% whereas the other months the average SOC is at 38.2%. This pattern is actually a daily pattern in Lebanon and not monthly, due to the fact the electricity cycles are daily as explained in section 2.1.

iv. Net Metering Values

As discussed in section 2.1, two tariff schedules exist in the setup in HOMER, the first one being the actual cost of electricity in Lebanon at 0.1 USD/kWh, and the second one is set at zero since it is considered at the time of blackouts no net metering can exist. Accordingly, the production in the right row of Table 19 does not produce any income for the user.

Table 19. Net Metering values for HOMER simulation of Meniara Public School

Month	Tariff 1 (0.1 USD/kWh)	Tariff 2 (0 USD/kWh)
January	59	61
February	47	51
March	60	90
April	71	57
May	69	93
June	63	59
July	148	133
August	144	149
September	78	106
October	68	65
November	69	79
December	51	53
TOTAL	**927**	**996**

v. PV back up power System Summary

Table 20 summarizes the results obtained from the simulation in HOMER2.68beta. The first 4 rows are input parameters while the remaining are the results. The levelized electricity cost is the actual cost of producing electricity from the system installed in the school per kWh taking into considerations all the costs associated with the system including replacement of equipment at the end of their lifetime (such as batteries) and their initial cost. The simulation was considered to spread across 25 years.

The capacity shortage signifies the loads that couldn't be met by the system due to the battery being empty and no grid or PV electricity is available. Grid input is the actual imported electricity from the grid and the battery life expectancy as calculated by HOMER is 12 years.

The COE shown in Table 20 is directly calculated from HOMER and not corrected according to Equation 4.

Table 20. System Summary for Meniara Public School Simulation

PV Generator	1.8 kW
Battery	300 A.h
System DC Voltage	48 V
Initial Capital	$ 10,030
Operating Cost	241 $/yr.
Levelized Electricity Cost (COE)	0.492 $/kWh
RE Fraction	0.74
Capacity Shortage (%)	4
Grid Input	1,189 kWh
Battery Life Expected	12 yrs.

b. Data Logging Result and Validation analysis

Putting in the data as discussed in the (previous) Chapter 2, with an inflation rate of 6%, the results for the simulation of the Meniara Public School system would give the below results:

i. Data Logging Table

The data span will be considered from August 2011 till May 2012, since net metering was enabled on this particular site since August 2011.Table 21 shows the different parameters which are obtained from the data logging, in the coming sections the data will be cross checked with the HOMER simulation results. June and July 2012 are marked in red and are not included in the calculation, since during those two months there was a major strike by the national electricity supplier, and electricity supply dropped significantly to between 2-5 hours of supply per day.

Table 21. Summary of data logging for Meniara Public School. Months in Blue are from 2012 and months in green are from 2011. June and July had no significant data since net metering was not enabled at the time, and the school is closed during those months. Irradiance is given in terms of hours per day at a solar irradiation of 1000W/m^2

Month	Irradiance (h/d)	PV Gen (kWh)	NRS1 (kWh)	AC cons (kWh)	AC 1 (kWh)	AC 2 (kWh)	Performance Ratio	Solar Fraction
January	1.8	77	70	108	163	14	58	35
February	3.2	129	45	142	150	34	64	48
March	3.7	164	38	166	129	63	67	59
April	4.4	187	25	186	20	122	70	88
May	4.1	171	24	170	25	78	67	88
June	4.2	87	10	77	0	52	35	90
July	4.1	80	10	76	0	54	32	89
August	4.2	124	19	128	0	109	49	87
September	4.1	137	17	136	33	89	56	83
October	4.2	197	29	202	59	81	77	79
November	3.2	139	58	162	96	47	67	63
December	3.3	128	42	131	129	34	55	52
TOTAL		**1453**	**367**	**1531**	**804**	**671**		
AVERAGE	**3.71**	**145.3**	**36.7**	**153.1**	**80.4**	**67.1**	**63**	**68.2**
HOMER AVG		277.6	64.1	173.8	99.1	77.3	---	73.7

ii. PV generation

HOMER projects a higher PV production than the data logging values; this could be a result of several factors such as weather, availability of solar energy in that same period, and many other factors that are not under human control.

Another reason for this difference lies in the capture losses, a main PV energy loss factor that occurs when the grid is not available and there is no other need for load while the PV generator is under conditions that allows it to produce electricity. As an example, one could study the PV electricity generation between the months of October and August, which have the same irradiance level but the system produces significantly more PV energy in October because of the higher need in this month when compared to August. The lost electrical production capacity in August is called the capture losses.

Since in HOMER the grid is always available for net metering, and the times of blackout were modeled as a zero-tariff schedule, there would be no capture losses in the simulation, since all the extra energy produced would be sold to the grid. Using the double tariff system makes it possible to account for the electricity that was sold to the grid during the hours that should be blackouts, by looking at the electricity sold at each tariff, as per equation 2.

To account for this difference, the amount sold to the grid at the zero-tariff rate can be subtracted from the PV generation and considered as the generation that is lost due to the intermittency of the grid, using equation 2.

$$\text{HOMER: PV}_{\text{actual}} = 3331 - 996 = 2335 \text{ kWh}$$

$$\text{HOMER: PV}_{\text{actual}} \text{ AVG} = \frac{2335}{12} = 194.58 \text{ kWh/Month}$$

From Table 19, the average PV generation per month obtained from HOMER is 277.6 kWh while when using the correction equation (equation 2) this value becomes 194.58 kWh per month. When compared to the actual data logged value of PV generation which is 145.3kWh/month, the corrected value is more in line with what was obtained from the site.

iii. Battery Storage

In Table 21, which summarizes the data logged parameters; two values related to the battery are mentioned. The first being the NRS1 parameter which describes how much energy was drawn from the grid to recharge the batteries. The simulation results of HOMER only mention how much total energy was used for recharging the batteries and does not separate this energy according to source. Accordingly, to compare battery results between the data logging and the HOMER results, the state of charge of the battery will be used.

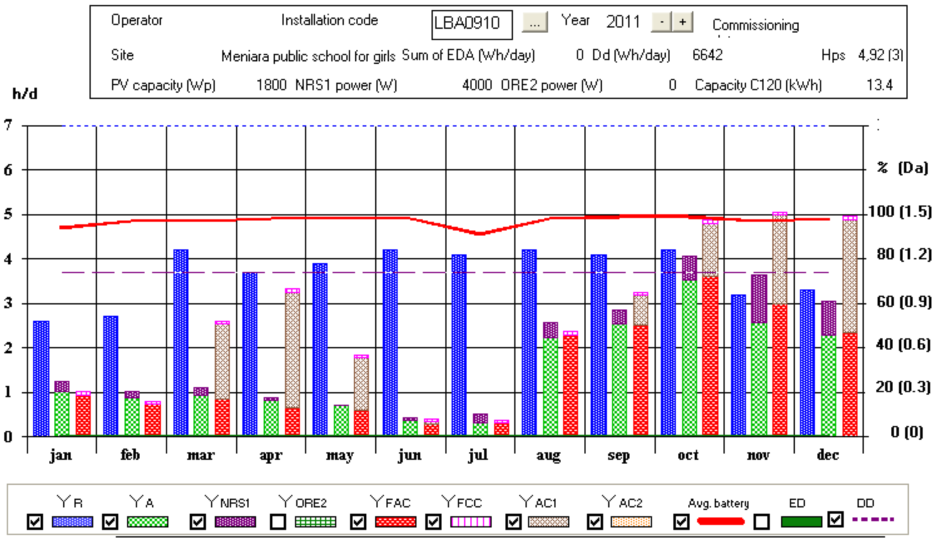

Figure 14. Data graph for Meniara for the year 2011. The red line at the top is the battery average state of availability for each month

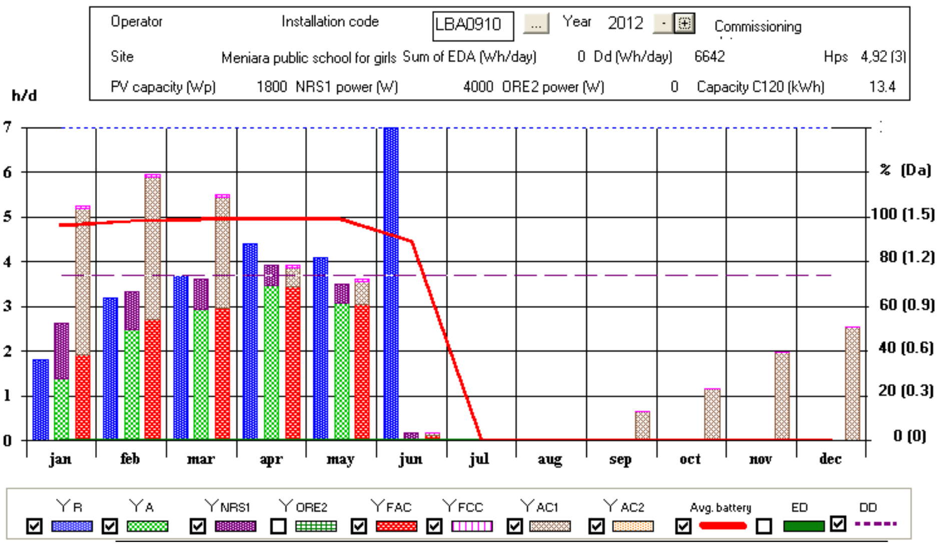

Figure 15. Data graph for Meniara for the year 2012. The red line at the top is the battery average state of charge for each month. Data stops in May, the unusual result for June is due to incomplete data

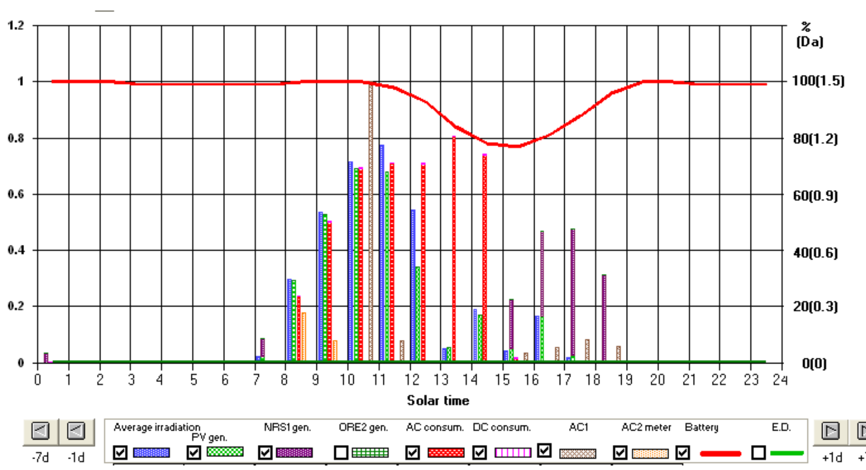

Figure 16. Example on daily data logging for Meniara Public School where battery SOC drops to 80%

Figures 14 and 15 show that the battery state of charge average stays around the 100% level for most of the year, this can also be seen in the frequency distribution graph from HOMER shown in figure 12. Figure 13 shows the state of charge fluctuations as a result from HOMER. Such a result can only be seen in the data logging if the data is studied each day at a time. Figure 14 shows the battery SOC dropping to around 80% which is the minimum SOC reached on most of the days. On some events the SOC drops down to as low as 40% or lower, but this happens only on occasions where electricity is not supplied for a whole working day of the school, which is not considered on HOMER, since it has a low occurrence.

iv. AC consumption parameters

A brief description of the terms related to the AC current parameters:

AC consumption is the energy consumed in the priority line of the school and also includes the excess electricity that is transferred from the priority line to the school's main line and eventually exported to the grid.

AC 1: Is the metered electricity input, which includes electricity consumed from the grid by the priority line, the NRS value which is used to charge the battery, and the electricity used for the non-priority line of the school.

AC 2: Is the electricity exported by the school to the grid through net metering

The percent difference between the values obtained from the data logging and those of the HOMER simulation calculated by equation 5 below are given in Table 22.

Equation 5

$$\% \, Difference = \frac{|HOMER\,Value - Logged\,Value|}{Logged\,Value} * 100\%$$

Table 22. % Difference of some AC parameters between HOMER and the data logging data

Quantity	% Difference
AC Consumption	13.52
AC 1	23.26
AC 2	15.20

It should be noted, that after the installation of the PV power system, the school has been implementing drastic energy efficiency measures which reflected significantly on their consumption values. The initial assumption of the consumption of the school was higher than what is the case in reality.

v. Performance Ratio and Solar Fraction

The Performance Ratio describes the performance of the system with respect to the nominal reference output of the panels at STC considering the governing local conditions. For example, a low performance ratio can be obtained for periods when the school has no load even if the PV generator is in its best conditions. While the solar fraction describes what part of the load is being obtained from the PV Plant with respect to the total consumption. This value is very close to the approximation obtained from the HOMER simulation.

3.2 Optimization on HOMER of RE model

The variation of the COE is monitored with the change in size of the PV generator and the batteries, but also the effect of the grid intermittency is observed. Accordingly this section will be split into 3 different setups defined by the varying grid intermittency, starting by the same intermittency discussed in Chapter 2, then decreasing the blackouts to 6 hours, then increasing the tariff rate with a blackout of 6 hours. The analysis is done according to the levelized cost of electricity of each plant, given that the battery minimum expected lifetime is maintained at 12 years, and the annual capacity shortage of the system is less than 10%. This value has been chosen given the current situation in the country, where a 10% annual blackout is acceptable. A lower capacity shortage could become a design selection criterion if requested for special uses or by beneficiaries and the model would allow a new analysis for the new requirement.

a. Setup 1: 12 hours blackout

While keeping the parameters in HOMER as discussed in Chapter 2, the PV generator sizing and battery sizing were varied according to the below increments:

- PV: Increments of 10% of the original size of 1.8 kWp starting from 10% (0.18 kWp) to 200% (3.6 kWp)
- Battery: the battery sizes simulated in percent of original size are: 0, 25, 50, 75, 100, 150, and 200.

- Using equation 3 the battery practical capacities were converted to days of autonomy provided according to the school's daily consumption, with the results shown in Table23.

Table 23. Conversion of battery size in percent to days of autonomy provided by the batteries using equation 3

Percent of Original Sizeof Battery	Total Capacity of Batteries	Site Consumption	Days of Autonomy Provided
(%)	(kWh)	(kWh/day)	(Days)
0	0	7.65	0.00
25	3.6	7.65	0.35
50	7.2	7.65	0.71
75	10.8	7.65	1.06
100	14.4	7.65	1.41
150	21.6	7.65	2.12
200	28.8	7.65	2.82

Appendix C shows the complete tabulated results for COE values for each simulation.

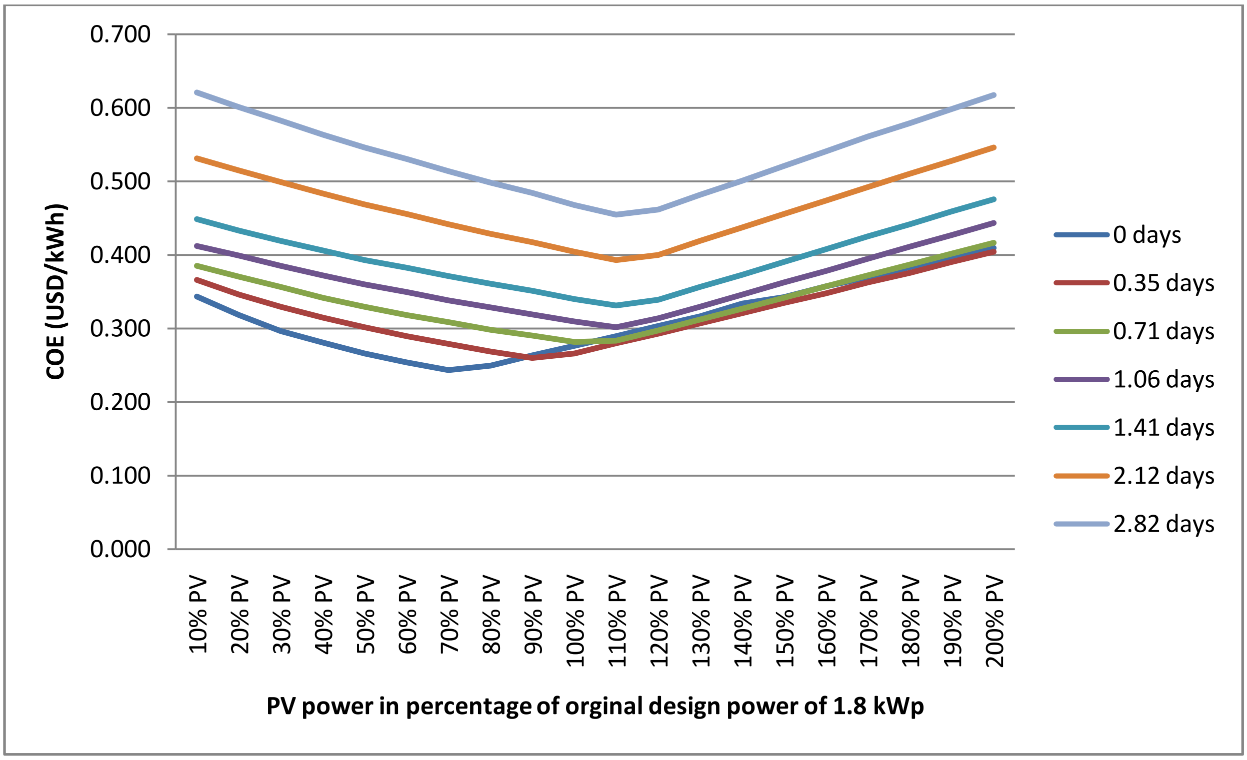

Figure 17. COE graphed versus PV generator size for different Battery capacities given in terms of days of autonomy provided for Meniara Public School

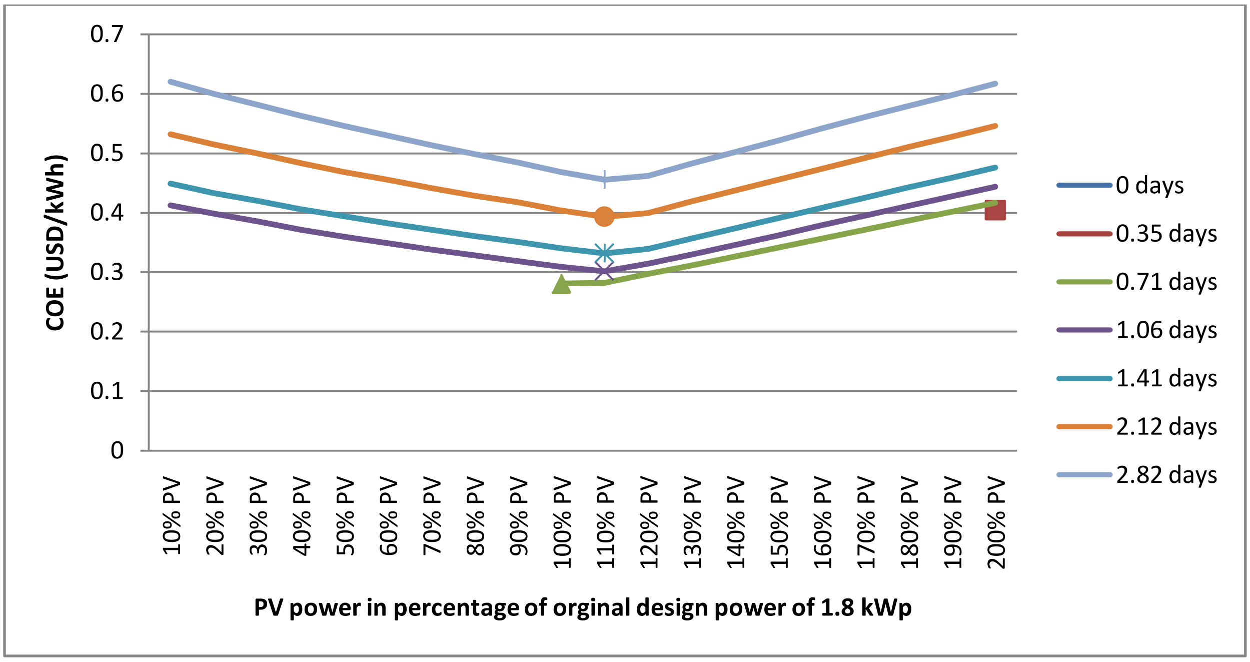

Figure 18. COE graphed versus PV generator size for different Battery capacities given in terms of days of autonomy provided for Meniara Public School. Values not meeting the capacity shortage and battery life criteria are removed

Figure 17 shows that the COE is higher with increased battery capacity and that there is a clear trough in the curve showing an optimum PV generator size for each battery size studied. An exception is the case with no battery, and this could be justified that due to the lack of batteries in the system, a large part of the energy generation potential of the PV array is lost (capture losses) during blackouts when no loads exist due to the lack of storage capacity. As discussed in the introduction of this chapter, all scenarios which result in battery lifetime loss or capacity shortage higher than 10% annually have been discarded. Figure 18 shows the same result as figure 17 but with only the accepted results graphed.

The graph is characterized by two regions:

a. The first region, the COE is decreasing. This region could be the region where all additional PV generation capacity added is being used by the load or traded with the grid. Relative to the bulk investment, the marginal cost of adding PV capacity is offset by the value of electricity produced.
b. The second region, the COE starts to increase after reaching a certain minimum. This region starts after a point of inflection after which, as we increase PV generator capacity, more PV electricity is produced than the site needs, and the delivery to the grid surpasses the purchasing from it.As explained in the net metering concept of Lebanon, this additional electricity is given to the grid for free and this explains that any additional PV capacity added beyond that point has an inherent financial loss due to this generation that is being given away. In equation 4, this could be seen as an increase in the annual investment cost *(C,annual)* and a decrease in useful electricity sold to the grid *(El,sold)*.

The high coincidencefactor between the hours of operation of the public institutions and the availability of solar energyreduces the throughput of the battery without reaching the cycling limit, resulting in battery life projections of 12 years, the maximum possible, for most of the cases. There are two cases which show a shorter battery life and are both within the case where provisioned battery autonomy was for 0.35 days with a PV capacity of 0.18 kWp or with no PV generation. Battery life is impacted negatively by numbers of cycles (charging and discharging) and the level of discharge at every cycle. The deeper the battery is discharged the less its life will be.

From figure 18,the plant with lower COE for such a site would be to use a 1.8kWpPV generator with batteries that provide autonomy for 0.71 days, a PV charge controller, and a 4.8kW 48V dual mode inverter.Details of the equipment are listed in Chapter 1 where the system is introduced. The selection is based on the lowest COE which is inside the acceptable limits of capacity shortage and battery lifetime.Originally the RE system installed atMeniara Public School was designed to provide energy for a daily load of 13.5 kWh as described in Table 2, but the efficiency measures implemented at the school lowered their consumption to 7.65 kWh which led to having an oversized system.

It could be recommended to the school administration that when the batteries are due to be changed, their total size could be half of the current one, if the consumption continues to be lower than initially foreseen.

A comparison between the installed and the recommended plant is provided in Table 24.

Table 24. Comparison between the installed and the recommended RE systems for the Meniara Public School based on minimum COE for 12 hours blackout

Parameter	Installed PV plant	Recommended PV Plant 1
PV Generator (kWp)	1.8	1.8
Battery Size (kWh)	14.4	7.2
Days of Autonomy (days)	1.41	0.71
Initial Capital (USD)	10,030	8,405
COE (USD/kWh)	0.340	0.281
Renewable Energy (%)	74	76
Capacity Shortage (%)	4	10
Battery Life (yrs)	12	12

The comparison table above shows that the recommended PV plant has more capacity shortage than the installed one, this capacity shortage could appear in the form of blackouts, unless the users save energy.

If the requirement was to match the installed plant's performance of having a maximum capacity shortage of 4%, then the new modeling will yield the result as shown in figure 19.

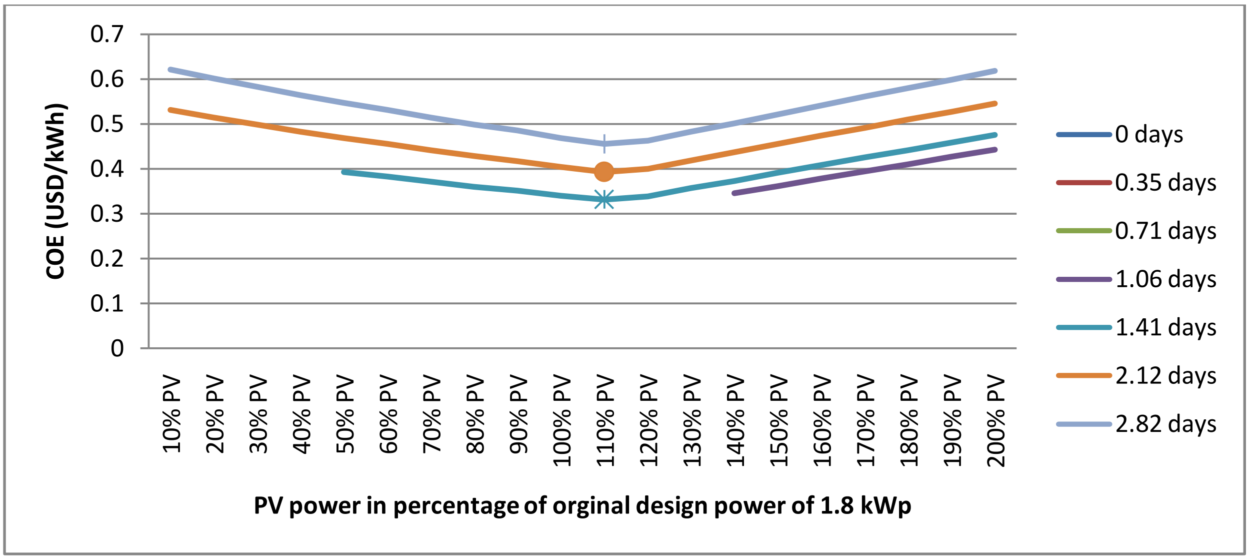

Figure 19. COE graphed versus PV generator size for different Battery capacities given in terms of days of autonomy provided for Meniara Public School. The rejected values have a capacity shortage above the accepted 4% and have a battery life less than 12 years.

Figure 19 shows that for achieving a capacity shortage less than 4% with thelowest COE possible, the renewable energy system will have a PV generator of 1.98 kWp, which is an increase of 10% from the initially installed array. The battery size is the same as the installed system, with a provision for 1.41 days of autonomy. Another possible plant could have battery autonomy of 1.06 days but with a PV generator 140% of the current one.Table 25 contains the comparison between the design options.

Table 25. Comparison table between the installed PV system and two recommendations based on maintaining maximum capacity shortage of 4%

Parameter	Installed PV plant	Recommended PV Plant 2	Recommended PV Plant 3
PV Generator (kWp)	1.8	1.98	2.52
Battery Size (kWh)	14.4	14.4	10.8
Days of Autonomy (days)	1.41	1.41	1.06
Initial Capital (USD)	10,030	10408	10730
COE (USD/kWh)	0.340	0.331	0.346
Renewable Energy (%)	74	77	84
Capacity Shortage (%)	4	4	4
Battery Life (yrs)	12	12	12
Electricity Used (kWh/yr)	3016	3127	2950
Annual Cost (USD)	1025	1036	1020

All 3 cases have similar values, and the selection could be based on several other criteria which are suitable for the site such as room for batteries, space on roof for panels, renewable energy fraction, etc. The total electricity used and the annual cost were included as reference to show that even if the system had the lowest COE, it doesn't mean it will have the least annual cost, and factors such as annual cost and payback period should also be treated as design options in actual implementations.

b. Setup 2: 6 hours blackout

This case includes an increase in grid feeding hours to 18 hours per day as shown in figure 11, the increment changes of PV and Battery sizing is kept the same as Setup 1:

- PV: Increments of 10% of the original size of 1.8 kWp starting from 0% to 200% (3.6 kWp)
- Battery: the battery sizes simulated in percent of original size are: 0, 25, 50, 75, 100, 150, and 200.
    - o Using equation 3 the battery practical capacities were converted to days of autonomy provided according to the school's daily consumption, with the results shown in Table 23

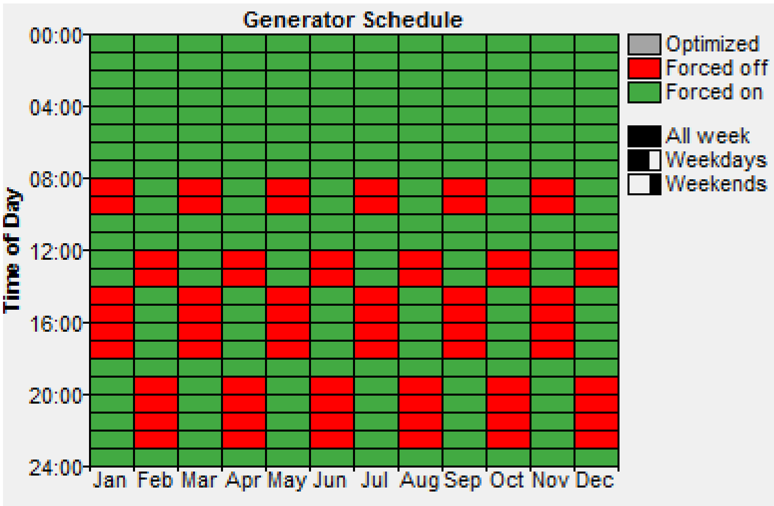

Figure 20. Grid supply and blackout schedules for Setup 2

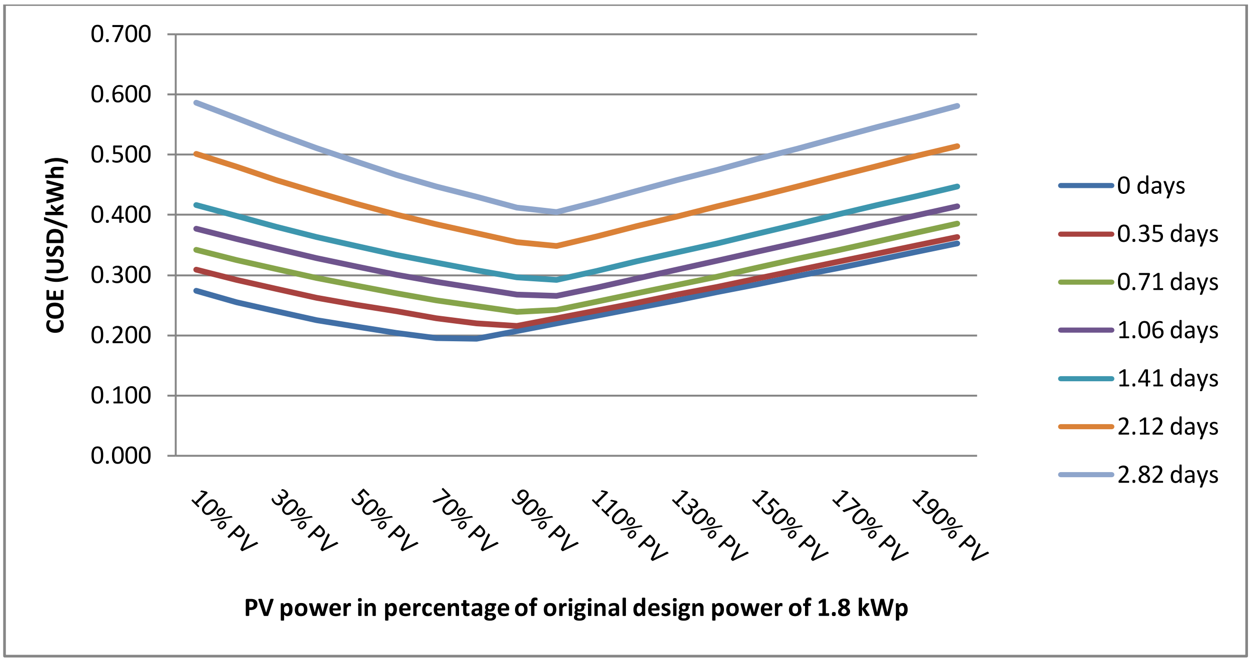

Figure 21. COE graphed versus PV generator size for different Battery capacities given in terms of days of autonomy provided, for Meniara Public School with decreased grid blackouts to 6 hours per day

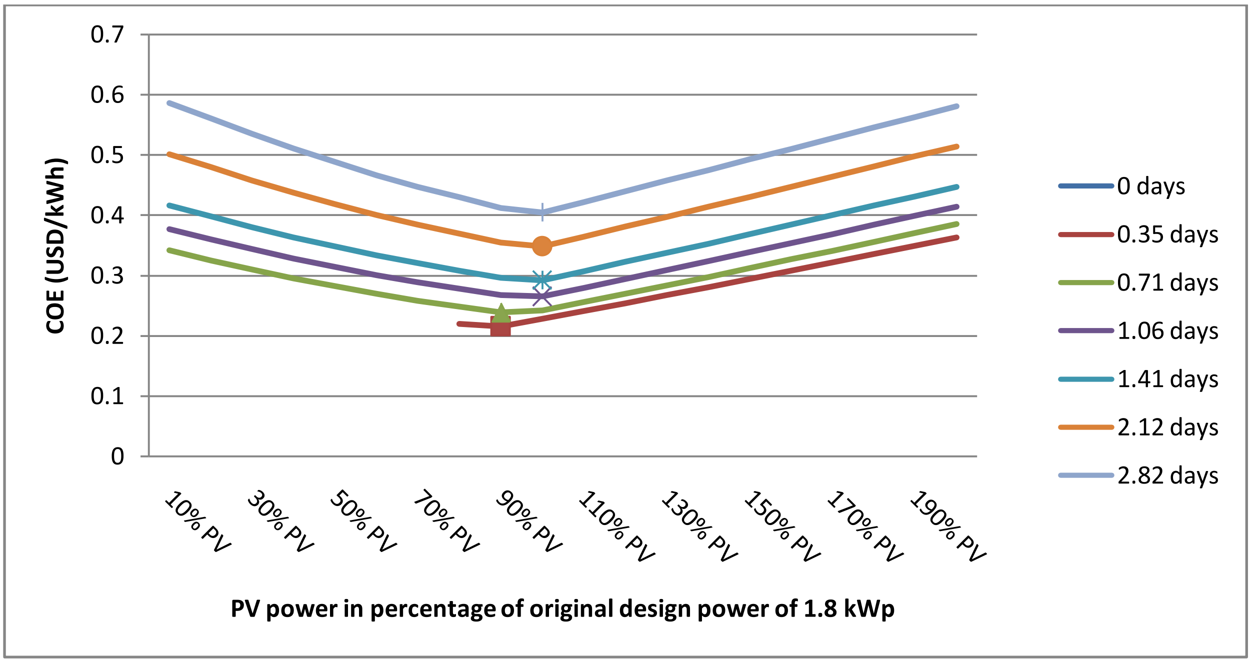

Figure 22. COE graphed versus PV generator size for different Battery capacities given in terms of days of autonomy provided for Meniara Public School with 6 hours daily blackout. Rejected values with capacity shortages above 10% and battery life less than 12 years are deleted from the graph

The analysis indicates that with the decrease in blackout hours less battery storage would be needed, consequently the cost of the recommended PV plants for a certain performance will be less.Table 26 has two alternative options that can be considered, according to the lower COE value.

Table 26. Comparison table between the installed PV plant and two recommendations for the PV plant in Meniara Public School for 6 hours daily blackout

Parameter	Installed PV plant	Recommended PV Plant 4	Recommended PV Plant 5
PV Generator (kWp)	1.8	1.62	1.62
Battery Size (kWh)	14.4	3.6	7.2
Days of Autonomy (days)	1.41	0.35	0.71
Initial Capital (USD)	10,030	7,215	8,027
COE (USD/kWh)	0.292	0.216	0.239
Renewable Energy (%)	72	72	70
Capacity Shortage (%)	1	10	4
Battery Life (yrs)	12	12	12

Several options can be considered for this case, but two of them are very close to each other. The recommended plants have 25% and 50%, respectively, of the battery capacity that is installed in Meniara in the original design and also have a 10% decrease in PV power.

c. Setup 3: 6 hours blackout and increase in grid supply price

Setup 3 tests the system in the case of increase in the grid electricity price, both when purchasing and when selling, to 0.1375 USD/kWh. This case is considered because in the Policy Paper the strategy of the government is to increase the supply price of electricity to this level by 2015 while increasing the supply hours incrementally. The increments of battery and PV generator sizing are kept the same as in the previous setups:

- PV: Increments of 10% of the original size of 1.8 kWp starting from 0% to 200% (3.6 kWp)
- Battery: the battery sizes simulated in percent of original size are: 0, 25, 50, 75, 100, 150, and 200.
    - Using equation 3 the battery sizes were converted to days of autonomy provided according to the school’s consumption, with the results shown in Table 23.

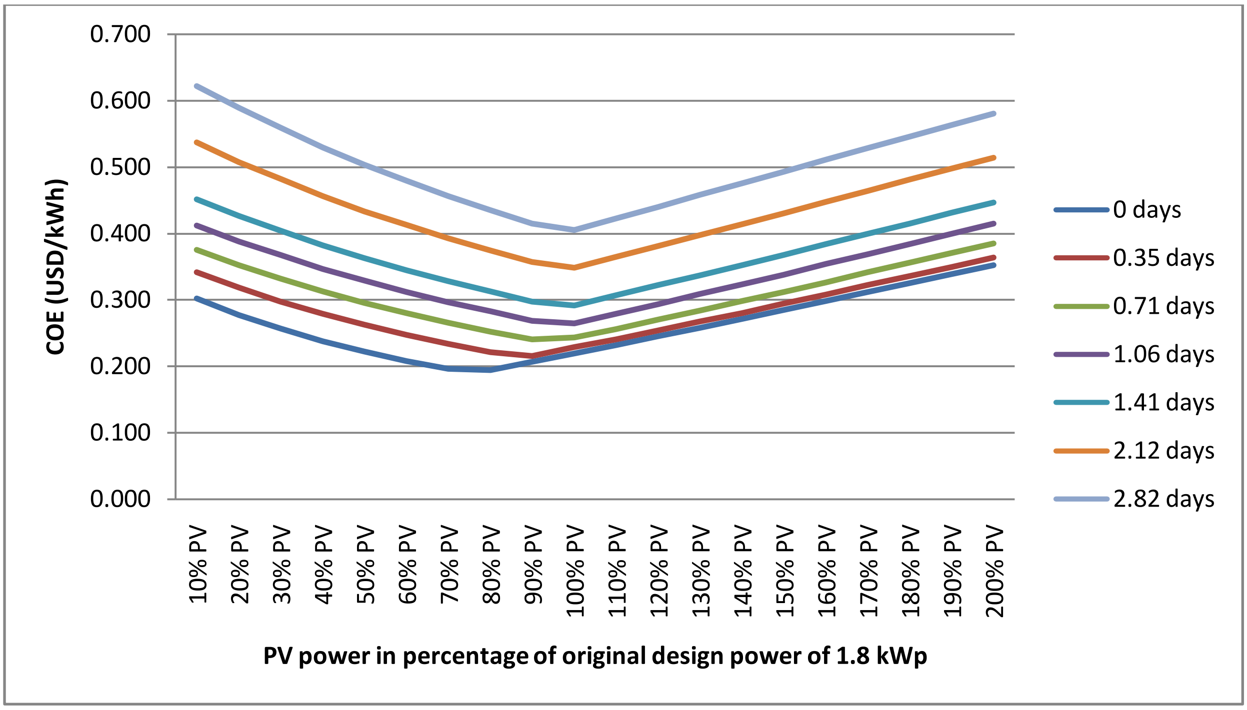

Figure 23. COE graphed versus PV generator size for different Battery capacities given in terms of days of autonomy provided for Meniara Public School. For 6 hours of daily blackout and increased grid tariff to USD 0.1375/kWh

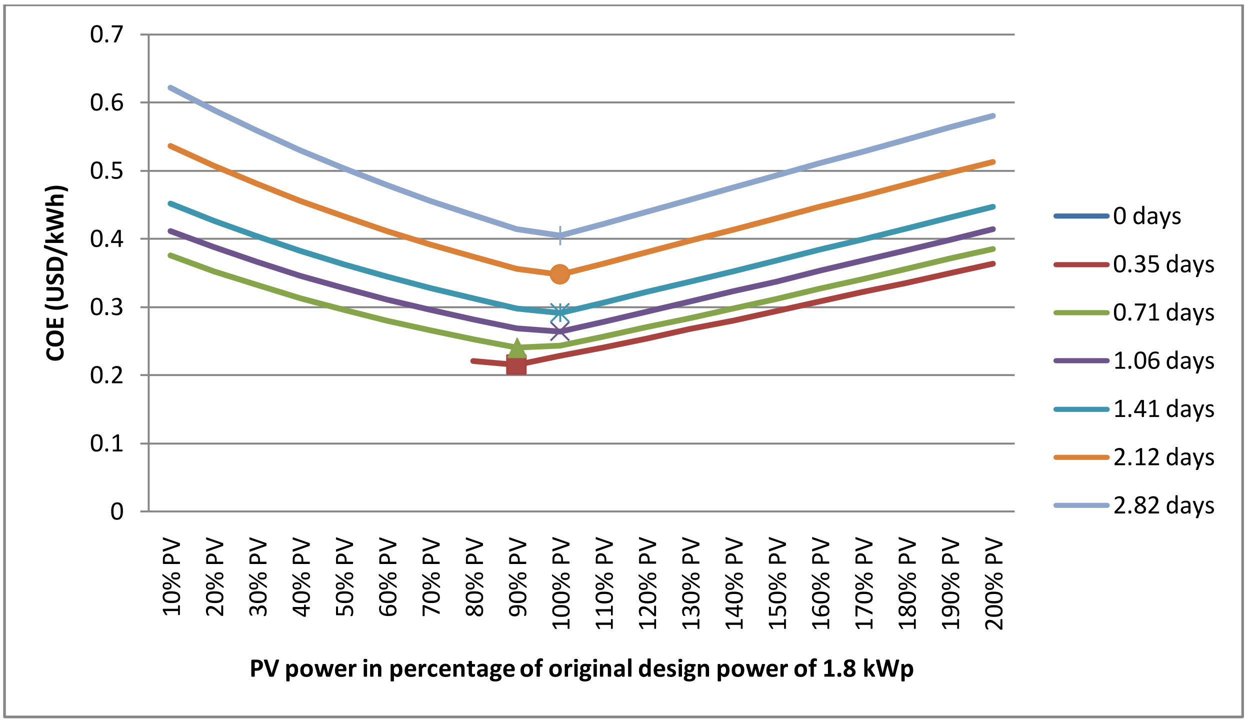

Figure 24. COE graphed versus PV generator size for different Battery capacities given in terms of days of autonomy provided for Meniara Public School, for 6 hours daily blackout and increased grid tariff to USD 0.1375/kWh. Values not meeting the design criteria of capacity shortage and battery life are removed from the graph

The figures showing the results of the simulation in setup 3 are similar to the figures in setup 2 since the values of the technical parameters remained the same. The difference lies in the financial parameters due to the increasein the grid electricity price.

Table 27. Comparison table between the installed PV plant and two recommendations for the PV plant in Meniara Public School for 6 hours daily blackout and increased grid tariff to USD 0.1375/kWh

Parameter	Installed PV Plant	Recommended PV Plant 6	Recommended PV Plant 7
PV Generator (kWp)	1.8	1.62	1.62
Battery Size (kWh)	14.4	3.6	7.2
Days of Autonomy (days)	1.41	0.35	0.71
Initial Capital (USD)	10,030	7,215	8,027
COE (USD/kWh)	0.292	0.216	0.240
Renewable Energy (%)	72	72	70
Capacity Shortage (%)	1	10	4
Battery Life (yrs)	12	12	12

Since the system cannot sell to the grid more electricity than it purchased from it, the balance of grid electricity is always in favor of purchasing from the grid. This balance causes the increase of electricity price to add to the COE of the PV plant the added cost of electricity purchased from the grid. The minimum values of the COE of setups 2 and 3 are close to each other, and even equal in several cases, due to the fact that those points lie where the balance of buying and selling to the grid is nearly zero. The graphs in setup 3 have a higher slope and reach higher values due to the more expensive electricity. Since no technical parameters were changed, the system recommendations remain the same as setup 2, noting the similar COE's for each case in the two setups.

Care should be taken in using the above recommendations in the current situation of the Lebanese electrical grid. The government projects reaching the above mentioned supply schedules and the respective tariff in 2015, thus the design of the system should take into account the years remaining till this situation is reached, specifically if any delays are expected. But if the design follows the minimum COE, the change in grid electricity cost will have little impact on the system financial parameters.

3.3 Analysis for Other Options

In this section, the validated model will be used to simulate the performance of the PV back up plant with other types of buildings, such as community centers and municipalities that have different load profiles.

a. Setup 4: Community Center

Public community centers in Lebanon have similar operation hours as public schools, the difference lies in the availability of equipment with high demand of electricity such as dentist chairs, sterilizing equipment, among others. Thisequipment usually has clear schedules, such as dentists might work for 2 hours in a given day per week, sterilizers are also used during giving birth or other special uses. This information would be used accordingly in the consumption pattern in HOMER. A small medicine refrigerator is always operating even during closing hours of the center, and this will be also simulated in the consumption pattern of the center. Community centers also don't have summer vacation days. The incremental changes of PV generator size and Battery sizing for the sensitivity analysis are kept as the setups mentioned for the school.

- PV: Increments of 10% of the original size of 1.8 kWp starting from 0% to 200% (3.6 kWp)
- Battery: the battery sizes simulated in percent of original size are: 0, 25, 50, 75, 100, 150, and 200.
    - Using equation 3 the battery sizes were converted to days of autonomy provided according to the school's consumption, with the results shown in Table 28.

Table 28. Consumption Pattern for Community Center

Time of Day	Consumption Weekday	Consumption Weekend
	kW	kW
0:00 – 8:00	0.15	0.15
8:00 - 9:00	0.8	0.15
9:00 - 10:00	1.5	0.15
10:00 - 11:00	1.75	0.15
11:00 - 12:00	2.25	0.15
12:00 - 13:00	1.5	0.15
13:00 - 14:00	0.75	0.15
14:00 – 24:00	0.15	0.15
TOTAL (kWh)	**11.25**	**3.6**

The 0.15kW represents the loads that are always present in the community center during closing times.

Using equation 3, the battery capacity sizes are transformed from percentage of original design size as calculated in the software to autonomy days supplied according to the load capacity calculated in Table 29.

Table 29. Conversion of battery size in percent to days of autonomy provided by the batteries using equation 3

Percent of Original Size of Battery Bank	Total Capacity of Batteries	Site Consumption	Days of Autonomy Provided
(%)	(kWh)	(kWh/day)	(Days)
0	0	11.25	0.00
25	3.6	11.25	0.24
50	7.2	11.25	0.48
75	10.8	11.25	0.72
100	14.4	11.25	0.96
150	21.6	11.25	1.44
200	28.8	11.25	1.92

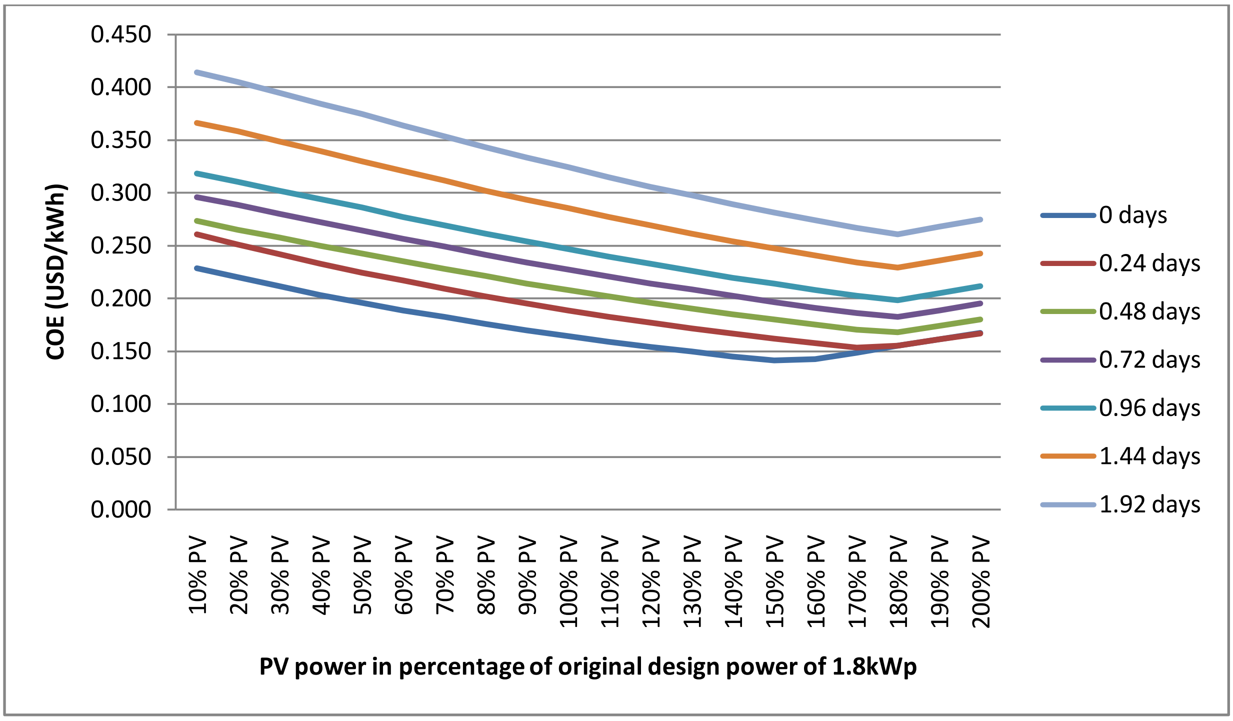

Figure 25. COE graphed versus PV generator size for different Battery capacities given in terms of days of autonomy provided for a community center, 6 hours daily blackout and grid electricity cost of USD 0.1375/kWh

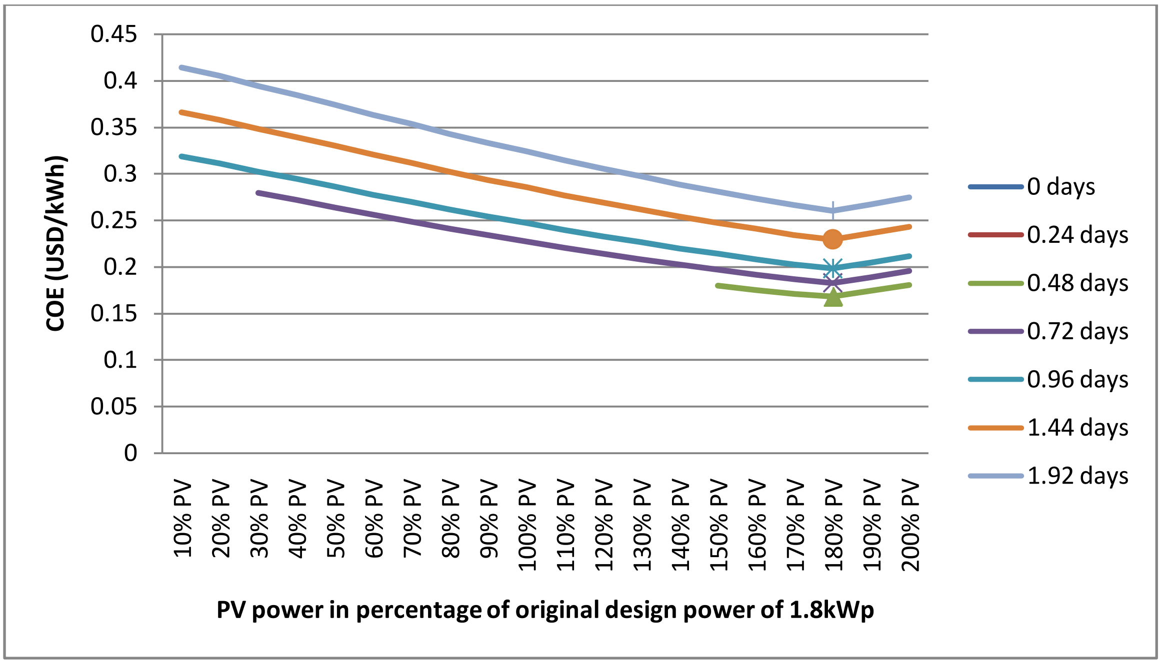

Figure 26. COE graphed versus PV generator size for different Battery capacities given in terms of days of autonomy provided for a community center, 6 hours daily blackout and grid electricity cost of USD 0.1375/kWh. Removed from the graph are all options that lower battery life from required 12 years, and have a capacity shortage higher than 1% of the annual load

For the plant installed for the school the minimum COE was around the 100% PV mark, whereas for the community center it is around 180% PV. This is due to the fact that the consumption of the community center is higher than that of the school, and thus the delivery to the grid from the PV generator only matches the purchase quantity from the grid at large PV generator capacities. As mentioned previously for the school, the point of inflection of the slope for the COE is when the system starts back-feeding to the grid without additional income for the exports.

Since a community center has base loads that need to be maintained all year round, such as the medicine refrigerator, the capacity shortage parameter for this case is taken to be at 1%. Based on the selection parameters and the lowest COE, a recommendation could be given as in Table 30.

Table 30. Comparison between the installed and the recommended RE systems for the community center

Parameter	Installed PV Plant	Recommended PV Plant 8
PV Generator (kWp)	1.8	3.24
Battery Size (kWh)	14.4	7.2
Days of Autonomy (days)	1.28	0.64
Initial Capital (USD)	10,030	11,429
COE (USD/kWh)	0.247	0.168
Renewable Energy (%)	55	73
Capacity Shortage (%)	1	1
Battery Life (yrs)	12	12
Electricity Used (kWh/yr)	5,036	6,201
Annual Cost of System	1,243	1,041

Additional investment in the PV generator and a decrease in investment in the batteries would lead to a better system for this particular case. The added investment is justified by the fact that the lower COE results in break even in around 7 years, after which the recommended system would become financially more competitive. Other advantages of the recommended system are the higher renewable energy percentage.

b. Setup 5: Municipal Center

Municipal centers in Lebanon also have similar operation hours as public schools, and have similar peaks related to using photocopying machines and other equipment, but municipal centers also play a social role which is usually by having afternoon events or gatherings, this is shown in the consumption pattern of such centers in Table 21 below. The incremental changes of PV generator size and Battery sizing are also maintained.

- PV: Increments of 10% of the original size of 1.8 kWp starting from 0% to 200% (3.6 kWp)
- Battery: the battery sizes simulated in percent of original size are: 0, 25, 50, 75, 100, 150, and 200.
    - Using equation 3 the battery sizes were converted to days of autonomy provided according to the school's consumption, with the results shown in Table 31.

Table 31. Consumption Pattern for Municipal Building

Time of Day	Consumption Weekday
	kW
7:00 - 8:00	0.25
8:00 - 9:00	0.5
9:00 - 10:00	0.65
10:00 - 11:00	0.8
11:00 - 12:00	0.8
12:00 - 13:00	1.0
13:00 - 14:00	1.0
14:00 - 15:00	1.0
15:00 - 16:00	0.1
16:00 - 17:00	1.5
17:00 - 18:00	1.0
TOTAL (kWh)	**8.6**

Table 32. Conversion of battery size in percent to days of autonomy provided by the batteries using equation 3

Percent of Original Size of Battery Bank	Total Capacity of Batteries	Site Consumption	Days of Autonomy Provided
(%)	(kWh)	(kWh/day)	(Days)
0	0	8.6	0.00
25	3.6	8.6	0.31
50	7.2	8.6	0.63
75	10.8	8.6	0.94
100	14.4	8.6	1.26
150	21.6	8.6	1.88
200	28.8	8.6	2.51

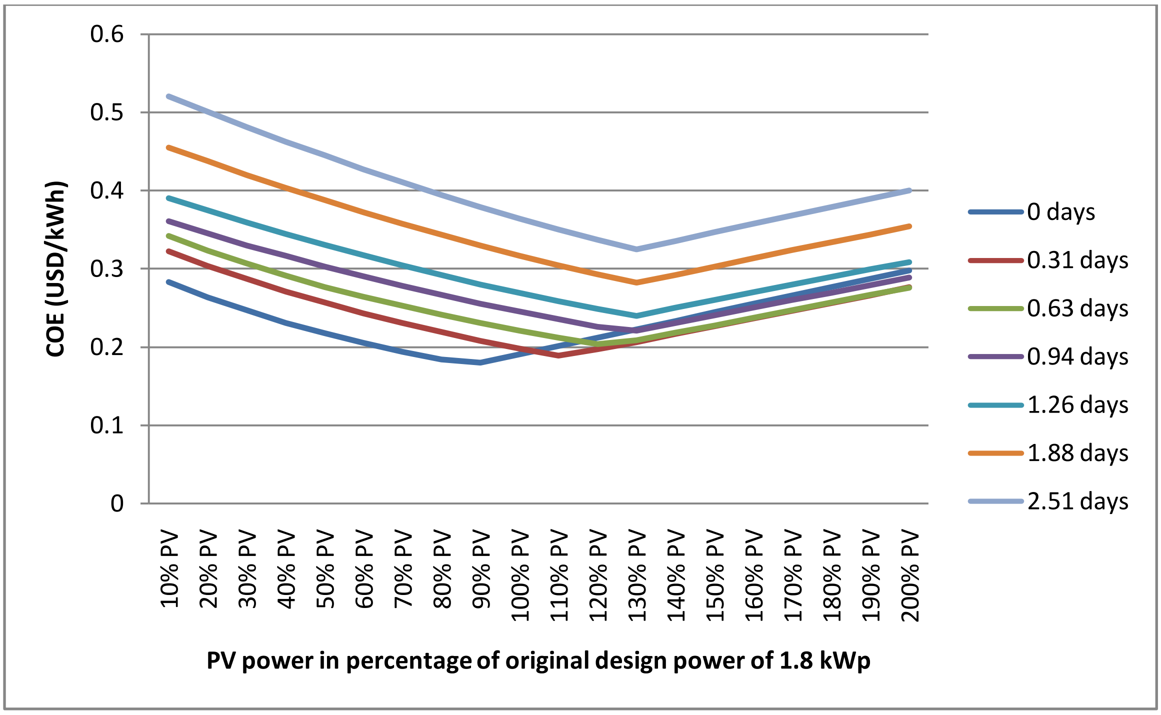

Figure 27. COE graphed versus PV generator size for different Battery capacities given in terms of days of autonomy provided for a municipal center, 6 hours daily blackout and grid electricity cost of USD 0.1375/kWh

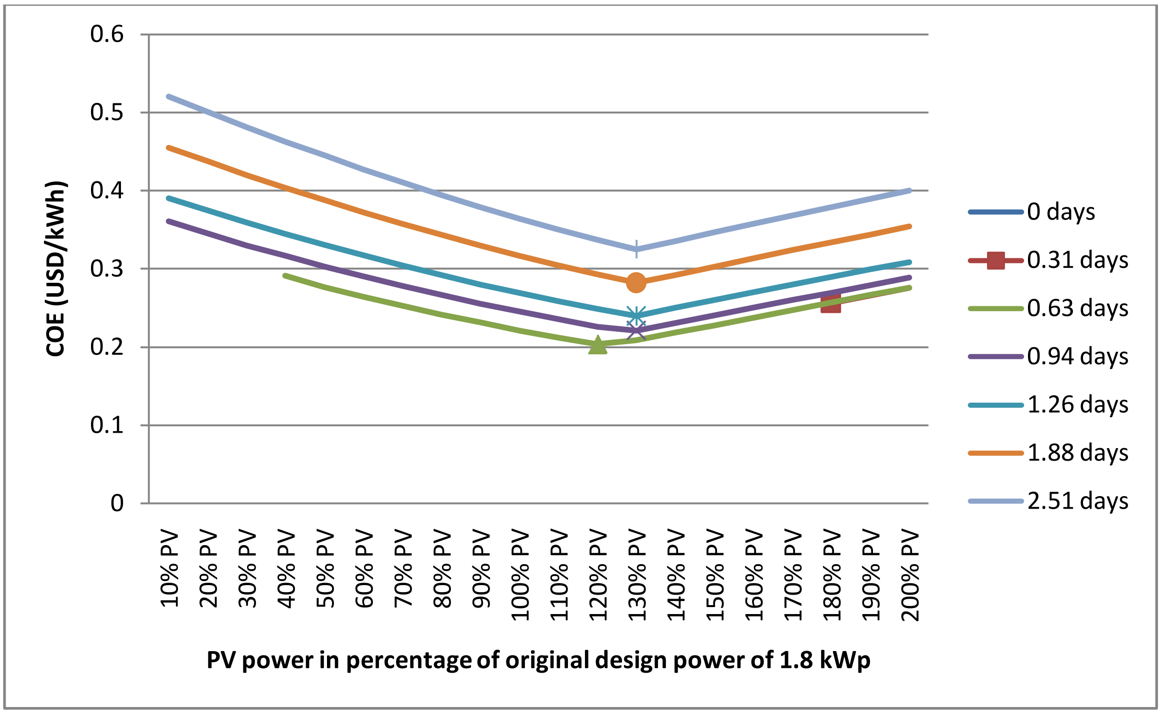

Figure 28. COE graphed versus PV generator size for different Battery capacities given in terms of days of autonomy provided for a municipal center, 6 hours daily blackout and grid electricity cost of USD 0.1375/kWh. Simulations that have battery lifetime of less than 12 years and a capacity shortage higher than 10% have been discarded from the graph

The analysis of the COE simulation and to the selection criteria is similar to the explanations for the cases before. Nevertheless the existence of the afternoon loads, for this case,increase the requirements of the battery. The lifetime of the battery starts dropping when 7.2kWh of storage or less is being used. A recommendation for the municipal center in this case would carry the parameters discussed in Table 33.

Table 33. Comparison between the installed and the recommended RE systems for a municipal center

Parameter	Installed PV Plant	Recommended PV Plant 9
PV Generator (kWp)	1.8	2.16
Battery Size (kWh)	14.4	7.2
Days of Autonomy (days)	1.26	0.63
Initial Capital (USD)	10,030	9,161
COE (USD/kWh)	0.269	0.204
Renewable Energy (%)	64	72
Capacity Shortage (%)	1	5
Battery Life (yrs)	12	12
Electricity Used (kWh/yr)	4,070	4,269
Annual Cost of System	1,095	872

4- Future Considerations

This research successfully reached its objective of creating a validated model for optimizing the PV generator and battery sizes for backup renewable energy micro power pants for the kind of grid available in Lebanon. Though there exists a potential for improving the model and adding value to it by considering several additional features as will be discussed in this section.

a. Projecting A Model for Residential and Industrial Sectors

The private sector in Lebanon is a very strong sector and the country depends largely on private investments in its development and advancement. Accordingly, having a validated model which can also be used for the residential or industrial sector will prove very beneficial and will help accelerate the investment in the renewable energy market by private funding, especially with the increasing problems in the electricity production by the national grid provider and with the increased instability of neighboring countries. The future model developments could consider private single residences and apartments as part of a whole building project. On the other hand the industrial and agricultural sectors which are privately owned businesses and mostly reliant on self-generation should also benefit from a model catered for their specific needs. Whether it would be for water pumping or supplying continuous electricity for mitigating the use of generators in the industrial sector, the benefits of PV generation are numerous with the high cost of self-generation and the intermittency of the grid.

b. Improving the Schedule of Grid Intermittency

As discussed in section 2.2, the intermittency of the grid in Lebanon cycles in a two day cycle, while in HOMER simulation it was only possible to cycle the intermittency per month. The ability to simulate a better matching intermittency schedule has an improvement on the statistics of the model, specifically related tothe cycling of the battery and the effects on its lifetime.

c. Including Or Comparing to Neighborhood Generation

Adding neighborhood and self-generation to the analysis would add an additional incentive for investment in RE, due to the fact that such comparison would show that RE is very cost effective when it replaces self-generation with a genset. Not to mention that prices of energy are increasing, and with the unrest in the gulf region where the petroleum products of Lebanon come from, it might be safer to assume that gasoil prices would continue to go up, and self-generation costs would continue to rise consequently. Appendix D contains a side note on self-generation and simple financial analysis of the benefits that Meniara public school obtained from stopping the neighborhood generation subscription.

d. Creating a More Valid Database for Solar Data

Most of the inputs used in software for solar data for Lebanon rely on international satellite or weather data readings and are usually the data for the capital city of Beirut. But for a country such as Lebanon with a diverse terrain and steep mountains spread across a small region, the variations in solar and weather data are significant even in fine grid sizes. A simulation carrying exact data for a specific region, or type of region, would yield more accuracy. This data could come from the PVGIS satellite data or from data collected and analyzed statistically from the 90 different PV sites of the CEDRO project. Those sites would be able to provide more specific data sets for solar irradiation and weather patterns for the country. Some of the sites have already been measuring data for over 3 years, and in the few years to come a database containing specific regional data should be used for simulation. The collection of this data is projected to start in 2013 and to continue to obtain as accurate data as possible for the future.

e. Introducing Wind Data

Micro-wind projects have been started by the CEDRO project and completion of the projects is scheduled by October 2013. But already a 1 year data set exists for several regions around the country where wind has proven to have a potential for generating electricity. The future simulation software should contain this data and should include micro-wind electricity generation due to its competitive price and simple installation, and the availability of do-it yourself kits. After the wind projects are completed and the data is set for use, a similar project should simulate and validate wind generation for Lebanon. It should be noted that 3 PV-Wind hybrid sites are scheduled to begin in late August and the data obtained from those sites would also be valuable.

f. Pollution and GHG Emissions

Even though this study focused largely on the financial benefits and considerations of renewable energy systems, the value of RE systems to the environment is unquestioned and the offsetting of self-generation which distributes the pollution all around the neighborhoods is a valuable asset that sometimes cannot be simply quantified in terms of economic data, but is as important. A study of pollution and GHG emissions offset by should also be considered, especially to create awareness on the benefits of RE generation and the damage cause by pollution to the environment and the livelihood of the country.

CONCLUSION

This study was able to meet its objective of finding a valid model for simulating a PV/Battery renewable energy plant design that accounts for the intermittent grid of Lebanon. A sensitivity analysis is carried out on the PV system installed at the reference site, Meniara Public School, and variations in PV generator size, battery size, blackout schedule, and grid electricity price were simulated and analyzed. After the model was validated with the data logging information from the Meniara Public School, it was used to simulate a PV plant for a community and a municipal center.

The levelized cost of electricity was used for the optimization design of the PV plant, where the minimum COE is considered as the best option once the requirements of allowed capacity shortages and minimum battery life are met. The results for the COE calculated directly in HOMER could not be used as is, a series of equations for calculating a corrected COE value are needed and have been developed in this research. One of the corrections is related to the rule in the Lebanese net metering bill which doesn't allow the subscriber to back-feed more electricity to the grid than what he is consuming, a value which is reset yearly. HOMER on the other hand, doesn't take into account this limit and accepts any electricity that is sold to the grid.

After the correction of the COE and electricity production and trading values, some general conclusions from the simulations are given below.

- Batteries have a high effect on the cost of electricity produced by the backup plant. Additional battery capacity increases the cost more significantly than additional PV panels.
- The reaction of the system to increased grid supply hours was also studied. The COE of the plant decreases due to the higher consumption of power provided by the grid and less use of batteries. In this case the system sizing could have also been reduced to save on investment cost. The situation where blackouts are decreased is expected to be reached in the year 2015, but care should be taken in designing systems for the future, since they plants should be also able to accommodate for the transition period.
- The Lebanese Ministry of Energy and Water projects that by the year 2015, the blackouts in the Lebanese grid would be reduced but the cost of grid electricity would be increased. It has been shown that the increase of grid electricity price has a marginal impact on the minimum COE reached by the PV plant, since at this point the system is selling electricity to the grid equal to what it is purchasing, thus the account balance with the grid is zero. The slope of the COE increases with increased grid electricity price, so as one moves away from the minimum COE, a higher rise in COE is expected the higher the grid electricity price is.

As a result of the sensitivity analysis, several recommendations for PV plant design optimization and sizing were given based on the minimum COE for each case. Two limiting criteria were used;

one is that the system recommended should maintain the battery life at its maximum of 12 years; the second is that the load is allowed to be unmet for only 10% of the total annual consumption. Thus if the load needs 1200 kWh per year, a maximum shortage of 120 kWh is allowed.

Table 34. Recommendations Summary for Meniara Public school PV plant. Different grid parameters are considered for each setup, 1st Setup considers 12 hours daily blackout and 0.1USD/kWh grid electricity price, 2nd setup has 6 hours blackout and similar grid elect

Parameters	ReferencePV Plant	Recommended System		
		Setup 1	Setup 2	Setup 3
Daily Consumption (kWh)	7.65	7.65	7.65	7.65
PV Generator (kWp)	1.8	1.8	1.62	1.62
Battery Size (kWh)	14.4	7.2	3.6	3.6
Days of Autonomy (days)	1.41	0.71	0.35	0.35
Initial Capital (USD)	10,030	8,405	7,215	7,215
COE (USD/kWh)	0.340	0.281	0.216	0.216
Renewable Energy (%)	74	76	72	72
Capacity Shortage (%)	4	10	10	10
Battery Life (yrs)	12	12	12	12

The selection criterion was based on the minimum COE for each case. For the situation currently existing in Lebanon, setup 1, it could be recommended that the system has half the storage capacity that it currently does. In part this is due to the fact that the system was designed for a particular load, but the school implemented strict energy efficiency measures which caused the actual consumption to be lower.

Other design requirements could be used, such as the capacity shortage limit. In the recommendations above, it could be seen that the recommended systems have 10% shortage in capacity while the installed system has only 4%. In some cases, the optimization could be carried out for the minimum COE but with a requirement of keeping the same capacity shortage value or improving it.

The value of lost load can also be considered as a design factor. The value of lost load, "VOLL", is a term used to put a cost for every kWh not supplied for a certain activity. For some institutions, the "VOLL", can be very high, such as hospitals and community centers. In such cases, the party installing a PV plant might request a lower capacity shortage. For the recommendations for the PV plant in the community center, a capacity shortage factor of <1 % is used.

Table 35. Recommendations for PV plants for a community and municipal centers. The grid is considered to have 6 hours of blackouts and 0.1375USD/kWh for electricity cost, as in setup 3 above

Parameters	Reference PV Plant	Recommended PV Plants	
		Community Center	Municipal Center
Daily Consumption (kWh)	7.65	11.25	8.6
PV Generator (kWp)	1.8	3.24	2.16
Battery Size (kWh)	14.4	7.2	7.2
Days of Autonomy (days)	1.41	0.64	0.63
Initial Capital (USD)	10,030	11,429	9,161
COE (USD/kWh)	0.340	0.168	0.204
Renewable Energy (%)	74	73	72
Capacity Shortage (%)	4	1	5
Battery Life (yrs)	12	12	12

The recommendations above and the validated system could be used for similar small scale institutions with maximum typical loads of 20-30 kWh/day. It should be noted that it's unrealistic to place batteries for storage capacities higher than 100 kWh/day of supply or 144 kWh/day of total storage capacity. Within the range mentioned, the parameters are scalable and can be used for referencing or checking designs. This is one of the reasons that battery size was given in days of autonomy instead of kWh or A.h.

Renewable energy technologies are a relatively new concept in Lebanon, given the lack of awareness for the past years. New financial schemes have been placed to encourage the investment in this sector, such as zero interest loans, net-metering, and lower taxes for RE applications. Providing a simulation software able to simulate and optimize the performance of PV plants for the specific conditions of Lebanon, including the intermittent grid, can be a strong incentive for investment in the renewable energy sector. The first attempt made in this research was to provide a simulation that can account for grid intermittency, and in the future improvements should be made to create a specific software that reliably replicates the conditions of the country.

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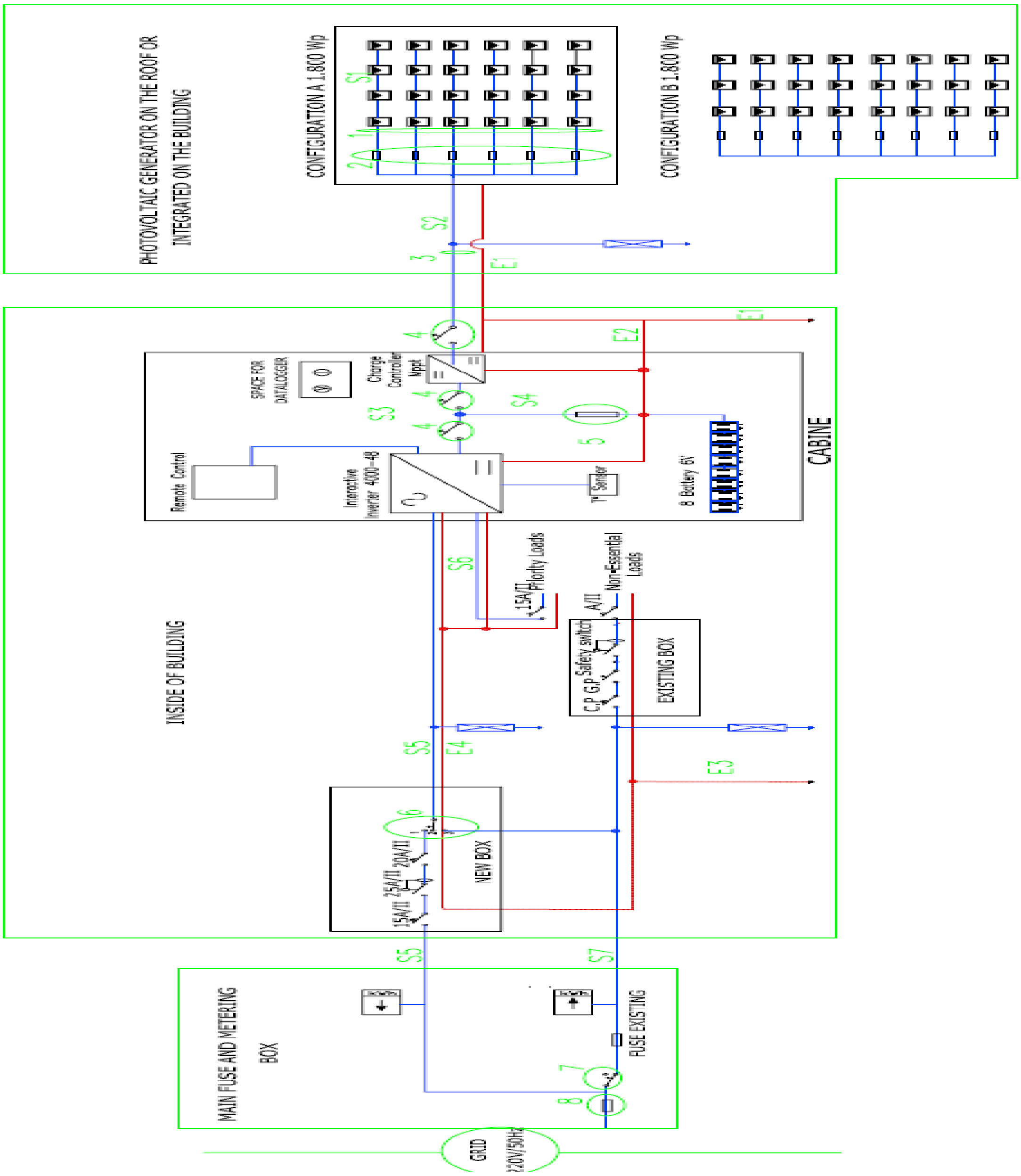
APPENDIX A

PV Generator

Line Diagram for PV system operation, Legend follows



Legend for Line Diagram and Method of Operation

Earth connection		
E1 Estructure Metallic	L<20 m.	1x16 mm2
E2 Controller,Inverter,Battery	L<10 m.	1x16 mm2
E3 Building Interior Intallation		Alredy Existing
E4 General Protection AC	L<5 m.	1x16 mm2

Section of cable

The cables be UV-resistant, water resistant and they be flexible (multistranded)
The specifications of the cables are of Cu Rv-k 0,6/1kV.

PV Strings	L<10 m.	2x2,5 mm2	S1
PV Generator Charger-Controller	L<20 m.	2x16 mm2	S2
Charge-Controller-Inverter	L<3 m.	2x16 mm2	S3
Charge-Controller-Battery	L<3 m.	2x35 mm2	S4
Inverter-Protection to Grid	L<35 m.	2x10 mm2	S5
Inverter-Priority Loads	L<35 m.	2x10 mm2	S6
Grid-Building		Alredy Existing	S7

Protection Devices

Protection against overcurrent

2	String fault current protection 8 A.
5	String fault current protection 250 A.
8	String fault current protection 30 A.

Cable rating

1	Tied to overcurrent protection rating 8A.
3	Trip current of the PV array overcurrent protection device-Tied to battery over-current rating 40A.

Disconnection Devices

6	Double pole, switch governed by Inverter
4-7	Double pole, switch

<table>
<tr><th colspan="8">MODES OF OPERATION</th></tr>
<tr><td rowspan="3">GRID ON</td><td rowspan="3">Swlth 7 on</td><td rowspan="3">Swltch Prlorlty Load off</td><td>A</td><td>Battery not full</td><td>Swlth 6 posltlon 3</td><td colspan="2">Grld feeds the loads and the battery</td></tr>
<tr><td>B</td><td>Battery full and load > PV productlon</td><td>Swlth 6 posltlon 2</td><td colspan="2">Grld feeds the loads</td></tr>
<tr><td>C</td><td>Battery full and load < PV productlon</td><td>Swlth 6 posltlon 1</td><td colspan="2">Grld feeds the loads and battery feeds the Grld</td></tr>
<tr><td rowspan="2">GRID OFF</td><td rowspan="2">Swlth 7 off</td><td rowspan="2">Swltch Prlorlty Load off</td><td>D</td><td colspan="2">Swlth 6 posltlon 3</td><td colspan="2">Battery feeds the Prlorlty load and PV generator charge battery</td></tr>
<tr><td>E</td><td colspan="2">Swlth 6 posltlon 3</td><td colspan="2">Battery feeds the Prlorlty load</td></tr>
</table>

Pictures of the System

Figure 29 PV Generator

Figure 30 Cabinet for Equipment, Inverter, Battery Bank, respectively from left to right

APPENDIX B

Significance of Data Logging Parameters as Explained by Equipment Manufacturer

Symbol	Term	Meaning / Definition	Unit	
Y_r	Reference Yield	**$Y_r = H_I / G_0$.** Y_r is equal to the time which the sun has to shine with G_0 = 1kW/m^2 to irradiate the energy H_I onto the solar generator.	$\frac{kWh/m^2}{d_* 1kW/m^2}$	[h/d]
L_c	Capture Losses	**Thermic capture losses L_{CT} :** - Losses caused by cell temperatures higher than 25^{o}C. **Miscellaneous capture losses L_{CM} :** - Wiring, string diodes, low irradiance - Partial shadowing, contamination, snow covering, inhomogeneous irradiance, mismatch - Maximum power tracking errors, reduction of array power caused by inverter failures or when the accumulator is fully charged (stand alone systems) - Errors in irradiance measurements - When irradiance is measured with pyranometer. Spectral losses, losses caused by glass reflections	$\frac{kWh}{d_* kWp}$	[h/d]
Y_a	Array Yield	**$Y_a = E_A / P_0$.** Y_a is equal to the time which the PV plant has to operate with nominal solar generator power P_0 to generate array (DC-)energy E_A	$\frac{kWh}{d_* kWp}$	[h/d]
L_s	System Losses	Inverter conversion losses (DC-AC), accumulator storage losses (stand alone systems).	$\frac{kWh}{d_* kWp}$	[h/d]
Y_f	Final Yield	**$Y_f = E_{use} / P_0$.** Y_f is equal to the time which the PV plant has to operate with nominal solar generator power P_0 to generate the useful output energy E_{use}. For grid connected plants: $E_{use} = E_{ac}$.	$\frac{kWh}{d_* kWp}$	[h/d]
PR	Performance Ratio	**$PR = Y_f / Y_r$.** PR corresponds to the ratio of the useful energy E_{use} to the energy which would be generated by a lossless, ideal PV plant with solar cell temperature at 25^{o}C and the same irradiation.		[1]

$$Y_r \xrightarrow{-L_C} Y_a \xrightarrow{-L_S} Y_f \qquad Y_r \xrightarrow{-L_{CT}} Y_T \xrightarrow{-L_{CM}} Y_a \xrightarrow{-L_S} Y_f$$

APPENDIX C

COE graphs for the cases considered

Summary of Results for Setup 1 with 12 hours of blackout for Meniara Public School

	0 days	0.35 days	0.71 days	1.06 days	1.41 days	2.12 days	2.82 days
10% PV	0.344	0.366	0.385	0.412	0.448	0.532	0.621
20% PV	0.319	0.346	0.370	0.399	0.433	0.514	0.600
30% PV	0.296	0.330	0.356	0.385	0.419	0.499	0.582
40% PV	0.281	0.315	0.342	0.372	0.406	0.483	0.563
50% PV	0.266	0.301	0.330	0.360	0.393	0.468	0.546
60% PV	0.253	0.289	0.318	0.349	0.382	0.455	0.530
70% PV	0.243	0.279	0.308	0.338	0.371	0.442	0.514
80% PV	0.250	0.269	0.298	0.328	0.361	0.429	0.498
90% PV	0.263	0.260	0.290	0.318	0.351	0.417	0.484
100% PV	0.276	0.266	0.281	0.309	0.340	0.404	0.468
110% PV	0.290	0.280	0.283	0.301	0.331	0.393	0.455
120% PV	0.303	0.293	0.297	0.314	0.339	0.400	0.462
130% PV	0.317	0.307	0.312	0.330	0.356	0.419	0.482
140% PV	0.334	0.321	0.326	0.346	0.373	0.437	0.501
150% PV	0.343	0.335	0.342	0.362	0.391	0.456	0.521
160% PV	0.357	0.348	0.357	0.378	0.408	0.474	0.541
170% PV	0.370	0.362	0.372	0.395	0.425	0.492	0.560
180% PV	0.383	0.376	0.386	0.411	0.442	0.510	0.579
190% PV	0.397	0.390	0.402	0.427	0.459	0.528	0.598
200% PV	0.410	0.404	0.416	0.443	0.476	0.546	0.617

Summary of Results for Setup 2 with 6 hours of blackout for Meniara Public School

	0 days	0.35 days	0.71 days	1.06 days	1.41 days	2.12 days	2.82 days
10% PV	0.274	0.309	0.341	0.377	0.416	0.501	0.587
20% PV	0.255	0.292	0.325	0.360	0.398	0.479	0.561
30% PV	0.240	0.277	0.310	0.344	0.380	0.458	0.536
40% PV	0.225	0.263	0.295	0.328	0.363	0.437	0.511
50% PV	0.214	0.251	0.282	0.314	0.348	0.418	0.488
60% PV	0.203	0.240	0.270	0.300	0.333	0.400	0.467
70% PV	0.195	0.229	0.259	0.289	0.320	0.384	0.447
80% PV	0.194	0.220	0.249	0.278	0.308	0.369	0.430
90% PV	0.207	0.216	0.239	0.267	0.296	0.354	0.412
100% PV	0.219	0.228	0.243	0.265	0.292	0.348	0.405
110% PV	0.232	0.241	0.256	0.279	0.307	0.364	0.422
120% PV	0.245	0.254	0.270	0.294	0.322	0.381	0.440
130% PV	0.258	0.267	0.284	0.309	0.337	0.397	0.457
140% PV	0.271	0.281	0.298	0.323	0.353	0.414	0.475
150% PV	0.284	0.294	0.312	0.338	0.368	0.430	0.493
160% PV	0.298	0.308	0.327	0.353	0.384	0.447	0.510
170% PV	0.311	0.322	0.341	0.369	0.400	0.464	0.529
180% PV	0.325	0.335	0.356	0.384	0.416	0.481	0.546
190% PV	0.338	0.350	0.370	0.399	0.431	0.497	0.564
200% PV	0.352	0.364	0.385	0.414	0.447	0.514	0.581

Summary of Results for Setup 3 with 6 hours of blackout for Meniara Public School, with grid electricity price of USD 0.1375/kWh

	0 days	0.35 days	0.71 days	1.06 days	1.41 days	2.12 days	2.82 days
10% PV	0.302	0.342	0.376	0.412	0.452	0.537	0.622
20% PV	0.277	0.318	0.352	0.388	0.427	0.507	0.589
30% PV	0.256	0.298	0.332	0.367	0.404	0.481	0.559
40% PV	0.238	0.279	0.312	0.347	0.382	0.456	0.530
50% PV	0.222	0.263	0.296	0.329	0.363	0.433	0.503
60% PV	0.208	0.247	0.280	0.311	0.345	0.412	0.479
70% PV	0.196	0.234	0.266	0.296	0.328	0.392	0.455
80% PV	0.194	0.221	0.252	0.283	0.313	0.374	0.435
90% PV	0.207	0.216	0.240	0.269	0.298	0.356	0.415
100% PV	0.219	0.229	0.243	0.265	0.292	0.348	0.405
110% PV	0.232	0.241	0.256	0.279	0.307	0.364	0.422
120% PV	0.245	0.254	0.270	0.294	0.322	0.381	0.440
130% PV	0.258	0.268	0.284	0.309	0.337	0.397	0.458
140% PV	0.271	0.280	0.298	0.323	0.353	0.414	0.475
150% PV	0.284	0.294	0.312	0.338	0.368	0.430	0.493
160% PV	0.298	0.308	0.326	0.354	0.384	0.447	0.511
170% PV	0.311	0.322	0.341	0.369	0.400	0.464	0.528
180% PV	0.325	0.336	0.356	0.384	0.415	0.481	0.546
190% PV	0.338	0.349	0.371	0.399	0.431	0.497	0.563
200% PV	0.352	0.363	0.385	0.415	0.447	0.514	0.581

Summary of Results for Setup 4 with 6 hours of blackout for Community Center, with grid electricity price of USD 0.1375/kWh

	0 days	0.24 days	0.48 days	0.72 days	0.96 days	1.44 days	1.92 days
10% PV	0.228	0.261	0.274	0.296	0.319	0.366	0.414
20% PV	0.220	0.251	0.265	0.288	0.311	0.358	0.405
30% PV	0.211	0.242	0.258	0.280	0.302	0.348	0.394
40% PV	0.203	0.233	0.250	0.272	0.294	0.339	0.385
50% PV	0.196	0.225	0.242	0.264	0.286	0.330	0.374
60% PV	0.189	0.217	0.235	0.256	0.277	0.320	0.364
70% PV	0.182	0.209	0.228	0.249	0.270	0.312	0.353
80% PV	0.176	0.202	0.221	0.241	0.262	0.302	0.343
90% PV	0.170	0.195	0.214	0.234	0.254	0.293	0.333
100% PV	0.164	0.189	0.208	0.228	0.247	0.286	0.324
110% PV	0.159	0.183	0.202	0.221	0.239	0.277	0.315
120% PV	0.154	0.177	0.196	0.214	0.233	0.269	0.306
130% PV	0.150	0.172	0.190	0.208	0.226	0.262	0.297
140% PV	0.145	0.167	0.185	0.202	0.220	0.254	0.289
150% PV	0.141	0.162	0.180	0.197	0.214	0.247	0.281
160% PV	0.143	0.158	0.175	0.191	0.208	0.241	0.274
170% PV	0.149	0.154	0.170	0.187	0.203	0.234	0.266
180% PV	0.155	0.155	0.168	0.183	0.198	0.229	0.260
190% PV	0.161	0.161	0.174	0.189	0.205	0.236	0.268
200% PV	0.167	0.167	0.180	0.195	0.211	0.243	0.275

Summary of Results for Setup 5 with 6 hours of blackout for Municipality, with grid electricity price of USD 0.1375/kWh

	0 days	0.31 days	0.63 days	0.94 days	1.26 days	1.88 days	2.51 days
10% PV	0.283	0.322	0.342	0.361	0.390	0.455	0.520
20% PV	0.264	0.304	0.323	0.345	0.374	0.438	0.501
30% PV	0.247	0.287	0.307	0.330	0.359	0.420	0.481
40% PV	0.231	0.271	0.291	0.316	0.345	0.403	0.463
50% PV	0.218	0.257	0.277	0.303	0.330	0.388	0.445
60% PV	0.205	0.244	0.264	0.290	0.317	0.372	0.427
70% PV	0.194	0.231	0.253	0.278	0.304	0.357	0.411
80% PV	0.184	0.219	0.242	0.267	0.292	0.343	0.394
90% PV	0.180	0.209	0.231	0.256	0.280	0.330	0.379
100% PV	0.191	0.199	0.222	0.246	0.269	0.317	0.364
110% PV	0.202	0.189	0.213	0.236	0.259	0.304	0.350
120% PV	0.212	0.197	0.204	0.227	0.249	0.293	0.337
130% PV	0.223	0.207	0.209	0.221	0.240	0.282	0.325
140% PV	0.234	0.217	0.219	0.231	0.250	0.292	0.336
150% PV	0.245	0.227	0.228	0.241	0.260	0.303	0.347
160% PV	0.256	0.237	0.238	0.250	0.269	0.313	0.358
170% PV	0.266	0.247	0.247	0.260	0.279	0.323	0.369
180% PV	0.277	0.257	0.257	0.270	0.289	0.334	0.379
190% PV	0.288	0.266	0.267	0.279	0.299	0.344	0.390
200% PV	0.298	0.276	0.276	0.289	0.308	0.354	0.400

APPENDIX D

NOTE ON SELF GENERATION AND NEIGHBORHOOD GENERATORS

Even though the COE's of around USD0.4/kWh which were obtained for the RE systems could be considered high compared to grid electricity prices for Lebanon or for most of the world. But the main financial comparison in this case should not be the offsetting of grid electricity as much as it is the offsetting of the use of polluting and expensive self-generation. By a study of the Ministry of Energy and Water of Lebanon published in the Policy Paper, it is shown that the price of self-generation by diesel generators has a cost of USD0.4/kWh and can be higher if it is a neighborhood generator considering that the supplier makes profit out of selling electricity. For example, after the installation of the PV system for Meniara Public School, they cancelled the subscription to the neighborhood generator which used to supply them with 5Amps worth of electricity at a price of 100 USD/month. These 5 Amps could only be used for lighting the school without the use of equipment such as the photocopying machine and others. The PV system that was installed allowed them to operate the school normally without intermittency and without having to sacrifice the use of photocopying machines and computers. The offset of nearly USD 1200 per year for a system that costs now around USD 12000 can be considered a sound financial investment given the added benefits of operating the whole school efficiently during the teaching hours and the non-intermittent supply of electricity.