AMERICAN UNIVERSITY OF BEIRUT

ENERGY MANAGEMENT SYSTEM FOR A SMART MICROGRID

by
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AN ABSTRACT OF THE THESIS OF

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In this thesis an energy management system of a microgrid is developed based on quadratic programming. The microgrid contains renewable energy resources, a battery and a diesel generator. The sizes of the components are changed to present a somehow maximized gain from the microgrid. The battery and the diesel generator sizes are found by trying a big size and checking if it is enough or if it is too big for the project. On the other hand, the number of photovoltaic modules to be used is found by finding the net present value (NPV) of the project while changing the number of modules until reaching the maximum NPV. A case study will be presented of a village in Lebanon. Different available resources are considered and the costs of the fuel, operation and maintenance, and the penalty cost incurred due to pollution are found. A comparison is done between various scenarios in the village.

The levelized cost of energy and the net present value for each of the scenarios is found to check the techno-economic viability of the project from the customer and from the investor’s point of view. Benefits due to pollution reduction are also considered by taking into account the penalty costs of pollutant generation. This project can give an idea of how beneficial it may be if the same microgrid concept presented in this thesis is applied over other villages and cities in Lebanon.

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NOMENCLATURE

$a(n, r)$	Annuity over a period n at an interest rate r
C	Roughness coefficient
C_{grid}	Cost of selling and purchasing from grid
C_{OMx}	Cost of O&M for source x
C_{pol}	Pollution cost
D	Diameter of the pipe (m)
D_i	Number of days in month i
E_i	Energy in month i
E_{ij}	Energy in months i and j
G	Ambient irradiance (W/m^2)
G_O	Irradiance under standard test conditions of 1000 W/m^2
h_e	Effective head loss (m)
h_f	Frictional head loss (m)
I	Investment
k_T	Temperature coefficient
L	Length of pipe (m)
n	Time to pay back the loan
$NOCT$	Nominal operating cell temperature
P_{BC}	Power of battery charge
P_{BD}	Power of battery discharge
P_{DG}	Diesel Generator power
P_{DM}	Demand power

P_{GP}	Power purchased from grid
P_{GS}	Power sold to the grid
P_{hydro}	Power generated from the hydro turbine (kW)
P_{ikW}	Power demand at hour h in month i
P_{ipu}	Per unit power demand at each hour of day
P_{PV}	Power generated from the PV cell (kW)
PR	Gain for pollution reduction
P_{RES}	Power from Renewable Energy Sources
P_{STC}	Maximum power generated under standard test conditions (kW)
Q	Flow (m^3/s)
R	Revenues
R_x	Ramp rate of source x
S	Insolation level
SOC	State of charge
T_a	Ambient temperature
T_C	Cell temperature (º C)
T_O	Temperature at standard test condition (ºC)
α	Proportion of the waterfall taken by the pipe
β_i	Current coefficient in pu/°C
β_v	Voltage coefficient in pu/°C
η	Efficiency of the micro hydro turbine
ρ	Inflation Rate

φ	Actualization Rate $\left(\frac{1}{1+\frac{i-\rho}{1+\rho}}\right)$

CHAPTER I

INTRODUCTION

The operation of the electricity grid in Lebanon is unreliable evidenced by the large number of power rationing hours, averaging around 8-9 hours a day. In addition, consumers are using expensive private diesel generators to compensate for power shortages caused by the unreliable grid hence further escalating the energy bill and the GHG emissions. The municipalities, which have administrative autonomy, would possibly benefit by investing in renewable energy systems (RES) because they have already been engaged in developing or supervising the operation of diesel power plants operating within their jurisdictions. The private sector (industrial, commercial, and residential) would also possibly benefit from investing in RE to reduce its increasing fuel bill for the diesel power plants it already owns.

The smart grid is a new technology grid that uses two-way digital communication in order to enhance the supply of electricity to consumers. The smart grid has energy management software which builds information on energy consumption of each consumer and provides them with this information to help minimize the consumption during peak-demand. This two-way communication would have been so hard was it not for the internet access in most houses. The word "smart" attached to grid means that it enables consumers, operators and even devices to respond directly if any changes occur in the grid conditions. The smart grid has the ability to repair itself, gives the customers the ability to participate in grid operations, and is more efficient.

A. Literature Review

In [1], the benefits, barriers, role, and pricing for the renewable energy integration in smart grids are discussed. The integration of renewable energy resources (RER) in smart grids helps in improving the effectiveness, reliability and quality of the power generated, while not forgetting of course, the fact that it decreases pollution and CO_2 emissions. Also, this integration will help allow consumers to be part of the electricity generation system. Even with all those benefits, there is a barrier for this emerging technology, and that is having many regulatory constraints and technology standards that delay the implementation of technologies needed for smart grids.

For the smart grid to be put into work with efficient deployment of distributed energy resources, microgrids should be installed in each part of the system. A microgrid is a small grid in a small geographical area that combines distributed generation units and loads in a distribution system [2]. They increase reliability, efficiency, and power quality. Those microgrids give way for small corporations to be able to generate power and be able to sell it to the main utility. [3]

The microgrid changes its grid connection status and thus may operate in on-grid or off-grid modes [4]. Consider an unreliable grid that is supplying electricity, and a microgrid is connected to it, when there is a fault or when the grid is not supplying, the microgrid is disconnected from the grid, and islanded mode operation is activated. In islanded mode operation, the grid's various sources should be managed to reduce the cost and fuel usage. The energy management system controls and monitors the network, and communicates with all the generators and loads. Other than that, it sometimes gets a weather forecast on locations with renewable power generators. Thus it could help predict the generation from renewable resources which would help in planning the usage of the conventional power plants.

Different microgrid demonstrations in China are introduced in paper [5]. Some demonstrations split the loads into basic loads, controllable loads, and randomness loads, with capacitors used for the compensation of reactive power. Other demonstrations divide the microgrid into two sub-microgrids that can operate each alone or integrated in one microgrid. The control strategy in this microgrid has four parts, the operation mode controller, the supervisor, the central controller, and the optimal controller.

To optimize the work of the microgrid two aspects are to be studied: the energy capacity and the EMS strategy. Many algorithms are used in literature including genetic algorithms, particle swarm optimization, and chaotic quantum genetic algorithms. To optimize the EMS strategy, the relevant costs and pollution are taken into account and minimized using the above algorithms. On the other hand, to optimize the capacity of the resources, a cost minimization technique is also commonly used. [3]

A linear programming approach for the energy management system of the microgrid problem was studied in [6] to minimize energy cost by scheduling the energy consumption of smart homes. On the other hand, authors in [7] work on the possibility of exchange of energy between meters or homes, where the energy is scheduled on that basis without loss of privacy.

Dynamic programming is applied in [8] to minimize fuel cost in each day and maximize the efficiency of energy storage. A case study is taken and an optimal solution for the EMS is found after imposing certain assumptions. The authors in [8] proposed a dynamic programming algorithm to optimize microgrid operation in grid-connected and isolated modes. In this paper, the forecasted data and the actual data are compared using the root mean square error (RMSE), the maximum absolute error (MAE), and the mean absolute percentage error (MAPE). Dynamic programming is also studied in [9] using prediction of load and weather conditions, 24-hours ahead, in order to reduce CO_2 emissions. Economic and stable operation is used for the optimization of the microgrid EMS, which has four stages. The first performs the long term (1 day- 1 month) forecasting of the uncertainty factors, the second performs short-term (30 min- 1 day) forecasting, the third finds a dynamic operation strategy based on the forecasting, finally, the fourth stage sends the command to the equipment. The objective function in the islanded mode is to minimize the sum of the quadratic equations of all the generating units over all times, with constraints. On the other hand, the objective function in grid-connected mode is maximizing the ratio of sale over purchase cost from the grid.

The authors in [10], work on a stochastic model in order to minimize cost, maximize renewable sources use, and minimize storage charging and discharging. Also, the work in [11] provides a new energy management system that minimizes the cost and utilizes renewable energy in the most efficient way taking into account a two-day weather forecast. The rolling horizon strategy minimizes the effect of uncertainties in the forecast. The objective function is taken to be the diesel generation cost and start-up cost and the penalty of unsupplied energy generated. An optimal solution for integrating distributed energy resources is found using a genetic algorithm approach in [12], taking into account the short term energy resource management is taken into account in and an optimal solution for integrating distributed energy resources is found using a genetic algorithm approach. The objective is to minimize the operation cost in every period, not forgetting to take the limits of generation limits as constraints. In paper [13], a genetic algorithm is proposed as well to integrate distributed energy resources into the smart grid. In this paper, the short-term energy resource management is taken into account and an optimal solution on integrating the DERs is found by minimizing the operation cost in every period.

Also, the authors in [14] describe an optimization model for the microgrid energy management system for efficient scheduling of the battery usage while taking into account uncertainties in the wind speed profile, it being the only renewable source in the paper's framework.

Authors in [15] present a model for scheduling under various policies where a linear diversity constraint is implemented.

Two approaches are discussed in paper [16], those are the centralized EMS and the distributed EMS. The first one is an EMS having a central agent that gathers all the relevant information to perform an optimization for the next period. Many techniques can be used for this optimization. The second one is an EMS that can be used for a competitive environment, where microgrid agents send bids to the central operator. The DEMS is very hard to implement in an isolated microgrid due to the small number of generators, the uneven share of installed power, and the lack of strong price signal from the main grid. Delfino et al [17] take the optimal management of the microgrid in order to minimize operational costs. Their paper talks about the advantages of the distributed energy resources (DERs), one of which being the closeness of the resources to the user facilities that reduces transmission losses. The objective function in the paper assumes minimizing the cost of operation of the resources added to the cost of exchanging electricity with the grid, subject to many constraints.

Ariki et al [18] studies an optimization in investment strategies in a microgrid with renewable energy resources under uncertainties in natural gas prices. It was noticed that as the gas price volatility increases, the attractiveness of having a renewable resource is increased since it decreases the risk of outage.

Eskandari et al [3] present a new approach in which the objective function is split into master and slave where one of the two above aspects serves to optimize the other. The master function is the one determining capacity which needs the slave function, the EMS strategy, to be optimized in order to find the optimum. PSO is used to solve the master function, while quadratic programming is used for the slave function. First, this paper introduces the models for each of the DG units, and then introduces the energy storage devices, the microgrid central controller, the load pattern, and the thermal load. Afterwards, the methodology is studied. In that part, the net present value is introduced as the difference between the revenues and the expenses of the investment on the microgrid.

In paper [19], linear programming is used to solve an efficient optimization algorithm proposed to reach a near-optimal solution. The cost of energy (COE) is calculated using annualized capital cost, replacement cost, energy output, O&M cost, fuel cost, and the earning by selling power to the grid and is required to be minimized. In [20], the minimization of the COE is done using the EADER software developed using C language to find the optimal sizes of the microgrid components.

Dynamic programming is used by Vallem et al [21] to find the optimal sizing and siting of DERs where the minimization of the cost is the objective. On the other hand, paper [22] uses the genetic algorithm in order to optimally size the microgrid components, it minimizes the annual cost while keeping the loss of power supply probability less or equal to the required measure. Also, the authors in [23] use the genetic algorithm to maximize the net present worth of the whole system including the net present worth of each of the sources.

Genetic algorithm is used in [24] as well, where a microgrid in an island with three modes of operation is studied. The first mode is when the renewable resources and storage are able to meet the load demand without the need for diesel generators, the second one is when diesel engines are needed with the renewable sources to supply the load and charge the batteries, and the third is a periodic mode, where the battery is discharged to its lower limit and then charged to its upper limit. The objective function considered is a multi-objective one, minimizing the cost and the total emissions where those two are normalized with respect to a base case, being a zero renewable supply and where all the load is supplied by the power grid. The power management is done for each of the modes, each with a safety factor to make up for the capacity penetration of each of the generating sources. In other literature, evolutionary strategy is proposed to select and size different generating units in the microgrid [25]. The problem is solved using a nonlinear mixed integer minimization for the minimization of capital and annual operational cost of the resources. Many microgrids are considered to be connected and a power transferring matrix is built.

Husseinian et al [26] explain the particle swarm optimization and use it to maximize the net present worth of the system after gaining data about the site under study.

A heuristic algorithm is used in [27] to find the optimal sizing of the microgrid components. The objective function is to minimize the inner cost, the environmental cost, and the compensation cost. The constraints in this objective function are the capacity limits of the sources, the emission limits, and the lack of power limits that is the reliability index.

In paper [28], a hybrid system model is proposed. In this model, the time dependent variables are identified and then time independent control strategies are developed and lastly the objective function is solved and the optimal sizing is presented. First of all, the distributed generators are modeled mathematically. Afterwards, the design variables from each of the generators are identified as the currents from each generation type, since the voltage is predefined by the nominal voltage of the DC bus. Then, the constraints are identified from the load balance equation, and the state of charge of the batteries. Finally, the objective function is set as to minimize the fuel cost from the diesel engine.

In [29], a new optimization design is followed. The objectives of the design are reduction in the battery charge/discharge cycles, maximization of renewable energy generation, and reduction in fuel consumption in diesel generator. The constraints are battery state of charge, current, and voltage limits, the diesel generator operating power and operating time limits, wind turbine and PV generator limits. A loss of power supply probability index is used in this algorithm.

B. Thesis Contribution

This thesis presents a case study in a village in Lebanon that can be adopted in the rest of the country. It takes into account the different resources available in the village and considers a microgrid in order to reduce pollution and cost on the consumer. The village under study is rich in hydro components in addition to solar energy resources, and thus, the microgrid considered integrates PV modules, micro-hydro turbines, batteries, and a diesel generator. Previous studies have focused on the sizing and EMS of the microgrid components, and have used many algorithms in order to find the optimal performance of the microgrid. The aim of this thesis is a case study that is essential in Lebanon considering the utility grid frequent outages and the high cost and pollution that follow the electricity generation. It shows the work of the microgrid while integrating renewable resources, and shows the economic benefits obtained on both the consumer and the investor. It also shows economic benefits due to pollution reduction and might give an idea of how much Lebanon is able to reduce its costs if this project is generalized to the whole country.

The EMS of the project is done using quadratic programming, since all the equations and constraints can be linearized with reasonable accuracy. Then, a heuristic approach is done to find an optimal sizing of the components of the microgrid. The net present value and the levelized cost of energy are found. Those values show the profit of the investor from the project. Also, the payment required from the consumer is found and compared between different cases and scenarios.

This chapter has examined the available research on microgrids and the sizing and energy management system of its various components. The next chapter will examine the system components of the microgrid. Chapter 3 will explain the method used to do the economic analysis and the sizing of the components. Chapter 4 will illustrate the case study and the analysis done to obtain the data used in the project underhand. Chapter 5 will give the results and chapter 6 will give a final conclusion.

CHAPTER II

SYSTEM COMPONENTS

A. PV Modules

PV cells are semiconductors that change sunlight into electricity. This ability is based on the photoelectric effect (a property of semiconductors to emit electrons when subjected to sunlight). A PV module is a collection of PV cells combined. A combination of different modules is called a PV array. PV arrays are of different sizes and thus different output power and are major blocks of PV systems. [30]

The power generated from the PV modules is actually a function of the ambient temperature and the irradiance. As the temperature increases, the band gap of the semiconductors decreases and thus, the open circuit voltage is the most affected parameter by this increase (2.3 mV drop per 1ºC). The current change is negligible with the temperature change. As for the irradiance it is the sun's energy reaching the surface of the earth (1KW/m^2 in STC). The voltage change is logarithmic with the variation of the irradiance but the short circuit current is directly proportional to the irradiance. [31]

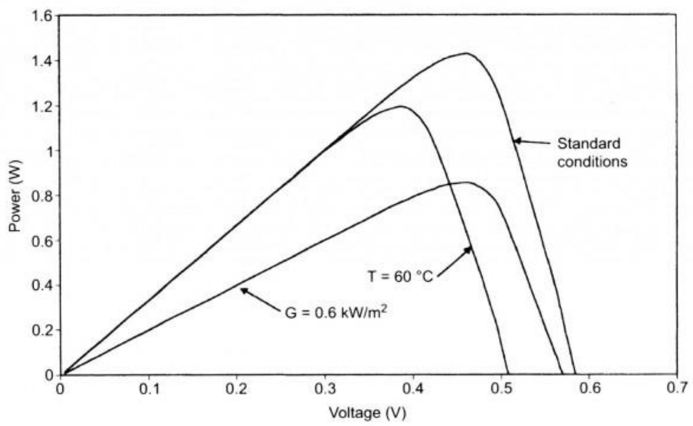


Figure 2.1: P-V curves of photovoltaic cell

Considering the voltage is related to the open circuit voltage by the following approximate relation:

$$V_m = V_{OC} \frac{V_{m0}}{V_{OC0}} \quad (1)$$

Where:

- V_{OC} is the open circuit voltage
- V_m is the voltage maximum
- V_{m0} is the maximum voltage at STC
- V_{OC0} is the open circuit voltage at STC

Similarly for the current:

$$I_m = I_{SC} \frac{I_{m0}}{I_{SC0}} \quad (2)$$

Where:

- I_{SC} is the short circuit current
- I_m is the current maximum
- I_{m0} is the maximum current at STC
- I_{SC0} is the short circuit current at STC

Then

$$P_m = V_m * I_m = \frac{V_{OC} * I_{SC}}{V_{OC0} * I_{SC0}} * P_{m0} \quad (3)$$

Where:

- P_m is the power maximum
- P_{m0} is the maximum power at STC

The open circuit voltage and the short circuit current variation with temperature and irradiance are as follows:

$$V_{OC} = V_{OC0} \left(1 + \frac{V_t}{V_{OC0}} \ln\left(\frac{G}{G_0}\right)\right)(1 + \beta_v \Delta T) \quad (4)$$

Where β_v is the voltage coefficient in per unit/°C, and is calculated by dividing the β_v given in mV/°C Celsius by the V_{OC} at standard test conditions (STC).

$$I_{SC} = I_{SC0} \left(\frac{G}{G_0}\right)(1 + \beta_I \Delta T) \quad (5)$$

Substituting in (3), and by noting that at 300K the thermal voltage $V_t = 0.0259\ N_S$ and that $V_{OC0} = 0.615\ N_S$ [32], then $\frac{V_t}{V_{OC0}} \cong \frac{1}{24}$, we get the following relation:

$$P_{PV} = P_{m0} * \frac{G}{G_0} * \left(1 + k_T(T_c - T_0) + \frac{1}{24}\ln\left(\frac{G}{G_0}\right)\right) \quad (6)$$

Considering the term $\frac{1}{24}\ln\left(\frac{G}{G_0}\right)$,we note that it is negligible at normal values of irradiance G, therefore we get:

$$P_{PV} = P_{m0} * \frac{G}{G_0} * \left(1 + k_T(T_c - T_0)\right) \quad (7)$$

Having the ambient temperature, we change that to the cell temperature using the following formula:

$$T_C = T_a + \frac{NOCT-20}{800} * G \quad (8)$$

Where:

- G is the irradiance
- G_0 is the irradiance at STC
- k_T is the temperature coefficient
- $NOCT$ is the nominal operating cell temperature
- T_C is the cell temperature
- T_0 is the STC temperature
- T_a is the ambient temperature

Also, another factor that affects the power generated by a PV module is the tilting of the module to face the sunlight. To do that, a solar tracking device should be installed on the module. If the module should stay fixed, though, it is found out that the nominal tilt to be used is the latitude of the site.

The modules that are used have a power of 230W [32].

The capital cost of the PV module including inverter and civil works is around $2000/kW, and the operation and maintenance cost is 2% of the capital cost, annually.

B. Micro-hydropower systems

Hydro power is exploited in many different ways using turbines. The type of hydropower is dependent on the size. Table 2.1 below shows the different types of hydropower turbines. [33]

Table 2.1: Types of Hydro Turbines

Large- hydro	More than 100 MW
Medium-hydro	15 - 100 MW
Small-hydro	1 - 15 MW
Mini-hydro	100 kW-1 MW
Micro-hydro	From 5kW up to 100 kW
Pico-hydro	From a few hundred watts up to 5kW

Microhydro turbines are used to convert the kinetic energy of the water into electric energy through its mechanism of wheel and blades. These turbines are of two types: impulse and reaction. The impulse turbines are used for high-head microhydro systems, whereas the reaction turbines are used for high pressure water instead of high-head or high velocity. [34]

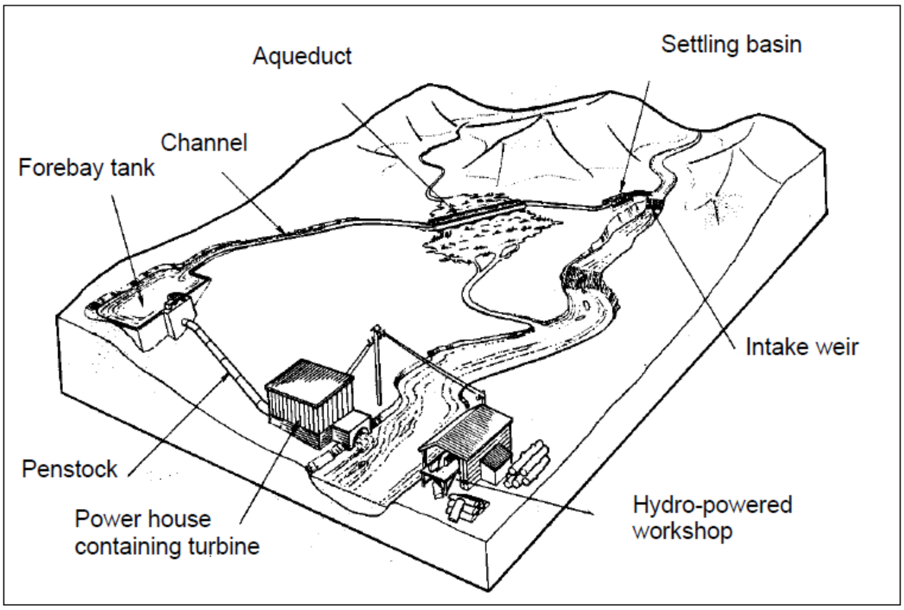


Figure 2.2: Typical Microhydro scheme [33]

The power from water is found using the following formula:

$$P_{hydro} = \eta \ \rho \, Q \, h_e \propto \quad (9)$$

To find out a nominal pipe diameter, we use the following formula:

$$h_f = \frac{10.67 \, Q^{1.85} \, L}{C^{1.85} \, d^{4.78}} \quad (10)$$

Where:

- η is the efficiency of the turbine
- ρ is the density of water
- Q is the water flow
- h_e is the effective head
- $\propto$ is the proportion of the waterfall taken
- L is the length of the pipe
- C is the roughness coefficient

- d is the pipe diameter

Capital cost of hydro turbine is complex and related to the site, thus, it is studied in the methodology section. The operation and maintenance cost of the hydro power is 0.1% of the capital cost.

C. Diesel Generator

The diesel generator is installed in the site to supply electricity in times of need. The formula governing the fuel consumption cost versus the power generated is as follows:

$$\phi(P_{DG}) = \alpha {P_{DG}}^2 + \beta P_{DG} + \gamma \quad (11)$$

$\alpha, \beta, and\ \gamma$ are coefficients that were calculated from data given by the manufacturer. Their values for the generator used were α = 0.0001, β = 0.1549, and γ = 1.6545.

The capital cost of the diesel generator is dependent on the size. It is tabulated in [35] and shown in table 2.2.

Table 2.2: Capital Cost of Diesel Generator

Diesel Generator power (kW)	Capital ($/W)
<10	1.25 - 2.00
10 - 100	0.30 - 1.25
100 - 500	0.20 - 0.30

D. Batteries

Batteries are storage devices that store energy in chemical form. The batteries are used in the case where all other energy sources are unable to supply the load, or if it is found that, using the battery is the most economic option.

The batteries' parameters that should be known are the efficiency, the energy capacity, the maximum number of cycles, the maximum depth of charge, and the initial state of charge.

We will use the lead based batteries. They are most widely used, they have low cost and high performance. 90% of industrial applications use these batteries. They possess the advantages of low cost, robust design, high efficiency. They include a range of 1-1000Ah, which tolerates flexibility in designs. [36]

The cost of the batteries is calculated as is given in [37]: $E \times \$100/\text{kWh}$, where E is the energy capacity of the battery in kWh. The operation and maintenance cost is 2% of the capital cost, annually.

E. Main Grid

The main grid is unreliable with a schedule of electricity cuts. The schedule is repeated every two days. In this project, selling to the grid is considered when the grid is on and excess energy is generated at the same price of buying from it. The on/off schedule over two days is shown in figure 2.3 below.

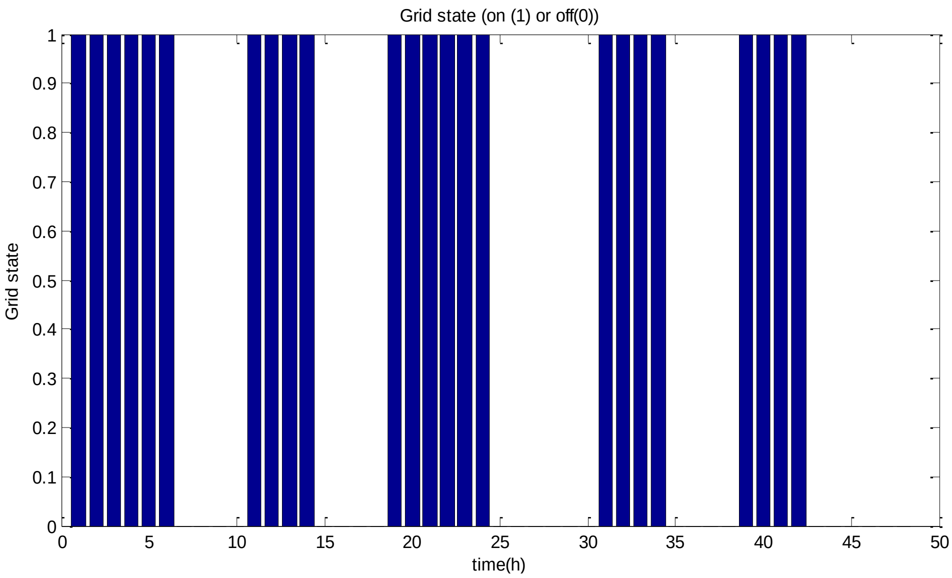


Figure 2.3: Grid On/Off Schedule

CHAPTER III

OPTIMAL SYSTEM OPERATION

A. Problem Formulation

The optimal EMS operation of the microgrid is found using quadratic programming. The microgrid in our site is shown in the figure below:

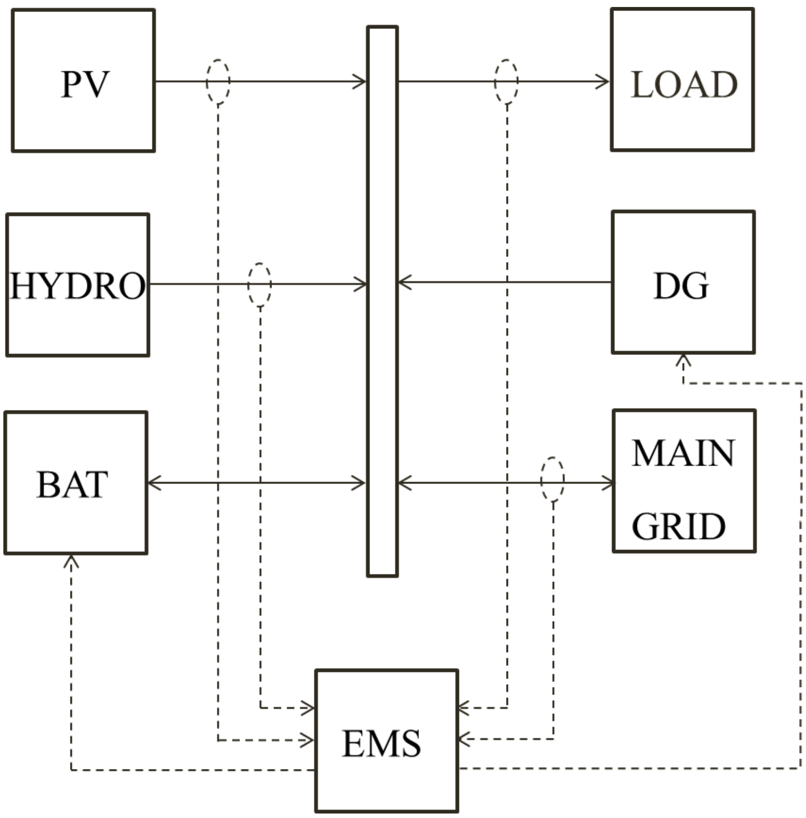


Figure 3.1: Microgrid components

1. Objective Function:

The aim of this program is to find the optimal way of supplying energy to the load while the grid is unreliable. The first step is to define the objective function. The objective is to reduce the cost of energy production by the following formula:

$$\Psi = Min\left(\Phi(P_{DG}(i))\Delta t + C_{OM_{DG}}P_{DG}(i)\Delta t + C_{pol} \times P_{DG}(i)\Delta t + C_G(P_{GP}(i) - P_{GS}(i))\Delta t\right) \quad (12)$$

Where:

- P_{DG} is the power generated by the diesel generator
- $C_{OM_{DG}}$ is the operation and maintenance cost of diesel generator
- C_G is the grid cost
- P_{GP} is the power purchased from grid
- P_{GP} is the power sold to grid

$\Phi(P_{DG}(i))$ is the fuel cost for the diesel generator, and is found in equation (11) above, and Δt is taken to be 1 hour.

The pollution cost is calculated as the sum of the cost of different pollutants from the diesel generator (CO_2, CO, NO_x, and SO_2). The penalty cost of each of these pollutants, and the amount of pollutant for every KWh is taken from paper [3].

Table 3.1: The Penalty Expense and Amount of Pollutants in the Diesel Generator

	CO_2	CO	NO_x	SO_2
Penalty expense ($/kg)	0.0013	0.022	0.28	0.131
Pollutant mass (g/kWh)	232.0373	2.3204	0.3314	0.4641

Using those values, the pollution cost using a weighted average procedure is taken to be:

$$C_{pol} = 5.06 \times 10^{-4} \$/\text{kWh} \quad (13)$$

2. Constraints

- Power balance constraint:

$$P_{DG}(t) + P_{BD}(t) - P_{BC}(t) + P_{GP}(t) - P_{GS}(t) + P_{RE}(t) - P_{W}(t) = P_{DM}(t) \quad (14)$$

- Maximum and minimum power generation by each unit:

$$P_{DGmin} \leq P_{DG}(t) \leq P_{DGmax} \quad (15)$$

$$P_{Bmin} \leq P_{BD}(t) \leq P_{Bmax} \quad (16a)$$

$$P_{Bmin} \leq -P_{BC}(t) \leq P_{Bmax} \quad (16b)$$

$$0 \leq P_{GP}(t) \leq P_{DMmax} \quad (17)$$

$$-P_{DMmax} \leq P_{GS}(t) \leq 0 \quad (18)$$

- Battery State of Charge :

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad (19)$$

- Ramp Rates:

$$-R_{DG}dt \leq P_{DG}(t) - P_{DG}(t-1) \leq R_{DG}dt \quad (20)$$

$$-R_{B}dt \leq P_{BD}(t) - P_{BD}(t-1) \leq R_{B}dt \quad (21)$$

$$-R_{B}dt \leq P_{BC}(t) - P_{BC}(t-1) \leq R_{B}dt \quad (22)$$

Where:

- SOC is the battery state of charge
- P_{BD} is the battery discharge power
- P_{BC} is the battery charge power
- P_{W} is the waste power
- R_{DG} is the diesel generator ramp rate
- R_{B} is the battery ramp rate
- P_{DM} is the demand power

- P_{RE} is the power generated from renewable energy systems

B. Optimization Technique

Quadratic programming (QP) is an optimization method used for maximizing or minimizing a quadratic function, which is subject to linear constraints. A procedure is available in MATLAB, where it returns a solution vector that minimizes the defined objective function. There are three most used algorithms with this function [38]:

- Interior point convex that is used for solving convex problems. The constraints can be of any combination for this algorithm.
- Trust-region-reflective which solves problems that are bound constrained or linear equality constrained.
- Active-set which solves problems with any combination of constraints.

The objective function involves quadratic functions representing the cost of the diesel generator. All the other variables in the objective function are linear except for the battery charge power curve and all the constraints are linear.

When the battery charge power curve is estimated and linearized as shown Fig. 3.2, then quadratic programming can be used as a method to solve the optimization problem and we will use the interior-point convex, since it is the most general algorithm and most effective in large problems.

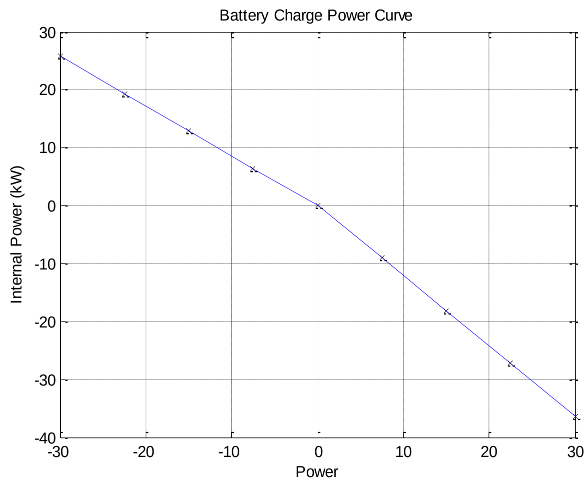


Figure 3.2: Battery Charge Power Curve

CHAPTER IV

SIZING AND ECONOMIC ANALYSIS

To study the economics of the project and check the economic feasibility of the actual implementation of the project, one must first find the levelized cost of energy and decide on the price per KWh that will be sold to the customer. After that, it is important to find the internal rate of return, and the net present value to check the viability of investing in such a project.

A. Levelized Cost of Electricity

The levelized cost of electricity (LCOE) generation is the cost at which electricity should be sold so that the project revenues equal to the costs with a return on the capital equal to the discount rate. It includes all the costs of the system, which are the initial investment, operation and maintenance, fuel cost, and the cost of purchasing from the grid. The formula for calculating the LCOE is given in reference [39] and is shown below:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t * a(n,r) + M_t + F_t + G_{Pt} - G_{St}}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (23)$$

Where $a(n,r)$ is the annuity and is found by the following formula:

$$a(n,r) = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (24)$$

Where:

- $LCOE$ is levelized cost of electricity
- I_t is the investment cost in year *t*
- M_t is the operation and maintenance cost in year *t*

- F_t is the fuel expenditures in year *t*
- E_t is the energy in year *t*
- G_{Pt} is the cost of power purchased from grid in year *t*
- G_{St} is the cost of power sold to grid in year *t*
- r is the discount rate
- i is the interest rate

There are no major future investments and thus this formula can be used for the calculation of the LCOE. In this research, the project is tested in the case that the investor took a loan from the bank with an interest rate of 3% [40].

B. Net Present Value and Internal Rate of Return

The net present value (NPV) of the project sums up the cash flow of the system; that is revenues minus the expenses. Usually, the net present value of a project shows the viability of the project from the investor's point of view. If the net present value is positive, then the investor will gain from the project under study and he may be willing to invest in it. On the other hand, if it were negative, the investor would be losing money and thus will not be willing to invest in the project.

The net present value is used to choose the number of photovoltaic modules used in the project. The number that returns the greatest NPV is taken as the optimum size of photovoltaic modules. The NPV takes into account the inflation rate and the formula for that is taken from [3] and is shown below:

$$NPV = \sum_{y=1}^{n} \frac{\varphi^y}{1+\rho} (R - \psi - OM_{RE} + PR) - I \quad (25)$$

Where:

- φ is the actualization rate

- ρ is the inflation rate
- R is the revenues
- OM_{RE} is the operation and maintenance cost of renewable energy systems
- PR is the pollution reduction
- I is the investment cost

The gain from pollution reduction (PR) is considered to be the pollutant mass reduced due to the switch from having just the diesel generator to having the microgrid with the renewable resources. A run is done with no RE generators to find out the amount of pollutants generated, then a run is done while adding the RE sources. Each pollutant has a penalty cost as shown in table 3.1. That is how the cost reduction due to decreasing the usage of the diesel generator is found and added to the NPV.

As for the internal rate of return (IRR), it is also a measure that shows if the investor would gain money or lose it by investing in this project. The IRR is a measure of the interest rate at which the NPV is equal to zero, which means the present value of returns equals the investment done on the project. The project is considered successful if the IRR is greater than the discount rate. It is found by trial and error using the annuity formula.

The reason why the NPV is used instead of IRR is because the two often the same conclusions are drawn from both. But it is stated that in a number of projects, especially those having non-constant or unknown discount rates, the NPV is a more accurate measure [41] [42]. Although we are going to consider a constant discount rate of 10% in our project, the NPV was used for keeping the options open in case a change in discount rate value was to be considered.

C. Sizing of Components

The components are the diesel generator, the battery, the microhydro turbines, and the PV modules. Sizing of the components was done in this project in a heuristic manner where no programming technique was used. Instead, after getting the results of the EMS of the microgrid changes are made in order to make the components more effective. Each of the components is sized in a certain way.

- Diesel Generators

Two generators are already installed in the village, they sum up to have a capacity of 350 kVA. Even so, it is not certain that the diesel generator supplier would want to invest in the project because it will be reducing the energy sold from him and even reducing the cost of the energy generated. We consider that the supplier from diesel generators won't be willing to invest in the project. That is why, we are assuming that the investor of the project is going to buy a new diesel generator to supply the microgrid, and thus the capital cost of the diesel generators is added. The size of the generators is taken to be almost equal to the peak demand of the load.

- Battery

The battery sizing was done in a trial and error fashion. First the battery size is set to a high value (i.e. 150 kWh), and is then decreased or increased based on the battery usage shown in the EMS results. If the battery is shown to be lightly utilized then the size has to be reduced. On the other hand, if the battery is shown to be highly utilized (i.e. SOC often reaching its minimum level), then increasing the battery size should be tried to check whether this will reduce the overall cost of energy.

- Microhydro Turbines

The microhydro turbine would have a maximum capacity of 100kW. Since we know that the village is an agricultural one with a great need of the water from the waterfall, we decided to use three microhydro turbines of 100kW capacity each and shut them off depending on the flow of the water. We considered using just one turbine in low flow seasons, two in medium flow seasons, and all three turbines in high flow seasons. We used the head, the flow, and the length of the pipes to determine the diameter that should be used for good results.

- PV modules

The number of PV modules was set to different values ranging from 800 modules to 1500 modules. Afterwards, the net present value is found in each of the cases after the EMS of the project returns the solution. The greatest NPV means the most returns to the investor and thus the best number of PV modules to be used.

CHAPTER V

METHODOLOGY

A. Case Study

In Lebanon, most municipalities run or supervise the management of diesel generators to cope with power supply shortage caused by the operation of the unreliable grid. This thesis will consider Beter El Shouf, a village in Lebanon, which contains renewable energy resources to substitute partially the operation of the diesel generators and the unreliable grid. Beter has a waterfall and creek that can be used to install microhydro plant and it has good solar resources so PV arrays will be installed. For this, the village load will be studied and the RE resources will be assessed. The village will be made to operate as a microgrid having a mix of classical generators (diesel + grid) and RE units (e.g. Microhydro, PV). Doing that, an energy management system will be developed to ensure the production of energy at minimum cost and enhanced reliability of supply.

B. Data Collection

1. Load Profile

For the demand of the village, we have been provided the load demand in Beter for every two months as shown in the table below:

Table 5.1: Load Demand in the Village

Months	Jan/Feb	Mar/Apr	May/Jun	Jul/Aug	Sep/Oct	Nov/Dec
Demand (MWh)	252	205	467	452	402	265

After having those values, we got the hourly per unit for a day in each month in the year 1974 from [43] and used those to transform the two months load demand into hourly data for every day for a year. Although the graphs are very old, but they are good enough when describing a village like Beter, which has characteristics very close to any village in the old times in Lebanon. The graphs for the percentage of the full load demand in every month are shown in the figures below.

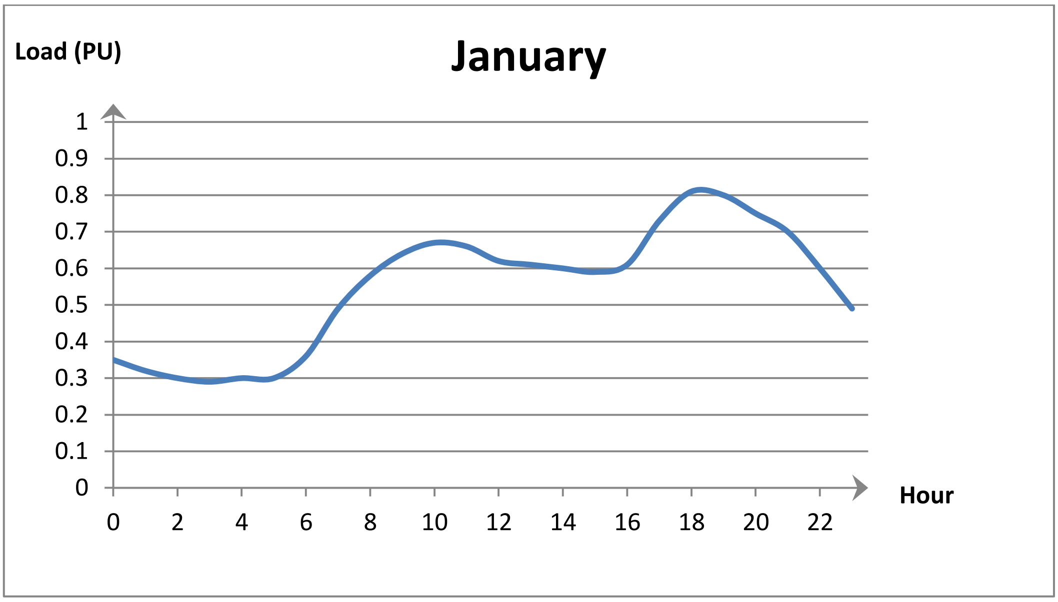


Figure 5.1: Per unit of full load for January

The total 2 month demand is converted to hourly values using the following formulas. In the formulas, January is taken as an example to show how the work is done:

$$E_1 = \frac{\sum_{i=1}^{24} P_{1pu}(i)}{\sum_{i=1}^{24}\left(P_{1pu}(i)+P_{2pu}(i)\right)} E_{12} \qquad (26)$$

Where E_1 is the energy in month 1,

E_{12} is the energy in months 1 and 2,

P_{1pu} and P_{2pu} are the per unit power demand at each hour of the day.

Then this energy of the month is divided by the number of days per month. For instance in January, it is divided by 31 days to get the daily consumption, assuming equal consumption each day in the month. Afterwards, the hourly consumption is found using the following formula:

$$P_{1KW}(h) = \frac{P_{1pu}(h)}{\sum_{i=1}^{24} P_{1pu}(i)} \frac{E_1}{D_1} \qquad (27)$$

Where $P_{1KW}(h)$ is the power demand at hour h,

D_1 is the number of days in months 1.

Thus the hourly demand in each day of the month is found. The demand in January is shown in figure 5.2 below.

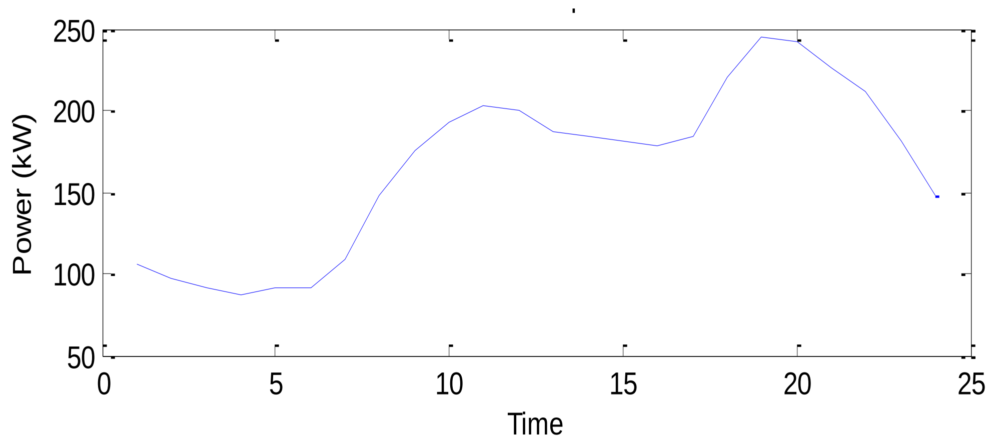


Figure 5.2: Power load demand in a day in January

2. Water Data

The flow was approximated and assumed constant during one day. After several visits to Beter El Shouf, and discussions with several people who have made studies on the waterfall, the maximum flow in the waterfall was considered to be 1.5 m^3/s estimated to take place in May.

After discussions with the village municipality and people from EDL, we have agreed that it would be a good idea to use a pipe from the creek of the waterfall down to the water treatment station that is 90m below, since it provides good water head and no effect on the aesthetics of the waterfall. In addition to that, transportation for operation and maintenance purposes is easy since a road already exists to the station. The station is 638m away from the waterfall. The figure below shows the measurements done using Google Earth.

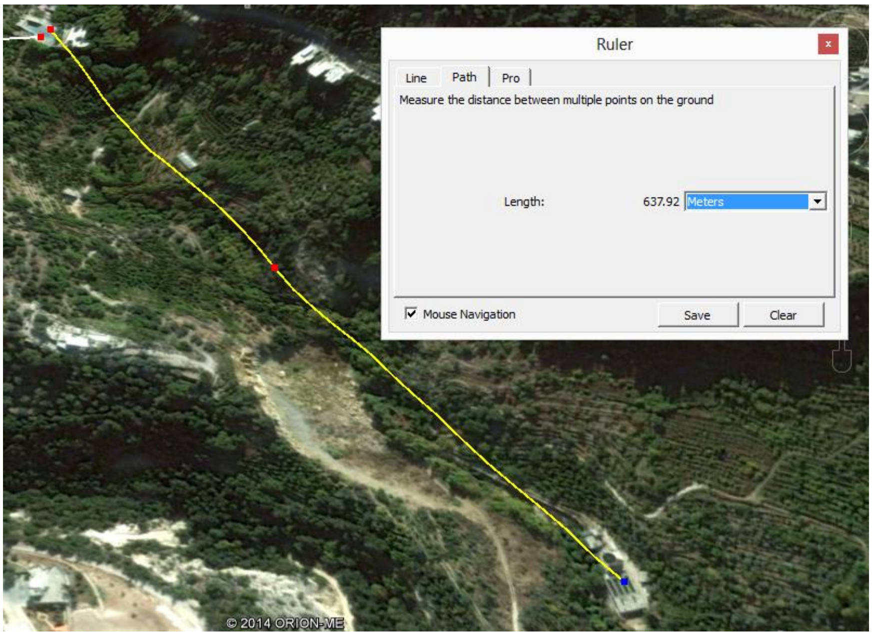


Figure 5.3: The distance from the waterfall to the turbine

A graph in [44] shows the average monthly flow in each month depending on the altitude for rivers in Lebanon. This graph is used for the estimation of the monthly flow in the village and is shown below.

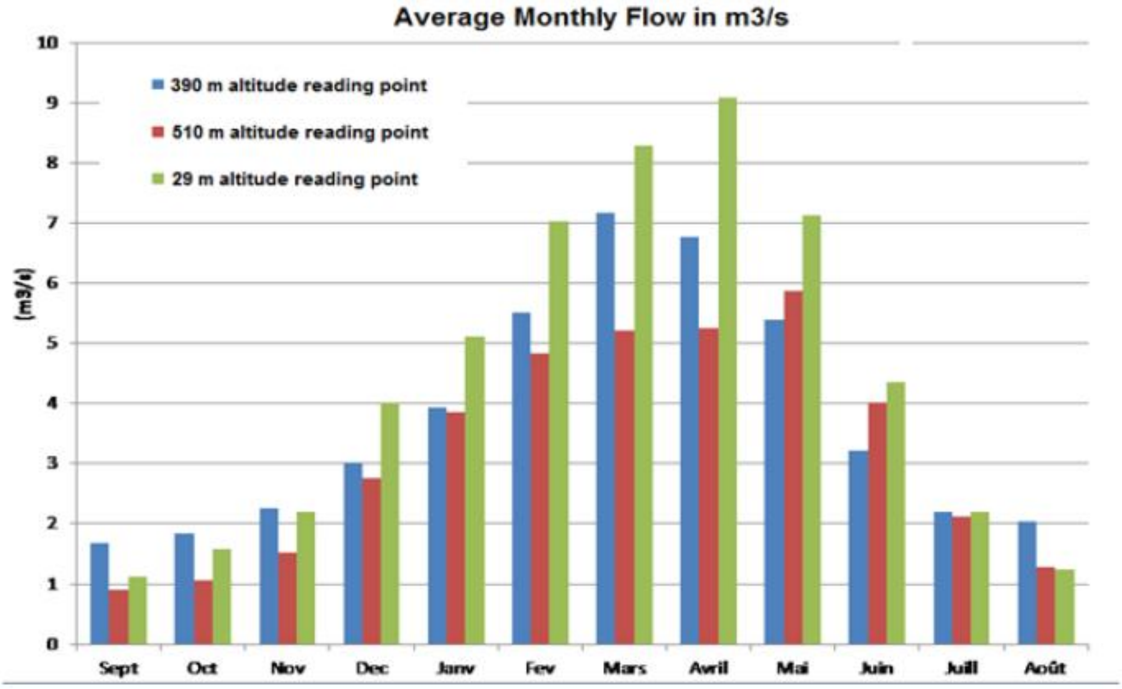


Figure 5.4: Average monthly flow depending on altitude

The altitude of Beter is 900m above the sea. Thus the closest of these curves is the 510m altitude reading point. The values are taken from this graph and scaled to have a maximum of 1.5 m^3/s to determine the average monthly flow. To smooth the curve on a daily basis, the flow between two monthly values was assumed to vary linearly; the hourly flow curve for the whole year is shown in the Figure 5.5 below.

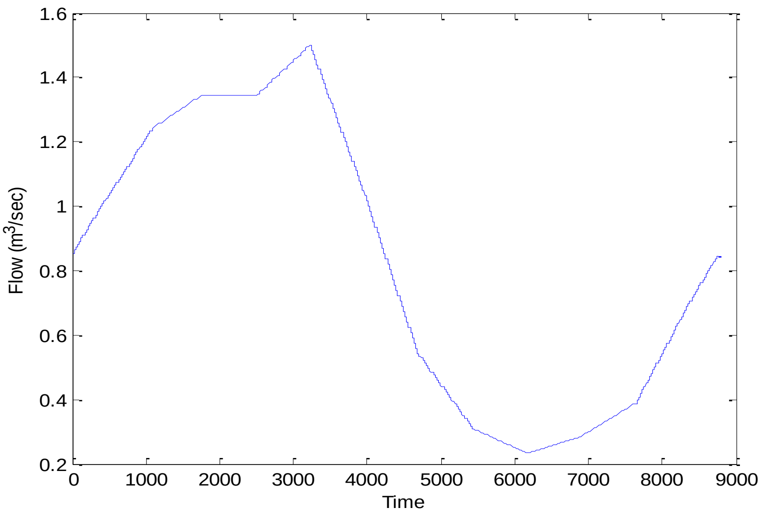


Figure 5.5: Hourly flow for the whole year

Taking the flow in the pipe to be 10% of the total creek flow and assuming the diameter of the pipe to be 15 cm, the frictional head loss (h_f) is found to be 424.2m when the total flow 1.5m^3/s, which is too high and thus not feasible, as it is larger than the available head. Then trying a pipe diameter of 30cm, gives a much more reasonable head loss (h_f=15.4m) which makes the effective head 74.6m.

The microhydro turbine used is to generate 100kW. Three turbines are used with three different pipes to generate up to almost 300kW. Knowing that, and taking into account that sometimes the water flow is very low and is needed, as in the summer for watering the crops in the fields, three states are taken. It is considered that there is always at least one turbine running. The states are shown below:

- If the flow is less than 0.4m^3/s, one pipe is used only,
- If the flow is between 0.4m^3/s and 0.8m^3/s, two pipes are used,
- If the flow is more than 0.8m^3/s, all three pipes are used.

• Capital Cost of Microhydro Turbine

Calculating the cost of the microhydro turbine is a bit complicated, unlike other components, because it is related to the site on which it is built. It depends highly on the head and the flow in the site. An experimental formula is proposed in [38] and was used in this work used to estimate the capital cost of the microhydro turbine.

Considering that the civil works of the hydro turbine consists of 40% of the cost as in reference [45], we will calculate the cost of the electrical and mechanical works and the equipment, then find the total cost.

In this project, we will use the Francis turbine which is a turbine having high efficiency and small size, and it is suitable for water head 20-300 meters. The cost of this turbine is taken from a shopping website [46] and is found to cost $80000. Other than that, we need to calculate the cost of the penstock pipes. We have 638m of pipe, and thus to be on the safe side, we will buy 700 m of pipe for each turbine. We got the cost of the pipes to be about $58000. By this, we get a total of $138000 for each turbine and penstock. Adding a 10% for engineering studies at the beginning of the project, we get $151800. This constitutes 60% of the total hydro plant cost including civil works, and thus to find the final cost, we need to divide by 0.6 to obtain $253000/100kW. Thus the capital cost for our site is $2530/kW, which falls in the range of typical installation costs of small hydro systems between $1800 and $8000/ kW as given in [44] .

3. Solar Data

The data for the PV power calculation consists of the solar irradiance and the temperature.

- Irradiance

To find the solar insolation, reference [47] was used. We entered the latitude to be 33 degree North, that being the latitude of Lebanon. Then using this latitude, we got the irradiance over the day every one eighth of an hour. To find hourly values of irradiance we took the average of every eight values during that hour.

After doing that, we found the percentage of sunny days during every month from reference [48], where the following values were given:

Table 5.2: Percentage of Sunny Days during the Month

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Percentage of Sunny Daylight Hours	42	47	52	63	73	82	83	81	79	71	65	48

After finding that, the percentage is multiplied by the solar irradiance during the month which gives an approximate value of the hourly irradiance during the month.

A graph showing the irradiance over the whole year, and two graphs showing one week in January and one week in June are shown below:

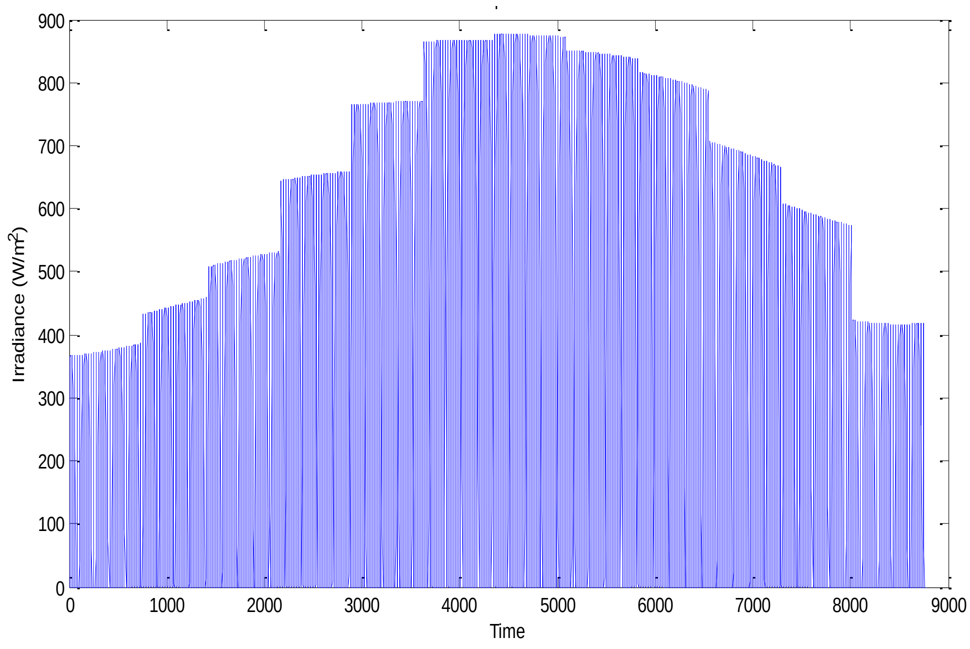


Figure 5.6: Hourly Irradiance over one year

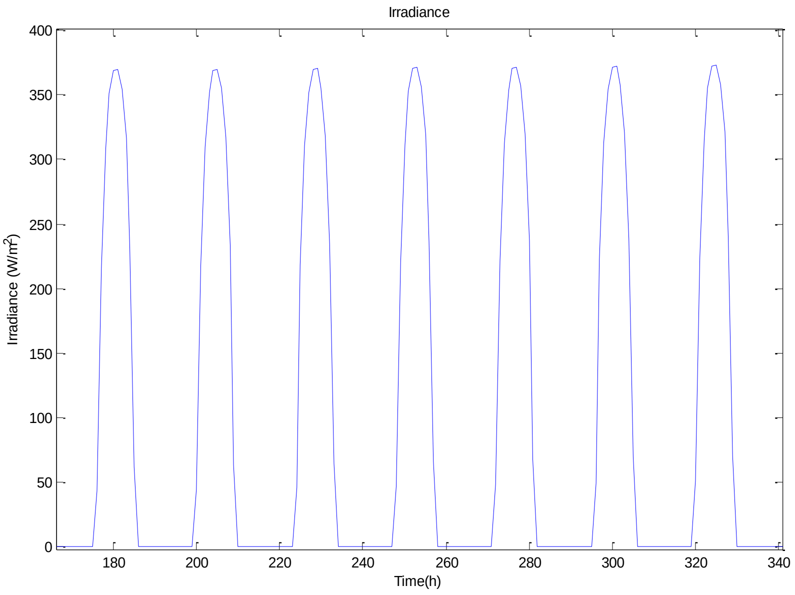


Figure 5.7: Hourly Irradiance in the second week in January

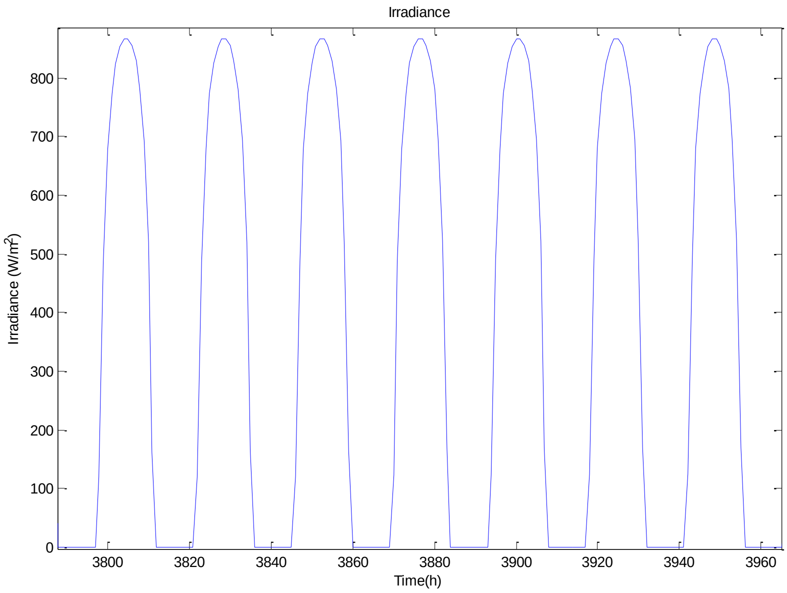


Figure 5.8: Hourly Irradiance in the second week in June

- Temperature

As for the temperature, it is found using reference [49], where average hourly temperature in each month is given in Baysour, Lebanon, with a 900m above sea level like Beter El Shouf. That is why the approximation is a good one.

After finding the temperature, the same procedure is followed to find the temperature each day as the one followed to find the flow every day.

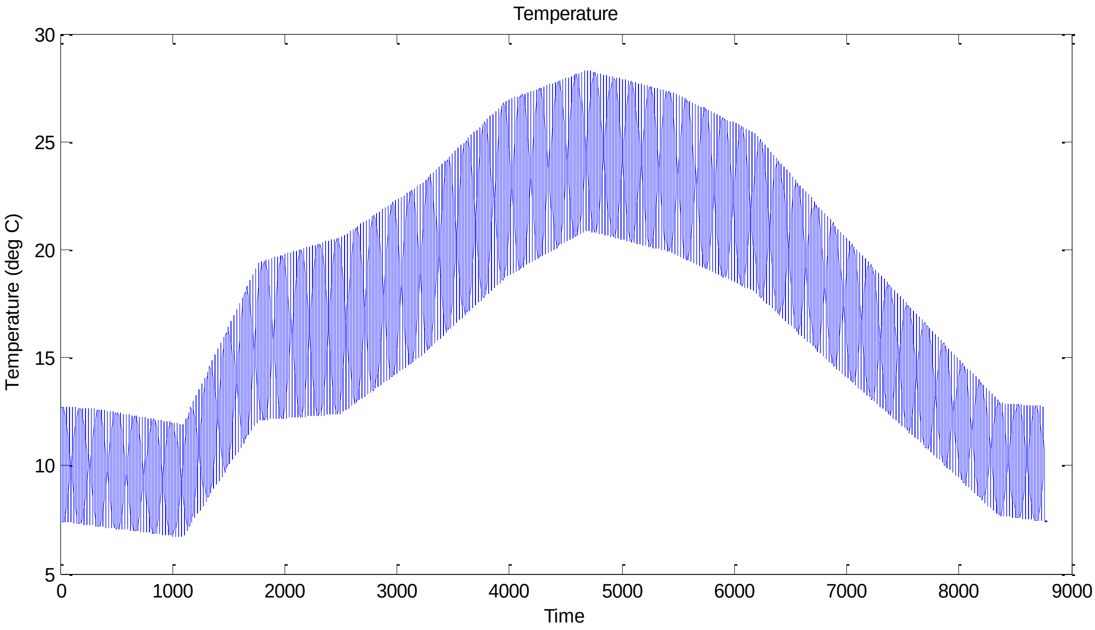


Figure 5.9: Hourly Temperature over one year.

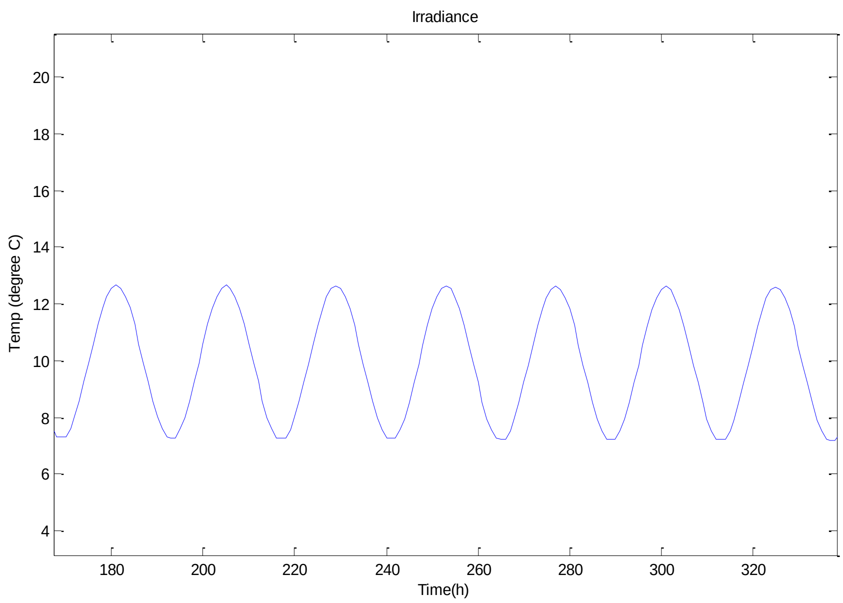


Figure 5.10: Hourly Temperature in the second week in January

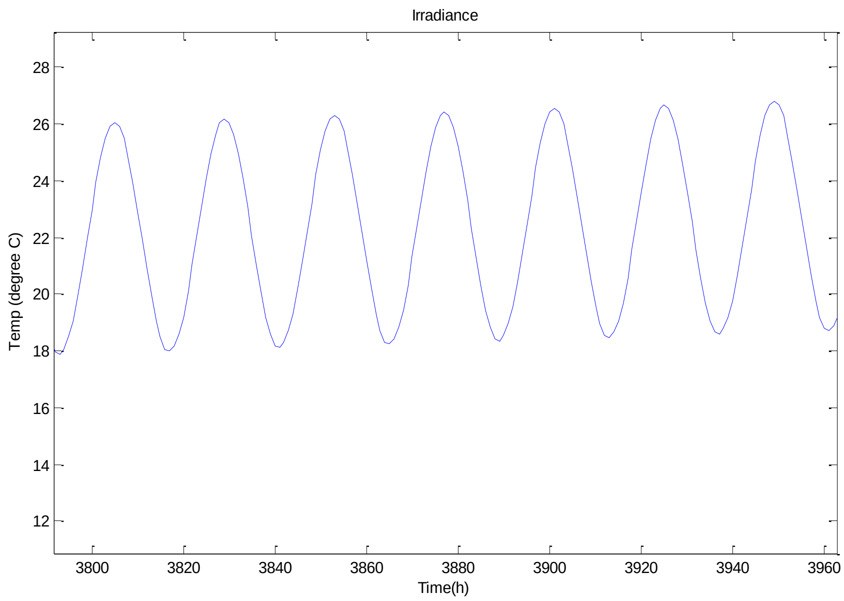


Figure 5.11: Hourly Temperature in the second week in June

CHAPTER VI

RESULTS

This chapter includes test cases done to test the program, and then real case study using the real data from the village. The cost of diesel fuel is taken to be 0.99 $/l. The grid cost is taken to be 9.66 c/KWh, since the whole microgrid is being paid as one and thus the load is considered an industrial one.

The diesel cost curve is taken from [50] and is shown below:

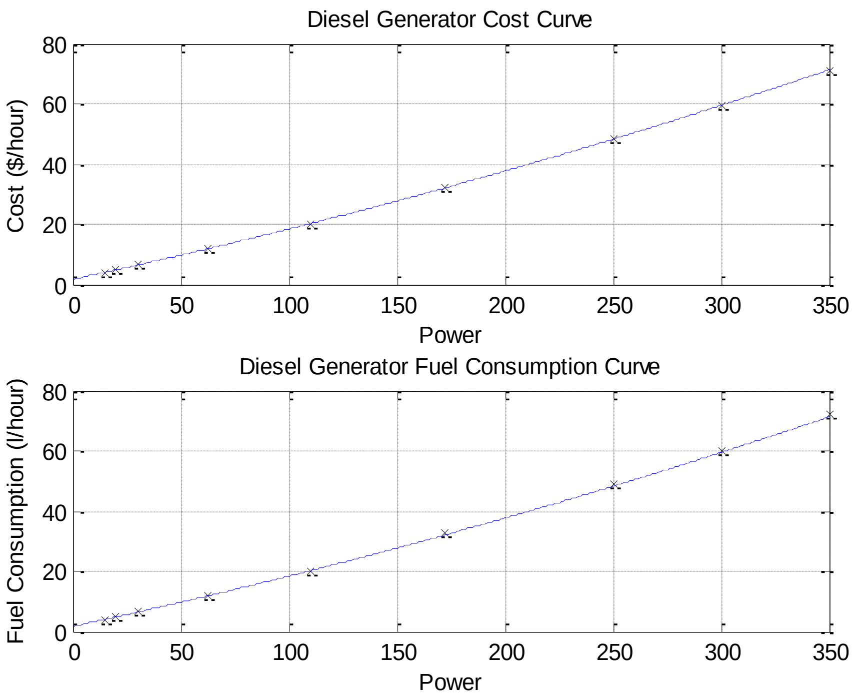


Figure 6.1: Diesel fuel consumption and cost curves

The power output from the PV and the hydro are both considered as negative loads. As for the grid, the cost is dependent on the energy spent per month. Table 6.1: Monthly Electricity Grid 1, found in reference [51], is shown below and it shows the prices of the grid energy supply for residential loads for each energy layer.

Table 6.1: Monthly Electricity Grid Prices

Energy (kWh)	Price (LL/kWh)	Price (c/kWh)
0-100	35	2.33
100-300	55	3.66
300-400	80	5.33
400-500	120	8
>500	200	13.33

Multiplying those numbers by 12 to find out approximately how much is paid yearly, we get the following table. Those are taken to estimate how much the customers are paying yearly when no RES are installed.

Table 6.2: Yearly Electricity Grid Prices

Energy (kWh)	Price (c/kWh)
0-1200	2.33
1200-3600	3.66
3600-4800	5.33
4800-6000	8
>6000	13.33

The number of households connected to the grid in Beter is 595 households, we multiply this by the energy in the table above to get the following table.

Table 6.3: Yearly Electricity Grid Prices for All Households

Energy (kWh)	Price (c/kWh)
0-714000	2.33
714000-2142000	3.66
2142000-2856000	5.33
2856000-3570000	8
>3570000	13.33

A. Test Runs

The test runs are done on one day and three days demand. Those tests are done mostly to build confidence in the program.

1. Test Run 1

The first test is done where the load demand is decided as shown below:

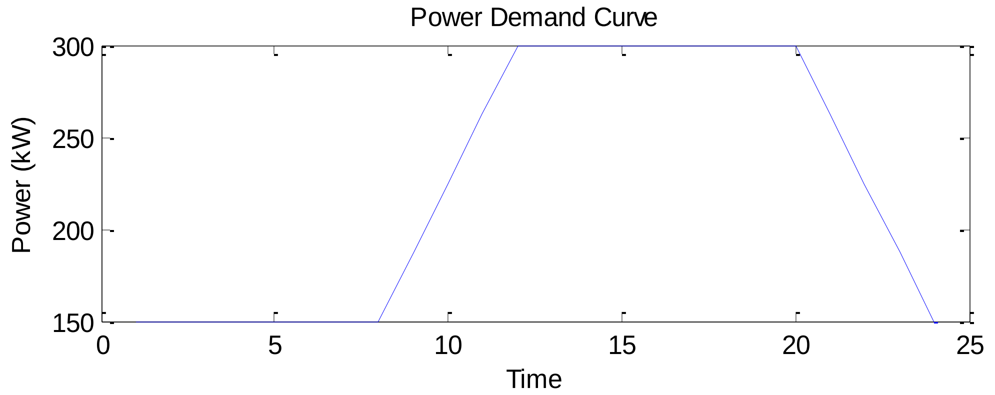


Figure 6.2: Sample power demand curve

The run is done for one day and three days. The sizes of the components are shown in Table 6.4: Components for Test Case 1 below:

Table 6.4: Components for Test Case 1

Component	Diesel Generator	Battery	PV modules	Microhydro
Size	350kW	10kWh	1000 module/0.23kW each	1 turbine/ 100kW

Using the above components and load, and using sample irradiance, temperature, and flow, the net power demand curve is thus considered to be the load demand minus the sum of generated PV power and hydro power.

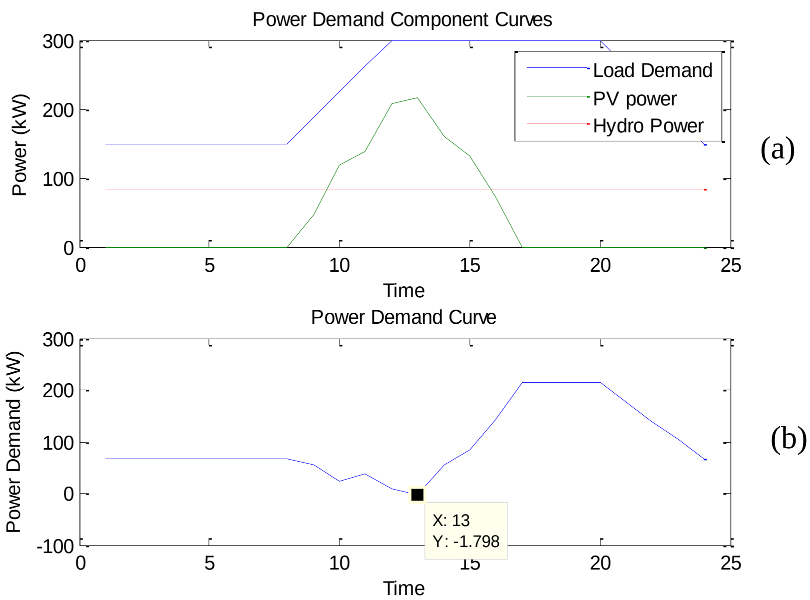


Figure 6.3: Power demand curve with PV and hydro supply (a), net power demand curve (b)

As can be seen in the graph, at hour 13 the power demand is negative (-1.798 kW), which means that the power generated by the renewable energy sources is greater than the load demand. Since the grid is available by that time, the excess energy generated should be sold to the grid. The power generated from each power source is shown below in Figure 6.4.

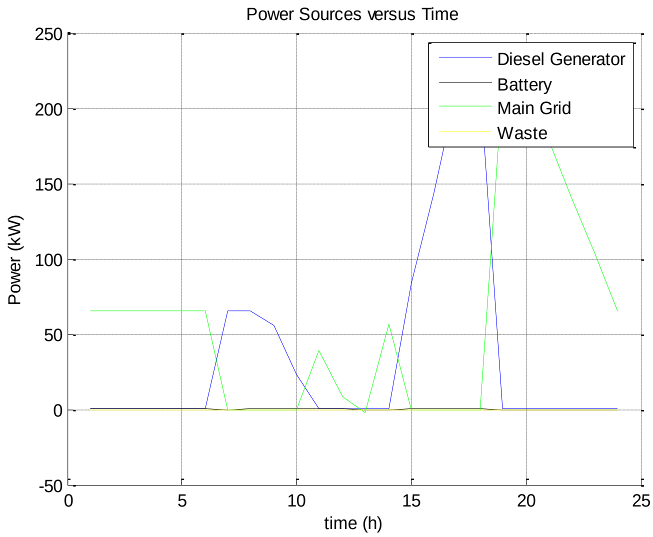


Figure 6.4: Power sources generation

As expected, the diesel generator only turns on when the main grid is not available, and the battery is negligibly used. Also, after 13 hours, the 1.798 kW generated power is sold to the grid. No waste is generated since there is no negative demand except when the grid is available at hour 13.

2. Test Run 2

The second run is done with the same load demand but for three days.

The run is done on the same conditions as the one above but with different irradiance and temperature. The power demand curves are shown in the figure below.

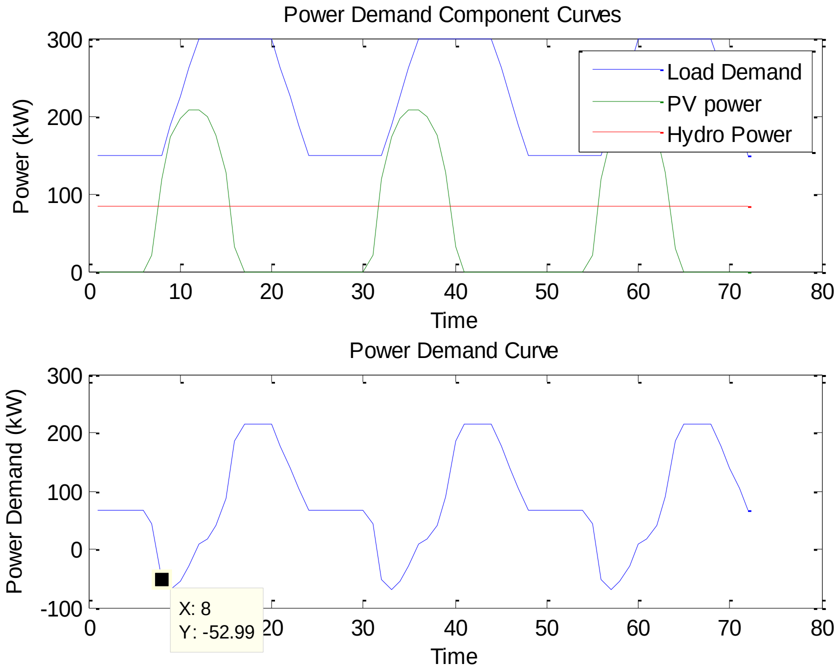


Figure 6.5: Sample Power demand

The net power demand curve is negative periodically, and thus it is expected that when the grid is on, the electricity is sold to the grid, while when it is not, they are to be dissipated as waste or for some good purpose like water heating or pumping. However, in this work the economic value of this usage was not evaluated despite it probably helping in the economic value of the project. The results obtained from the optimizing EMS is shown in Figure 6.6 below.

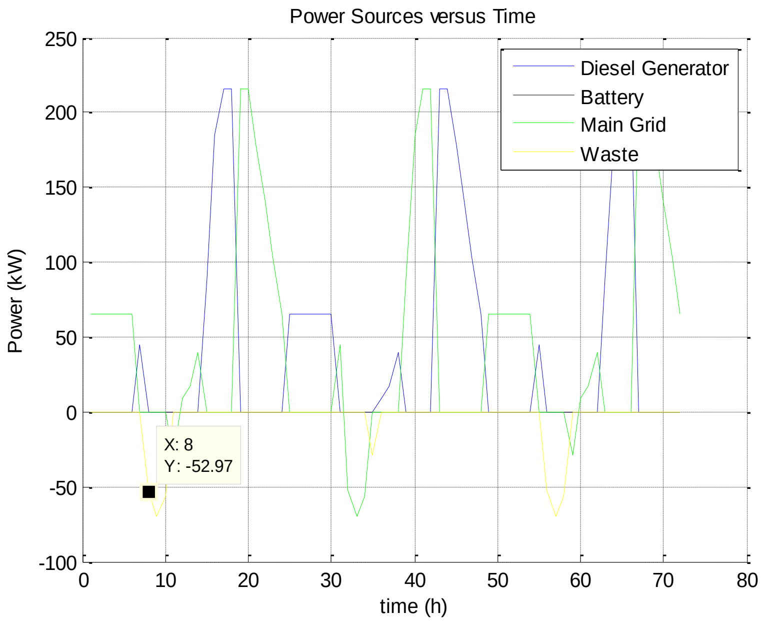


Figure 6.6: Power Sources generation

As can be seen, at hour 8, there is negative energy demand, and thus the microgrid will try to find the best way to get rid of the excess energy in the most cost efficient way. At hour 8, the grid is off, and thus, the energy generated can't be sold, that is why, as expected, they are shed as waste.

The diesel generator energy used per hour and the battery energy remaining are shown in the figure. The battery is being charged and thus it is expected that the energy supplied be negative as will be shown in the results.

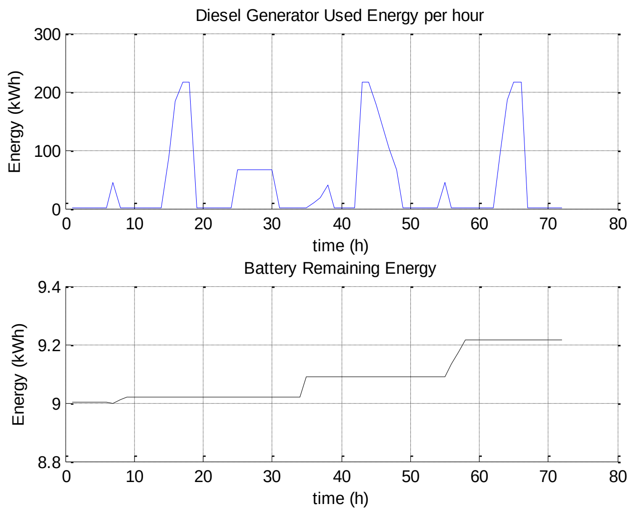


Figure 6.7: Diesel and battery Energy

The investment cost is the same in this case and in the one above, since the same equipment is used.

3. Test Run 3

The third run is done on a sample load demand for one day.

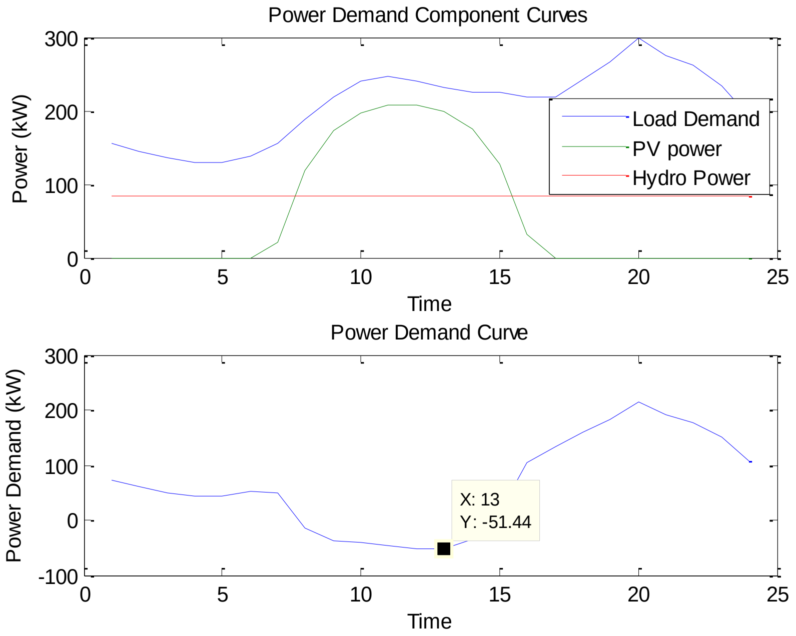


Figure 6.8: Sample demand curve

From hour 8 to about hour 15, the net demand is negative, and thus, the excess energy should be dissipated as waste or sold to the grid depending whether the grid is on or off.

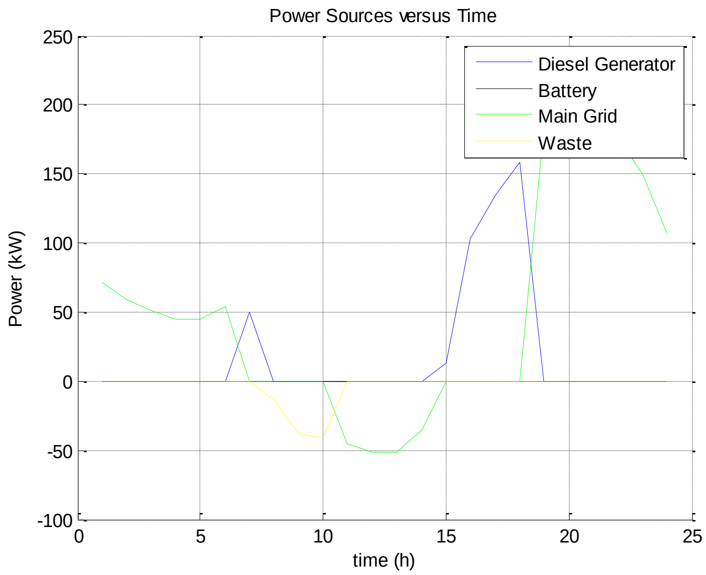


Figure 6.9: Power Sources generation

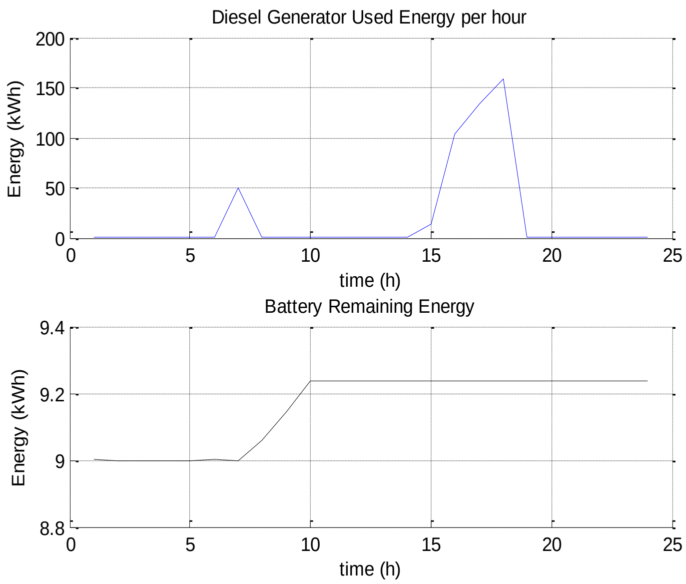


Figure 6.10: Diesel and battery energy

The battery is being charged as well when it is found feasible and economic and that's why, the energy supplied by the battery should be negative.

B. Case Study

The runs are made as specified in Chapter 4. At first the battery is chosen having a size of 150kWh and a maximum power of 350kW, and 1000 PV modules are used. Then after the run was done, the battery is checked to see how much is used and then the size is reduced. As for the PV modules, the NPV is found for different number of modules varying from 800 to 1500, while considering that the electricity is sold to the customer at an average tariff higher than the LCOE of the microgrid (approximately 10%); the NPV is determined with and without considering the reduction in pollution as added revenue. The number of PV modules selected corresponds to the largest NPV found.

The lifetime of the project is taken to be 40 years which is the lifetime of the PV modules and the microhydro turbine. The battery has a lifetime of 7 years, and thus the cost of new batteries is added every 7 years. Knowing the data of the village under study, several scenarios were investigated by altering the assumptions on the availability of different resources:

1. Base Case, situation as is currently, i.e. diesel generator and an unreliable grid;
2. Scenario 2, a reliable grid without RE sources and without diesel generator;
3. Scenario 3, an unreliable grid plus a new diesel generator and microhydro turbines;
4. Scenario 4, Renewable energy (RE) resources (i.e. Hydro and PV) plus a new diesel generator and the current unreliable grid;
5. Scenario 5, RE resources (i.e. Hydro and PV) plus a reliable grid;

6. Scenario 6, Renewable energy (RE) resources (i.e. Hydro and PV) plus a new diesel generator, but without a grid;

Runs were done with and without considering penalty expenses on pollutant generation. The LCOE of each of the components in each scenario is found by dividing the annuity paid to the component by the energy generated by the component.

1. Base Case

When no renewable energy sources are available, the diesel generator should be sized as to fulfill the peak load demand when the grid is not available.

The load demand for the year is found as discussed in chapter 5. The demand curve for the whole year is shown in Figure 6.11. The peak demand is 366 kVA and thus the current total diesel generator capacity is 370kVA. It is expected that in this run, no waste should be generated, and no energy is sold to the grid. The generation of the power sources is shown in Figure 6.12. Figure 6.14 and figure 6.16 shows one day in January and one day in June to view more clearly what is happening.

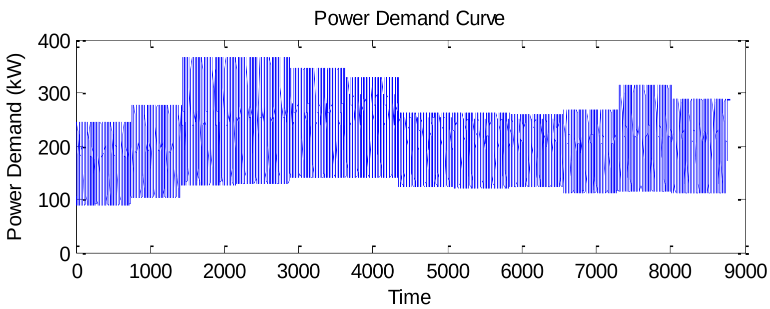


Figure 6.11: Power Demand

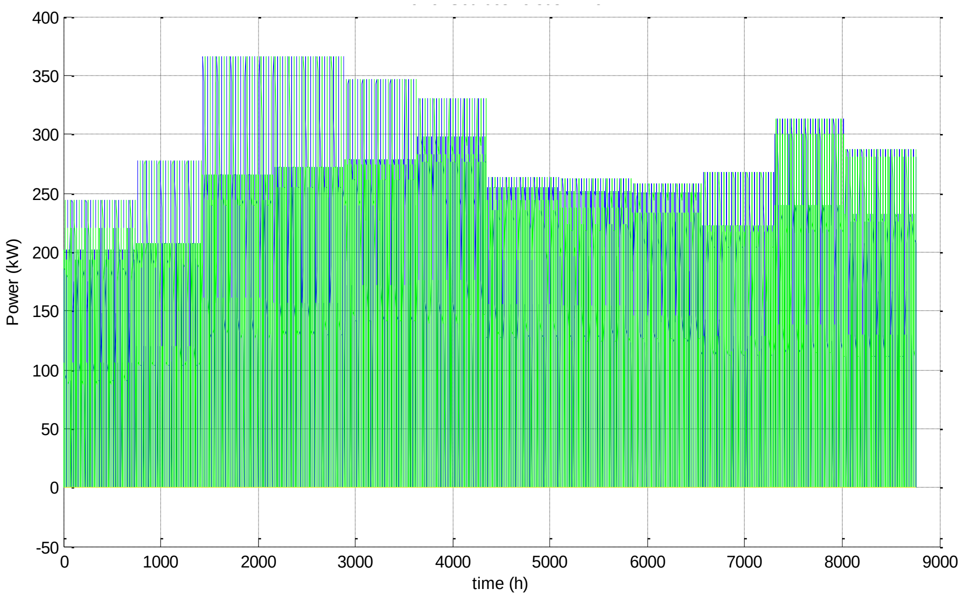


Figure 6.12: Power Sources generation

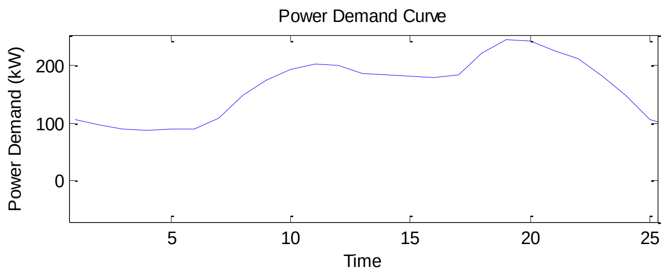


Figure 6.13: Power demand during one day in January

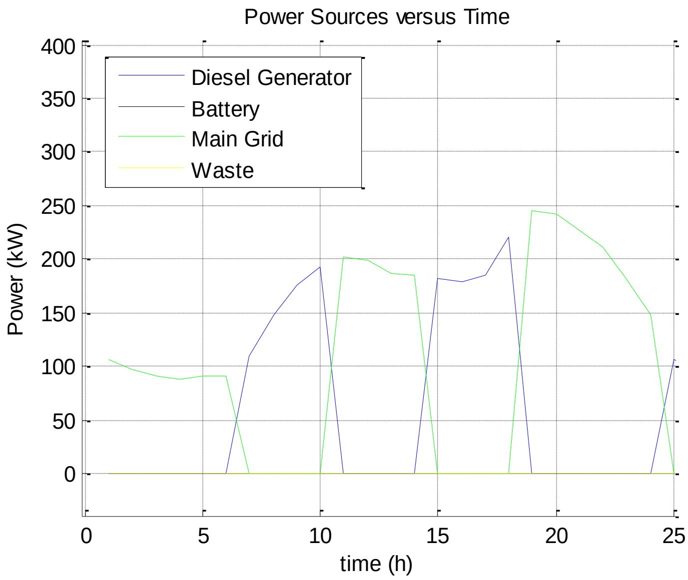


Figure 6.14: Power Sources generation during one day in January

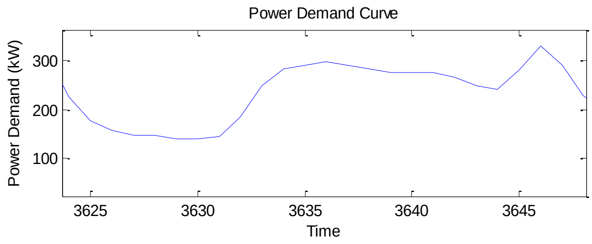


Figure 6.15: Power demand during one day in June

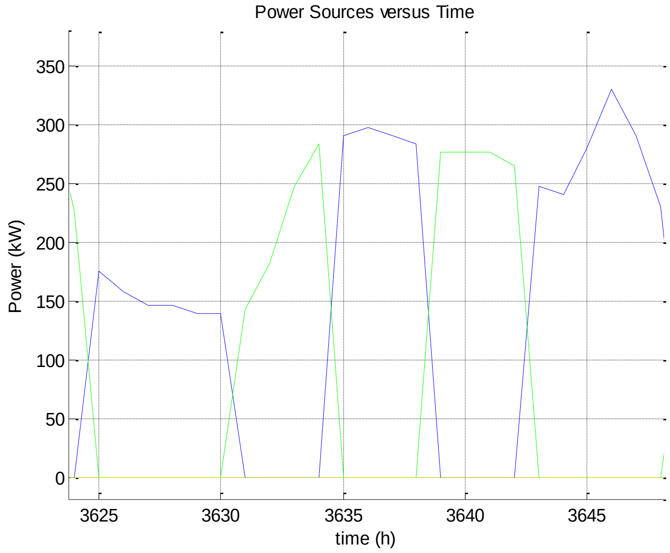


Figure 6.16: Power Sources generation during one day in June

This case is actually the base case to which we will measure the reduction in pollution and the change in cost. The costs considered here are while the microgrid is not there and thus the energy supplied by the grid is paid by the customer directly.

The current supplier from the diesel generator sells the kWh at about 55 cents in Beter. The energy results of the Base Case run are given in Table 6.5, thus the total payments by the customers are calculated using the following formula:

$\sum_{i=1}^{5}(Energy\ supplied\ by\ grid\ at\ layer\ i * cost\ at\ layer\ i) + 0.55 * Energy\ from\ diesel\ generator$ = 714000* 0.0233 + 179905* 0.0366 + 892747* 0.55 = $ 514,231. Table 6.6 shows the pollutants emitted in this base case, so they would be compared to the other case with renewable energy sources.

Table 6.5: Results from Base Case Run

Energy Supplied at first cost layer (kWh)	714000
Energy Supplied at second cost layer (kWh)	179905
Energy Supplied diesel generator (kWh)	892747

Table 6.6: LCOE calculated from Base Case Run

LCOE of Diesel Generator ($/kWh)	0.3
Total payments by consumers ($)	514,231.00
Cost On consumers ($/kWh)	0.288

Table 6.7: Pollutants Emitted from Diesel Generator in Base Case

CO_2 emitted (kg)	207151
CO emitted (kg)	2072
SO_2 emitted (kg)	414
NO_s emitted (kg)	296

2. Scenario 2

In this case the grid is always available and the energy results of the EMS are shown Fig. 6.23 and Table 6.7 below. All the energy demand in this case is supplied by the grid. This means that the cost on the consumers of buying from the grid (0.0313/ kWh) is calculated as: 714000*0.0233 + 1072652*0.0366 = $55,895.

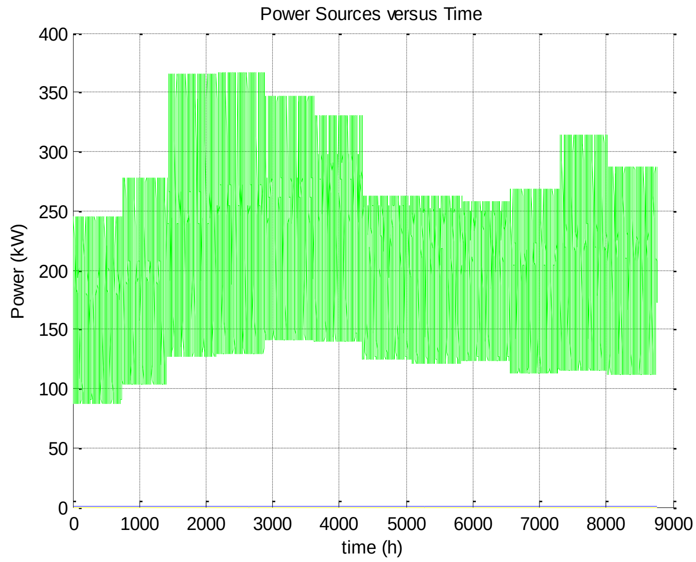


Figure 6.23: Grid supply in case of no RES and full grid availability

Table 6.8: Results from 2nd Scenario Run

Energy Supplied at first cost layer (kWh)	714000
Energy Supplied at second cost layer (kWh)	1072652
Total payments by consumers ($)	$55,895.00
Cost On consumers ($/kWh)	0.0313

3. Scenario 3

In this run, the grid is unreliable and we have a new diesel generator along with microhydro turbines. After the first run is done, the maximum demand found is used to set the generator capacity. The maximum power demand after deducting the hydro power is 257.15 kW. Thus, the diesel generator is chosen to have a capacity of 300 kW. The grid is considered unreliable as shown in chapter 2.

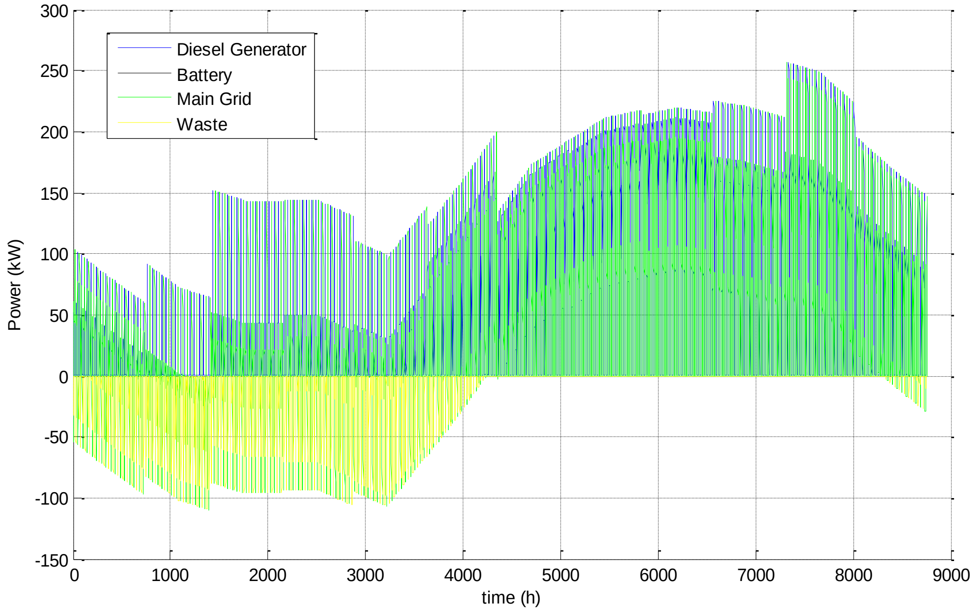


Figure 6.21: Power Sources generation

Table 6.9: Results from 3rd Scenario Run

Energy Supplied at first cost layer (kWh)	349185
Energy Supplied by diesel generator (kWh)	348915
Energy sold to the grid (kWh)	52140
Energy Dissipated as waste (kWh)	51891

Table 6.10: LCOE calculated from 3rd Scenario Run

LCOE ($/kWh)	0.105
LCOE of Diesel Generator ($/kWh)	0.214
LCOE of Microhydro Turbine ($/kWh)	0.074
Cost On consumers ($/kWh)	0.115

Table 6.11: Pollutants from Diesel Generator in 3rd Scenario

CO_2 emitted (kg)	80961

CO emitted (kg)	810
SO_2 emitted (kg)	162
NO_x emitted (kg)	116

As we can see, the pollutants in this scenario are significantly lower (about 39.1%) than those of the Base Case scenario. The cost on the consumer is taken to be 11.5 cents/kWh (10% above LCOE). It is seen that the average cost of the kWh on the consumer is much lower (about 40%) than that of the base case.

4. Scenario 4

In this scenario, the unreliable grid is considered with a new diesel generator, microhydro turbines, and batteries. First, the batteries and PV modules are sized.

- Sizing of components:

The battery is initially taken to have a capacity of 150kWh and an initial state of charge of 0.75 the capacity.

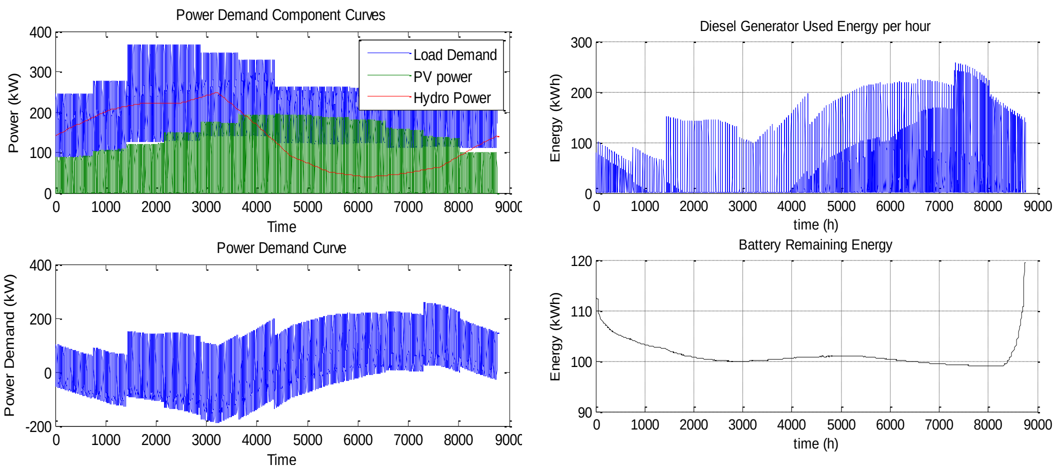


Figure 6.17: Demand curve (left) and diesel and battery energy (right)

The last 1000 hours show the most change in battery energy and is shown in the figure below.

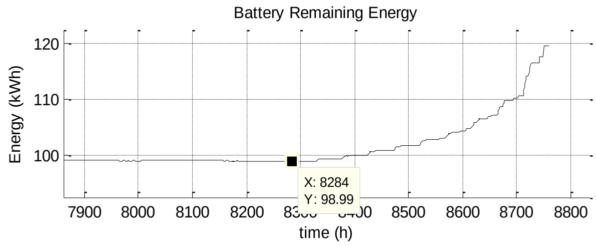


Figure 6.18: Battery Energy remaining

It is noticed from the figure that the maximum energy reached is 119.5kWh and the minimum is about 99 kWh thus only about 21kWh are used from the battery, and the minimum state of charge of the battery is 40% of the maximum capacity of the battery. Knowing that the maximum change is approximately 21kWh, thus we can find the battery capacity by using the following formula:

$21+0.4E_{max} = E_{max}$

We get the battery capacity to be 35kWh, so the battery is chosen to have a capacity of E_{max} = 35kWh.

After choosing the battery capacity, the number of PV modules is changed to get the highest NPV and lowest LCOE, first considering the value of fuel pollution decrease and then without considering that. The cost of one kWh is taken to be 10.5 cents. The results are shown in table 6.10 and table 6.11 below.

Table 6.12: NPV ($) and LCOE ($/kWh) with Different PV Sizes with Pollution

Size	800	900	1000	1100	1200	1300	1400	1500
NPV	587360	605610	620060	618830	620690	617950	613620	608610

LCOE	0.0922	0.0919	0.0917	0.0922	0.0925	0.0929	0.0935	0.0940

Table 6.13: NPV ($) and LCOE ($/kWh) with Different PV Sizes without Pollution

Size	800	900	1000	1100	1200	1300	1400	1500
NPV	582420	600580	614960	613690	615510	612750	608410	603390
LCOE	0.0924	0.0921	0.0919	0.0924	0.0927	0.0931	0.0937	0.0942

It is noticed in the runs that when 1000 PV modules are installed, the NPV is the highest in all the cases tried above. Thus, 1000 PV modules are used throughout the project since it is gives the highest return for the investor.

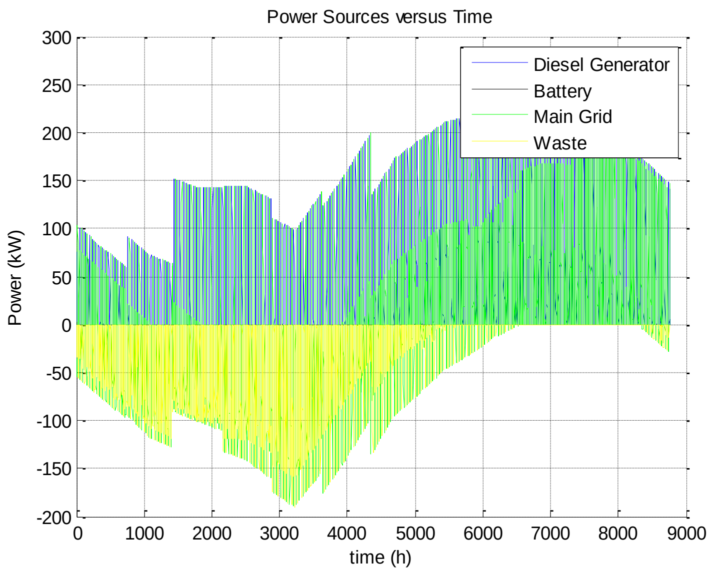
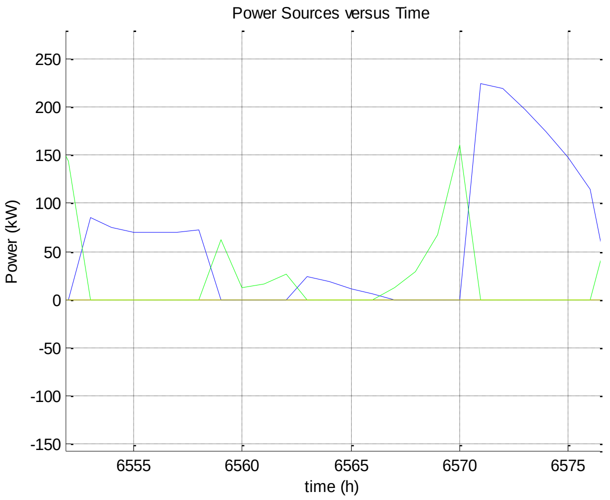
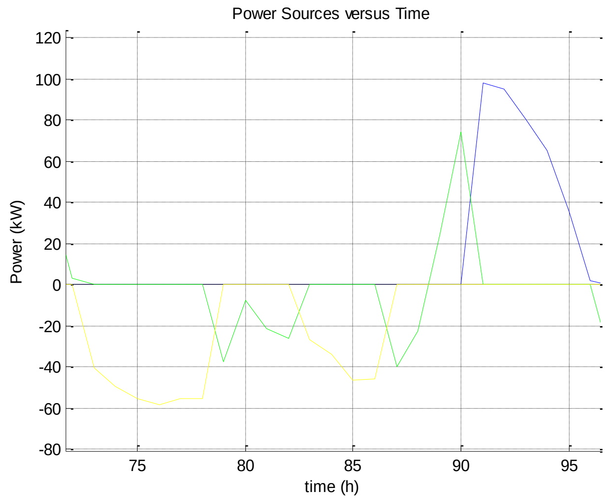


Figure 6.19: Power Sources generation

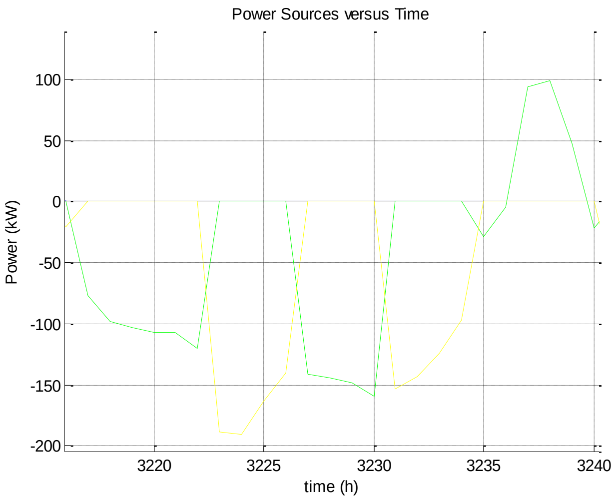
A day in each season is shown below to explain further the typical generation of the power sources in each season.


Power Sources versus Time
Power (kW)
250
200
150
100
50
0
-50
-100
-150
6555
6560
6565
6570
6575
time (h)

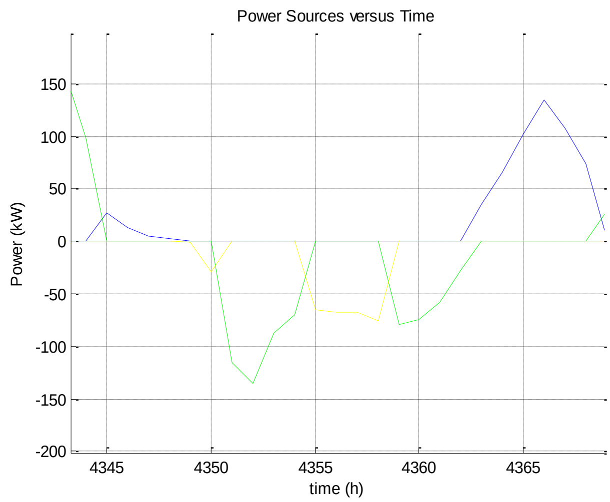
(a)


Power Sources versus Time
Power (kW)
120
100
80
60
40
20
0
-20
-40
-60
-80
75
80
85
90
95
time (h)

(b)


Power Sources versus Time
Power (kW)
100
50
0
-50
-100
-150
-200
3220
3225
3230
3235
3240
time (h)

(c)



(d)

Figure 6.20: Power Sources generation (1 day each season) Fall (a), Winter (b), Spring (c), Summer (d)

The optimum management of the sources of the microgrid components is found in the figures using the quadratic programming. The energy used, the costs, and pollution using this microgrid are shown in Tables 6.12 and 6.13 below. Afterwards, a comparison is done between the cost of electricity in this case and that in the case of no renewable energy integration.

As we can notice, the energy wasted is high, which means that if the grid were always available, this energy could be sold.

Taking the average tariff of one kWh to be 10.12 cents (10% above the LCOE), the customers will pay 1786652 * 0.1012 = $180,809.

Table 6.14: Results from 4th Scenario Run

Energy Supplied at first cost layer (kWh)	191139
Energy Supplied by diesel generator (kWh)	190879
Energy sold to the grid (kWh)	147176
Energy Dissipated as waste (kWh)	146833

Table 6.15: LCOE from 4th Scenario Run

LCOE ($/kWh)	0.092
LCOE of Diesel Generator ($/kWh)	0.246
LCOE of Microhydro Turbine ($/kWh)	0.074
LCOE of PV System ($/kWh)	0.083
Cost on consumers ($/kWh)	0.1012

Table 6.16: Pollutants from Diesel Generator in 4th Scenario

CO_2 emitted (kg)	44295
CO emitted (kg)	443
SO_2 emitted (kg)	89
NO_x emitted (kg)	63

This means that the cost on the consumers is reduced by approximately 65% if compared to the base case. Also, the cost is less than scenario 3 with microhydro only. The pollutants emitted in this scenario are much lower (about 21%) than those of the base case and also significantly less than those of scenario 3.

5. Scenario 5

In this scenario, PV modules and microhydro turbines are installed, along with a reliable grid. Here, the grid is supplying all the time, which means the diesel generator will not be supplying. Also, none of the excess generated energy will be dissipated as waste. We can get rid of the diesel generator in this case.

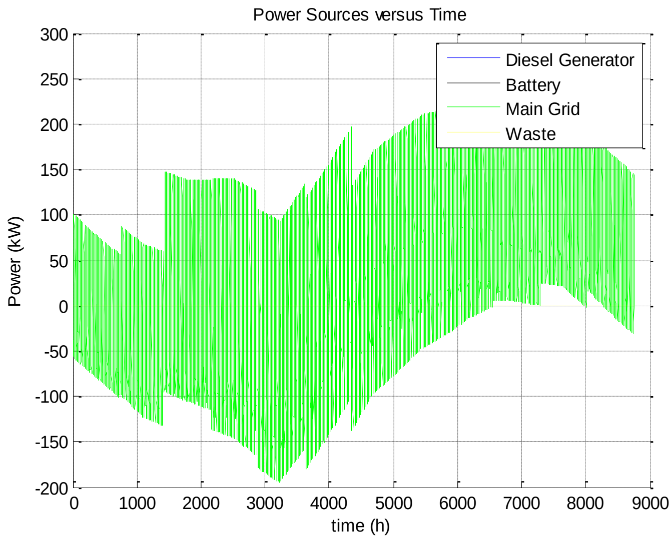


Figure 6.22: Power Sources generation

Table 6.17: Results from 5th Scenario Run

Energy Supplied at first cost layer (kWh)	373151
Energy sold to the grid (kWh)	308995

Table 6.18: LCOE calculated from 5th scenario

LCOE	0.06
LCOE of Microhydro Turbine ($/kWh)	0.074
LCOE of PV System ($/kWh)	0.083
Cost On consumers ($/kWh)	0.066

The cost to be paid by the consumers in this case is higher than the average cost paid in scenario 2, but, if the grid is to be always available, the cost of the kWh will probably be increased to be able to meet the generation costs of the electricity that reach approximately 20 cents/kWh.

Afterwards, the LCOE is found considering the grid to be unreliable for the next 5 years and reliable over the rest of the lifetime, and the microgrid with microhydro and PV systems installed. The LCOE in this case is found to be 0.0683 cents/kWh, and therefore, the cost of the kWh on the consumer in this case can be set to 7.513 cents.

6. Scenario 6

In this scenario, a diesel generator is installed, along with PV systems and microhydro turbines. The grid is considered unavailable all the time in this scenario. As expected, in this case, all the excess energy generated by the microgrid is thrown as waste, meaning dissipated for instance for heating or water pumping.

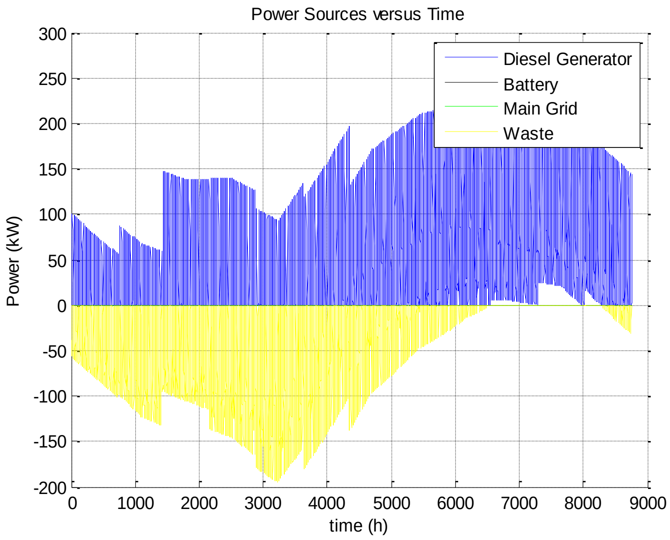


Figure 6.24: Power Sources generation

Table 6.19: Results from 6th Scenario Run

Energy Supplied by diesel generator (kWh)	373143
Energy dissipated as waste (kWh)	308990

Table 6.20: LCOE calculated from 6th Scenario Run

LCOE	0.132

LCOE of Diesel Generator ($/kWh)	0.213
Cost On consumers ($/kWh)	0.149

In this case, there is no income and no selling to the grid. The kWh in this case should be sold at about 14.9 cents, so the investor would gain.

On the consumer's side, for sure, paying 14.9 cents/kWh is better than paying 55 cents/kWh, that being the cost of kWh as sold by the current diesel generator provider.

CHAPTER VII

CONCLUSION

The thesis presented an approach for finding a good solution to the energy management system of a microgrid and the sizing of its components for maximum benefit. Quadratic programming was used for the energy management system, and the sizing was done by trial and error. Quadratic programming generated satisfying outcomes about the timing of the supply of each component of the microgrid. It gave the costs, the energy generated, and the pollution generated with the performance of the microgrid. After that was done, the battery and the diesel generator were sized according to their usage as seen by the first run. Afterwards, the net present value and the levelized cost of electricity were found to find the favorable number of PV modules to be used.

Test runs were done to build confidence in the algorithm at hand. Afterwards, the real case was studied under different scenarios. Several runs were done with different scenarios to compare the generation cost and the cost on the consumers for each case. First, the run was carried out with no renewable energy sources (RES) available. This case generated a lot of pollution and a lot of cost on the consumer. The second run was done while considering the grid is always available and no RES are integrated. A third scenario was done while adding microhydro turbines and a new diesel generator to the unreliable grid. Afterwards, PV systems were also added to the third scenario. Then a scenario with the RES integrated with a reliable grid is studied, and lastly, a scenario is tested where the RES are integrated with a diesel generator without a grid.

After doing this study, it is clear that it is economically and technically feasible to install renewable energy sources in villages where resources are available. The cost of electricity to the consumer in the base case, where current diesel generator providers are operating when electricity from the grid is cut, is $0.288/kWh. However, the cost where the microgrid is functioning and the utility grid is unreliable is significantly lower at about $0.092/kWh, which is 32% of the base case cost. On the other hand, if the utility grid is always available starting now, this cost is reduced further to be $0.060/kWh, and if the grid is considered to start supplying all the time starting 5 years from now, the LCOE becomes $0.068/kWh. Furthermore, if the grid is always unavailable, the cost is $0.132/kWh, which is still less than the Base Case cost, even though no energy is sold.

As for the consumer, the kWh costs 28.8 cents in the current case. This gets reduced to 11.5 cents/kWh where microhydro is installed with the unreliable grid and a new diesel generator, then reduced further to reach 10.1 cents/kWh when PV systems are added as well. If the grid is always supplying currently, the cost is 3.13 cents/kWh without the RES installed, which, though less than the cost while having a reliable grid and RES (6.6 cents/kWh), is so unrealistic and very likely to increase. On the other hand, if the grid becomes always supplying 5 years from now with the microgrid currently installed, the cost on the consumer could be reduced to 7.51 cents/kWh.

It is seen to be beneficial to both the consumers and the investor, even with the high investment costs. Also, it is beneficial for nature since it produces less pollution.

In addition to that, in a country like Lebanon where getting fuel is very expensive and hard in terms of transporting it, it is advisable that microgrid systems be installed in all regions which will reduce further the fuel consumption and will improve of the grid. Investing in projects like this one over the whole country will prove beneficial to both the government and the people. To maximize benefits, this will have to come with an improvement in grid availability to buy (or sell) electricity from (or to) whichever region through the installed microgrid.

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