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OPTIMAL DESIGN OF HYBRID RENEWABLE ENERGY SYSTEMS IN LEBANON

by
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AN ABSTRACT OF THE THESIS OF

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The objective of this thesis is to develop an optimization methodology based on Single Step Dynamic Programming (SSDP) and Ordinal Optimization (OO) to operate and size the components of a hybrid power system in Lebanon in order to fulfill the electricity demand in a reliable, affordable and sustainable manner with a cost effective solution. The system consists of three sources of energy: the unreliable utility supply of EDL, a diesel generator, PV solar panels and a storage consisting of a battery bank. Using SSDP, the model would simulate the operation of the system to deduce the levelized cost of electricity (LCOE) during one year of operation for a given set of source sizes. A simple model, based on operation simulated over two typical summer and winter weeks, would run much faster. Such simple model would be used to sample a large number of designs quickly and estimate the LCOE over the whole year considering that each one of these two weeks represents the behavior of the system over half a year.

Ordinal optimization uses SSDP to simulate the operation of the system to sample *N* designs in a large search space Θ, resulting from different source sizes. In order to select a finite set of "good enough" alternatives, the simple model is used to evaluate the *LCOE* of the *N* designs and sort them in an ascending order to select the top-*S* designs. As per OO theory, the rank is more robust than value so the use of the simple model in sampling the *N* designs and ranking them appropriately will speed up their initial evaluation. Then using an "accurate model" of yearly operation, the top-*S* designs will be evaluated and the best solutions will be identified.

The model is tested to design a hybrid power system for Qaraoun, a village located in the West Beqaa district, where data on power consumption trends, available space and solar radiation were acquired. The model also investigates how the LCOE is affected when adding or removing a battery bank, varying energy prices and allowing a net metering policy.

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CHAPTER I

INTRODUCTION

A. Motivation and Objective

Lebanon's power generation has declined dramatically from exporting power to its neighbour Syria four decades ago to suffering from a shortage gap between demand and production since the civil war [1].

As population grows and power demand increases, the available power plants fail to meet peak demands resulting in blackouts all around the year reaching 13 hours per day in some cities [2]. Thus the Lebanese people are suffering from unreliable electricity and low quality service that forces them to rely on local private generators to insure their electricity needs during utility outages [2]. While the highly subsidized EDL energy is sold between 2.33 and 13.33 ¢/kWh [3], private generators charge 20-30 ¢/kWh; consequently customers end up paying two electric bills: one for EDL and a second more expensive one for the backup generation.

Alongside insufficient generation, the environmental drawbacks of fossil fuels, their depleting nature and prices instability urge the investment in clean energy as Lebanon has set a goal to reach a 12% renewables' share of electric supply by 2020 [4]. The goal is achievable since Lebanon lies in the solar belt of the world characterized by 300 sunny days per year, [4] and high average daily insolation of 5.28kWh/m^2/day [5].

Furthermore the Central Bank of Lebanon (BDL) initiated the National Energy Efficiency and Renewable Energy Action (NEEREA) to encourage clean energy investments by offering subsidized, interest-free, long term loans [4]. Such financial incentives have helped create job opportunities, and increased the total capacity of PV installed in Lebanon [4]. Thus with the decreased investment burden and low operation and maintenance costs, adding PV to the energy mix will not only decrease the reliance on diesel generators and cut CO_2 emissions but will reduce the overall cost of energy.

This thesis aims to offer a cost efficient solution for continuous disruption in the electric supply in Lebanese villages by developing a methodology to optimally design an on-grid hybrid power system consisting of EDL electricity, solar PV arrays, a diesel generator and batteries.

B. Literature Review

Due to the increasing demand for clean energy, renewable sources have become popular since their fuel is derived from natural and available resources which produces little or no waste products, reduces the costs of operation and requires less maintenance [6]. Hence, renewable energy has become of great interest in research work and case studies to model, simulate and optimize hybrid power systems both off and on-grid to achieve reliable, efficient and cost-effective systems.

Teshale [7] designed a hybrid power system for irrigation in the rural villages of Wonji-Shoa in Ethiopia. The system, depending on three sources wind, solar and diesel, is modelled and simulated in Matlab and SIMULINK. A fuzzy logic controller is used to switch between the energy sources depending on the resources availability during sunny, windy and rainy days. The system relies on the wind turbine and PV arrays while the diesel generator is used as a backup.

For off-grid power generation, Kumar et al. [8] developed a renewable energy hybrid system consisting of two main sources, a solar cell and a wind turbine. A proton exchange membrane fuel cell in parallel with an ultracapacitor are used for energy smoothing. Conventional controller methods are adopted to operate the system based on changes in demand load, wind speed, radiation and ambient temperature. Excess energy is used by an electrolyzer model to produce hydrogen that is stored for later usage.

Similarly Madaci et al. [9] proposed and tested a stand-alone hybrid energy system to meet load demand. The system is composed of a solar PV panel, wind turbine, fuel cell, an electrolyzer and a battery. A control algorithm is used to manage the operation of the system: when the renewable power generated is not sufficient, the battery is used to satisfy the load given that its state of charge is within its limits; otherwise the fuel cell is used. On the other hand, excess power is used to charge the battery and generate H2 in the electrolyzer when the battery is fully charged.

Saeed and Erceleb [10] modelled and simulated, in Matlab and SIMULINK, an on-grid hybrid power system consisting of a 90kW solar PV, 10kW wind turbine based permanent magnet synchronous generator, a 10,000Ah nickel metal hydride battery and a 3.123MVA diesel generator. A simple load-based control strategy is adopted to switch efficiently between the power sources to meet the demand. The system is tested for three different loads.

Venkobarao et al. [11] modelled an on-grid hybrid power system and designed a supervisory controller to determine the operation mode of each generation subsystem in order to satisfy the electrical demand and charge a battery bank while maximizing the utilization of renewable energy sources. A wind turbine is the main generator while a solar subsystem and the grid play complementary roles. Diesel generator is not used, thus load shedding is inevitable when the generation is not sufficient.

Fitriana et al. [12] used Firefly Algorithm (FA) to minimize generation cost and loss of battery life in a stand-alone microgrid. FA is a meta-heuristic algorithm optimization based on a population that is inspired by movement of fireflies. Attractiveness is proportional to brightness where the less bright one will be attracted and move towards the brighter one. In the minimization problem, the firefly with the lowest objective function has the brightest light intensity.

Majed et al. [13] optimized operation of a fuel cell hybrid electric vehicle using single step dynamic programming (SSDP) to minimize the cost of hydrogen and battery degradation. SSDP was used for its readiness to be implemented in real time since it only requires a one-step-ahead speed forecast. SSDP is compared to forward dynamic programming (FDP) and found to give close results in significantly less solution time. The difference in the results is justified based on the nature of the optimization model, where FDP solves all possible cases and traces back the optimal path while SSDP is a forward looking model that depends only on a step-ahead forecast.

Rahimi and Chowdhury [14] sized an emergency hybrid system to serve residential loads during natural-disasters-related-outages. The system consisting of PV arrays and a plug-in hybrid vehicle (PHEV) would allow the use of major household appliances during different seasons until the grid power is restored. The system was sized so that PV and the car would each satisfy half of the load during winter while PV alone would be sufficient to serve the summer load.

Khoury [15] optimized sizing and operation for a PV-battery backup system connected to the unreliable grid in Lebanon. The work aims to replace diesel generators in serving the load of a residential house. The backup system is modelled to only feed the load during outages; when the grid is available, the battery is charged form the PV and EDL if needed. To validate optimal sizing, genetic algorithm and particle swarm optimization (PSO) are applied and compared; both methods led to the same results. It is also found that coupling solar electric water heater with the backup system reduces the components' sizes and achieves a better economical solution. Demand Side Management (DSM) is used to shift the load profile and avoid peak consumption during blackouts in order to reduce further the size of the system.

Singla et al. [16] designed a battery-genset backup system for unreliable grid to minimize carbon footprint. The battery bank is sized for two scenarios: absence of a generator given a target loss power probability, and presence of a generator given a limit of allowable carbon emissions. Both designs are tested for 100 homes assuming an average of two outages per day with an average duration of one hour.

Zhang et al. [17] proposed a PV-battery system to be used during outages in developing countries. Source selection control would choose either the grid or the PV system depending on grid availability. The operation of the system is optimized by combining feedback control and MPPT of a DC-DC converter. The system is tested on a lighting application.

Cheung et al. [18] offered another solution for unreliable grid through an incineration generated system. The ash resulting is to be used as fertilizers or cement, and the CO_2 produced is to be filtered and consumed by algae farms which will in turn provide bio-fuel. A feasibility study was carried and the system is found to be profitable, environmental and efficient.

As for on-grid systems, Roy et al. [19] sized battery and supercapacitor storage systems for optimal operation of 1MW grid connected PV. Optimal operation is based on low pass filter used to allocate the power between the battery and supercapacitor, and operation constraints are enforced by rule-based algorithms. The system is simulated at one hour increments for an entire day; at each interval, the minimum required energy of the battery and supercapacitor are calculated. Then the capacities are sized based on the maximum energy that was required during the selected day. The authors also compared the use of lead-acid and li-ion batteries and found the latter to be more economical and have a longer lifetime.

Jarnut et al. [20] investigated the use of Zinc Bromine (ZnBr) flow battery for energy storage in a small scale microgrid containing renewable energy sources, and compared its properties to that of the lead acid (LA) and Li-ion batteries. It was found that the operating range of the ZnBr battery is tight compared to the other two types, and the stored energy density and specific energy of the ZnBr are lower than that of the LA and Li-ion batteries thus requiring more space for installation. On the other hand, the flow battery has longer lifetime and higher DOD. As for *LCOE*, it has lower cost than LA and expected to be lower than the Lithium technology in the near future.

Lambert et al. [21] used simulated annealing to design a least cost electrification system for a remote village. The approach aims to compare between two options: centralized generation which supply many houses through small distribution networks and an isolated system in which a small renewable energy source provides for a house. For a given set of demand nodes, the algorithm selects which option is most economical for the different nodes. A modified minimum spanning tree algorithm is also used in the initial state of the process to improve computational speed.

Ramoji et al. [22] presented a genetic algorithm (GA) based optimization technique to size a PV-wind hybrid energy system incorporating a storage battery. The authors aimed to minimize the total cost and serve the load reliably. The proposed technique can be adjusted for changes in insolation, wind speed, load demand, and initial cost of each component. It also proved to be feasible for sizing PV-wind hybrid energy system, stand-alone PV, and stand-alone wind system. The researchers concluded that PV-wind hybrid energy systems are the most economical and reliable solution for electrifying remote areas.

Ko et al. [23] also used genetic algorithm to optimize the component sizes of a hybrid system that integrates both fossil fuel systems and renewable energy systems providing four types of energy demands: heating, cooling, hot water, and electricity. The optimization goals are to minimize the life cycle cost, maximize penetration of renewable energy and minimize annual greenhouse gas. GA is used due to its popularity and success in solving large scale and combinatorial optimization problems.

Mesquita [24] developed gradient swarm optimization (GraSO) algorithm to optimize the design of a stand-alone hybrid system that is composed of wind, hydro, solar resources, batteries and a diesel generator. Pre-selected designs are not required for the optimization process, only the renewable data and operation constraints are needed for the GraSO to return the optimum solution to the problem. This algorithm can optimize both load following and cycle charging dispatch strategies.

Ordinal optimization has been used in different applications. Karaki et al. [25] used forward dynamic programming (FDP) and ordinal optimization (OO) to size the components of a fuel cell hybrid electric vehicle for the purpose of reducing hydrogen consumption and minimizing the overall cost. FDP provides the total vehicle cost for a set of N designs for two mixed roads which results in a large search space. The OO samples this space using a simple and another accurate model and orders the evaluated designs in an ascending manner to find a good enough solution. The best design always showed up in the top-S designs of the simple model runs.

Nanchian et al. [26] also used OO to estimate the transformer tap position in unbalanced three phase distribution network. Simulation results showed that OO gave more accurate and faster results than the weighted less square (WLS) technique; when compared to Hybrid PSO results, OO gave matched results with significantly faster solution time.

Horng and Lin [27] merged artificial immune system (AIS) with OO to determine optimal resource allocation of a network-flow production line. The proposed method was tested on a ten-node production line and gave more accurate and faster results when compared to ant colony system (ACS), artificial bee colony (ABC) and PSO.

Jabr and Pal [28] used OO to locate and size distributed generation to make best use of existing network infrastructure. The sampled alternatives are first evaluated by an efficient linear programming model. Then the top-S designs are simulated by optimal power flow to find a good enough solution. By comparing the obtained results to that of GA-OPF approach, OO gave better results with 9 fold reduction in computational effort.

Authors have also used HOMER to carry feasibility studies. Chedid et al. [29] presented a techno-economic study to test the feasibility of a hybrid PV-diesel generator -unreliable grid in Lebanon. The study assumed an unreliable grid for the first four years of the project and a reliable grid during the following 21 years. Using HOMER it is shown that the PV cost is lower than that of the diesel generator but higher than the utility's cost. Different scenarios are tested and it is found that with additional incentives form the government to encourage green investments, the overall cost of the system can be decreased to 13 ¢/kWh.

Fikari [30] investigated the implementation of a microgrid in a remote village in Kenya to cover the basic needs of electrification and clean water. The hybrid system consists of PV arrays, a wind turbine, along with a diesel genset as a backup and batteries for storage. First a techno-economical optimization is implemented using HOMER based on load profile study, radiation and wind data acquired through TRNSYS software. Then the optimal system is modeled and simulated in SIMULINK.

Ugirimbabazi [31] presented an optimal hybrid power system solution for off-grid electrification of a remote rural village in Rwanda based on its demand profile and available renewable energy resources. Using the software HOMER for modeling and optimization, the best configuration of the system is found to consist of a 20kW micro hydropower plant, 10 kW diesel generator and a 55.5 kWh battery bank. The obtained system has a 0.2$/kWh cost of energy.

A similar approach was used by Yaungket et al. [32] to design a PV hybrid system for four villages in different regions of Thailand where grid extension is unlikely due to high cost and low power demand. Data is collected from field studies, and HOMER is also used to find the optimal solution. In three of the villages, the optimal system is found to consist of PV panels, batteries and a diesel generator while the fourth village there is an additional need for hydro plant since it is located in a region with eight rainy months per year.

Vani and Khare [33] built a hybrid energy power system in Madhya Pradesh, India where efficient electricity generated from hydro and thermal power plants is not fulfilling the demand. The system is designed based on site empirical weather and load data and optimized using HOMER to minimize total net present cost, operating and running costs. The electricity production of the optimal system is generated from solar PV arrays, wind turbine and diesel generator contributing 31%, 35% and 34% respectively.

In summary, authors have optimized operation and sizing of both on and off-grid systems using conventional control strategies or optimization methods. However few papers have offered solutions for unreliable grid; [14] designed backup system for emergency outages during natural disasters which is not the case in Lebanon where outages follow a scheduled pattern. Proposed backup systems for developing countries included PV-battery [15] [17], diesel-battery [16], or incineration and biofuel [18]; while [15] considered the case of Lebanon, the PV-battery backup system designed for a single house was not allowed to feed the load during grid availability.

This work proposes a new approach to design and operate a hybrid energy system based on Ordinal Optimization (OO) and Single Step Dynamic Programming (SSDP). SSDP is chosen since it is a reliable and fast method that may be used in a real-time application and gives a near optimum operational solution for a given choice of system sizing [13]. And OO has a high probability of finding a good enough solution of the various system's components sizes saving computational time and effort [25, 34]. While SSDP was used to optimize two sources in [25], SSDP is extended in this work to determine the optimal mix of three different sources, including the modeling of the unreliable electric supply in Lebanon. Moreover, this work offers a cost efficient solution for the unreliable electric supply by developing a methodology to optimally design a hybrid power system consisting of the unreliable grid, solar PV arrays, a diesel generator and batteries.

The proposed methodology is tested to offer an economic solution for the Lebanese village Qaraoun and meet its load demand by designing a hybrid system connected to the unreliable grid consisting of a PV, diesel generator and li-ion battery. The program will investigate how the LCOE changes when removing or adding a battery, changing fuel costs and implementing a net metering policy.

CHAPTER II

SYSTEM MODELLING

The first step in designing the energy hybrid system is collecting data and selecting models. This chapter presents the data needed to achieve our objective in satisfying energy demand at a low cost: consumption habits, ambient temperature, solar radiation and EDL outages pattern. Then the hybrid system components are presented with their characteristics and cost.

A. Data Collection

In this section, the load profile data collected for a Lebanese village is presented. Then horizontal solar radiation is obtained and used to calculate the radiation incident on an inclined surface using the HDKR model.

1. Load Profile

The load profile is obtained by collecting data of the year 2016 from EDL. The measurements are taken in 15 minutes interval from the Qaraoun feeder in West Beqaa. When outages occur the load power is zero hence linear interpolation was used to estimate the power consumed during the rationing hours.

Figure 1 shows typical load trend during a day in spring, summer, autumn and winter. Load peaks around noon from 12 to 2 pm and at night after 8 pm.

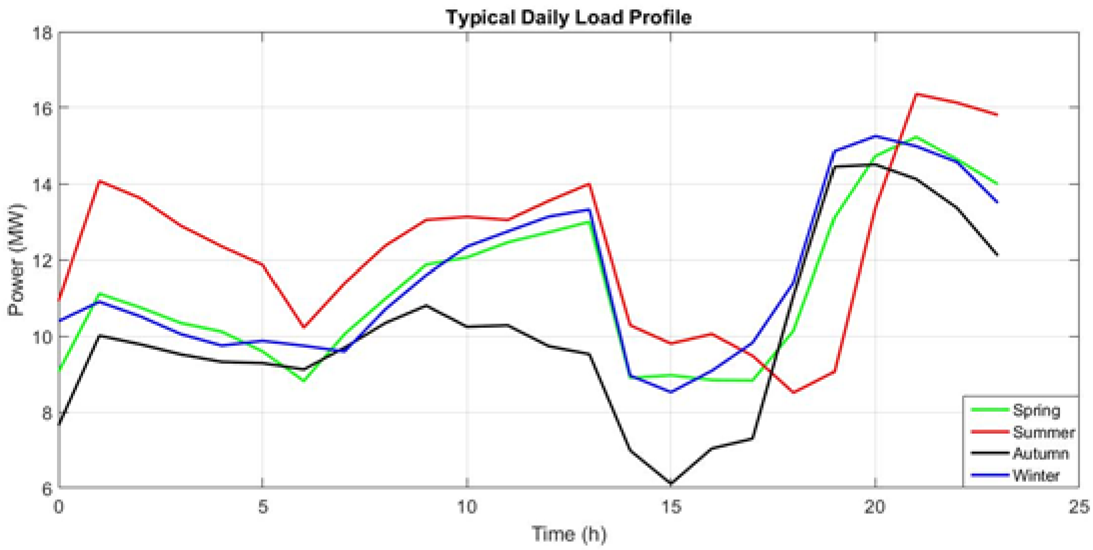

Figure 1. Typical daily load profile during different seasons

Qaraoun, located at a 33.56° N latitude and a 35.7° E longitude, has over 600 houses, three schools, factories and restaurants. This is reflected in the load trends as power consumption starts increasing after 6.30 am as people wake up, factories start running and schools open to prepare and heat classes. The demand peaks at night when all the family members are home after work or school and restaurants are filled with people. Peak load in the year 2016 is 23 MW while the average load is 9.7 MW.

2. Solar radiation

Hourly global horizontal solar radiation in the Beqaa area is obtained from Meteoblue [35].

To calculate the incident radiation falling on a solar collector tilted at an angle β, the HDKR model is used since it takes into consideration the circumsolar and horizontal brightening components [6] according to equation (1):

$$G_T = (G_{bh} + G_d A_i)R_b + G_d(1 - A_i)\frac{1+cos\beta}{2}\left[1 + f sin^3\left(\frac{\beta}{2}\right)\right] + G_h \rho_g \frac{1-cos\beta}{2} \quad (1)$$

where G_h is the horizontal radiation

G_{bh} is the beam radiation normal to the horizontal

G_d is the diffuse radiation

R_b is the ratio of beam radiation on the tilted surface to that on a horizontal surface

A_i is the anisotropic index

f is the modulating factor

ρ_g is the ground reflectance factor

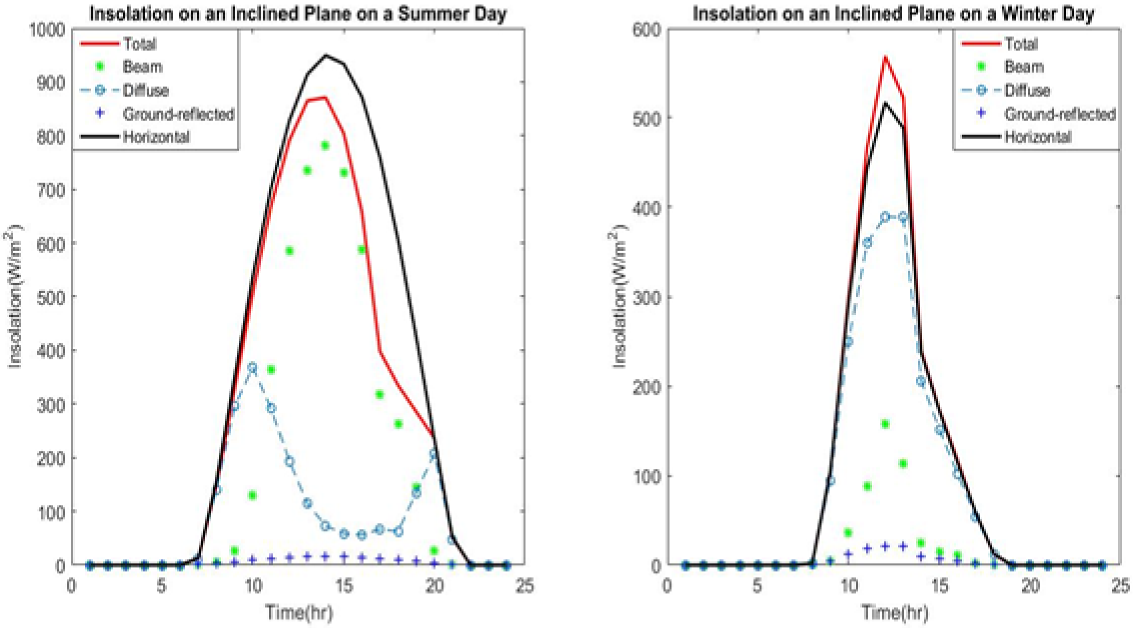

Figure 2. Insolation components after using HDKR model on two typical summer and winter days

Figure 2 illustrates the radiation components calculated by the HDKR model on an inclined plane tilted at latitude. During a summer day, the skies are clear, the clearness index is high and the ground is dry so the beam radiation is high while the diffuse and ground reflected radiation are low. As for a winter day, the clearness index is low as the sky is filled with clouds so the diffuse radiation is high while the beam is low. The ground reflected radiation is higher than that of summer since the ground is wet or occasionally covered with snow.

B. Systems Components

The system consists of PV panels, EDL, diesel generators and batteries. The characteristics and cost of each source is explained in this section.

1. PV Model

a. Electrical and Technical Data

The chosen PV model is Suniva Opt340; the monocrystalline module is made of 72 cells and is known for their quality and long-term reliability [36]. The test data for the Opt340 module is given in Table 1.

Table 1. Electrical Data for Suniva Opt340 [36]

Electrical Data Measured at STC: G=1000 W/m^2, AM= 1.5, Tc=25˚C		
Peak Power	P_{max}	340 W
Panel Efficiency	η	17.43%
Rated voltage	V_{mpp}	37.8 V
Rated Current	I_{mpp}	8.99 A
Open-Circuit voltage	V_{oc}	46.0 V
Short-Circuit Current	I_{sc}	9.78 A
Power Temperature Coefficient	α_P	-0.42%/k

The maximum power output produced by the solar module is given by [12]:

$$P_m = P_{max} \frac{G}{G_o} \left(1 + \alpha_P (T_c - T_{c,STC})\right) \quad (2)$$

where the maximum power P_m and the power temperature coefficient α_P are supplied by manufacturers under standard conditions and given in Table 1.

G is the solar irradiance incident on the panels obtained from HDKR model (W/m^2)

G_0 is the solar irradiance at STC and is equal to 1000W/m^2

The cell temperature T_C depends only on the ambient temperature and solar irradiance:

$$T_C = C_T\, G + T_a \quad (3)$$

$$C_T = (NOCT - 20)/800 \quad (4)$$

NOCT is the normal operating cell temperature given by a manufacturer test for G=800Wm^{-2}, *AM*= 1.5, Normal beam incidence, T_a =20°C, and wind speed is 1 m/s. For the Opt340 module, the *NOCT* is 46˚C. Hourly ambient temperature data was obtained from Meteoblue [35].

The AC power reaching the load will be reduced due to the losses in the boost DC-DC converter and the AC inverter. So the PV power at the AC load is calculated from (5)

$$P_{PV} = P_m \eta_{DC} \eta_{AC} \qquad (5)$$

where the efficiencies of the converter and inverter are assumed to be 95%.

b. PV System Cost

The levelized cost of electricity (LCOE) of the PV system is calculated in $/kWh as follows:

$$LCOE = \frac{AC}{EP_Y} \qquad (6)$$

where EP_Y is the total energy produced by the PV system during a year.

AC is the annual cost in $/year and is equal to the sum of the annuity of the installation costs (A_{IC}) and the operation and maintenance cost (*OM*):

$$AC = A_{IC} + OM \qquad (7)$$

$$A_{IC} = IC \frac{r(1+r)^n}{(1+r)^n - 1} \qquad (8)$$

where *IC* is the PV investment cost and it includes installation and labor costs valued at $940/kWp based on local market data.

OM is assumed to be 1% of the investment cost

r is the discount rate (7%)

n is the project lifetime (25 years)

As for the inverter, the investment cost is valued at $300/kW based on local market data.

c. PV Optimal Inclination and Orientation

Since the power produced by a PV depends on the incident radiation falling on its surface, PVs are tilted and oriented in such a way to maximize power produced given a certain location, date and time. Figure 3 shows how the solar irradiance in Lebanon varies as the inclination angle is varied. A 45˚ inclination increases the incident irradiance during autumn and winter but decreases it in spring and summer as compared to the horizontal. While a 90˚ inclination decreases significantly the overall yearly irradiance.

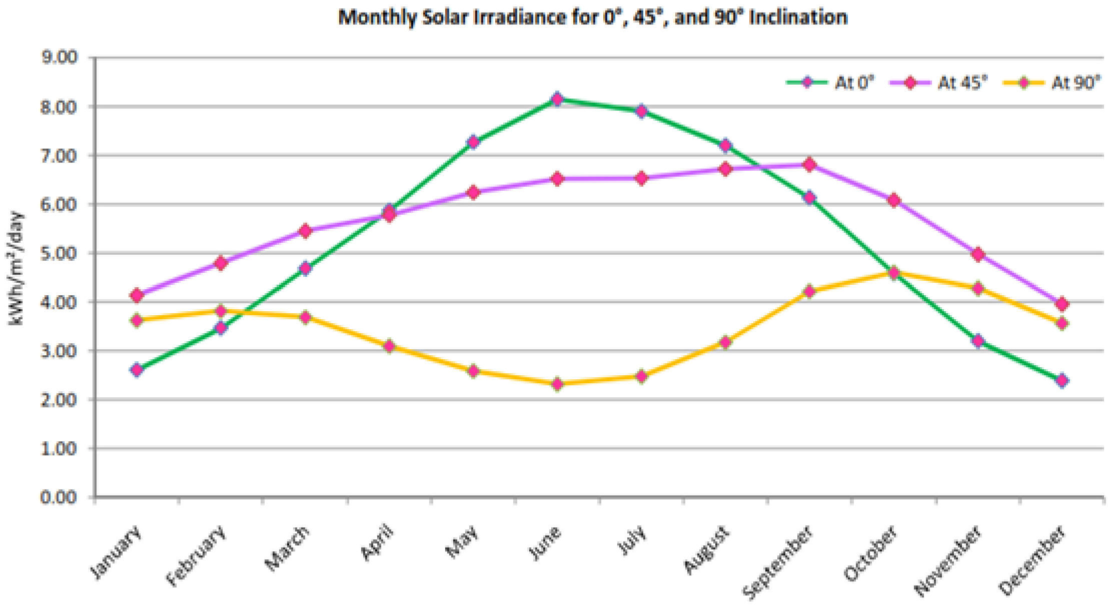

Figure 3. Monthly solar irradiance in Lebanon at different inclination angles [5]

To find the best inclination angle for Qaraoun, the total energy produced by one Opt340 PV module is calculated for different angles between 0˚ and 45˚. The results are summarized in Table 2. The maximum overall yearly energy was produced at an inclination of 20˚.

Table 2. PV Energy Production at Different Tilt Angles

	PV Energy (kWh)				
Beta	Spring	Summer	Autumn	Winter	Yearly Total
0˚	197.47	208.29	116.01	103.18	624.95
20˚	197.94	209.54	123.64	109.83	640.95
Latitude = 33.5˚	190.96	202.48	124.70	110.74	628.88
40˚	185.51	196.83	124.05	110.17	616.56

After fixing the inclination angle at 20˚, the orientation angle is investigated to maximize the hours of exposure to the sun. Since Lebanon lies in the northern hemisphere, the PVs are usually oriented due south since the sun rises in the south. Figure 4 compares between incident insolation on a PV inclined at 20˚ for three different orientations: south, west of south and west (180˚).

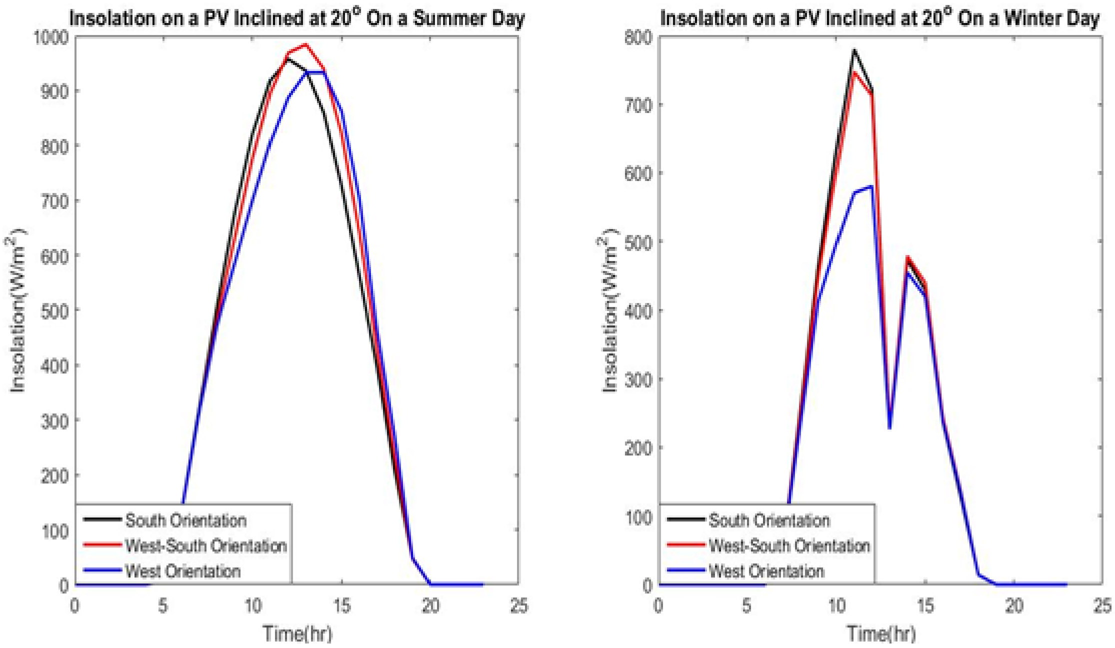

Figure 4. Insolation at different orientations

During summer, a west-south orientation increases insolation at and after noon while a west orientation increases insolation only in the afternoon as the PV is facing the west as the sun sets. On a winter day, a west orientation does not give a desired outcome since the sun is low in the sky. While the west-south orientation improves insolation after noon. Therefore orienting the PV due west-south increases PV power production at the afternoon peak hours. To find the best orientation angle, the yearly PV energy produced was computed for different angles summarized in Table 3; the maximum overall production is found to be at 32˚ west of south.

Table 3. PV Energy Production at 20˚ Inclination for Different Orientation Angles

	PV Energy (kWh)				
Orientation	Spring	Summer	Autumn	Winter	Yearly Total
0˚	197.94	209.54	123.64	109.8361	640.95
10˚	199.08	210.83	124.13	110.1876	644.22
20˚	200.12	211.84	124.26	110.2399	646.45
30˚	200.85	212.50	124.05	109.9906	647.39
40˚	201.27	212.8	123.49	109.4464	647.00

2. EDL

In most cities, the utility outages follow a pattern characterized by five outages every two days as shown in Figure 5. There are 913 outages per year of which 548 are four-hour outages and 365 are six-hour outages.

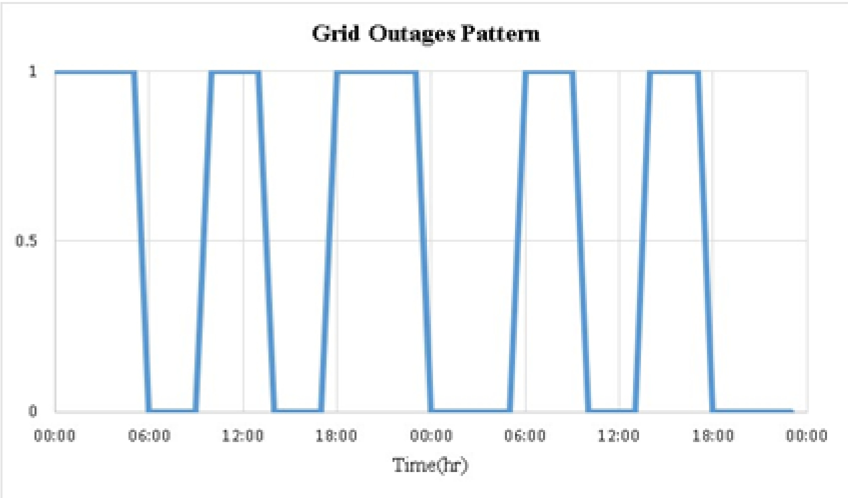

Figure 5. EDL outages pattern

The electricity generated costs EDL 22.73 ¢/kWh [4] while the monthly consumed energy is sold between 2.33 and 13.33 ¢/kWh [3] according to an incremental basis given in Table 4:

Table 4. EDL Prices for Monthly Consumed Energy [3]

Slab	Energy Consumed (kWh)	Price (LBP/kWh)
1	100	35
2	200	55
3	100	80
4	100	120
5	> 500	200

Based on EDL bills collected in the neighbourhood, the average energy consumed by a Lebanese house is 1200 kWh per month. Assuming all the energy is served from the utility, the energy will cost 9.69 ¢/kWh. After adding taxes and TVA, the average cost will be around 12 ¢/kWh.

Moreover, a net metering policy is implemented in Lebanon allowing projects to export power back to the grid. Any excess energy produced during a month is "banked" to offset future power consumption [37]. At the end of each year, excess energy remaining in the "bank" is donated to the grid and thus the meter is zeroed [37].

Since the energy production of EDL relies on distillate fuel oil, the CO_2 emission factor of the grid is 73.16 kg/MBTU [38] which is equivalent to 0.75 kg CO_2/kWh.

3. Diesel Generator

Since fuel consumption behaves in a non-linear fashion, a diesel fuel consumption chart is obtained [39] depending on the generator size and the loading level. An illustration is given in Table 5.

Whenever a size is selected, the data is obtained from the nearest size in the chart. Then the curve is rescaled to the given size and more points are added to the curve by curve-fitting. A correction factor is applied to diesel consumption to account for the power the generator uses internally for cooling. An example is given in Figure 6 plotting the consumption curve for a 100 kW generator.

Table 5. Diesel Generator Fuel Consumption Chart [39]

Generator size (kW)	1/4 load (l/hr)	1/2 load (l/hr)	3/4 load (l/hr)	Full load (l/hr)
20	2.27	3.41	4.92	6.06
100	9.84	15.52	21.96	28.01
125	11.73	18.93	26.88	34.45
135	12.49	20.44	28.77	37.10
200	17.79	29.15	41.64	54.51
230	20.06	33.31	47.32	62.84
400	33.69	56.40	80.63	108.26
1000	81.76	137.79	197.22	269.14
2250	182.08	307.00	440.62	604.15

The diesel generator operation cost is obtained from the diesel consumption curve by multiplying the consumption rate by the diesel fuel price taken at 0.59$/l (obtained on February 28, 2018) [40].

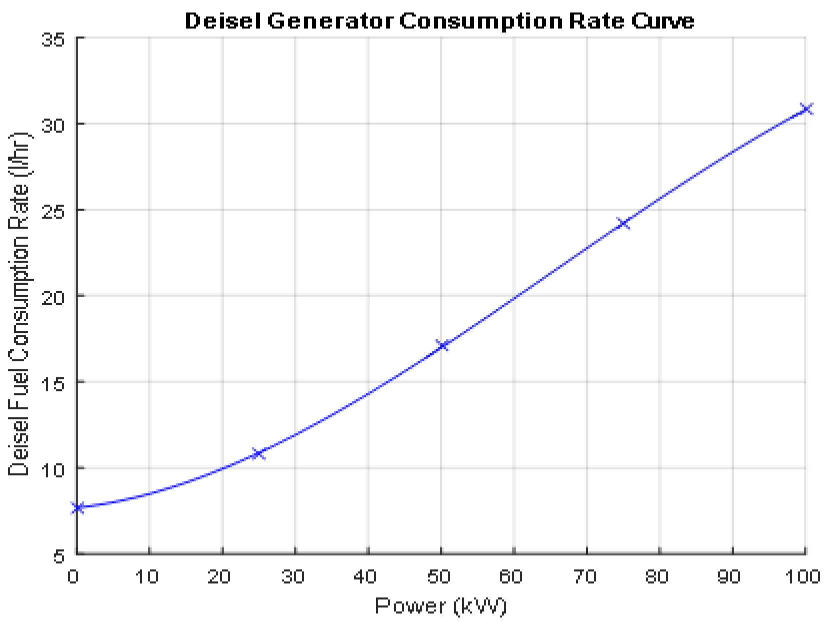

Figure 6. Diesel consumption curve for a 100kW generator

The efficiency of the generator is the ratio between the electrical output and the diesel fuel input (9). Figure 7 shows how the efficiency of a generator changes as a function of its output.

$$\eta = \frac{Pout}{fuel\,input * LHV\ of\ diesel} * 100 \tag{9}$$

The life time of the generator is assumed to be 25000 hours. The minimum loading allowed is 30% of its rated power.

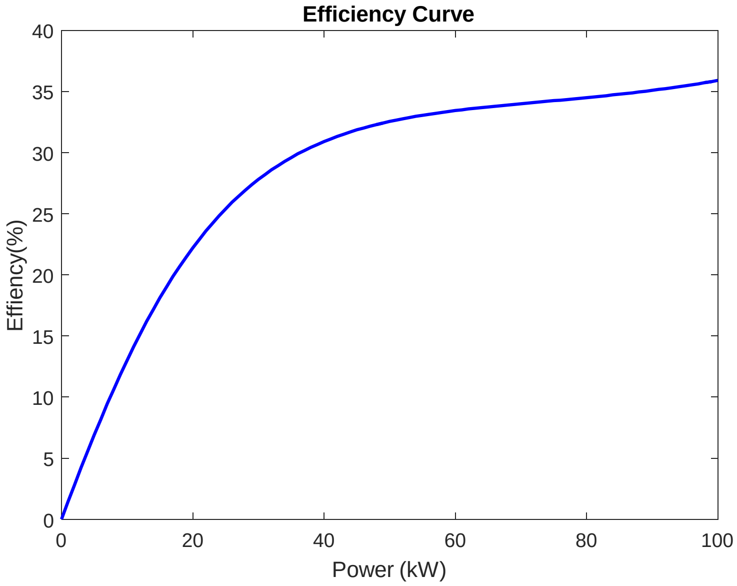

Figure 7. Efficiency curve of a 100 kW generator

As for the investment price of generators, prices for a variety of Perkins diesel generators are collected from Americas Generators [41]. It is found that the investment price of generators sized 50kW and above can be approximated by equation (10) taking into account both shipping cost and taxes.

$$IC_D = 250 * P_D \tag{10}$$

The operation and maintenance cost of the generator is \$0.010 per kWh [42] while the transportation cost is taken at 500 L.L./tank of diesel [43].

The CO_2 emission factor of a diesel generator is 22.4 pounds of CO_2 per gallon of diesel [44] which is equivalent to 2.68 $kgCO_2/l$.

4. Battery

Li-ion batteries have high energy per unit mass, high power-to-weight ratio, high energy efficiency, good high-temperature performance, and low self-discharge [45].

The battery used has a capacity of 50 kWh and rated power of 150kW; different sizes will be obtained from parallel arrangement of this module.

The battery charge map is adopted from [25], and is assumed to have a life of 2500 cycles at 90% DOD. Assuming the battery completes one cycle daily, the battery will last 7 years.

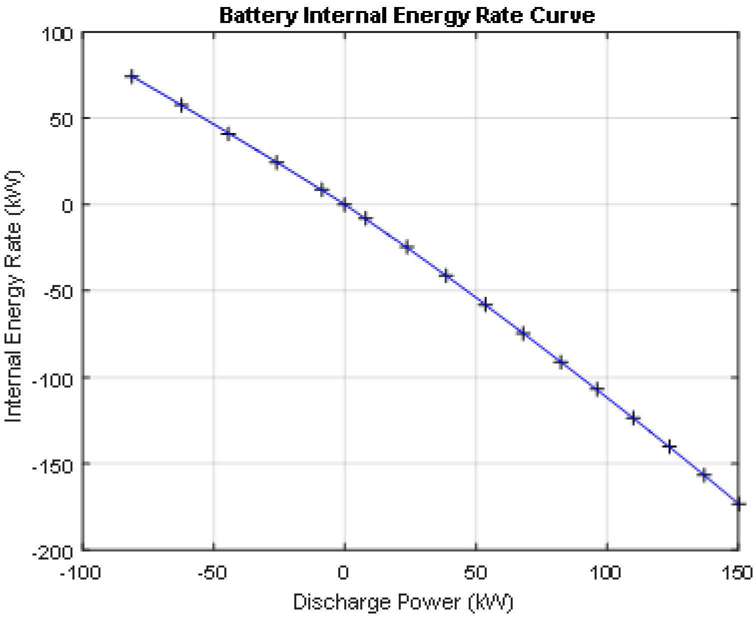

Figure 8. Battery charge map

Today's average Li-ion price has dropped to $209/kWh an 80% drop since 2010 [46] and will be assumed at $280/kWh to account for shipping and profit. As for the operation cost in this work, it is set to a value lower than the incremental cost of the diesel generator at the average load calculated during every period over a number of previous observed demands.

CHAPTER III

SYSTEM OPERATION AND OPTIMIZATION

In this chapter, two optimization problems are formulated: operation optimization and size optimization, identifying the objective, variables and constraints of each problem.

For the optimal operation, a set of sizes is given to serve a load. Single step optimization will satisfy the hourly load from the diesel generator, EDL, or the battery in order to minimize the operation cost within specified operation constraints. Then ordinal optimization samples different designs and find the optimal sizes that minimize the LCOE of the system.

A. Optimal operation using Single Step Dynamic Programming

The system, represented by Figure 9, consists of photovoltaic arrays, the electric utility grid (EDL), a diesel generator for backup, and a battery bank for energy storage. The operation is based on one-hour interval where data is collected on the load, ambient temperature, solar radiation, battery SOC and grid status. For a specified set of source sizes, the power supplied by PV, $P_{PV}(t)$, is calculated from equation (5) and the net load power is deduced ($P_L - P_P$).

EDL power, P_E, is assumed to satisfy the load based on k levels; in the first level EDL is not used ($P_E = 0$), for the $k/2$ level EDL would satisfy half of the load and in the k^{th} level EDL would supply the whole load.

The diesel generator's power is discretized based on n levels where the first level is $P_D = 0$, in the second level $P_D = P_{Dmin}$ and in the n^{th} level $P_D = P_{Drated}$.

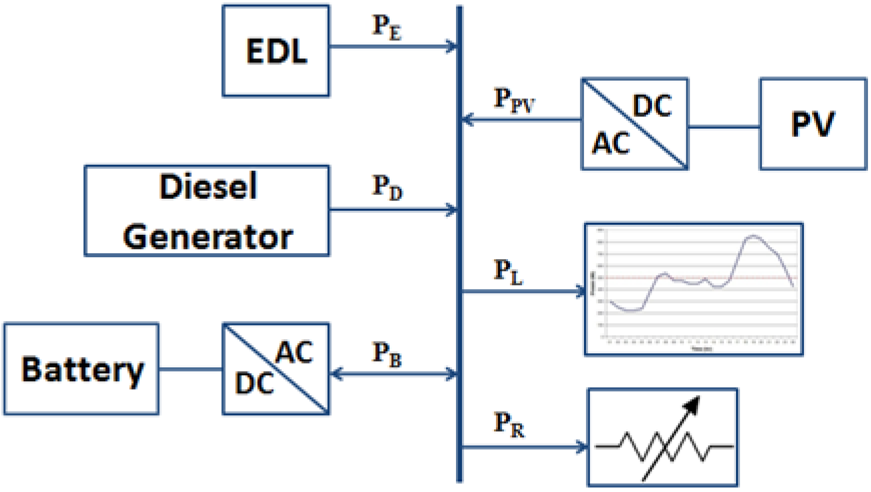

Figure 9. Schematic of the proposed hybrid system

The objective of the SSDP optimization is to determine for each interval *t* the EDL level, the generator level and the battery level, which minimize the cost of operation consisting of the sum of the three sources' cost. At each stage the EDL and generator power levels can be in one of the discrete levels explained above; for each level the battery power, P_B, and the resistor or dump power, P_R, are determined from the power balance equation (11).

$$P_E(t) + P_D(t) + P_B(t) - P_R(t) = P_L(t) - P_{PV}(t) \qquad (11)$$

The optimal level of each source at interval *t* is determined by enforcing the operation constraints by a penalty cost method. The battery and generator operation constraints are given in equations (12) to (17):

The upper and lower limit of the battery power:

$$P_B^{min} \leq P_B(t) \leq P_B^{max} \qquad (12)$$

Ramping rate limitation of the battery:

$$R_{dB}\Delta t \leq P_B(t) - P_B(t-1) \leq R_{uB}\Delta t \qquad (13)$$

Upper and lower limitation of the battery state of charge:

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \qquad (14)$$

The dynamic update on the SOC in period *t* given the battery power and the SOC in period *t*-1:

$$SOC(t) = SOC(t-1) + \psi_B(P_B(t))\,\Delta t \quad (15)$$

where $\psi_B(P_B)$ defines a charge power map relating internal energy rate to power output.

The upper and lower limit of the generator power:

$$P_D^{min} \le P_D(t) \le P_D^{max} \quad (16)$$

Ramping rate limitation of the generator:

$$R_{dD}\Delta t \le P_D(t) - P_D(t-1) \le R_{uD}\Delta t \quad (17)$$

At the end of the operation optimization, the LCOE of the system is calculated by dividing the total annualized cost of the system plus the cost of unmet energy by the sum of total energy demand and energy export to the grid. The annualized cost of the PV system is explained in chapter 2 section B.1.b and it includes the investment, operation and maintenance costs. The annualized EDL cost is calculated by multiplying the EDL energy tariff by the difference between the purchased and exported energy. In case the exported energy exceeds the purchased energy, EDL cost is zeroed. As for the generator, the annualized cost includes the investment, replacement, operation and maintenance costs, and the fuel cost based on operation hours and loading levels calculated by SSDP. Similarly the battery's annualized cost includes investment, replacement and operation costs.

B. Size optimization using Ordinal Optimization

Ordinal optimization (OO) is a method of speeding up the process of stochastic optimization by narrowing down the search to a "good enough" subset. OO is based on two tenets. The first tenet is "order" is more robust than "value" i.e. determining whether A is greater or less than B is a simpler task than determining the value of A-B.

The second tenet is settling for the ‘‘good enough with high probability’ instead of getting the "best" since the retreat from "nothing but the best" to a softer goal with an increased successful probability contributes to the significant decrease in search and hence computational cost [34].

As per OO theory, a "good enough solution" can be found from top-S designs. Let $G \subset \Theta$ be the good enough subset representing the top-1% of the design space based on system performances, and $S \subset \Theta$ be the selected subset that represents the estimated top-1% designs. By requiring the probability of $|G \cap S| \neq 0$ to be very high, the search can be narrowed speeding the optimization process [34].

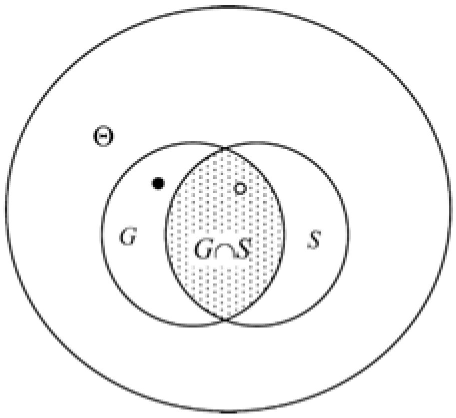

Figure 10. Graphical illustration of OO search space [34]

The alignment probability is given by (18)

$$AP = Prob[|G \cap S| \geq k] \tag{18}$$

where k is the alignment level meaning that there are k truly good enough designs in S.

There are two selection rules: blind pick and horse race: In blind pick, the S designs are blindly picked out without any evaluation of the performances. While in horse race, the performances of N samples are estimated using a crude model: the samples are sorted according to their estimated performances, then the observed top-S designs are selected as the set S. Then these S designs will be assessed based on an accurate model to determine the good enough solution [34]. Horse race rule offers higher reduction in search effort and will be used in this work.

The size of the set S depends on the class of the problem, *g* the size of the good enough subset (G), the required alignment level *k*, the error bound *W*, and the alignment probability *AP* (19):

$$Z(k,g) = e^{z_1} k^{z_2} g^{z_3} + z_4 \tag{19}$$

where z_1, z_2, z_3 and z_4 are obtained from a table of regression coefficient for a specified *AP* and the error bound *W*.

The class of the problem is obtained by normalizing the ordered performance curve (OPC) by equations (20) and (21) [34]:

$$y_i = \frac{J_{[i]} - J_{[1]}}{J_{[N]} - J_{[1]}} \tag{20}$$

$$x_i = \frac{i-1}{N-1} \tag{21}$$

where *J*[*i*] is the estimated performance of design *i*.

The objective of this work is to find the sizes of the hybrid system components that minimize the total levelized cost of electricity (*LCOE*) of the system. Ordinal Optimization uses SSDP to optimize operation of different sets of sizes and calculate the system’s LCOE. The given set of sizes results in *N* distinct designs that form a large search space ϴ. OO samples this search space to find a “good enough” solution. The objective function *J* in $/kWh is minimized over a set of designs i=1 to N and is symbolically described in equation (22):

$$J = min_{n=1,N}(LCOE(i)) \tag{22}$$

In this work, the simple model will have a run time of two typical summer and winter weeks, three EDL levels and 21 generator levels. While for the accurate model, the run time is 365 days with five EDL levels and 81 generator levels.

CHAPTER IV

RESULTS

To emphasize the capabilities of the program developed, operation optimization is run for a simple load to compare the results for different scenarios: removing a source, varying the sources sizes, variation of EDL and diesel fuel costs, adding net-metering policies and enforcing a charge sustaining or charge depleting operation. Then the OO is run to find the optimal sizes for the simple load and the results are validated by comparing them to HOMER. Finally the optimal design will be presented for the village Qaraoun.

A. Testing SSDP

A simple load is considered to test the program developed; the load shown in Figure 10 is given for a winter and summer week where it is supposed to follow a similar pattern but with higher power consumption during summer [47].

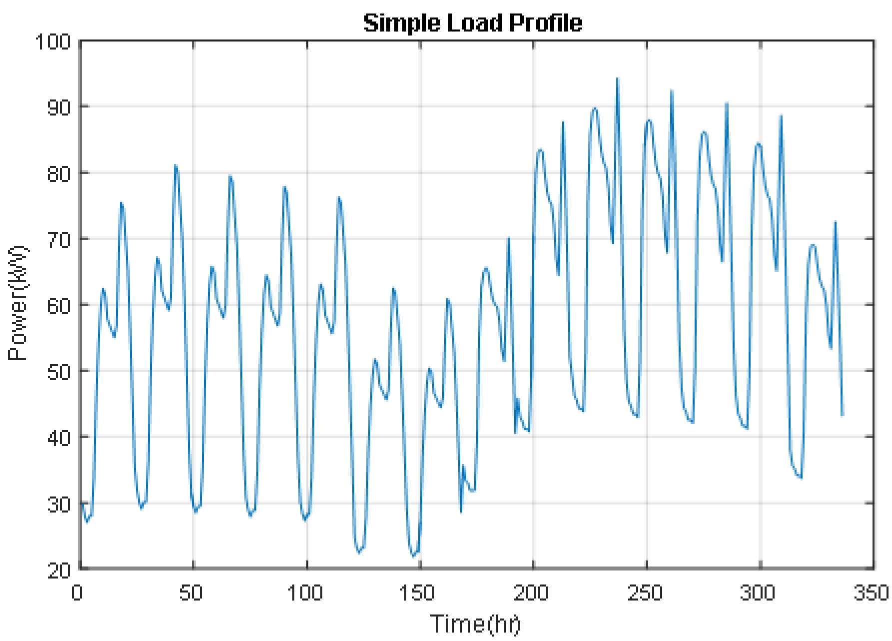

Figure 11. Simple load profile [47]

The system is simulated for different sizes of sources during the above two weeks and the results are scaled to obtain costs for the whole year. The PV panels are tilted at 20˚ and due 32˚ west of south to maximize the solar irradiation falling on the panels.

In the first runs, three cases are considered: EDL is not available, EDL is available with scheduled outages, and EDL is always available. PV, diesel and battery sizes are constant in this scenario at 100kW, 80kW and 50kWh respectively. Results are tabulated in Table 6.

Table 6. Results at Different Grid Operation Status

100kW PV 80kW generator 50kWh battery	Off-grid		Unreliable grid		100% reliable grid	
	Energy (MWh)	LCOE ($/kWh)	Energy (MWh)	LCOE ($/kWh)	Energy (MWh)	LCOE ($/kWh)
PV	152.17	0.059	152.17	0.059	152.17	0.059
EDL	0	-	170.89	0.120	345.88	0.120
Generator	348.78	0.259	176.8	0.263	0	-
Battery	7.64	0.372	4.88	0.582	1.43	1.99
System	496.82	0.214	496.82	0.166	496.82	0.117
Unmet Energy (MWh)	0.62		0.38		0	
Dump Load (MWh)	4.38		3.2		1.25	
% of battery charged from generator	96%		90%		0%	
EDL emissions (Tons)	0		128		259	
Generator CO2 emissions (Tons)	350		178		0	

Table 6 shows that a stand-alone system has the highest LCOE while a reliable grid system has the lowest. As expected when the grid is always available the generator and battery are no longer needed since EDL is enough to serve the load at a low price of 12¢/kWh. However the total LCOE of the system is still 11.7¢/kWh since the system is taking into account the generator and battery investment costs. If both generator and battery are removed and the load is served by a reliable grid coupled with PV the LCOE would decrease to 10.8¢/kWh.

It is evident that the battery is being charged by the generator. One reason is that the PV capacity is not large enough to produce excess energy to charge the battery. The second reason is the operation constraints of the generator that cannot be operated below 30% of its rated power. So whenever the load demand is lower than the generator's P_{min}, the excess power will charge the battery.

Using the same sizes at 100kW PV, 80kW generator and 50kWh battery, the system is tested again for different electricity prices. In the first run the utility sells electricity at the production cost 22¢/kWh. In the second run EDL retail price is assumed to follow a simple curve where price increases at peak hours (from 1 to 9 pm) as shown in Figure 12. While in the third run, energy is sold at the current average tariff of 12¢/kWh. The results are summarized in Table 7 below.

Figure 12. EDL retail price for the second test run

Table 7. Results at Different EDL Electricity Prices

100kW PV 80kW generator 50kWh battery	$0.22/kWh		$0.15/kWh off-peak $25/kWh peak		$0.12/kWh	
	Energy (MWh)	LCOE ($/kWh)	Energy (MWh)	LCOE ($/kWh)	Energy (MWh)	LCOE ($/kWh)
PV	152.17	0.059	152.17	0.059	152.17	0.059
EDL	63.04	0.220	114.34	0.155	170.89	0.120
Generator	284.91	0.252	233.65	0.256	176.8	0.263
Battery	7.10	0.400	6.54	0.434	4.88	0.582
System	496.82	0.204	496.82	0.187	496.82	0.166
Unmet Energy (MWh)	0.3		0.32		0.38	
Dump Load (MWh)	3.29		3.39		3.2	
% of battery charged from generator	95%		95%		90%	
EDL emissions (Tons)	47		86		128	
Generator CO2 emissions (Tons)	278		231		178	

When the utility price is fixed at the actual production cost ($0.22/kWh), 57% of the load is satisfied by the generator, 30% by PV and 12.7% by EDL with a negligible share by the battery. The LOCE of the system is $0.204/kWh.

When EDL electricity is sold at a variable tariff the percentage of load supplied by EDL increases from 12.7% to 23% and the energy supplied by the generator and battery decreases with an 8% decrease in the LCOE of the system to $0.187/kWh.

When the cost is returned to its current tariff of $0.12/kWh, the dependence on EDL significantly increases to cover 34.4% of the load while the contribution of both the generator and the battery drops. The LCOE also drops 11% to become $0.166/kWh. The results reflect the behavior of the system should any future changes occur to the retail prices of electricity.

Another test is varying the diesel cost; the system is previously run for the current cost of $0.59/l so the behavior of the system is investigated for a lower and a higher cost. Looking at the years 2010 to 2018 the highest diesel cost recorded was in May 2011at 32,100 L.L. ($1.07/l) while the lowest was in February 2016 at 10,000 L.L. ($0.33/l) [40]. Results are given in Table 8 below.

Table 8. Results for Fuel Price Variation

100kW PV 80kW generator 50kWh battery	Diesel cost $0.33/l		$0.59/l		$1.07/l	
	Energy (MWh)	LCOE ($/kWh)	Energy (MWh)	LCOE ($/kWh)	Energy (MWh)	LCOE ($/kWh)
PV	152.17	0.059	152.17	0.059	152.17	0.059
EDL	76.86	0.120	170.89	0.120	171.89	0.120
Generator	271.10	0.157	176.8	0.263	176.00	0.442
Battery	6.87	0.414	4.88	0.582	5.99	0.474
System	496.82	0.136	496.82	0.166	496.82	0.230
Unmet Energy (MWh)	0.33		0.38		0.38	
Dump Load (MWh)	3.35		3.2		3.36	
% of battery charged from generator	95%		90%		93%	
EDL emissions (Tons)	58		128		128	
Generator CO2 emissions (Tons)	265		178		177	

When the diesel fuel price drops to $0.33/kWh, it is more economic to turn on the generator to cover the load and consume less energy from the utility. The generator is serving 54.5% of the load while EDL’s share is 15.5%. The low fuel price decreased the generator’s LCOE and consequently that of the system ($0.136/kWh). When the cost is increased to the current price at $0.59/l, the generator’s share in serving the load decreases to 35.6% and EDL’s share increases to 34.4%; and the LCOE increases to $0.166/kWh. However a further increase in the fuel prices to $1.07/l gives similar results to the base case (at $0.59/l) in terms of source share in serving the load since there is a priority in satisfying the load thus the generator has to be used during grid outages despite the high fuel price. Consequently the LCOE is increased to $0.23/kWh.

Now the system will be run for different sizes of PV, battery and generator to note their effect on the contribution of each source and the LCOE of the system.

Table 9. Results for Various Source Sizes

Fuel price: $0.59/l EDL tariff: $0.12/kWh No net metering	200 kW PV 80 kW generator 100 kWh battery		300 kW PV no generator 500 kWh battery		200 kW PV 70 kW generator no battery	
	Energy (MWh)	LCOE ($/kWh)	Energy (MWh)	LCOE ($/kWh)	Energy (MWh)	LCOE ($/kWh)
PV	304.33	0.059	456.50	0.059	304.33	0.059
EDL	138.95	0.120	112.20	0.120	140.40	0.120
Generator	135.96	0.265	0	0	145.19	0.253
Battery	9.97	0.571	87.33	0.498	0	0
System	496.82	0.168	496.82	0.301	496.82	0.163
Unmet Energy (MWh)	0.11		87		2.76	
Dump Load (MWh)	82		159		95.87	
% of battery charged from generator	31		0		-	
EDL emissions (Tons)	104		84		105	
Generator CO2 emissions (Tons)	137		0		141	

When the size of PV is increased from 100kW to 200kW, the percentage of battery charged form the generator decreased from 90% to 31% but the dump load increased which implies that the batteries capacity can be increased. The LCOE is $0.168/kWh. Increasing the PV and battery capacities while removing the diesel generator increased the reliance on the battery and increased the cost of the system to $0.3/kWh. The unmet energy also increased from a negligible 0.022% to 17.5% of the load demand. An advantage of this system is decreasing the total CO_2 emissions to 84 Tons per year.

In the third case, the battery is removed and a smaller size generator with a 200kW PV are adopted. A lower LCOE of $0.163/kWh is achieved and the unmet energy is 0.8% of the load which means that the load can be served at a more economical cost without a battery bank.

Next the sizes are fixed at 300kW PV, 75kW generator and a 100kWh battery; the system is run for three cases: power export to the grid not allowed, net metering with excess energy donated to the grid, and net metering with excess energy sold at retail price. The system is run for the whole year for accurate results that are summarized in Table 10.

Table 10. Results for Different Net Metering Policies

<table>
<tr><td rowspan="2">300kW PV
75kW generator
100kWh battery</td><td colspan="5">System Energy: 489.79
PV Energy: 520.62 MWh LCOE: 0.052
Generator Energy: 117.76 MWh LCOE: 0.260
Battery Energy: 10.95 MWh LCOE: 0.519</td></tr>
<tr><td>EDL energy (MWh)</td><td>Exported Energy (MWh)</td><td>Dump Energy (MWh)</td><td>EDL cost ($)</td><td>System LCOE ($/kWh)</td></tr>
<tr><td>Net metering not allowed</td><td>118</td><td>0</td><td>266</td><td>14,182</td><td>0.18</td></tr>
<tr><td>Net metering with excess energy donated</td><td>118</td><td>129.6</td><td>136</td><td>0</td><td>0.12</td></tr>
<tr><td>Net metering with excess energy sold at retail price</td><td>118</td><td>130.86</td><td>136</td><td>-1366</td><td>0.117</td></tr>
</table>

The excess energy produced by the large sized PV is greater than the total energy purchased from the grid. When net metering is not allowed, excess PV energy is dissipated in the dump load and the EDL bill is paid based on consumption. When net metering is allowed with excess energy donated, the EDL bill is zeroed and the total LCOE is decreased. When excess energy is sold at retail price the LOCE is decreased further.

The next runs are done for two different operating strategies: charge sustaining and charge depleting. In both cases the initial SOC of the battery is 0.8; the final SOC is required to be 0.8 for the charge sustaining mode and 0.4 for the charge depleting mode. The sizes are chosen to be 200kW PV, 70kW generator and 100kWh battery. Note that all the previous runs operated on a charge sustaining strategy.

Table 11. Results at Different Operating Strategies

200kW PV 70kW generator 100kWh battery	Charge sustaining		Charge depleting	
	Energy (MWh)	LCOE ($/kWh)	Energy (MWh)	LCOE ($/kWh)
PV	304.33	0.059	304.33	0.059
EDL	137.24	0.120	133.69	0.120
Generator	136.54	0.255	128.49	0.257
Battery	11.03	0.516	21.07	0.271
System	496.82	0.166	496.82	0.163
Unmet Energy (MWh)	1.02		1.72	
Dump Load (MWh)	81.86		70.85	
% of battery charged from generator	36%		15%	
EDL emissions (Tons)	103		100	
Generator CO2 emissions (Tons)	133		126	

When implementing a charge depleting strategy, the battery's contribution increased in satisfying the load but without having a significant impact on the system's LCOE.

B. Results validation

To validate the results using HOMER, first the load profile and grid outages pattern were imported to the design, solar radiation and temperature were downloaded by HOMER given Qaraoun's coordinates. PV model is chosen to have similar properties to the Suniva model; a 100kWh generic battery is selected having a nominal power of 300kW which is the same as two parallel batteries of our chosen battery module. As for the generator, HOMER sets an autosize genset that sizes itself to meet the peak load.

HOMER assumes a linear fuel consumption curve with an intercept of 3.36 and a slope of 0.251 l/h/kW so our program is adjusted to match HOMER's operation. Net metering policy is allowed and a charge depleting strategy is adopted with an 80% initial SOC and a 40% minimum SOC. Using HOMER optimizer the lowest net present cost of $879,443.30 is obtained for 300kW PV, 110kW generator and a 100kWhLi-ion battery. The second accepted solution has a net present cost of $928,522.20 for a 300kW PV, 110kW generator but without a storage battery. The same sizes are run using SSDP and the results are compared in Table 12.

Table 12. Results Comparison between HOMER and SSDP

	300kW PV 110 kW generator 100kWh battery		**300kW PV 110kW generator No battery**	
	HOMER	**SSDP**	**HOMER**	**SSDP**
LCOE ($/kWh)	0.124	0.121	0.129	0.124
Initial capital ($)	398,809	398,808	372,341	372,341
PV production (MWh)	521.9	520.6	521.9	520.6
Renewables fraction (%)	57.8	60	50.6	52
Battery discharge(MWh)	21.9	19.9	-	-
EDL purchased energy (MWh)	119	117	130	121
EDL exported energy (MWh)	119	127	130	137
Generator production (MWh)	137	111	176	176
Generator operating hours	3,288	2,500	4,374	2,785
Total diesel fuel (l)	45,687	39,919	58,999	58,989
Fuel cost ($)	26,955	23,552	34,809	34,803

The PV production differs slightly due to the difference in the solar radiation data. For the first case, the contribution of EDL and the battery are close while the generator production is higher in HOMER results. This is due to the difference of operation algorithms between the two programs; another reason could be that in HOMER the battery might be more efficient running for fewer hours and discharging 21 MWh and the generator running for more hours producing 137 MWh. While for the SSDDP the battery is running more and the generator is running for 2500 hours instead of 3288 hours as per HOMER. The LCOE achieved by HOMER is 0.124 $/kWh while that by SSDP is 0.121 $/kWh. The main reason for the difference is the lower fuel cost and lower replacement cost of the generator which is assumed to have a lifetime of 25000 hours; in the case of SSDP the generator has a lifetime of 10 years and is replaced twice during the lifetime of the project. While the HOMER generator lasts 7.6 years and is replaced three times during the 25 years of the project.

For the second case, the difference also lies in the total generator operation hours however in both programs the load was completely satisfied. To be able to compare the results, the SSDP was modified to oblige the generator to run at three levels and thus matching the generator output of HOMER to 176 MWh per year. The LOCE obtained is $0.129/kWh by HOMER and $0.124/kWh by SSDP. The main difference is again due to the generator replacement cost.

If SSDP is run for 20 generator levels, the generator output would be 134 MWh per year and the system LCOE would be $0.113/kWh. Therefore SSDP seems to be able to find a more efficient solution.

C. Hybrid System Design for Qaraoun

Since applying a net metering policy gives more economic results, net metering will be applied to size a hybrid power System at Qaraoun with excess energy donated to the grid.

The peak load at Qaraoun is 23 MW while the average load is 9.7 MW. To narrow down the set of sizes that should be simulated by Ordinal Optimization, a range of sizes is first selected resulting in 144 runs:

PV sizes = [5, 10, 15, 20, 25, 30] MW

Generator sizes = [5, 10, 15, 20, 25, 30] MW

Battery sizes = [0, 1, 5, 10] MW

The simple model is run for two typical summer and winter weeks, three EDL levels and 21 generator levels. Simulation is carried on a computer having an Intel® CORE™ i7-4770 CPU running at 3.40 GHZ with 16 GB installed memory. The simple model solution time was 2.4 minutes and the top 20 solutions are tabulated in Table 13.

The ordered performance curve is plotted in Figure 13 and the class obtained is bell shape. The size of set S is obtained from equation (19):

$$Z(k, g) = e^{z_1} k^{z_2} g^{z_3} + z_4 \qquad (19)$$

The size of the good enough subset is g = 30; the required alignment level is k = 1. The regression coefficients are obtained for an alignment probability of AP =0.95 and low error bound of 0.5: z_1 = 8.1998, z_2 = 1.9164, z_3 = -2.0250 and z_4 = 10.

Z(k,g) = 13.7 so the solution lies in the top-14 solutions of Table 13 which indicates that the best solution could be found for PV sizes between 25 and 30MW, generator between 10 and 20 MW and battery between 0 and 10 MW.

Table 13. OO Simple Model Results for 144 runs

Run No.	PV size (MW)	Generator Size (MW)	Battery Size (MWh)	System LCOE ($/kWh)	Unmet Load (MWh)	Export to grid (MWh)	Dump Load (MWh)
130	30	15	1	0.130	4	7467	7857
129	30	15	0	0.131	17	7467	8312
131	30	15	5	0.132	0	7171	7216
132	30	15	10	0.135	0	7000	7031
134	30	20	1	0.136	0	7463	8276
133	30	20	0	0.136	0	7467	8666
135	30	20	5	0.137	0	7227	7384
106	25	15	1	0.137	2	4627	5402
105	25	15	0	0.137	17	4671	5933
126	30	10	1	0.138	1703	7435	7419
125	30	10	0	0.139	1772	7467	7849
107	25	15	5	0.139	0	4246	4876
136	30	20	10	0.140	0	7027	7092
127	30	10	5	0.140	1524	7000	7321
108	25	15	10	0.142	0	3988	4732
128	30	10	10	0.142	1335	7000	7041
139	30	25	5	0.142	0	7285	7493
138	30	25	1	0.142	0	7323	8839
137	30	25	0	0.143	0	7467	9305
82	20	15	1	0.143	2	2303	3401

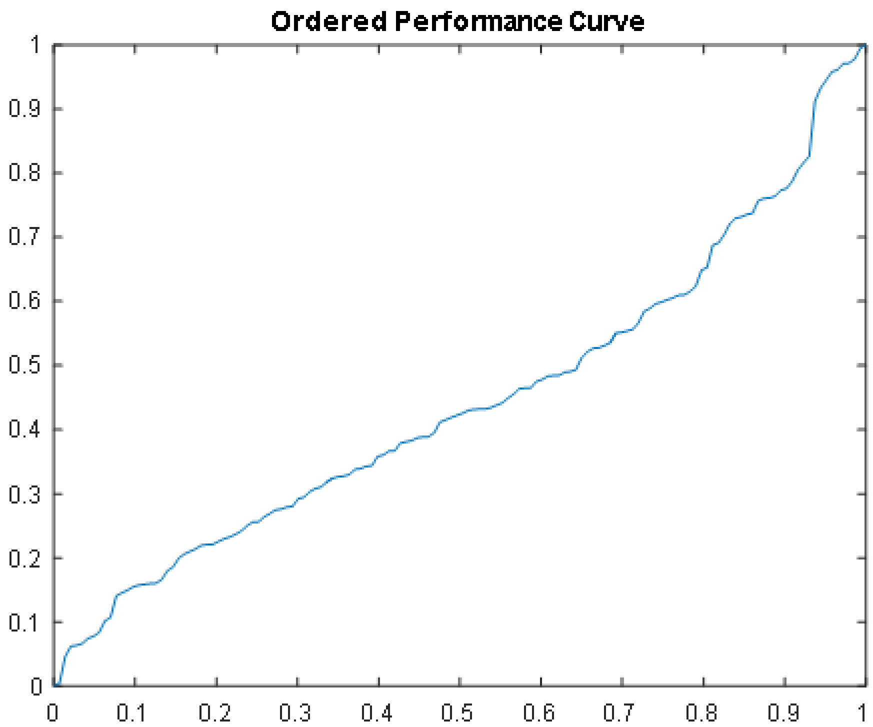

Figure 13. Ordered performance curve for the first simple run

So the next run will narrow down the search space to the following sizes resulting in 726 runs:

PV sizes = [25:30] MW

Generator sizes = [10:20] MW

Battery sizes = [0:10] MW

The solution time for the simple model was 12 minutes and the top-14 solutions are tabulated in Table 14. The ordered performance curve obtained was also a bell shape and therefore the top-14 solutions are run using the accurate model. The solution time was 20 minutes and the results are given in table 15.

Table 14. Final Run OO Simple Model Results

Run No.	PV size (MW)	Generator Size (MW)	Battery Size (MWh)	System LCOE ($/kWh)	Unmet Load (MWh)	Export to grid (MWh)	Dump Load (MWh)
662	30	15	1	0.130	4	7467	7857
663	30	15	2	0.131	0	7301	7636
661	30	15	0	0.131	17	7467	8312
652	30	14	2	0.131	170	7296	7496
651	30	14	1	0.131	193	7365	7819
664	30	15	3	0.131	0	7227	7463
653	30	14	3	0.131	163	7296	7300
674	30	16	2	0.131	0	7467	7617
541	29	15	1	0.131	2	6781	7293
650	30	14	0	0.131	227	7467	8276
543	29	15	3	0.131	0	6789	6698
542	29	15	2	0.131	0	6810	7057
665	30	15	4	0.131	0	7142	7329
675	30	16	3	0.132	0	7312	7394
662	30	15	1	0.130	4	7467	7857
663	30	15	2	0.131	0	7301	7636
661	30	15	0	0.131	17	7467	8312

Table 15. Final Run OO Accurate Model Results

Run No.	PV size (MW)	Generator Size (MW)	Battery Size (MWh)	System LCOE ($/kWh)	Unmet Load (MWh)	Export to grid (MWh)	Dump Load (MWh)
10	30	14	0	0.122	210	6291	9842
3	30	15	0	0.122	103	6291	9865
1	30	15	1	0.122	96	6125	9744
5	30	14	1	0.122	198	6097	9768
4	30	14	2	0.123	188	5961	9811
2	30	15	2	0.123	91	5969	9808
9	29	15	1	0.123	96	5521	9074
7	30	14	3	0.123	180	5940	9768
6	30	15	3	0.123	87	5940	9770
8	30	16	2	0.123	61	5954	9823
12	29	15	2	0.124	91	5415	9085
13	30	15	4	0.124	83	5935	9710
14	30	16	3	0.124	59	5942	9771
11	29	15	3	0.124	87	5411	9024

The best design consists of 30 MW PV, 14MW diesel generator and no battery achieving a low LCOE of 12.2¢/kWh compared to the current average cost of energy at 18¢/kWh (12¢/kWh for EDL and 20-30 ¢/kWh for the generator).

The 30 MV PV requires an area of 0.172 km^2 which is feasible given that the space available in Qaraoun is 1 km^2:

$$A = \frac{Size\ (kW)}{1\frac{kW}{m^2} * \eta} = \frac{30{,}000}{0.174} = 172{,}413\ m^2 \quad (23)$$

Figure 14 shows the contribution of each source between the days 72 and 76. The net load is negative when the PV power exceeds the load; since there is no battery, the excess power is exported to the grid when it is online otherwise excess power is dissipated in the dump load. While EDL and the generator follow the load serving it.

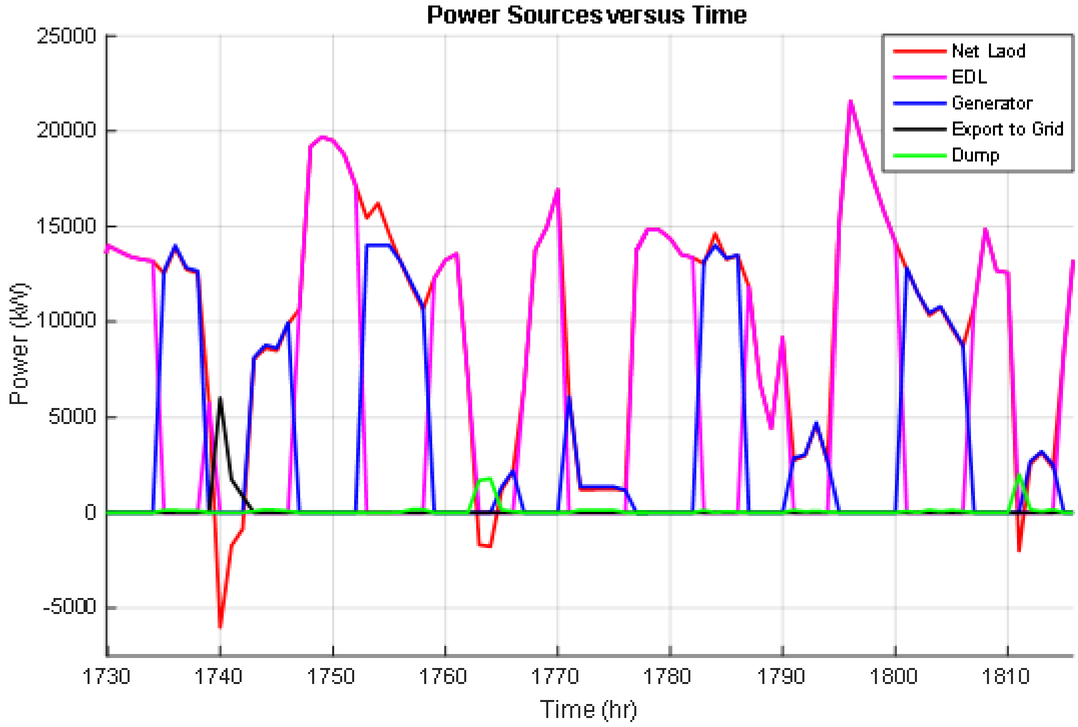

Figure 14. Source contribution for the best design

At times, the generator is running at a power level higher than the load due to the discretization levels and the excess power is dissipated in the dump load. At other times, a small part of the load is not satisfied even though the generator is running at peak load. This amounts to the total 210 MWh of unmet energy during the year.

Table 16 summarizes the results and cost analysis of the best design operation. After subtracting the dump energy, the total PV production is 41.9 GWh which saves 31,844 tons of CO_2.

Table 15. Results and Cost Analysis of the Best Design

Total Load Demand (GWh)	85.2
Energy Supplied By PV (GWh)	51.5
Energy Supplied By EDL (GWh)	31.9
Energy Export to Grid (GWh)	6.3
Energy Supplied By Generator (GWh)	17.6
Energy Dissipated in Dump Load (GWh)	9.8
Unmet Energy (GWh)	0.2
Renewable Energy Fraction (%)	45.7
Investment Cost of PV (million$)	28.200
Investment Cost of the Generator (million$)	3.500

Investment Cost of inverter (million$)	9.000
Total Investment Cost (million$)	40.70
EDL Operating Cost (million$)	3.078
Diesel Fuel Cost (million$)	3.217
Diesel Fuel Transportation Cost (million$)	0.0926
Total Annualized System Cost (million$)	10.956
LCOE of PV system ($/kWh)	0.053
LCOE of EDL($/kWh)	0.097
LCOE of Diesel Generator($/kWh)	0.234
LCOE of System($/kWh)	0.122
CO_2 Emissions of EDL (Tons)	19,238
CO_2 Emissions of Generator (Tons)	14,899

D. Further Runs

1. Validating Choice of Sizes Range

To validate the choice of sizes range, the simple runs were repeated over different source with a small incremental step resulting in 7436 runs:

PV sizes = [5:30] MW

Generator sizes = [5:30] MW

Battery sizes = [0:10] MW

The simulation time for the simple model was 2.3 hours; the ordered performance curve plotted in figure 15 gives a smoother bell shape class given the larger number of runs. Thus the top-14 solutions were run using the accurate model and the same results were obtained as that of Table 15 proving the validation of the method used to narrow down the sizes range and saving computation time.

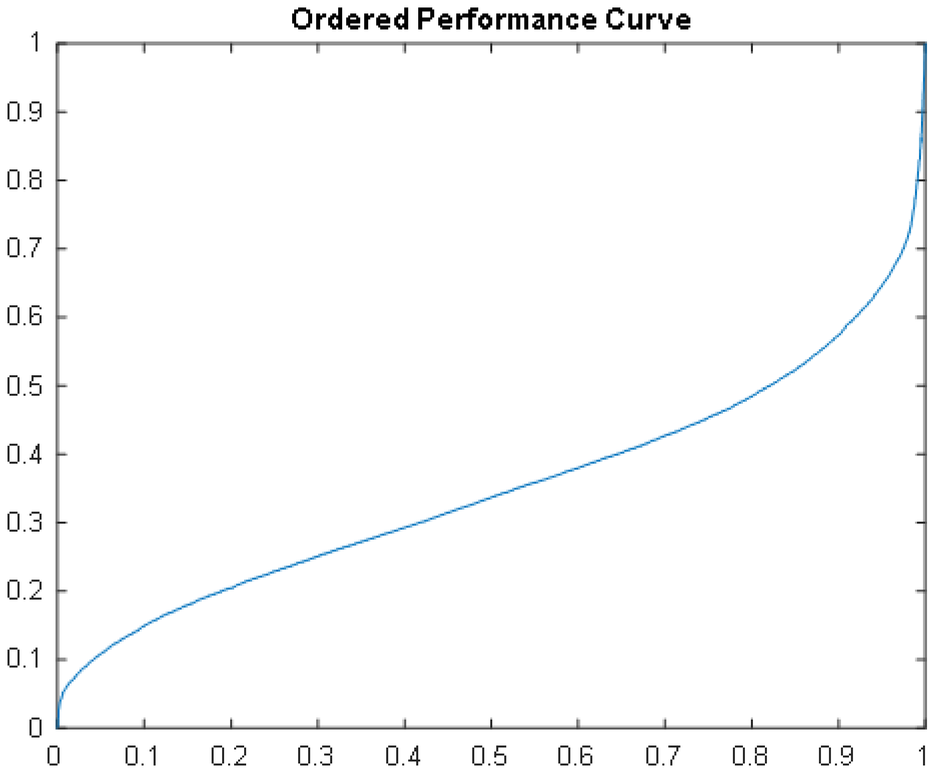

Figure 15. Ordered performance curve for 7400 runs

2. Increasing PV Losses

For the previous runs, the PV power at the AC load is assumed to be reduced by 10% due to converter and inverter losses as per equation (5). However in order to account for operating conditions (dirt, shading and aging), a derating factor of 20% is assumed; thus the total PV losses will amount to 28%:

$$P_{PV} = \eta_{DC}\eta_{AC} f_{PV} P_m = 0.95 * 0.95 * 0.8 * P_m = 0.72 * P_m \qquad (24)$$

The OO simple and accurate runs are repeated to test the effect of such reduction on the system design and cost. The results of the accurate model are given in Table 17. The best design remains unchanged with 30 MW PV, 14 MW generator and no battery but with an 11.5% increase in the LCOE of the system from 12.2 to 13.6¢/kWh.

Table 16. Design Results assuming 28% PV Losses

Run No.	PV size (MW)	Generator Size (MW)	Battery Size (MWh)	System LCOE ($/kWh)	Unmet Load (MWh)	Export to grid (MWh)	Dump Load (MWh)
11	30	14	0	0.136	212	3005	5976
4	30	15	0	0.136	104	3005	5998
5	30	14	1	0.137	200	2870	5824
2	30	15	1	0.137	97	2878	5823
14	30	16	0	0.137	66	3005	6016
9	29	14	1	0.137	201	2518	5325
3	30	14	2	0.137	191	2782	5818
12	29	15	1	0.137	97	2498	5348
1	30	15	2	0.137	93	2789	5816
13	30	13	2	0.137	344	2788	5812
6	30	14	3	0.138	183	2766	5771
8	30	15	3	0.138	89	2772	5768
10	29	14	3	0.138	184	2402	5290
7	30	15	4	0.138	85	2753	5728

CHAPTER IV

Conclusion

This thesis presented a new approach based on single step dynamic programming (SSDP) to optimize operation of a hybrid energy system and ordinal optimization (OO) to size the system sources. This work has offered a solution for the unreliable electricity of EDL that is characterized by scheduled outages throughout the year.

For a given set of source sizes, the PV power production is calculated to obtain the net load demand and the power output of the generator and EDL is discretized into levels. At every time interval, SSDP is used to determine the level of EDL and the generator and deduce the power output of the battery while satisfying the load and minimizing operation cost. At the end of the simulation, the LCOE is calculated for yearly operation. Then OO uses SSDP to evaluate the performance of a large set of sizes, through a simple and fast model, and order them based on minimum LCOE. The top-*S* solutions are evaluated using an accurate model to identify the best design.

The two methods proved to offer an efficient and fast approach to find a good enough design in a large search space as it is used to design a hybrid system for Qaraoun village; the best design consists of 30 MW PV system and 14 MW generator connected to the unreliable grid. The best design was found when removing the battery and applying a net metering policy. In addition to achieving a low LCOE of 12.2 ¢/kWh, the hybrid plant cut the production of 31,844 tons of CO_2 yearly.

For future work, further investigation could be carried to study the large scale PV penetration impact on the system's stability.

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