An-Najah National University

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MODELING OF OPERATIONAL ALGORITHMS FOR HYBRID PHOTOVOLTAIC/DIESEL GENERATOR/BATTERY SYSTEM

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Dedication

To the purest of two hearts in my life-" My dear parents"

To whom I shared good times and bad, and stood by my side--"My beloved wife"

To those who believed in me and did not spare me in giving - "My wonderful brothers and sisters"

To those who have given me all the support-"My dear husband's parents"

I dedicate this effort to you, and I pray to God that you like it

Acknowledgments

At the outset, all thanks to Allah, who bestowed upon me the grace to be able to reach this beautiful achievement. I also hope that this will be my beginning in the field of research.

It is an honor for me to be able to express my gratitude to my supervisor, Dr. Tamer, for his insightful advice and encouragement. Without his encouragement and assistance, this endeavor would not have been feasible.

I'd want to express my gratitude to the staff of the clean energy and energy conservation master program especially Dr. Mohammad Alsayed, Dr. Abdulraheem Abosafa , Dr. Imad Break, Dr. Amer Hamouz , Prof. Marwan Mahmoud Dr. Moein Omar and Dr. Moutasem Baba, I will be grateful to you as long as I live.

Declaration

I, the undersigned, declare that I submitted the thesis entitled:

MODELING OF OPERATIONAL ALGORITHMS FOR HYBRID PHOTOVOLTAIC/DIESEL GENERATOR/BATTERY SYSTEM

I declare that the work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification.

Student's Name: ______________________________

Signature: ______________________________

Date: ______________________________

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MODELING OF OPERATIONAL ALGORITHMS FOR HYBRID PHOTOVOLTAIC/DIESEL GENERATOR/BATTERY SYSTEM

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Abstract

Due to the fast increase of electrical demand and the high cost of electrical network infrastructure expansion in rural areas, a Hybrid PV/diesel generator/battery system is presented as an optimal solution because of its high reliability and low energy cost compared with other conventional energy sources. This thesis aims to obtain the optimum controlling dispatch-size strategy as per the requirements and concerns of the operating conditions, the used methodology in this thesis is to study, simulate, and summarize the main, three controlling dispatches with their operating strategies of hybrid PV/DG/Battery. While the overall optimal controlling dispatch-size strategy found in this thesis is Cycle Charge dispatch, for each requirement (reduction in PV-Battery size, reduction in a time when batteries at minimum state of charge, reduction in the diesel generator working minutes, reduction in the frequent switching between diesel and batteries, increasing sharing energy from renewable source, reduction in consumed fuel and reduction in unused excess energy percentage) an optimal controlling dispatch-size strategy can be obtained.

The summery comparison results between different strategies is as the following:

- Intuitive method simulation showed 59% of the consumed energy came from renewable parameters while 41% was generated from the diesel generator. 2800 minutes of the simulated time, batteries were at the minimum value of state of charge. 24% of the generated energy is considered as excess energy of the system and 328 Liters of fuel was consumed

- Cycle Charge simulation showed 90% of the consumed energy came from renewable parameters while only 10% was generated from the diesel generator. Only 26 minutes of the simulated time, batteries were at the minimum value of state of charge. 35% of the generated energy is considered as excess energy of the system and 156 Liters of fuel was consumed

Load Following simulation showed 73% of the consumed energy came from renewable parameters while 27% was generated from the diesel generator. 708 minutes of the simulated time, batteries were at the minimum value of state of charge. 71% of the generated energy is considered as excess energy of the system and 226 Liters of fuel was consumed.

Keywords: Hybrid System, Modeling, Diesel generator, Photo voltage, Optimum Method, Controlling dispatch, renewable Energy, Energy Storage, State of Charge.

Chapter One
Introduction

The rapid depletion of fossil resources and rising energy consumption have sparked concerns about future energy supplies [1]. Furthermore, the usage of conventional energy sources derived from fossil fuels has led to massive increases in CO2 emissions, the principal driver of global warming [2]. in [3], the author shows that 70% of emitted Green House Gasses (GHG) (includes water vapor, carbon dioxide, methane, nitrous oxide, ozone) comes from fossil fuel burning, and in order to limit the effects of CO2 emission in the form of global warming, there are two main options, either to leave the fuel in the ground or to use carbon capture storage. As a result of these concerns, researchers have identified alternative energy sources that have the potential to minimize pollution and generate a long-term energy supply [4]. The unpredictability and intermittent nature of renewable energy sources (RES) power generation is, however, a key disadvantage, such as bioenergy, direct solar energy, geothermal energy, hydropower, wind, and ocean energy [2,5].

In remote areas, where is the electrical network is hard to reach since the initial cost of network extension is high, commonly, load demand covered by using a diesel generator (DG). Even though the DG solves the reliability issue, it still makes the same issue of environmental impact, fuel needs to be transported through long transportation and the electricity cost is high [6]. These issues can be fixed by combining several energy sources to create a hybrid energy system [7].

One type of hybrid power system is a PV/diesel system; such a system has been used all around the world [8]. This system can be mainly classified into series and parallel topology [9]. In the first topology “series topology”, the battery could be charged from the generated energy from either Photovoltaic (PV) or the diesel generator, diesel generator cannot supply the load directly since it is connected in series with the inverter. Even series topology has its simple design and it is easy to perform, it suffers from the following disadvantages [10]:

- Low system components efficiency, such as batteries and inverter efficiencies, lead to low overall system efficiency and energy loss.

- Large inverter size: since all supplied energy to the load should be transmitted through the inverter.

In the second topology “parallel topology”, diesel generator, PV, and battery systems can fully or cooperative supply the load directly which leads to higher overall system efficiency, compared with series topology, parallel topology has the following advantages [10]:

- Load demand can be covered optimally
- Diesel fuel efficiency can be maximized due to higher average operating power.
- Reduction in maintenance and operation cost of the diesel generator since the operation time is reduced.
- Reduce the sizing of the system components such as PV, diesel generator, and battery system.
- System ability to feed the load peak demand.

A typical PV-diesel-battery hybrid system includes a PV array that consumes sunlight and converts it to Direct Current (DC), a diesel generator that converts the thermal heat by burning the fuel to generate Alternating Current (AC), a battery system to store surplus energy as a chemical reaction ready to resupply this energy in the times where the PV power is not capable to supply the load and to avoid the frequent turning on of the diesel generator, and other power electronic components such as DC-DC converters, AC-DC converters, ATS (automatic transfer switch), and charge-controllers.

In general, a Hybrid system such as PV/Diesel-battery system can achieve the aimed advantages from both traditional energy sources represented by the high reliability and the ability to feed the load continuously and the low electricity cost by the renewable energy sources, as well as the reduction of both disadvantages represented as the high maintenance and operational cost of fuel consumption generators and the low reliability of renewable sources.

For a Hybrid PV/Diesel-battery system, many software can design, size, and optimize systems such as HOMER, TRNSYS, While and Hybrid2 [6], HOMER software is a powerful tool that is capable to size the system parameter using numerical analysis to find the optimum value with respect to capital cost and maintenance and operational cost [5,11,12].

Finally, in this research, the main hybrid PV/Diesel/battery controlling strategies which are: intuitive method (INT) strategy, load following strategy (LF), and cycle charge strategy (CC), will be studied to model their algorithms.

1.1 Problem Statement

A complex modeling is required for such a hybrid system because of its dispachable components and the way they behave [5], optimization and simulation of hybrid PV/DG/Battery system using software will optimize the system parameter values financially without specifying the operator needs of preferred energy supply sharing between the hybrid system component (PV-Diesel-Battery) which can be affected by many variables such as fuel price, fuel transportation, fuel storage, generator maintenance, battery maintenance, battery replacement, excess energy percentages, etc [13], the simulation results cannot be shown as data to check the optimal operational strategy as the operator requirements as the main code is not shared

1.2 Objectives

In this research main four objectives that aimed to be fulfilled as below:

1.2.1 To model Cycle Charge dispatch strategy.

1.2.2 To model Load Following dispatch strategy.

1.2.3 To model Intuitive Method dispatch strategy.

1.2.4 To conduct a comparison between these three dispatch strategy.

1.3 Research Methodology

WP.1 Literature Review

T 1.1 literature review on hybrid PV/Diesel system concept and components.

T 1. literature review on hybrid PV/Diesel system sizing methods.

T 1.3 literature review on hybrid PV/Diesel system operation strategy.

T 1.4 literature review on diesel generator consumption models.

T 1.5 Solar radiation data collection for Palestine.

WP.2 Measure a real load in Palestine

WP.3 Design of the hybrid PV/diesel/battery system sizes using the main three methods

T 3.1 Load Following sizing method.

T 3.2 Cycle charge sizing method.

T 3.2 Intuitive sizing method.

WP.4 Validation of the designed sizes using HOMER

T 4.1 Validate Load Following size based strategy using HOMER.

T 4.2 Validate Cycle Charge size based strategy using HOMER

WP.5 Generate simulation codes

T 5.1 Create Matlab code to simulate Load Following Strategy.

T 5.1 Create Matlab code to simulate Cycle Charge Strategy.

T 5.1 Create Excel sheet to simulate Intuitive Method Strategy.

WP.6 Simulate Hybrid PV/Diesel/Battery system

T 6.1 to simulate the proposed Load considering load flowing strategy with the different sizes.

T 6.2 to simulate the proposed Load considering cycle charge strategy with the different sizes.

T 6.3 to simulate the proposed Load considering intuitive method strategy with the different sizes.

WP. 7 Performance comparisons between the main strategies and sizes

T 7.1 to conduct a comparison between these strategies with the different sizes.

T 7.2 to conduct an overall comparison between these strategies.

Chapter Two
Literature Review

2.1 Hybrid PV/DG/Battery System Concept

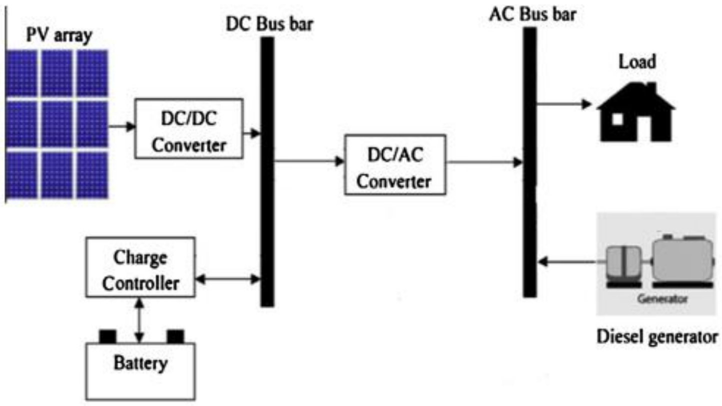
In a comparison between traditional diesel generator (diesel_only) that used to be the favored solution for electrical energy supply, due to the low price, in remote areas where grid infrastructure cannot be extended, and the cooperation between renewable energy, diesel generator and battery system (Hybrid PV/DG/Battery system), the following advantages can be provided [14]:

- Reduce environmental impact
- Reduce maintenance and operational cost
- Increase system reliability
- Reduce energy cost

The concept of the hybrid system is to share supplying the load demand between different sources (renewable PV and at least one diesel generator) with the support of a storage battery system [16], as shown in Fig.1, parallel configuration of such hybrid system can be divided into two main sides, An Alternating Current bus-bar (AC-Bus) that is connected with a both diesel generator and the load, and Direct Current bus-bar (DC-Bus) that is connected with both PV modules and Battery system. Both AC-Bus and DC-Bus are coupled with either a single or bi-directional inverter [16].

Fig.1

Hybrid PV/DG/Battery system component



2.2 Hybrid PV/DG/Battery System Components

As mentioned previously, a Hybrid PV/DG/Battery system is consisting of two Bus-bars, with some connected components of each bus-bar depending on the current type, either alternating or direct current (AC or DC), these components are as the following:

2.2.1 PV Modules

A PhotoVoltaic system is considered as the most elegant strategy to generate electrical energy just from converting the ample sunlight into electricity in the form of Direct Current without the need for any mechanical movements or emission impact or noise [16].

The output energy of the PV modules can be affected by many variables such as Solar Radiation (diffused and direct SR), Ambient Temperature (Ta), Humidity, Dust, Shade, Wind velocity, and Wind direction. The most effective variables of PV modules output energy are Global Solar Radiation(G) and the Ambient Temperature(Ta) [17].

The modeling of generated energy of the PV system by the time [w/min] with both variables G & Ta, the following modeling is needed to be considered [18]:

$$P_{pv}(t) = P_{peak} * \left[\left(\frac{G(t)}{G_{standard}} \right) - \alpha_T [T_c(t) - T_{standard}] \right] * \eta_{wire} \qquad (1)$$

Where $G_{standard}$ is the standard testing condition solar radiation [1000W/m^2], $T_{standard}$ is the standard testing condition temperature [25 C^0],

α_T is PV module output power temperature coefficient [-0.370% / C^0],

μ_{wire} is the efficiency of the wires.

T_C is the cell temperature which can be calculated from the following equation [19]:

$$T_C(t) = Ta(t) + \frac{NOCT-20}{800} G(t) \qquad (2)$$

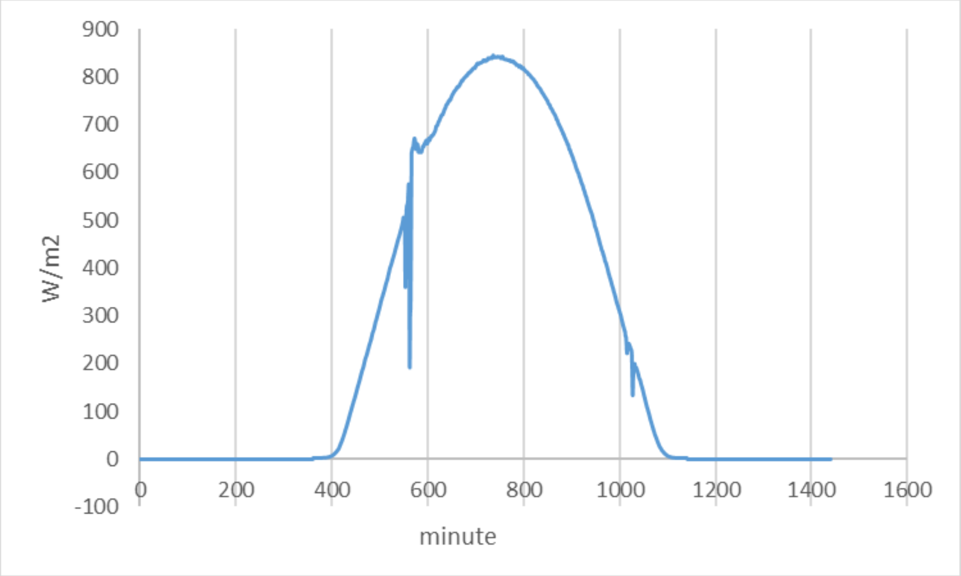
Where NOCT is the nominal operating temperature of the PV module which can be measured when the PV module is under 800 W/m^2 solar radiation and 20C^0 ambient temperature.

Ta is the actual ambient temperature at a time when T_C is calculated.

Solar radiation data in the form of W/m^2* Minuit has been collected [Fig.2] for 12 days to represent the 12 months of the year to simulate the generated energy of the PV system in the Hybrid PV/DG/Battery system.

Fig.2

Solar Radiation profile for a day in Qalqilya [W/m2]



2.2.2 Battery System

The battery has been used as an energy storage source in the hybrid system to alternate the output power of PV modules and the diesel generator and to adjust any surplus or deficit of generated energy. The battery bank will start to charge when the total output power of the solar modules and the diesel generator exceeds the specified load capacity [19].

Batteries could be charged from either the generated energy from the PV system or the diesel generator or both as per the operation strategy and the inverter type [20].

The equivalent circuit of the battery is represented in Fig.3 where V_{OC} and R_O are the battery internal voltage and the battery internal resistance respectively, the magnitude and direction of the battery current i(t) majorly depend on the system voltage V_{batt} if the voltage is greater than the internal voltage it means that the battery current i(t) is entering the battery as a charging current. On the other hand, if the voltage is smaller than the internal battery voltage, the current will flow from the battery to the system and discharge the battery energy [21-22].

The percentage of stored energy in the battery to the battery capacity is called State of Charge (SOC) and the available energy percentage to be stored is called Depth of Discharge (DOD).

$$SOC = 1 - \frac{Q}{C}, \quad 0 \leq SOC \leq 1 \tag{3}$$

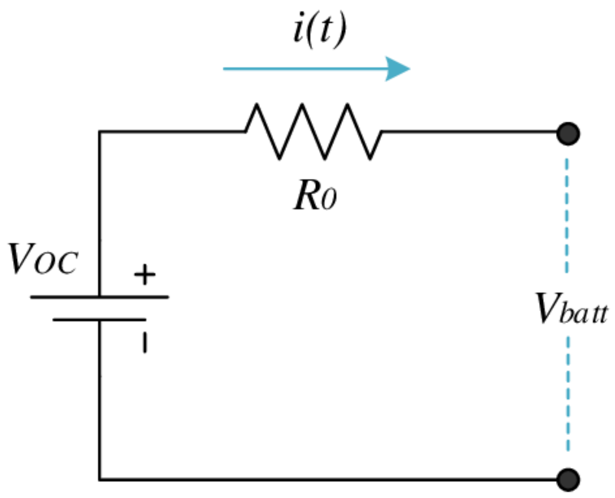
$$DOD = 1 - SOC \tag{4}$$

Where Q is the battery charge.

C is the capacity of the battery.

Fig.3

Battery equivalent circuit (Rint Model)



To understand the modeling of charging and discharging of the battery, it is required to check each by its assumption and equations [21-22].

2.2.2.1 Charging Mode

When the applied voltage is greater than the internal voltage, the current will flow toward the battery to charge it, in this case, V_{OC} and R_O will be called V_{ch} and R_{ch}, then V_{ch} and R_{ch} is given as the following [23]:

$$V_{ch} = (2+0.148\ \beta)*\ Ns \tag{5}$$

$$\beta = \frac{SOCinitial}{SOCmax} \tag{6}$$

where Ns is the number of cells in the battery 2V voltage.

SOCinitial is the initial state of charge before charging.

SOCmax is the maximum state of charge of the battery.

$$R_{ch}=\left[\frac{0.758+\frac{0.1309}{1.06-\beta}}{SOCmax}\right]Ns \tag{7}$$

From the equivalent circuit in Fig.3, it can be shown that

$$V_{batt} = V_{ch} + I_{ch} * R_{ch} \tag{8}$$

Then the equation can be used to calculate the SOC of the battery

$$SOC(t+dt) = SOC(t)\left[1-\frac{D}{3600}\,dt\right]+ K[V_{bat}\, I_{bat} - R_{ch}\, I^2{}_{bat}]dt \tag{9}$$

In which K is the efficiency of charging the battery, D is the rate of battery discharging.

2.2.2.2 Discharging Mode

When the applied voltage is smaller than the internal voltage, the current will flow from the battery to the system and discharge the battery, in this case, V_{OC} and R_O will be called V_{disch} and R_{disch}, then V_{disch} and R_{disch} is given as the following [23]:

$$V_{disch} = (1.926+0.124\,\beta)* Ns \tag{10}$$

$$R_{disch}=\left[\frac{0.19+\frac{0.1037}{\beta-0.14}}{SOCmax}\right]Ns \tag{11}$$

$$V_{batt} = V_{disch} + I_{disch} * R_{disch} \tag{12}$$

2.2.3 Inverter

As shown in Fig.1 the parallel configuration of the hybrid system consists of two different bus-bars, one is AC bus-bar and one is DC bus-bar [16]. In order to couple these bus-bars with each other to allow power flow between the DC and AC system, an DC to AC converter is required which is named an inverter.

As [24], authors point to that the concept of DC/AC converter is continuous-switching to the DC source either from PV modules or from battery banks in a sinusoidal form with controlled AC electrical parameters to meet the requirements of the load [24].

There are two types of inverters that could couple the two bus-bars, either single direction DC to AC converter or bi-directional DC/AC converter, these types are selected upon the controlling dispatch, the single directional inverter means that the energy flow only from the DC side to AC side, in other words, charging batteries could only be occurred from the PV arrays while inverter cannot share the excess energy with the batteries. On the Bi-directional inverter, energy can flow from any side to another, batteries can be charged from either PV or DG, the size of the required inverter is affected by the maximum amount of power that should be transferred and converter, which means the required size of each type is different from others [23-27].

The efficiency of the inverter is represented as the ratio of the output AC power to the input DC power as shown in Fig.4 [23].

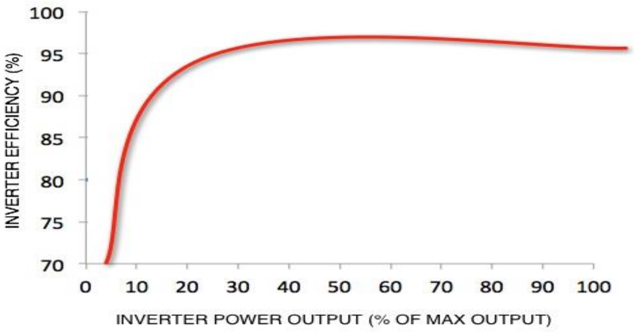
$$\eta_{INV} = \frac{Pout}{Pin} \qquad (13)$$

While the voltage Total Harmonic Distortion (THD) is defined as the following equation [23]:

$$\mathrm{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \qquad (14)$$

Fig.4

Inverter Efficiency curve



2.2.4 Diesel Generator

Diesel Generator (DG) is the main AC source that can supply the load directly without transferring its power through the inverter since it is connected to the same AC bus with the load, DG has been used in hybrid PV/DG/battery as a backup power source in a case when the generated power from the PV or battery cannot meet the demanded power of the load [19].

A Diesel generator can either be set to work at its rated power whenever the need to supply the load which may cause excess energy, or to meet the load demand required power with no output excess energy which may lead to a reduction in the DG efficiency (wet staking) due to low fuel temperature and reduction in the generator lifetime [14].

The consumption of fuel in the diesel generator [L/kWh] changed as per the output generated energy to the rated energy of the generator, the formula of the fuel consumption can be modeled as the following formula [14,19,28]:

$$CF_{DG} = A_{DG} * P_{DGO} + B_{DG} * P_{DGR} \qquad (15)$$

Where CF_{DG} is the consumed fuel of the generator (L/kWh)

A_{DG} is the fuel consumption officiant for rated energy (A_{DG} = 0.246L/kWh)

B_{DG} is the fuel consumption officiant for output (B_{DG} = 0.08145 L/kWh)

P_{DGO} is the output power of the DG.

P_{DGR} is the rated power of the DG.

2.2.5 Load Demand

The main goal of electrical systems (grid-connected, standalone RE, single DG, and Hybrid system) is to feed the load demand, load demand converts the electrical supplied energy to another form of energy such as mechanical, thermal, chemical, and radiant energy [29-31].

Loads can be defined with different parameters to be categorized as the following [29-31]:

- Consumer type (residential, commercial, industrial).
- Time of demand (continuous, single period, multi-period, fluctuating).
- The Shape of demand (flat, step load, single peak, double peak).

Each type of load demand can be studied and simulated to give different optimum strategies & sizes to be chosen for a hybrid PV/DG/battery system.

In this research, load demand has been chosen to be industrial, continuous, and single peak shape.

2.2.6 Dumping Load

As author [20] mentioned, in cases where the PV modules or DG (when the controlling strategy allow the DG to charge the batteries) generates energy that is more than the required demand energy of the load, and the SOC of the batteries are 100%, excess energy cannot overcharge the batteries and this surplus energy should be consumed elsewhere. A dumping load is considered a thermal load that can consume any excess generated energy and convert it into heat. This excess energy consumption will ensure the stability of the system [32,33].

2.3 Real Load

In this research, in order to get a real result that can lead to applicable recommendation and optimization of such hybrid PV/DG/battery system, a real load has been taken from an industrial consumer (dairy products manufacturing) that consume electrical energy continuously and the load profile of the load is about to be constant over different seasons and weekdays and weekend, the factory consumes electrical energy in pasteurization, storing, heating, cooling, lighting, and packing, load profile of the load has been measured in minutes for a full day.

Fig.5 shows the daily load demand curve of the real load for 24 hours / 1440 min, the load consumes total energy of 2566 kW/minute.

The load demand can be divided into three categories [34-36]:

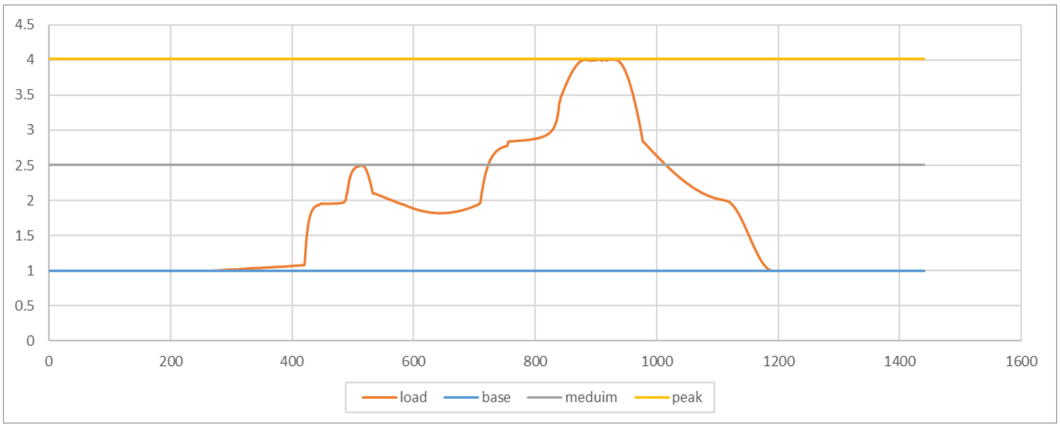
1- Baseload: which is the minimum consumed energy with a value of the load power that is being demanded continuously for 24 hours (base power =1kW).

2- peak load: the value of demanded energy that the load will request for a short interval of time during the day with the maximum power for all-day (peak power =4.01 kW).

3- medium load: the value where the load consumes energy in a power range that is greater than the base and less than the peak where the demanded time is a long period of time (1kW< medium power < 2.5kW).

Fig.5

daily load curve of the real load



After studying the real load curve and components, table 1 summarizes the load demand parameters.

Table 1

load demand parameters.

	Energy [kWh]	Power (kW)
Baseload	7.133333333	≥1kW
Medium load	19.91666667	> 1kW, ≤2.5kW
Peak load	15.71880144	>2.5kW, ≤ 4.01kW

The maximum energy consumption of the real load falls in the medium load part since its power value is greater than the base value and the period time is longer than the peak load, total energy consumption is 42.8 kWh in 1440 minutes per day with a minimum power value of 1kW and peak power value of 4.01 kW, this behavior is due to many factors, the storage system, in the night where there is no manufacturing required, the storage system work at its standby value to keep the storage temperature fixed to ensure than the raw materials will keep safe from getting mold. after working hours starts, the storage system will keep opening and closing which fluctuates the temperature and the storage system will keep following the temperature by starting and standby the refrigerant, after some time, the industrial electrical devices will start consuming the electrical power which varies the load curve as shown in Fig.5.

2.4 Operational Methods of Hybrid PV/DG/Battery System

In controlling Hybrid PV/DG/battery system after sizing its parameters, the two main controlling dispatches are either Load Following dispatch (LF) or Cycle Charge dispatch (CC) [37,38], Load following dispatch strategy tend to be optimal in the location where the renewable energy sources are rich, usable and reliable [38] which is effects the renewable to total size fraction of load-following strategy, while Cycle Charge dispatch strategy tend to be optimal in the location where the renewable energy sources are poor, unusable, unavailable or unreliable [38] which is effects the renewable to total system size fraction of Cycle Charge strategy.

Additionally, the intuitive method is considered an inaccurate method to size and control such a system which may lead to the high cost or low reliability since the interaction between system components is not taken into account, even the method has been driven by experiences [39].

Before simulating the different sizes, operational and controlling methodologies priority, power-sharing, and relations between components should be taken into account.

2.4.1 Load Following Dispatch Strategy

Fig.6 shows the logical chart of Load Following dispatch controlling strategy modeling.

Modeling starts by importing solar data in minutes for both solar radiation (SR) and ambient temperature (Ta) of the proposed location and the real load demand curve in minutes.

The next step is a calculation of the generated energy from PV for all input data is required.

Basically, the strategy can be divided into three main cases after a comparison between the generated power of the PV modules (P_{PV}) and the load demand P_L [37].

$$P_{NET}=P_{PV} - P_L \qquad (16)$$

The first case is when the net value is equal to zero means that generated energy from PV modules is equal to the load demand (P_{NET}=0), the generated energy will directly supply the load by the required energy, neither diesel generator power is needed nor discharge current from the batteries, moreover, as well as there is no surplus energy is available to either charge the batteries or to be dumped as excess energy or deficit energy in this case [40,41].

The second case is when the difference between the generated energy from the PV modules and the load demand is positive (P_{NET}= +ve) or in other words, the generated energy from PV modules exceeds the required energy from the load (P_{PV}>P_L), the required load demand will be covered from the generated energy of the PV modules and an amount of excess energy appears [37]. On the first hand, if the battery system is full and its state of charge is 100% (SOC= SOC_{MAX} = 1), excess energy will be damped in dumping load and to be considered in the excess energy matrix, neither energy is needed from the diesel generator nor energy needed from batteries nor deficit energy is considered. On the second hand, if the battery system state of charge is less than the maximum state of charge (SOC<SOC_{MAX}), the excess energy will be directed toward the batteries as a charging current to raise its state of charge, the new SOC needed to be calculated for the next comparison step, still no energy is needed from the diesel generator and no deficit energy is considered.

The third and final case is when the difference between the generated energy from the PV modules and the load demand is negative (P_{NET}= -ve) or the generated energy from PV modules is less than the demanded energy from the load (P_{PV}<P_L), in this case, there are two subcases,

- The first subcase is when the battery system is having stored energy which means either it was not used before (SOC = SOC_{MAX}) if the system started with fully charge batteries or the battery state of charge is greater than the minimum state of charge ($SOC > SOC_{MIN}$) [51], then the demanded energy by the load will be covered by shared energy between the generated energy of PV modules and the stored energy in the batteries.

hence, the system requires a calculation of a new state of charge is required while no energy is needed to be drawn by the diesel generator and there is no deficit energy.

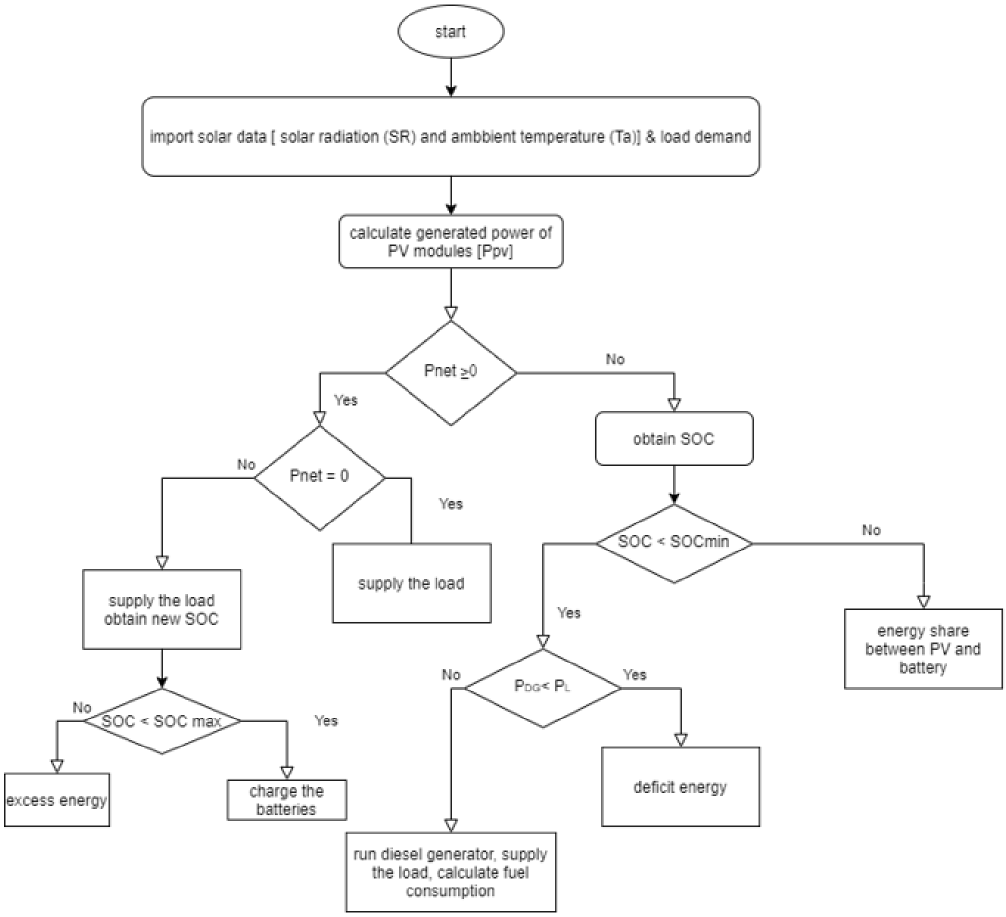
- The second subcase is when the battery is empty, which means the state of charge of the battery system is less or equal to the minimum state of charge ($SOC \leq SOC_{MIN}$), in this subcase, the energy demand by the load should be fully supplied by a drawn current from the diesel generator, and here there are two scenarios,

  1- The first scenario is when the diesel generator is capable to supply the load, it means that the maximum peak of the DG is greater or equal to the load peak at that time ($P_{DG} \geq P_{LOAD}$), the diesel generator will start and supply only enough power to that required by the load demand [49]. Moreover, if there is any generated energy by the PV modules, this energy will be transferred to the batteries to charge them and to calculate the new state of charge of the battery system after charging, otherwise, this energy will be considered as excess energy to be damped at the dumping load if the state of charge either at its maximum value or its reach its maximum value. Fuel consumption should be calculated and no deficit energy is considered.

  2- The second scenario is when the diesel generator maximum peak value is less than the load peak at that time ($P_{DG} < P_{LOAD}$), in this scenario, neither the diesel generator nor the shared energy of PV and battery system can supply the load demand, the load demand energy will be considered as deficit energy of the system.

Fig.6

algorithm of Load Following dispatch controlling strategy modeling



2.4.2 Cycle Charge Dispatch Strategy

Fig.7 shows the logical chart of Cycle Charge dispatch controlling strategy modeling.

Modeling as the same as Load Following strategy modeling starts by importing solar radiation (SR), ambient temperature (Ta), and load demand data in minutes.

Then, a calculation of the generated energy from PV for all input data is required.

The first two cases of modeling Cycle Charge dispatch are the same as the first two cases in the Load following [42,43],

The first case is whenever the generated energy by PV modules is equal to the required energy by the load, PV energy will directly supply the load with no drawn power from the DG or charging/discharging of the battery system [42].

The second case is when the net generated energy from PV modules is larger than the demanded energy by the load, the PV will supply the load and the surplus energy will be directed to either the batteries if its state of charge is less than the maximum state of charge [49], or will be dumped in the dumping load if the battery state of charge reaches its maximum value of 100%.

The third and final case is when the difference between the generated energy from the PV modules and the load demand is negative (P_{NET}= -ve) or the generated energy from PV modules is less than the demanded energy from the load (P_{PV}<P_L), in this case, there are two subcases [43],

- The first subcase is when the battery system is having stored energy which means either it was not used before ($SOC = SOC_{MAX}$) if the system started with fully charge batteries or the battery state of charge is greater than the minimum state of charge ($SOC > SOC_{MIN}$) [40], then the demanded energy by the load will be covered by shared energy between the generated energy by PV modules and stored energy in the batteries [38], hence, a calculation of the new state of charge is required while no energy is needed from the diesel generator and there is no deficit energy.

- The second subcase is when the battery is empty, which means the state of charge of the battery system is less or equal to the minimum SOC ($SOC \leq SOC_{MIN}$), in this subcase, the energy demand should be fully supplied from the diesel generator [42], and here there are three scenarios,

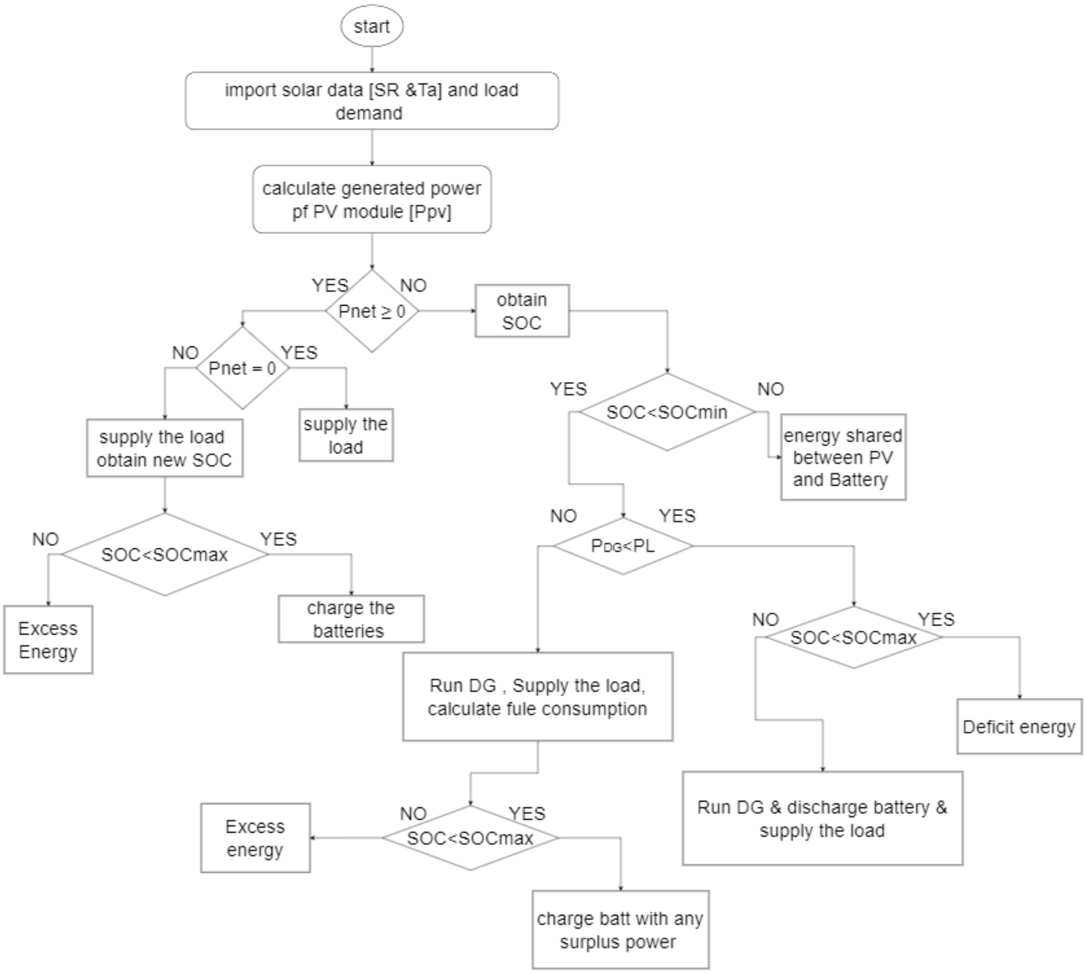
  1- The first scenario is when the diesel generator is capable to supply the load, it means that the maximum peak of the DG is greater or equal to the load peak at that time ($P_{DG} \geq P_{LOAD}$), the diesel generator will start generating at its rated power to supply the required energy by the load demand [38]. The surplus energy of the DG be transferred to the batteries to charge them if the SOC is less than the maximum SOC, then, calculate the new state of charge of the battery system after charging, otherwise, this surplus energy will be considered as excess energy and to be damped at the dumping load [42]. Fuel consumption should be calculated and no deficit energy is considered.

2- The second scenario is when the diesel generator maximum peak value is less than the load peak at that time ($P_{DG} < P_{LOAD}$) and the battery system is fully charged or greater than the minimum state of charge, in this scenario, both diesel generator and battery system will contribute to supply the load by its required energy.

3- The third scenario is when DG maximum peak value is less than the load peak at that time ($P_{DG} < P_{LOAD}$) and battery system SOC is less or equal to the minimum SOC, neither the diesel generator nor the shared energy of PV and battery system nor shared energy of DG and battery system can supply the load demand, the load demand energy will be considered as deficit energy of the system [40].

Fig.7

algorithm of Cycle Charge dispatch controlling strategy modeling



2.4.3 Intuitive Method Strategy

Fig.8 shows the logical chart of intuitive controlling strategy modeling.

Modeling starts by calculating the generated energy from PV modules with the help of solar data in minutes for both solar radiation (SR) and ambient temperature (Ta).

The strategy can be divided into two main cases after comparing with the load demand power PL with the references peak value (peak) [44].

The first case is when the load is consuming energy at the peak ($P_L \geq P_{PEAK}$). On the first hand, if diesel generator rated power is less than the required power of the load, diesel generator could not supply the load and the load demand will be taken as deficit energy. On the other hand, if the diesel generator rated power is equal to or greater than the required power of the load, the diesel generator will run at its full rated power to supply the load, the surplus energy will be directed to the battery as a charging current to raise its state of charge until it is maxed ($SOC=SOC_{MAX}$) [37], then the surplus energy will be damped at the dumping load and fuel consumption will be calculated.

The second case is when the load is requesting power that is less than the peak value, in this case, two subcases are needed.

- The first subcase is when the power drawn by the PV modules is greater than or equal to the required by the load ($P_{PV} \geq P_L$), PV will directly supply the load with its generated energy and no energy is needed from the DG, the surplus power if appear will charge the battery system if its state of charge is less than the maximum state of charge ($SOC<SOC_{MAX}$) otherwise will be considered as excess energy [37].

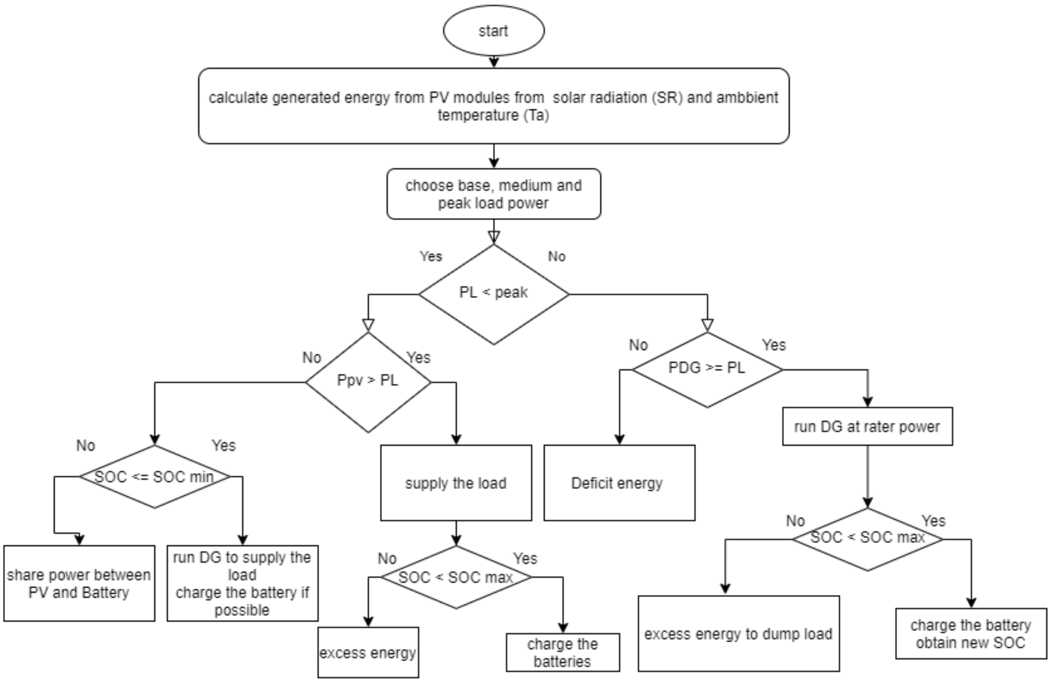
- The second subcase is when the generated power of the PV modules is less than the required power for the load demand, in this subcase, there are two scenarios.

    1. In the first scenario, if the batteries are at a state of charge that is greater than the minimum state of charge ($SOC > SOC_{min}$), load demand will be supplied by a shared power between PV modules generated energy and discharging energy from the battery system, a new state of charge will be calculated, no diesel generator supply is required, no deficit energy and no excess energy in this scenario.

2. The second scenario is when the state of charge of the battery is equal to or less than the minimum state of charge ($SOC \leq SOC_{MIN}$), then, the generator will run at its full power, since it already checked that the rated power of the diesel generator is greater than the required energy of the load demand at this time, and supply the load, while the excess power of the diesel generator will be a charging current of the batteries [37], a new state of charge will be calculated, no deficit energy and no excess energy unless the batteries reach their maximum state of charge, the fuel consumption will be calculated in this scenario.

Fig.8

Logical chart of Intuitive controlling modeling



Chapter Three

Hybrid PV/DG/Battery Sizing strategies

After reviewing researches [45-52], sizing the main components of hybrid PV/DG/battery system which are PV modules, Diesel generator size, and battery capacity for the initial point can be assumed differently depending on the controlling strategies of the system, basically, these system components will be sized as the load demand parameters (base, medium, and peak) to be into two parts: first, battery capacity and PV modules, secondly, diesel generator, as the following.

3.1 Strategies Sizing

3.1.1 Hybrid PV/DG/Battery Sizing Using Intuitive Method Strategy

To design a hybrid PV/DG/battery using the intuitive method, the battery has to be designed first, battery capacity should supply the stored energy for the base and medium energy value of load demand for the number of nominal days assumed no source could charge the batteries in these days.

Secondly, PV modules should be calculated in order that the generated energy of the maximum solar radiation of the year should supply the battery to charge it from zero to full charge.

Finally, the diesel generator will supply the load in the peak demand and the rated power of the generator should exceed the maximum power of the load and no loss of load will be occurring.

3.1.2 Hybrid PV/DG/Battery Sizing Using Load Following Strategy (LF)

At designing the system in the load following strategy, the battery has to be designed first. Firstly, battery capacity should supply the stored energy for double the base demand and medium demand for the number of nominal days since PV is the only source to charge the batteries.

Secondly, PV modules should be calculated in order to charge the batteries fully from empty to fully charged in one day, assuming this is the maximum solar radiation day of the year.

Finally, diesel generator full rated power should be selected to ensure that no-load power will be requested above this value.

3.1.3 Hybrid PV/DG/Battery Sizing Using Cycle Charge Strategy (CC).

Sizing of hybrid PV/DG/battery using Cycle Charge strategy, the battery has to be sized first then the PV modules in parallel with the diesel generator as the following:

Battery capacity should be able to supply the stored energy for only the medium demand energy of load demand for a number of nominal days since the capability of the DG to supply the excess energy to the batteries in case no solar radiation and no output are generated energy of PV modules.

PV modules should be sized so that the generated energy of the maximum day solar radiation of the year will be transferred to the battery to charge it from zero states of charge of the battery to fully charge it.

The diesel generator will supply the load in the case where no other source is capable to cover the demand energy or power to the load, the rated power of DG should cover the maximum peak demand of the load.

3.2 Hybrid PV/DG/Battery Types of Selected Parameters

In order to size and calculate the hybrid PV/DG/battery system parameters, the following PV and battery types have been selected:

PV modules as shown in Fig.9-10 (Canadian solar max power cs6u-340m).

Fig.9

Data Sheet for selected PV module

Fig.10

Data Sheet Information for selected PV module

ELECTRICAL DATA / STC*

CS6U	330M	335M	340M	345M
Nominal Max. Power (Pmax)	330 W	335 W	340 W	345 W
Opt. Operating Voltage (Vmp)	37.5 V	37.8 V	37.9 V	38.1 V
Opt. Operating Current (Imp)	8.80 A	8.87 A	8.97 A	9.06 A
Open Circuit Voltage (Voc)	45.9 V	46.1 V	46.2 V	46.4 V
Short Circuit Current (Isc)	9.31 A	9.41 A	9.48 A	9.56 A
Module Efficiency	16.97%	17.23%	17.49%	17.74%
Operating Temperature	-40°C ~ +85°C			
Max. System Voltage	1000 V (IEC) or 1000 V (UL)			
Module Fire Performance	TYPE 1 (UL 1703) or CLASS C (IEC 61730)			
Max. Series Fuse Rating	15 A			
Application Classification	Class A			
Power Tolerance	0 ~ + 5 W			

* Under Standard Test Conditions (STC) of irradiance of 1000 W/m², spectrum AM 1.5 and cell temperature of 25°C

MECHANICAL DATA

Specification	Data
Cell Type	Mono-crystalline, 6 inch
Cell Arrangement	72 (6 x 12)
Dimensions	1960 x 992 x 40 mm (77.2 x 39.1 x 1.57 in)
Weight	22.4 kg (49.4 lbs)
Front Cover	3.2 mm tempered glass
Frame Material	Anodized aluminium alloy
J-Box	IP67, 3 diodes
Cable	4 mm² (IEC) or 4 mm² & 12 AWG 1000V (UL), 1160 mm (45.7 in)
Connector	T4 (IEC/UL)
Per Pallet	26 pieces, 635 kg (1400 lbs)
Per Container (40' HQ)	624 pieces

ELECTRICAL DATA / NOCT*

CS6U	330M	335M	340M	345M
Nominal Max. Power (Pmax)	238 W	242 W	245 W	249 W
Opt. Operating Voltage (Vmp)	34.2 V	34.5 V	34.6 V	34.7 V
Opt. Operating Current (Imp)	6.96 A	7.01 A	7.10 A	7.17 A
Open Circuit Voltage (Voc)	42.1 V	42.3 V	42.4 V	42.6 V
Short Circuit Current (Isc)	7.54 A	7.62 A	7.67 A	7.74 A

* Under Nominal Operating Cell Temperature (NOCT), irradiance of 800 W/m², spectrum AM 1.5, ambient temperature 20°C, wind speed 1 m/s.

TEMPERATURE CHARACTERISTICS

Specification	Data
Temp. Coefficient (Pmax)	-0.41 % / °C
Temp. Coefficient (Voc)	-0.31 % / °C
Temp. Coefficient (Isc)	0.053 % / °C
Nominal Operating Cell Temperature	45±2 °C

PV module has a maximum generated power of 340 Wp per module with an efficiency of 17.74 at standard testing condition

The selected battery is (Enersys Powersafe tvs5) Lead-Acid battery with 1.02 kWh nominal storage, 2V DV voltage, and 20% minimum state of charge.

3.3 Hybrid PV/DG/battery Sizing Calculation

from the above review of different sizing methodologies of hybrid PV/DG/battery system components and the real load data and parameters, three sizes are calculated in this research.

3.3.1 Intuitive Method Calculation

The first sizing calculation is the intuitive method sizing of the real load

- Battery capacity sizing:

$$\text{battery capacity} = (\text{base energy} + \text{medium energy}) \times \text{Nd} \qquad (17)$$

$$\text{number of batteries} = \frac{batteries\ capacity}{stored\ energy\ for\ one\ battery} \qquad (18)$$

where Nd is the number of nominal days (Nd=2)

- PV module sizing:

$$\text{PV kWp} = \frac{number\ of\ batteries * capacity\ of\ the\ battery}{maximum\ day\ solar\ radiation} \qquad (19)$$

Where PV kWp is the peak kilowatt peak of the PV modules

Maximum solar radiation of the proposed load that is in Qalqilya city = 7.7 kWh/m^2/day as per HOMER Global Horizontal Irradiance (GHI) in Fig.11 (Appendix-C page 74)

- Diesel generator sizing:

As mentioned in the sizing strategy, DG rater power should be greater than the maximum power that the load will request at any time of the load curve, Hence the selected rated power of the DG = 4.5 kW

3.3.2 Load Following Calculation

$$\text{battery capacity} = (2\text{xbase energy} + \text{medium energy}) \times Nd \tag{20}$$

- Diesel generator sizing:

As mentioned in the sizing strategy, DG rater power should be greater than the maximum power that the load will request (4.01kW) at any time of the load curve, Hence the selected rated power of the DG = 4.5 kW

3.3.3 Cycle Charge Calculation

$$\text{battery capacity} = (\text{medium energy}) \times Nd \tag{21}$$

- Diesel generator sizing:

As mentioned in the sizing strategy, DG rater power should be greater than the maximum power that the load will request (4.01kW) at any time of the load curve, Hence the selected rated power of the DG = 4.5 kW.

3.4 HOMER Software

To simulate and size such a hybrid system, there are many computer software that is considered powerful tools to do so such as HYBRID, RETScree, TRNSYS, iHOGA, SAM, PVsyst, and HOMER [11], where HOMER is considered one of the best optimization tools, that is widely used for electrical supplying systems where renewable and non-renewable sources are used [53].

HOMER is a powerful micro-power design tool created by the National Renewable Energy Laboratory in the United States in 1992. HOMER simulates and optimizes stand-alone and grid-connected power systems with any combination of wind turbines, photovoltaic arrays, hydropower, biomass, Generators, fuel cell, battery system, and hydrogen storage, serving both electric and thermal loads. All costs (including any pollution) are also included [11,53-55].

In order to size and simulate these systems and estimate the output power from renewable resources, HOMER imports the necessary database of solar radiation, clearness factor, wind energy, average temperature, and other factors from NASA surface meteorology and solar energy database as per the considered site coordination [53].

HOMER simulates a variety of system topologies before deciding on the best one with the lowest total Net Present Cost (NPC) and Cost of Energy (COE) [11,53].

Since the economic part is playing an important role in the simulation process of HOMER software, it is important to mention that renewable and non-renewable sources are different in the characteristic of cash flow components. In general, renewable energy sources have a high capital cost comparing the low Maintenance and Operational Cost of M&O, while non-renewable energy sources are having a low capital cost comparison with the high maintenance and operational cost. So that the life cycle of the energy resources and storage systems should be taken into consideration with all other system parameters such as capital cost, maintenance cost, operational cost, replacement cost, salvage value and any constrain that effects analysis of NPC and M&O for Homer to achieve the optimum economical size for different controlling strategies after comparing large system sizes and configurations and a varying amount of conventional and renewable energy sources [55].

Chapter Four
Simulation, Results, and Discussion of Hybrid PV/DG/Battery Systems

4.1 Hybrid PV/DG/Battery Sizing Results

The resulted hybrid PV/DG/battery parameter sizes from the calculation equations (17-21) are as the following:

4.1.1 Intuitive Method Size Results

Referring to equations number (17) and (18), 53 batteries are needed with a total capacity of 54.1 kWh

The required PV as per equation (19) is 7.02 kWp

Diesel generator required power is 4.5 kW

4.1.2 Load Following Size Results

Referring to equations number (20) and (18), 67 batteries are needed with a total capacity of 68.36 kWh

The required PV as per equation (19) is 8.86 kWp

Diesel generator required power is 4.5 kW

4.1.3 Cycle Charge Size Results

Referring to equations number (21) and (18), 39 batteries are needed with a total capacity of 39.83 kWh

The required PV as per equation (19) is 5.16 kWp

Diesel generator required power is 4.5 kW

4.2 HOMER Sizes Results and Comparison with Calculated Sizes

In order to ensure the proposed load hybrid PV/DG/battery system sizes, HOMER software has been used since the main dispatch strategies used in HOMER are Load Following strategy and Cycle Charge strategy [52] which are the same dispatch strategy of this research.

Fig.12 (Appendix-C page 74) shows the components as a schematic diagram of the hybrid system with both DC and AC bus-bars coupled by DC/AC inverter as the parallel configuration, with the connected diesel generator and load demand on the AC bus-bar while PV modules and battery system is connected to the DC bus-bar.

Fig.13 (Appendix-C page 75) is the map and coordination with latitude and longitude of the real load location (Qalqiliya $23^{0}11.1^{'}$N, $34^{0}59.8^{'}$E), so that HOMER imports the solar, wind, temperature databases for the selected location as Fig.14-16, while Fig.17 shows the daily load curve of the load demand. (Appendix-C page 75-76)

After simulating the system with both Load Following and Cycle Charge controlling strategies, the results as shown in Fig.18-19 (Appendix-C page 77) are summarized in table.2.

Table 2

HOMER simulation results for LF & CC strategies

	HOMER results		
size based strategy	PV [kWp]	DG [kW]	Number of batteries
SLF	8.86	4.5	67
SCC	5.9	4.5	36

While Table.3 compare hybrid PV/DG/battery system sizes between the calculation and the simulated results

Table 3

sizing comparison between calculation sizes and HOMER sizes

	HOMER results			Calculated results		
size based strategy	PV [kWp]	DG [kW]	Number of batteries	PV [kWp]	DG [kW]	Number of batteries
SLF	8.86	4.5	67	8.7	4.5	67
SCC	5.9	4.5	36	5.16	4.5	39
SInt				7.02	4.5	53

As shown in table-3 the calculated sizes for LF and CC are close enough to that resulted by the simulation at HOMOR software, it means that the result of the calculated size is accepted to be simulated in the generated Matlab code to achieve the goals of this research.

4.3 Simulation of Hybrid PV/DG/Battery Systems

To achieve the desired results of this research, the calculated sizes have been simulated using the three proposed controlling strategies.

Optimization software of hybrid systems are available to be used such as HOMER which is considered as a techno-economic assessment software for such system [44], the issue is not only that it considered as a black box since its source code is not available to the users, in case of any modification or improvement is required [13], many variables are supposed to be taken into account when the decision-maker is going to decide the optimal size and controlling strategy as per his requirements.

To solve these issues, Matlab codes for each Load Following and Cycle Charge dispatch have been generated in Appendix-A and Appendix-B consecutively with the help of the modeling equations and operational methods that have been discussed in the previous chapters.

For the Intuitive method, Excel Sheet has been created with the modeling and operational method formulas to obtain the results for later comparison with other dispatches.

Each of these methodologies simulates the proposed real load for twelve days for the three calculated sizes, the twelve days represent the different solar radiation of the year to see the behaver of the system components in poor and rich solar radiation conditions.

The input data of solar radiation and load demand is shown in Fig.20 (Appendix-C page 77) for one day (1440 minutes/day) while Fig.21 (Appendix-C page 77) shows the input data for 12 days (17280 minutes/12 days).

Hybrid PV/DG/battery systems simulations as the following

4.3.1 Load Following Dispatch Simulation

For a better understanding of the behavior and relations between hybrid system components under Load Following controlling dispatch, calculated sizes (SLF, SCC, SInt) in table.3 were simulated individually using the generated Matlab code in Appendix-A.

4.3.1.1 Load Following Simulation for SLF Size (LF-SLF)

Load following size based strategy (SLF) in the load following dispatch simulation results can be shown in Fig.22. (Appendix-C page 78)

Load Following dispatch at its own sizing strategy has a high dependence on the renewable energy source represented by the high renewable fraction [28], that appears when the solar radiation and the output generated power from the PV modules are high, the system runs smoothly supplying the load and charging battery system while some excess energy (EE) appears and less need to diesel generator supply, the battery keeps charging and discharging without reaching the minimum value.

The issue appears when the solar radiation is reduced resulting in the output energy from the PV modules being reduced, batteries and PV modules will keep supplying the load until there is not sufficient energy from the PV modules to handle the load as well as battery system reaches its lowest state of charge since the only source of charging the batteries is PV modules [56].

Diesel Generator will start running on about the required power of the load until batteries are charged to a specific value then supplying the load will be switched to the battery system for some time reputedly [52]. This switching between batteries and the diesel generator may result in an early replacement and maintenance need.

Still, there is no Deficit energy (DE) since the diesel generator is capable to handle the load as its rated power is greater than the peak value of the load curve.

4.3.1.2 Load Following Simulation for Sint Size (LF-SInt)

Intuitive Method size based strategy (SInt) in the load following dispatch simulation results can be shown in Fig.23. (Appendix-C page 79)

Since load following dispatch has a high dependence on the renewable energy source and the PV modules size of Intuitive method strategy (SInt) size is less than the Load Following size based strategy (SLF), the advantage of renewable source represented by the PV modules feeding the load demand falls even in the rich day of solar radiation, even though there is more required time of the diesel generator to supply the load demand, batteries mostly stayed at low state of charge specially in low solar radiation days, the state of charge stayed at the minimum state of charge (SOC_{MIN}=20%) for the most of day which appears in the rapid falls at the first day when batteries enters the day at maximum stored energy since the only charging current comes from the PV modules and the diesel generator generates energy at the power of the required demand only [56], still a high switching between batteries and diesel generator occurs, especially in days where the solar radiation is available but with low intensity, this switching may results to an early replacement and maintenance need [58-60].

there is no Deficit energy (DE) since the diesel generator is capable to handle the load as its rated power is greater than the peak value of the load curve and no excess energy in the system.

4.3.1.3 Load Following Simulation for SCC Size (LF-SCC)

Cycle Charge size based strategy (SCC) in the load following dispatch simulation results can be shown in Fig.24. (Appendix-C page 80)

As shown in table-3, Cycle Charge size based strategy (SCC) has the lowest renewable fraction between the different sizes since the PV modules and the number of batteries is the lowest size while diesel generator size stayed the same, the advantage of renewable source represented by the PV modules feeding the load demand about to disappear in the poor radiation days while it’s still weak even in the rich days of solar radiation, simulation shows that supplying load demand mostly came from the diesel generator around the twelve days (17,280 minutes/ 12 days).

As shown in Fig.24, the battery system state of charge falls rapidly on the first day to its minimum state of charge value (SOC_{MIN} =20%) and stayed on that level for a long time before surplus energy charges it from PV modules. the diesel generator generates energy at the required power of the load demand only, a very high switching between batteries and diesel generator occurs due to low solar radiation charges the batteries, especially in days where the solar radiation is available with low intensity, this switching may results to an early replacement and maintenance need [58-60].

there is no Deficit energy (DE) since the diesel generator is capable to handle the load as its rated power is greater than the peak value of the load curve and no excess energy in the system.

4.3.2 Intuitive Method Simulation

For a better understanding of the behavior and relations between hybrid system components under the Intuitive controlling method, calculated sizes (SLF, SCC, SInt) in table.3 were simulated individually using the Excel sheet with modeling formulas.

The Intuitive method is a controlling strategy that depends on scheduling the Hybrid PV/DG/battery system components each as its rule [41] unless a constrain that cannot be obtained.

4.3.2.1 Intuitive Method Simulation for SLF Size (Int-SLF)

load following size based strategy (SLF) in the Intuitive Method simulation results can be shown in Fig.25. (Appendix-C page 81)

As shown in table-3, Load Following size based strategy is considered oversize comparing to Intuitive method own sizing, which is resulting to a high battery system state of charge in all days even in the days with low solar radiation since PV is not the only charging source of the batteries and the diesel generator scheduled to run daily at specific load peak value considering the peak value cannot be handled by PV modules or Battery system [57], the behavior of batteries is that they will keep supplying the load until PV modules energy drawn and handle the load before the peak value of the load occurs, in a time when PV modules supply the load and there is surplus generated energy, this energy will charge the batteries to raise its state of charge, at the peak value of the load appears, diesel generator will work at its rated power and supply the load, hence, the surplus energy of the diesel generator charges the batteries until their state of charge reaches the maximum value, when state of charge is maxed, any surplus energy will be considered as excess energy of the system and to be damped at the dumping load as shown in Fig.25. (Appendix-C page 81)

The divided load supplying time between PV, DG, and battery system can be noticed in Fig.26. (Appendix-C page 82)

Even with no deficit energy in the system and the load is supplied smoothly without any switching, there is high excess energy in the systems.

4.3.2.2 Intuitive Method Simulation for Sint Size (Int-SInt)

Intuitive Method size based strategy (SInt) in the Intuitive Method simulation results can be shown in Fig.27 . (Appendix-C page 82)

Intuitive method simulation under its own size is working under the correct scheduled timing between its components in the rich solar radiation days. In consecutive poor radiation days, the state of charge reaches its minimum value without the ability of PV modules to handle the load demand by themselves resulting in frequent switching between the diesel generator working at rated power to charge the battery system by the surplus energy and the battery system stored energy [57], therefore, early maintenance and replacements my needed for either generator components or batteries [58-60].

Even that there is no deficit energy in the system since the diesel generator is capable to supply the load whenever there is a shortage in renewable energy sources, high amount of daily unused excess energy in the system.

The divided load supplying time between PV, DG, and battery system can be noticed in Fig.28. (Appendix-C page 83)

4.3.2.3 Intuitive Method Simulation for SCC Size (Int-SCC)

Cycle Charge size based strategy (CC) in the Intuitive Method simulation results can be shown in Fig.29. (Appendix-C page 83)

As shown in table-3, Cycle Charge size based strategy is considered as undersized comparing to Intuitive method own sizing, the less number of batteries resulting in reduction of the amount of energy to be stored, therefore a rapid decrease of battery system state of charge in all days even in the days with high solar radiation since, as well as that, reduction in the peak value of PV modules reduce the charging source of the batteries and the diesel generator runs in both scheduled time and the time where the batteries reach their minimum state of charge while PV modules cannot handle the load demand [57], as noticed in Fig.29 (Appendix-C page 83) battery system state of charge reaches the minimum value in every day, each time PV charge batteries to specific value, diesel generator will stop and allow batteries to supply the load since the cost of energy from batteries is cheaper than the energy generated from the diesel generator [57], batteries with low state of charge cannot supply the load for a long time and it will falls again to the minimum state of charge to oblige diesel generator to rerun again, this frequent switching between batteries and diesel generator will cause an early maintenance and replacement of the components [58-60]. in a time when PV modules supply the load and there is surplus generated energy, this energy will charge the batteries to raise its state of charge, at the peak value of the load, the diesel generator will run at its rated power and supply the load, hence, the surplus energy of the diesel generator charges the batteries until their state of charge reaches the maximum value when the state of charge is maxed, any surplus energy will be considered as excess energy of the system and to be damped at the dumping load.

The divided load supplying time between PV, DG, and battery system can be noticed in Fig.30. (Appendix-C page 83)

Even with no deficit energy in the system, there is high excess energy in the systems.

4.3.3 Cycle Charge Dispatch Simulation

For a better understanding of the behavior and relations between hybrid system components under Cycle Charge controlling dispatch, calculated sizes (SLF, SCC, SInt) in table.3 were simulated individually using the generated Matlab code in Appendix-B.

4.3.3.1 Cycle Charge Simulation for SLF Size (CC-SLF)

Load following size based strategy (SLF) in the Cycle Charge dispatch simulation results can be shown in Fig.31. (Appendix-C page 84)

As shown in table-3, Load Following size based strategy is considered as oversize compared to cycle charge dispatch's own size. the Cycle charge method has its lowest renewable fraction between the other dispatches since batteries can be charged from different sources of energy [61].

Hybrid PV/DG/battery system working under Cycle Charge controlling dispatch with Load Following size based strategy resulting in high feeding dependency on both battery system and PV modules mainly in the rich solar radiation days, on the other hand, at the poor solar radiation days, batteries may reach the minimum value of the state of charge without enough generated power from PV modules, that obliged diesel generator to run and supply the load since Cycle Charge dispatch runs the diesel generator at its full rated power [61], surplus power is going to be directed to charge batteries and raise its state of charge to high value[62], then batteries and PV modules will supply the load again. No deficit energy at the system and a small amount of excess energy appear only when the generated energy from PV modules exceeds the required energy of the load and the state of charge of the battery system at its maximum value. Still, there is no Deficit energy (DE) since the diesel generator is capable to handle the load as its rated power is greater than the peak value of the load curve.

4.3.3.2 Cycle Charge Simulation for SLF Size (CC-SInt)

Intuitive method size (SInt) in the Cycle Charge dispatch simulation results can be shown in Fig.32. (Appendix-C page 85)

As table-3, the Intuitive method size in the PV module’s peak value and the number of batteries is greater than the cycle charge dispatch’s own size. However, both battery system and PV modules supply the load demand most of the time while diesel generator runs at full rated power for most of the rich and poor solar radiation days whenever PV modules and battery system could not supply the load and charge batteries with any surplus power [61-62],

The Cycle charge method has its lowest renewable fraction between the other dispatches since batteries can be charged from different sources of energy [61].

It’s clear from the simulation result in Fig.32 that the battery system has been charged from both sources (PV & DG) which results in a variance state of charge percentage without prejudice to either maximum or minimum state of charge value.

No deficit energy in the system, a small amount of excess energy damped in the dumping load whenever a surplus power from PV modules or DG could not be transferred to batteries due to a mixed state of charge.

Whenever the diesel generator runs for a specific time and power, diesel consumption will be calculated.

4.3.3.3 Cycle Charge Simulation for SLF Size (CC-SCC)

Cycle Charge size based strategy (SCC) in the Cycle Charge dispatch simulation results can be shown in Fig.33. . (Appendix-C page 83)

At Cycle Charge Dispatch simulating under its own size, battery supply the load demand most of the time, when PV modules are having generated energy due to solar radiation availability, either both systems will supply the load with a shared power from batteries or be totally supplied by the PV and any surplus power will be used to charge the batteries [63]. Due to the low renewable fraction of Cycle Charge size based strategy, diesel generator runs at rated power once or twice a day to fulfill the lack of renewable generated/stored energy at supplying the load [62], hence no deficit energy, fuel consumption will be calculated every time diesel generator runs.

The battery system state of charge varied from minimum to high value without reaching a maximum state of charge value, hence no excess energy in the simulated system.

4.4 Simulations Result

Simulations outputs, represented by Battery to load energy percentage, PV to load energy percentage, DG to load energy percentage, number of minutes that battery system reached the minimum state of charge, number of minutes generator was running, number of minutes battery was charging, number of minutes battery was discharging, number of minutes PV supplied the load, percentage of excess energy to total demanded energy, percentage of deficit energy to total demanded energy, the total consumed fuel, number of times that DG started to run, number of time that Battery started to charge and number of time that battery started to discharge of the three calculated sizes simulated in the three dispatched of load following, Intuitive method, and Cycle charges are summarized in table-4, table-5 and, table-6 consecutively.

Table 4

Load following dispatch simulations summery

	size based strategy	LF	int	CC
energy supply to load from(%)	batt	34.8	24.3	16.3
	PV	55.5	48.9	38.3
	DG	9.7	26.8	45.4
number of time (minuets)	SOC=0.2	61	203	444
	DG operating	2589	6937	10460
	batt ch	4834	5259	5487
	batt disch	10080	6712	4333
	PV to load	8713	7732	6360
total	EE(%)	1.9	0.0	0.0
	DE(%)	0.0	0.0	0.0
	CF (L)	28	76	121
number of time	DG op	61	203	444
	Batt Ch	90	235	479
	Batt Disch	88	231	468

Table 5

Intuitive method simulations summery

	size based strategy	LF	int	CC
energy supply to load from(%)	batt	47.0	48.0	39.2
	PV	15.6	13.7	12.1
	DG	37.4	38.3	48.8
number of time (minuets)	SOC=0.2	0	166	2634
	DG operating	3516	3682	6149
	batt ch	4005	4865	6057
	batt disch	11318	11457	9439
	PV to load	2446	2211	2173
total	EE(%)	14.0	15.5	41.1
	DE(%)	0.0	0.0	0.0
	CF (L)	86	90	151
number of time	DG op	12	83	500
	Batt Ch	28	102	511
	Batt Disch	28	102	511

Table 6

Cycle Charge dispatch simulations summery

	size based strategy	LF	Int	CC
energy supply to load from(%)	batt	40.8	43.1	43.4
	PV	55.1	48.4	39.2
	DG	4.2	8.6	17.5
number of time (minuets)	SOC=0.2	3	8	15
	DG operating	1012	2058	3278
	batt ch	4677	4960	5547
	batt disch	11755	11835	11733
	PV to load	8930	8707	7992
total	EE(%)	4.7	2.9	0.0
	DE(%)	0.0	0.0	0.0
	CF (L)	25	51	81
number of time	DG op	3	8	15
	Batt Ch	28	30	36
	Batt Disch	28	30	36

For more clarification of tables 4,5 and 6, a comparison between tables can be divided as the following:

4.4.1 Supplying Load Demand Energy Between Hybrid PV/DG/Battery System Components

For load following dispatch strategy, load demand energy supplied mostly by renewable source (PV) and storage system that charged from the PV modules at strategy own size as expected [28], however, as the renewable source size reduced the diesel generator sharing percentage increased as represented in table-4 when the SCC size simulated, the DG took 45.5% of the load supplied energy, PV sharing percentage took an accepted percentage of load demand supplied energy starting from 55.5% ending 38.3% as the PV size reduced.

For the Intuitive method strategy, the diesel generator sharing percentage was high in all different sizes since the strategy select the schedule timing even if renewable or storage systems are having enough power to feed the load [41], like PV and Battery size reduced, the diesel generator sharing percentage increased. The least amount of energy is supplied by PV modules with a maximum value of 15.6%.

For the Cycle Charge dispatch strategy, since the battery is supplied from both PV modules and diesel generator surplus power, diesel generator ran to supply the load demand for a small percentage at any of calculated sizes while PV sharing percentage took an accepted percentage of load demand supplied energy.

4.4.2 Components Behavior with Respect to Time

For load following dispatch strategy, as renewable fraction decreased, the time that batteries reached their minimum state of charge increased, operating time of diesel generator increased, charging time of battery barely increased and both of discharging time of battery system and the time of PV modules feeding the load are decreased.

For Intuitive Method simulation results in table-5, the battery system did not reach the minimum value when it was at high PV modules and batteries number, while as the size or renewable energy source and storage system reduced, a rapid increase in the time where the state of charge at the minimum value, it can be noticed at SCC size, 15.2% of the time, state of charge was at the minimum value (SOC_{MIN}=20%). As PV size and battery storage increased, both battery system charging time and diesel generator operating time is increased while battery system discharging time decreased, for PV modules supplying energy to load barely reduced as renewable fraction decreased.

For Cycle Charge dispatch strategy, battery system state of charge reached its minimum value for a maximum of 15 minutes in the simulated time (17,280 minutes) at the strategy own size, both operating time of diesel generator and charging time of battery system slowly increased and PV modules supplying time to load demand decreased as the PV and battery system sizes decreased, battery system discharging time can be considered fixed as different sizes simulated in the Cycle Charge dispatch strategy.

4.4.3 Deficit Energy, Excess Energy, and Fuel Consumption

All strategies simulation with the different calculated sizes have no deficit energy in the simulated days because of two reasons:

1- Diesel generator rated power is higher than the maximum demanded power of the load.

2- In any case, when neither PV modules nor battery system nor both could not supply the load demanded energy, diesel generator runs to supply the load.

Excess energy to total demanded energy increased as the size of both PV modules and Battery system decreased, however, the Intuitive method showed a high unused excess energy in the system where it reached h 41.1% at SCC size, both of Load Following and Cycle Charge have either small or zero excess energy in the system.

The amount of consumed fuel in a liter (L) is varied between different dispatch strategies, as shown in table-5, Intuitive method draws the biggest amount of consumed diesel liters compared with other strategies, while the Cycle Charge dispatch strategy consumed the least diesel liters in all different sizes.

4.4.4 Fluctuating of The Battery System and Diesel Generator

As mentioned in [57,60], the frequent switching between battery system and diesel generator will cause early maintenance of diesel generator and replacement of batteries, Load Following dispatch strategy suffers from high frequency switching for load feeding between battery systems and diesel generator especially in poor radiation days and small PV and Battery system sizes as shown in table.4 and Fig.22-24 while Intuitive method strategy started to appear when the PV and battery sizes are reduced to reach the maximum number of diesel generator runs and number of time battery has either discharged or charged as shown in table.5 and Fig.25,27,29

Cycle charge dispatch strategy did not have any frequent switching between battery system and diesel generator in any simulated size all days as shown in table.6 and Fig.32,33,34

4.5 Controlling Strategies Comparison

For better understanding results for controlling strategies simulation results, table.7 has been generated for each strategy dispatch as a total with all strategies sizes.

For intuitive method controlling strategy, most of the supplied energy drawn from the battery storage system and diesel generator, while energy from PV modules directly supplied to load demand did not exceed more than 14%, it can be noticed that batteries suffer from long timing with the minimum state of charge and the high fluctuating between battery system and diesel generator for supplying the load, only 24% excess energy appears in the simulated results while the 328 liters of diesel consumed in the twelve days simulation.

Load Following dispatch strategy has its highest amount of supplying switching between battery system and diesel generator and high energy supplying directly from the PV to the load, 708 minutes of simulated time battery state of charges at the minimum value, 71% excess energy to load demanded energy is drawn in the system and 226 liters of diesel was consumed.

For the Cycle charge controlling strategy, 90% of direct load supplying energy comes either from PV modules or from batteries which keeps 10% of supplied energy comes from the diesel generator, the system has no frequent switching between battery system and diesel generator and only consumed 156 liters of diesel in 12 days, 35% excess energy to load demanded energy in the system.

Table.8 can be used for further comparison between overall controlling strategies.

Table 7

controlling strategies results for all different sizes

	strategy	int	CC	LF
usage of (%)	batt	44.7	42.4	25.2
	PV	13.8	47.5	47.5
	DG	41.5	10.1	27.3
number of minuets	SOC=0.2	2800	26	708
	DG operating	13347	6348	19986
	batt ch	14927	15184	15580
	batt disch	32214	35323	21125
	PV to load	6830	25629	22805
total	EE(%)	23.5	35.3	70.6
	DE(%)	0.0	0.0	0.0
	CF (L)	328	156	226
number of time	DG op	595	26	708
	Batt Ch	641	94	804
	Batt Disch	641	94	787

Battery system supplying energy appeared mostly in the INT method followed by CC dispatch while both LF and CC have equal usage of PV percentage, diesel generator used mostly in INT method which reflects the highest fuel consumption.

Both INT and LF are having high switching fluctuating compared to CC strategy.

CC dispatch strategy has the best usage of renewable source and storage system, least time batteries spent with minimum state of charge, lowest fuel consumption, and lowest switching between batteries and DG.

Table 8

Comparison results between different strategies

	strategy	int	CC	LF
(%)	batt	39.8	37.8	22.4
	PV	12.7	43.7	43.6
	DG	52.6	12.8	34.6
(%)	SOC=0.2	79.2	0.7	20.0
	DG operating	33.6	16.0	50.4
	batt ch	32.7	33.2	34.1
	batt disch	36.3	39.8	23.8
	PV to load	12.4	46.4	41.3
(%)	EE	18.2	27.3	54.5
	DE	0.0	0.0	0.0
	CF	46.0	22.0	31.8
number of time	DG op	44.8	2.0	53.3
	Batt Ch	41.7	6.1	52.2
	Batt Disch	42.1	6.2	51.7

4.6 Discussion

From the previous nine scenarios simulations and simulations result, the following recommendations are obtained:

1- The best overall controlling strategy is the Cycle Charge dispatch strategy.

2- Load Following and Intuitive method strategies are not recommended to be used as a controlling strategy of Hybrid PV/DG/battery system if the PV and battery size are at Cycle Charge size based strategy.

3- In case when fuel consumption is the highest concern to be minimized, Cycle Charge controlling strategy with Load Following size based strategy (CC-SLF) is recommended.

4- In case when renewable source size is the highest concern to be minimized with the highest energy supply, Cycle Charge controlling strategy with Cycle Charge size based strategy (CC-SCC) is recommended.

5- The optimal scenario when the concerns are reduction PV source size, highest possible sharing energy to load from a renewable source, reduction in diesel generator sharing energy, reduction in fuel consumption, reduction in time when batteries reach the minimum state of charge, reduction in unused excess energy and avoid the frequent switching between diesel generator and batteries, Cycle Charge controlling strategy with Intuitive size based strategy (CC-SInt) is recommended

Chapter Five
Conclusion and Future Work

5.1 Conclusion

The main objective of this thesis is to study different controlling strategies (load following, Cycle Charge, and Intuitive method) with their sizing methods of hybrid PV/DG/Battery systems.

Nine scenarios were simulated and compared with each other, where all of these scenarios had the ability to fulfill the required demanded proposed load, where the proposed load required continuous energy supplying for twelve days with different solar radiations that represent a year, different simulations behavior study between system components and the output results study, used to classify the optimum scenario to be used as the requirement and consideration of the operator, these considerations are the renewable fraction of the system, the time that batteries reach the minimum value of the state of charge, diesel generator working time, percentage of unused excess energy, fuel consumption and the frequent switching between battery system and diesel generator at supplying the load.

Based on the results and comparisons between these simulations, the overall optimum controlling strategy is the Cycle Charge dispatch, while the optimal controlling strategy with a specific size is to operate the Cycle Charge dispatch strategy with Intuitive method size based strategy of hybrid PV/DG/Battery system components (CC-SInt).

5.2 Future Work

This thesis achieved its goal by simulating and comparing different scenarios to define the optimum size and strategy of the hybrid PV/DG/Battery system to be used for a specific load.

- It is recommended to apply this simulation and comparison for a different load demand with different behavior to check whether the results of this thesis are applicable with other load demands

- More parameters can be taken into accounts such as the diesel generator fuel temperature, timing of the diesel generator to start feeding the load to achieve the maximum efficiency and inverter losses due to temperature

List of Abbreviations

Abbreviation	Meaning
AC	Alternating Current
COE	Cost Of Energy
DC	Direct Current
DG	Diesel Generator
DOD	Depth of Discharge
E	Energy
G	Global Solar Radiation
GHG	Green House Gasses
GHI	Global Horizontal Irradiance
M&O	Maintenance and Operational Cost
Nd	Number of nominal days
NOCT	Nominal Operating Cell Temperature
NPC	Net Present Cost
P	Power
PV	Photovoltaic
RES	Renewable Energy Sources
SCC	Cycle Charge Size based strategy
SInt	Intuitive Method Size
SLF	Load Following Size based strategy
SOC	State Of Charge
SOCmax	Maximum state of charge
SOCmin	Minimum state of charge
SR	Solar Radiation
Ta	Ambient Temperature
THD	Total Harmonic Distortion

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Appendices

Appendix-A

```
%% (1) importing data
fileName="real12.xlsx";
sheetName="Sheet1";
G =xlsread(fileName, sheetName, "A2:A17281");
T= xlsread(fileName, sheetName, "C2:C17281");
P_L= xlsread(fileName, sheetName, "B2:B17281");
%%(2) system specification
W=0; %% still no discharge at the batteries
SOC1=1;
Battery_SOCmax=100;
SOCmax=1; %% maximum state of charge
SOCstart=1; %% starting state of charge at the first day
DOD=; %% depth of discharge
WM=; %% battery watt minuit
P_PVmax= ;
IDiesel= ; %% diesel generator rated power
 SOCmin=SOCmax/(1-DOD);
SOC3=0.2;
SOCmin= ; %% minimums tate of charge
K=0.8;
D=1e-5;
ns=;%% number of 2V batteries in series
SOC2=SOC1;
A=0.2461;%% alpha
CT=0.081451;
n=0; %% diesel generator is not working
%%(3)SAPV simulation
P_PV=P_PVmax*[G/1000+(alpha*(T-25))];
SOC=[]; %% battery state of charge matrix
P_Load=[];%% load demand matrix
P_Charge=[]; %% battery charging energy matrix
P_Discharge=[];%% battery discharging energy matrix
P_Deficit=[]; %% deficit energy matrix
```

```
P_Damp=[]; %% excess energy matrix
P_Diesel=[]; %% diesel generator generated energy matrix
C_F=[]; %% consumed fuel matrix
P_Battery=[]; % input and output battery energy matrix
L=length(P_L);
t1=(1/(10*WM));
for i=1:1:L;
P_net(i)=P_PV(i)-P_L(i);
x(i)=i;
%% (4) IPV=IL
if P_net(i)==0 ;
if n==0;
P_Load(i)=0;
P_Charge(i)=0;
P_Discharge(i)=0;
P_Deficit(i)=0;
P_Damp(i)=0;
P_Diesel(i)=0;
C_F(i)=0;
P_Battery(i)=0;
if i==1;
SOC(i)=SOCstart;
lseif W==0;
SOC(i)=SOC1;
elseif W==1;
SOC(i)=SOC(i-1);
end
end
% (5) IPV>IL
elseif P_net(i)>0 && n==0;
P_Load(i)=P_L(i);
f i==1;
SOC(i)=SOCstart;
P_Charge(i)=0;
P_Discharge(i)=0;
P_Deficit(i)=0;
```

```
P_Damp(i)=P_net(i);
P_Diesel(i)=0;
C_F(i)=0;
P_Battery(i)=0;
elseif i>1;
if W==0;
SOC(i)=SOCstart;
P_Charge(i)=0;
P_Discharge(i)=0;
P_Deficit(i)=0;
P_Diesel(i)=0;
C_F(i)=0;
P_Battery(i)=0;
P_Damp(i)=P_net(i);
else W==1;
if SOC(i-1)>=SOCmax;
OC(i)=SOC1;
P_Charge(i)=0;
P_Discharge(i)=0;
P_Deficit(i)=0;
_Damp(i)=P_net(i);
P_Diesel(i)=0;
C_F(i)=0;
P_Battery(i)=0;
elseif SOC(i-1)<SOCmax;
P_Charge(i)=P_net(i);
_Discharge(i)=0;
P_Battery(i)=0;
P_Deficit(i)=0;
P_Damp(i)=0;
P_Diesel(i)=0;
C_F(i)=0;
%% find new SOC after charging
for t=(1);
B=SOC2;
V1=(2+0.148*B)*ns;
```

```
R1=(0.758+(0.1309/(1.06-B)))*ns/SOCmax;
R1=double(R1);
syms v;
ee=double(int((K*V1* P_Charge(i)-D*SOC2*SOCmax),v,0,t1));
SOCn=SOC1+SOCmax^-1*ee;
SOC2=SOCn;
End
SOC2=double(SOCn);
SOC(i)=SOC(i-1)+abs((SOC1-SOC2));
if SOC(i)>SOCmax;
OC(i)=SOCmax;
End
SOC2=SOC(i);
End
End
End
%% (6) IPV<IL
elseif P_net(i)<0 || ( P_net(i)>0 && n>0);
%%(6.1)
if W==0;
SOC2=SOCstart;
if n==0;
P_Discharge(i)=P_L(i)-P_PV(i);
P_Load(i)=P_L(i);
P_Battery(i)=P_Discharge(i);
P_Charge(i)=0;
P_Deficit(i)=0;
P_Damp(i)=0;
P_Diesel(i)=0;
C_F(i)=0;
for t=(1);
B=SOC2;
V1=(1.962+0.124*B)*ns;
R1=(0.19+(0.1037/(B-0.14)))*ns/SOCmax;
syms v;
e=double(int((K*V1*P_net(i)-D*SOC2*SOCmax),v,0,t1));
```

```
SOCn=SOC2+SOCmax^-1*ee;
SOC2=SOCn;
End
SOC2=double(SOCn);
OC(i)=SOC2;
if SOC(i)<SOCmin;
SOC(i)=SOCmin;
end
SOC2=SOC(i);
W=1;
End
elseif W==1;
if SOC(i-1)>SOCmin  &  n==0 ;
P_Discharge(i)=P_L(i)-P_PV(i);
P_Load(i)=P_L(i);
P_Battery(i)=P_Discharge(i);
P_Charge(i)=0;
P_Deficit(i)=0;
P_Damp(i)=0;
P_Diesel(i)=0;
C_F(i)=0;
for t=(1);
B=SOC2;
V1=(1.962+0.124*B)*ns;
R1=(0.19+(0.1037/(B-0.14)))*ns/SOCmax;
syms v;
ee=double(int((K*V1*P_net(i)-D*SOC2*SOCmax),v,0,t1));
SOCn=SOC1+SOCmax^-1*ee;
SOC2=SOCn;
end
SOC2=double(SOCn);
SOC(i)=SOC(i-1)- abs((SOC1-SOC2));
if SOC(i)<SOCmin;
SOC(i)=SOCmin;
end
%% (6.2) enter diesel Generator
```

```
elseif SOC(i-1)<=SOC3 || n>0;
if IDiesel>=P_L(i);
P_Load(i)= P_L(i);
P_Diesel(i)=P_Load(i);
 P_Discharge(i)=0;
P_Deficit(i)=0;
if SOC(i-1) <SOC1;
P_Charge(i)=P_PV(i);%%charging current from the PV only if available
P_Battery(i)=-1*P_Charge(i);
P_Damp(i)=0;
for t=(1);
B=SOC2;
V1=(2+0.148*B)*ns;
R1=(0.758+(0.1309/(1.06-B)))*ns/SOCmax;
R1=double(R1);
syms v;
ee=double(int((K*V1* P_Charge(i)-D*SOC2*SOCmax),v,0,t1));
SOCn=SOC1+SOCmax^-1*ee;
SOC2=SOCn;
End
SOC2=double(SOCn);
SOC(i)=SOC(i-1)+abs((SOC1-SOC2));
if SOC(i)>SOCmax;
SOC(i)=SOCmax;
End
SOC2=SOC(i);
else
P_Charge(i)=0;
P_Battery(i)=0;
P_Damp(i)= P_PV(i);
SOC(i)=SOC(i-1);
End
C_F(i) = (A*P_Diesel(i))+(CT*IDiesel);
n=n+1;
%%R6.4
elseif IDiesel<P_L(i);
```

```
P_Discharge(i)=0;
P_Load(i)=0;
P_Battery(i)=0;
P_Charge(i)=0;
P_Deficit(i)=P_L(i);
P_Damp(i)=0;
P_Diesel(i)=0;
C_F(i)=0;
End
if n>=4 && SOC(i)>0.2010 ;
n=0;
end
end
end
end
end
```

Appendix-B

```
%% (1) importing data
fileName="real12.xlsx";

sheetName="Sheet1";
G =xlsread(fileName, sheetName, "A2:A17281");
T= xlsread(fileName, sheetName, "C2:C17281");
P_L= xlsread(fileName, sheetName, "B2:B17281");
SOCmax=1;
V_B=12;
SOCstart=1;
DOD=0.8;
WM=;%% battery watt minuit
P_PVmax=5.16;
IDiesel=4.5; %% rated power of diesel generator
 SOCmin=SOCmax/(1-DOD);
alpha=-0.00437;
SOC3=0.2;
SOCmin=0.2;
K=0.8;
D=1e-5;
ns=6;
SOC2=SOC1;
A=0.2461;
CT=0.081451;
n=0;%DG not working
%%(3) PV simulation
P_PV=P_PVmax*[G/1000+(alpha*(T-25))];
SOC=[];
P_Load=[];
P_Charge=[];
P_Discharge=[];
P_Deficit=[];
```

```
P_Damp=[];
P_Diesel=[];
F_Cf=[];
P_Battery=[];
L=length(P_L);
t1=(1/(10*WM));
for i=1:1:L;
x(i)=i;
P_net(i)=P_PV(i)-P_L(i);
%%(4) IPV=IL
if P_net(i)==0 ;
if n==0;
P_Load(i)=0;
P_Charge(i)=0;
P_Discharge(i)=0;
P_Deficit(i)=0;
P_Damp(i)=0;
P_Diesel(i)=0;
F_Cf(i)=0;
P_Battery(i)=0;
if i==1;
SOC(i)=SOCstart;
elseif W==0;
SOC(i)=SOC1;
elseif W==1;
SOC(i)=SOC(i-1);
End
end
%% (5) IPV>IL
elseif P_net(i)>0 && n==0;
P_Load(i)=P_L(i);
if i==1;
SOC(i)=SOCstart;
```

```
P_Charge(i)=0;
P_Discharge(i)=0;
P_Deficit(i)=0;
P_Damp(i)=P_net(i);
P_Diesel(i)=0;
F_Cf(i)=0;
P_Battery(i)=0;
elseif i>1;
if W==0;
SOC(i)=SOCstart;
P_Charge(i)=0;
P_Discharge(i)=0;
P_Deficit(i)=0;
P_Diesel(i)=0;
F_Cf(i)=0;
P_Battery(i)=0;
P_Damp(i)=P_net(i);
else W==1;
if SOC(i-1)>=SOCmax;
SOC(i)=SOCmax;
P_Charge(i)=0;
P_Discharge(i)=0;
P_Deficit(i)=0;
P_Damp(i)=P_net(i);
P_Diesel(i)=0;
F_Cf(i)=0;
P_Battery(i)=0;
elseif SOC(i-1)<SOCmax;
P_Charge(i)=P_net(i);
P_Discharge(i)=0;
P_Battery(i)=0;
P_Deficit(i)=0;
P_Damp(i)=0;
```

```
P_Diesel(i)=0;
F_Cf(i)=0;
 %% find new SOC after charging
for t=(1);
B=SOC2;
 V1=(2+0.148*B)*ns;
R1=(0.758+(0.1309/(1.06-B)))*ns/SOCmax;
R1=double(R1);
syms v;
ee=double(int((K*V1* P_Charge(i)-D*SOC2*SOCmax),v,0,t1));
SOCn=SOC1+SOCmax^-1*ee;
SOC2=SOCn;
End
SOC2=double(SOCn);
SOC(i)=SOC(i-1)+abs((SOC1-SOC2));
if SOC(i)>SOCmax;
SOC(i)=SOCmax;
End
SOC2=SOC(i);
End
end
end
%% (6) IPV<IL
elseif P_net(i)<0 ||( P_net(i)>0 && n>0);
%%R6.1
if W==0;
SOC2=SOCstart;
if n==0;
P_Discharge(i)=P_L(i)-P_PV(i);
P_Load(i)=P_L(i);
P_Battery(i)=P_Discharge(i);
P_Charge(i)=0;
P_Deficit(i)=0;
```

```
P_Damp(i)=0;
P_Diesel(i)=0;
F_Cf(i)=0;
for t=(1);
B=SOC2;
V1=(1.962+0.124*B)*ns;
R1=(0.19+(0.1037/(B-0.14)))*ns/SOCmax;
syms v;
ee=double(int((K*V1*P_net(i)-D*SOC2*SOCmax),v,0,t1));
SOCn=SOC2+SOCmax^-1*ee;
SOC2=SOCn;
End
SOC2=double(SOCn);
SOC(i)=SOC2;
if SOC(i)<SOCmin;
SOC(i)=SOCmin;
End
SOC2=SOC(i);
W=1;
End
elseif W==1;
if SOC(i-1)>SOCmin && n==0 ;
P_Discharge(i)=P_L(i)-P_PV(i);
P_Load(i)=P_L(i);
P_Battery(i)=P_Discharge(i);
P_Charge(i)=0;
P_Deficit(i)=0;
P_Damp(i)=0;
P_Diesel(i)=0;
F_Cf(i)=0;
for t=(1);
B=SOC2;
V1=(1.962+0.124*B)*ns;
```

```
R1=(0.19+(0.1037/(B-0.14)))*ns/SOCmax;
syms v;
ee=double(int((K*V1*P_net(i)-D*SOC2*SOCmax),v,0,t1));
SOCn=SOC1+SOCmax^-1*ee;
SOC2=SOCn;
End
SOC2=double(SOCn);
SOC(i)=SOC(i-1)- abs((SOC1-SOC2));
if SOC(i)<SOCmin;
SOC(i)=SOCmin;
end
%% (6) enter diesel Generator
elseif SOC(i-1)<=SOCmin || n>0;
%%R7.1
if IDiesel>=P_L(i);
P_Load(i)= P_L(i);
P_Diesel(i)=IDiesel;
P_Discharge(i)=0;
P_Deficit(i)=0;
if SOC(i-1)<SOC1;
P_Charge(i)=P_PV(i)+IDiesel - P_L(i);%%charging current should come from the DG
P_Battery(i)=-1*P_Charge(i);
P_Damp(i)=0;
for t=(1);
B=SOC2;
V1=(2+0.148*B)*ns;
R1=(0.758+(0.1309/(1.06-B)))*ns/SOCmax;
R1=double(R1);
syms v;
ee=double(int((K*V1* P_Charge(i)-D*SOC2*SOCmax),v,0,t1));
SOCn=SOC1+SOCmax^-1*ee;
SOC2=SOCn;
End
```

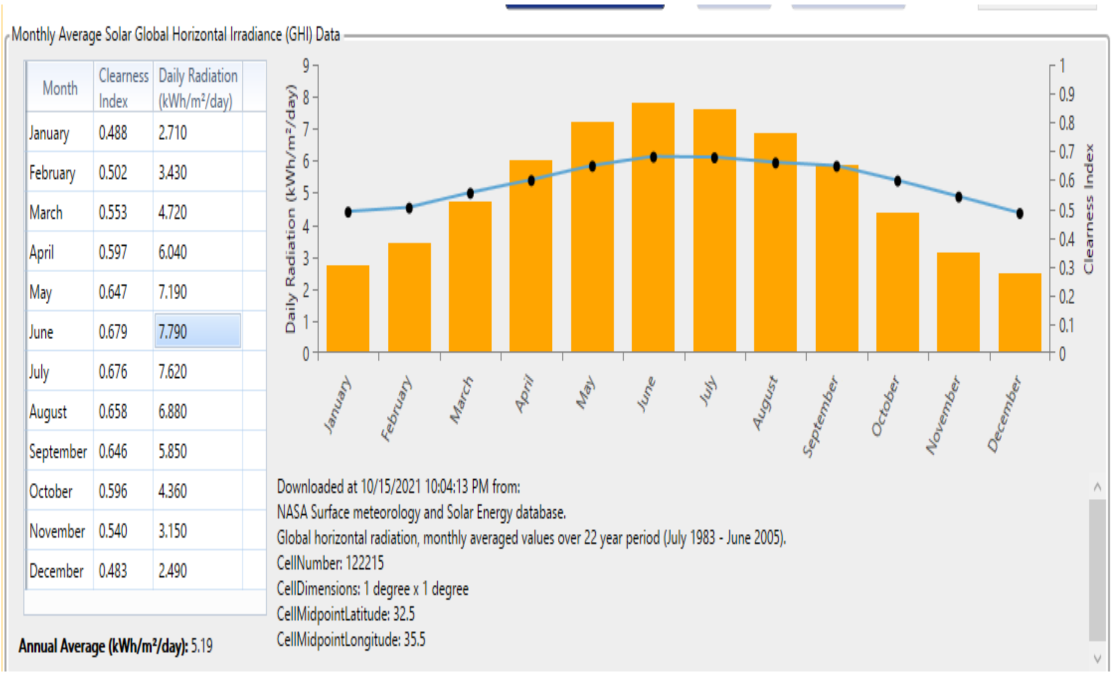
```
SOC2=double(SOCn);
SOC(i)=SOC(i-1)+abs((SOC1-SOC2));
if SOC(i)>SOCmax;
SOC(i)=SOCmax;
end
SOC2=SOC(i);
else
P_Charge(i)=0;
P_Battery(i)=0;
P_Damp(i)= P_PV(i)+IDiesel-P_L(i);
SOC(i)=SOC(i-1);
End
F_Cf(i) = (A*P_Diesel(i))+(CT*IDiesel);
n=n+1;
%%R7.2
elseif IDiesel<P_L(i) && SOC(i-1) >=0.8;
P_Discharge(i)=P_L(i)-IDiesel;
P_Load(i)=P_L(i);
P_Battery(i)=P_Discharge(i);
P_Charge(i)=0;
P_Deficit(i)=0;
P_Damp(i)=0;
P_Diesel(i)=IDeisel;
F_Cf(i)=0;
for t=(1);
B=SOC2;
V1=(1.962+0.124*B)*ns;
R1=(0.19+(0.1037/(B-0.14)))*ns/SOCmax;
syms v;
ee=double(int((K*V1*P_Discharge(i)-D*SOC2*SOCmax),v,0,t1));
SOCn=SOC1+SOCmax^-1*ee;
SOC2=SOCn;
End
```

```
SOC2=double(SOCn);
SOC(i)=SOC(i-1)-abs(SOC1-SOC2);
if SOC(i)<SOCmin;
SOC(i)=SOCmin;
End
SOC2=SOC(i);
W=1;
%%7.3
elseif IDiesel<P_L(i) && SOC(i-1)<=0.3;
P_Discharge(i)=0;
P_Load(i)=0;
P_Battery(i)=0;
P_Charge(i)=0;
P_Deficit(i)=P_L(i);
P_Damp(i)=0;
P_Diesel(i)=0;
F_Cf(i)=0;
End
if SOC(i)>0.8;
n=0;
end
end
end
end
end
```

Appendix-C

Fig.11

GHI for Qlqilya city [HOMER]



Month	Clearness Index	Daily Radiation (kWh/m²/day)
January	0.488	2.710
February	0.502	3.430
March	0.553	4.720
April	0.597	6.040
May	0.647	7.190
June	0.679	7.790
July	0.676	7.620
August	0.658	6.880
September	0.646	5.850
October	0.596	4.360
November	0.540	3.150
December	0.483	2.490

Fig.12

HOMER schematic diagram

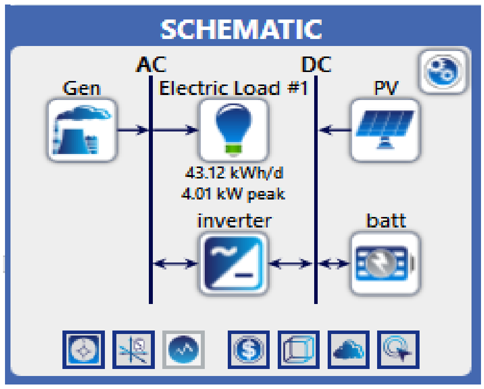


Fig.13

selected real load coordination in HOMER

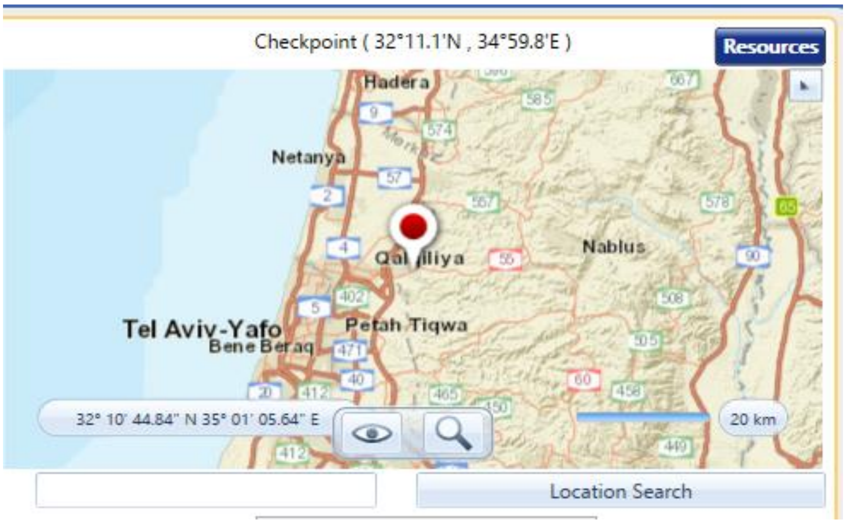


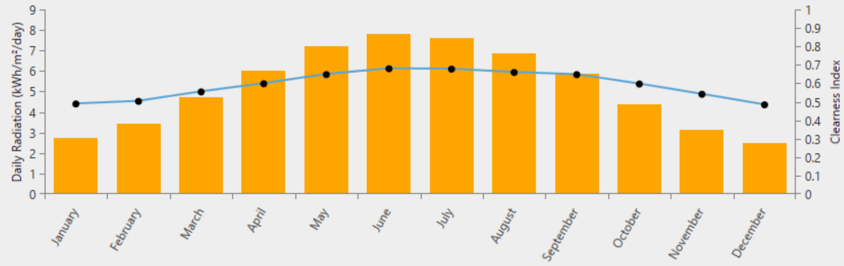
Fig.14

HOMER global solar radiation data

Monthly Average Solar Global Horizontal Irradiance (GHI) Data

Month	Clearness Index	Daily Radiation (kWh/m²/day)
January	0.488	2.710
February	0.502	3.430
March	0.553	4.720
April	0.597	6.040
May	0.647	7.190
June	0.679	7.790
July	0.676	7.620
August	0.658	6.880
September	0.646	5.850
October	0.596	4.360
November	0.540	3.150
December	0.483	2.490

Annual Average (kWh/m²/day): 5.19



Downloaded at 8/30/2021 8:02:28 PM from:
NASA Surface meteorology and Solar Energy database.
Global horizontal radiation, monthly averaged values over 22 year period (July 1983 - June 2005).
CellNumber: 122215
CellDimensions: 1 degree x 1 degree
CellMidpointLatitude: 32.5
CellMidpointLongitude: 35.5

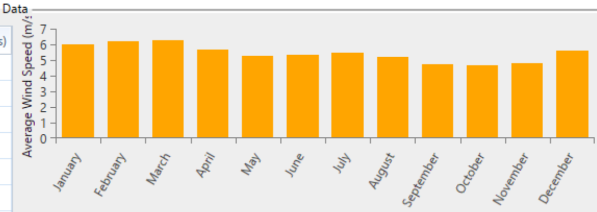
Fig.15

HOMER wind speed data

Monthly Average Wind Speed Data

Month	Average (m/s)
January	6.020
February	6.190
March	6.260
April	5.650
May	5.280
June	5.360
July	5.450
August	5.180
September	4.730
October	4.670
November	4.800
December	5.570

Annual Average (m/s): 5.43



Downloaded at 8/30/2021 8:02:30 PM from:
NASA Surface meteorology and Solar Energy database.
Wind speed at 50m above the surface of the earth for terrain similar to airports, monthly averaged values over 10 year period (July 1983 - June 1993)
CellNumber: 122215
CellDimensions: 1 degree x 1 degree
CellMidpointLatitude: 32.5
CellMidpointLongitude: 35.5
AnemometerHeight: 50

Parameters | Variation With Height | Advanced Parameters

Altitude above sea level (m): 0

Anemometer height (m): 50

Fig.16

HOMER wind speed data

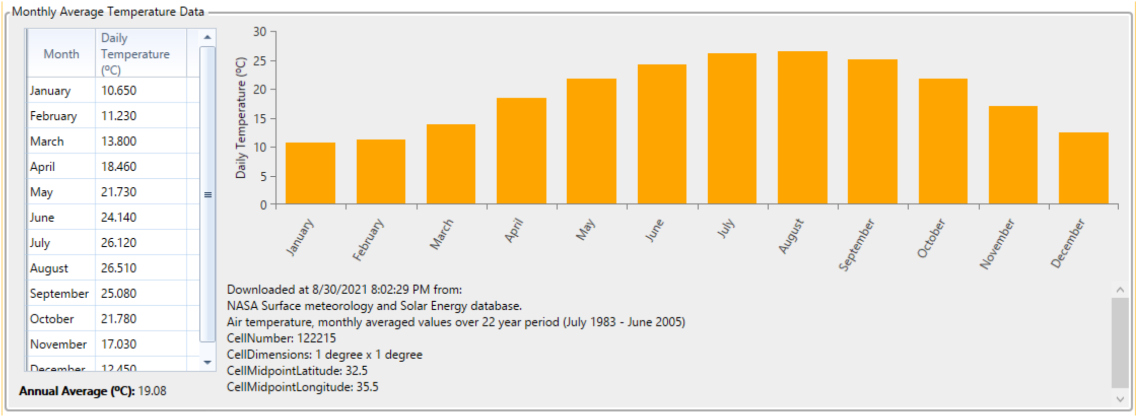


Fig.17

Real Load data in HOMER

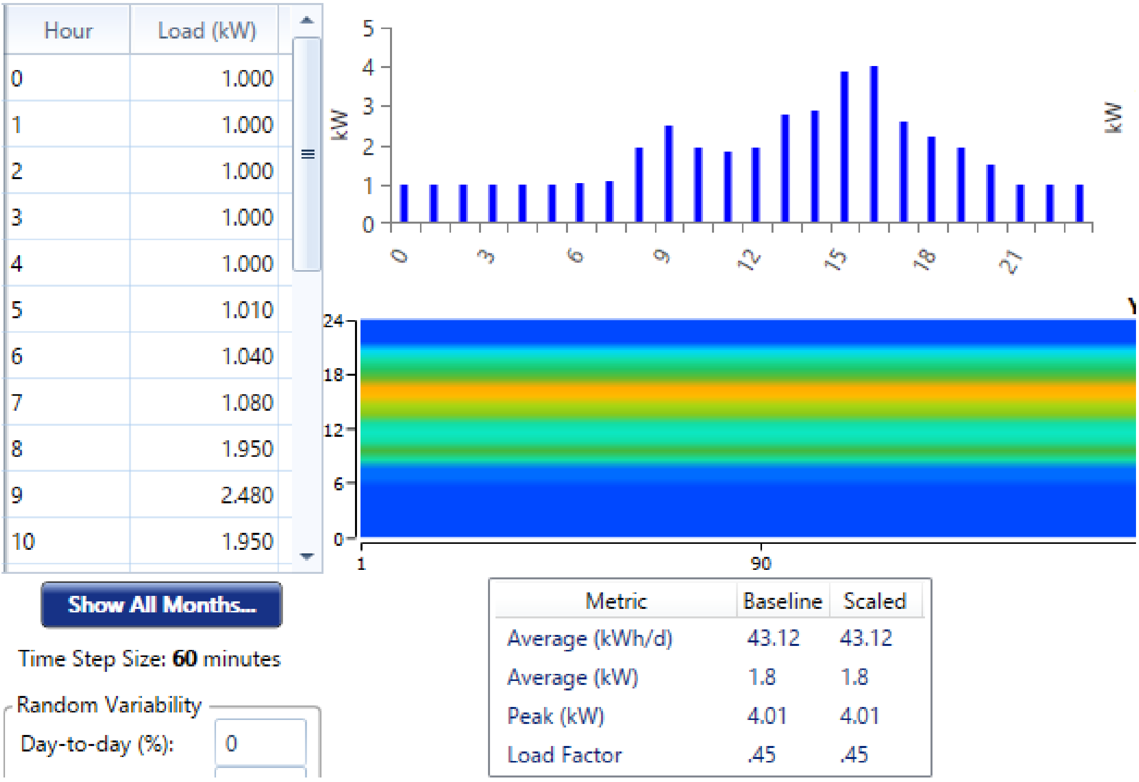


Fig.18

Load Following dispatch results in HOMER

PV (kW)	Gen (kW)	batt	inverter (kW)	Dispatch
8.86	4.50	67	4.48	LF

Fig.19

Cycle Charge dispatch results in HOMER

PV (kW)	Gen (kW)	batt	inverter (kW)	Dispatch
5.90	4.50	36	3.30	CC

Fig.20

Input Data for one day

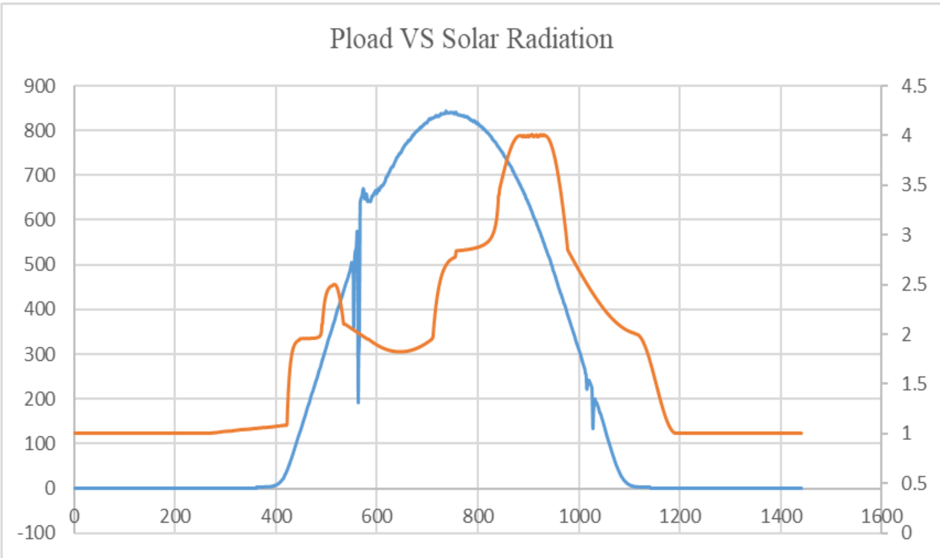


Fig.21

Input Data for 12 days

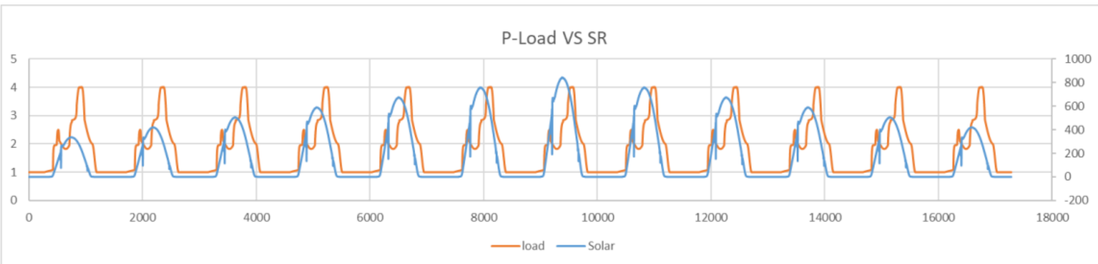


Fig.22

load following dispatch simulation of the load following size based strategy (LF-SLF)

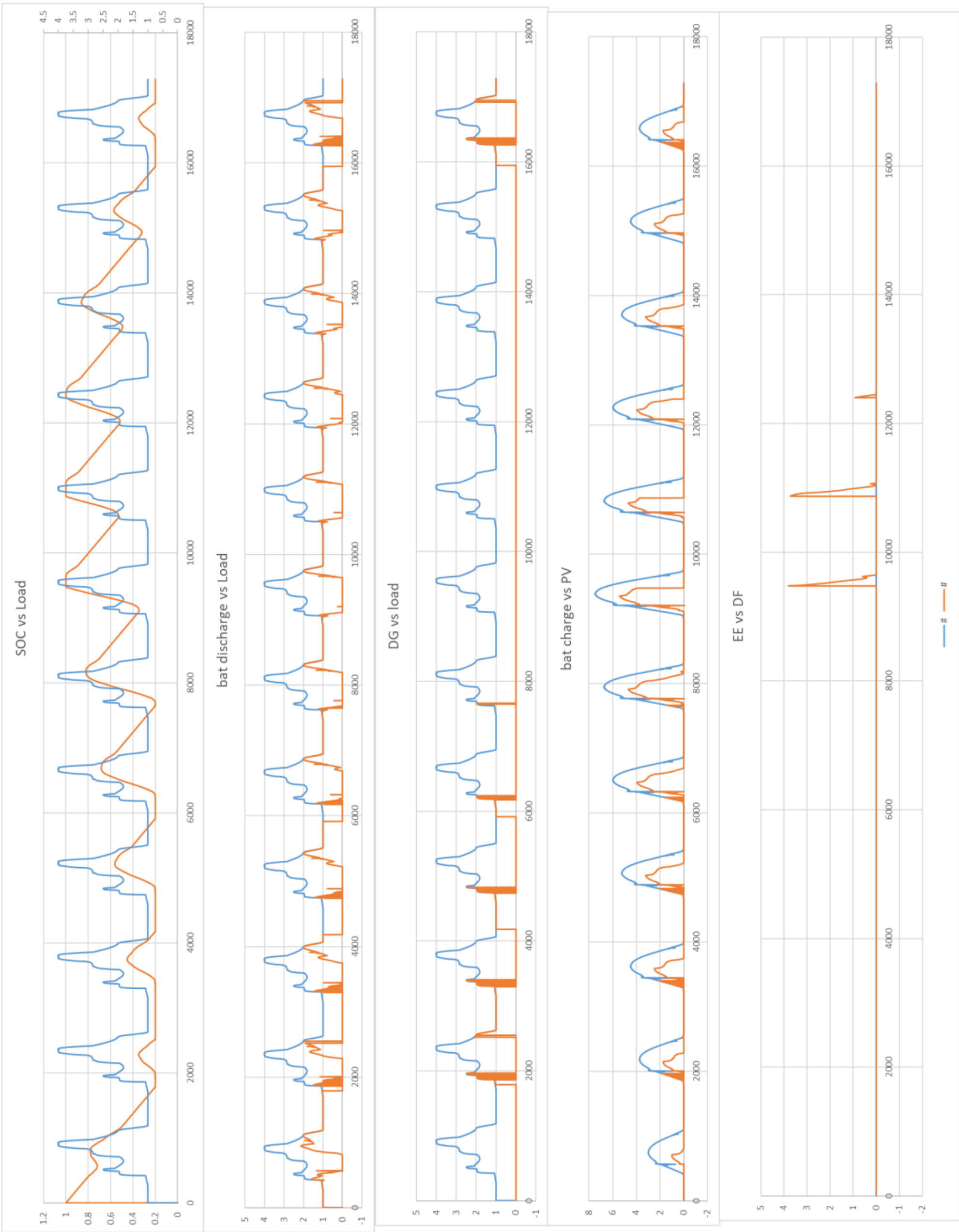


Fig.23

load following dispatch simulation of the Intuitive method size based strategy (LF-SInt)

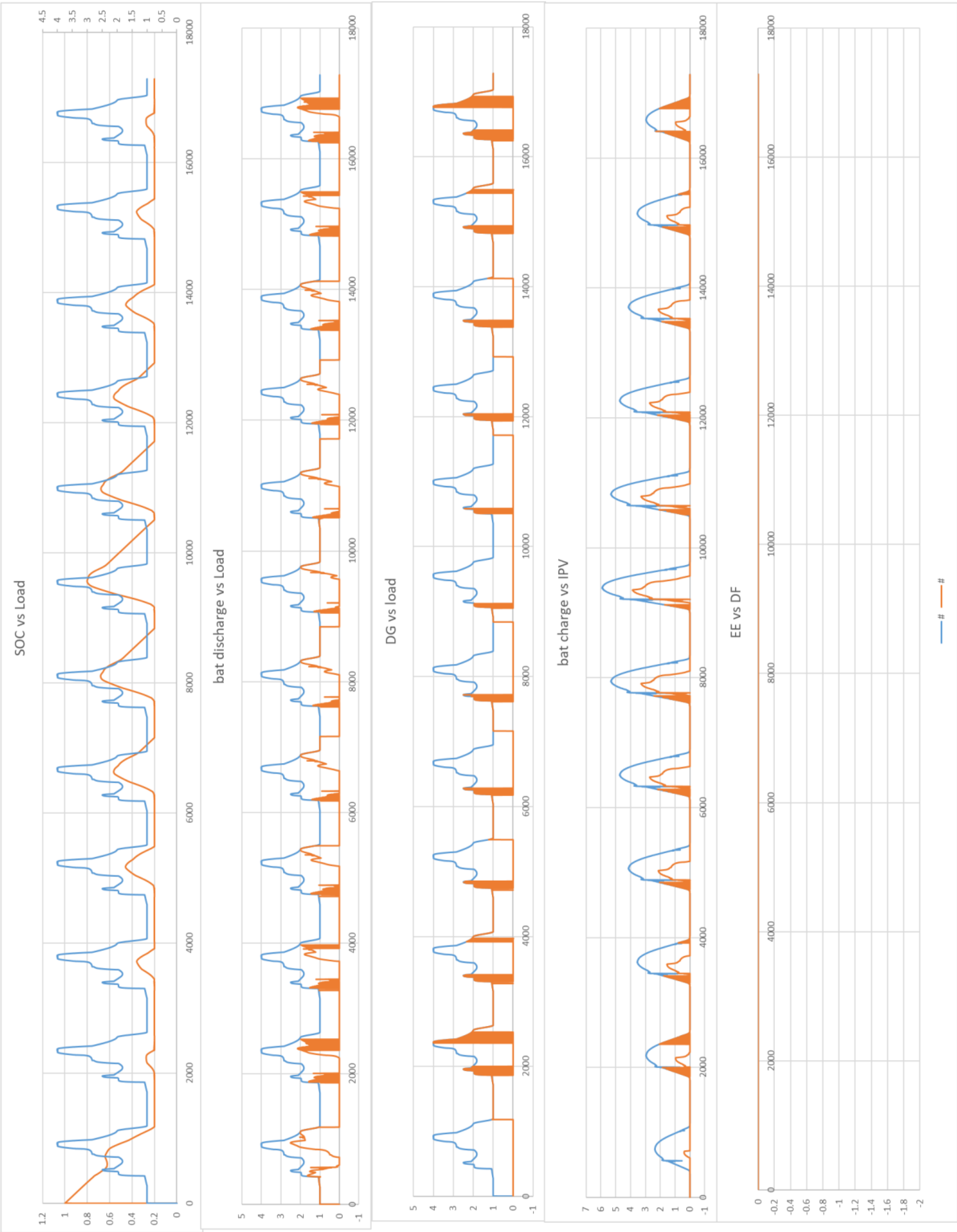


Fig.24

load following dispatch simulation of the Cycle Charge size based strategy (LF-SCC)

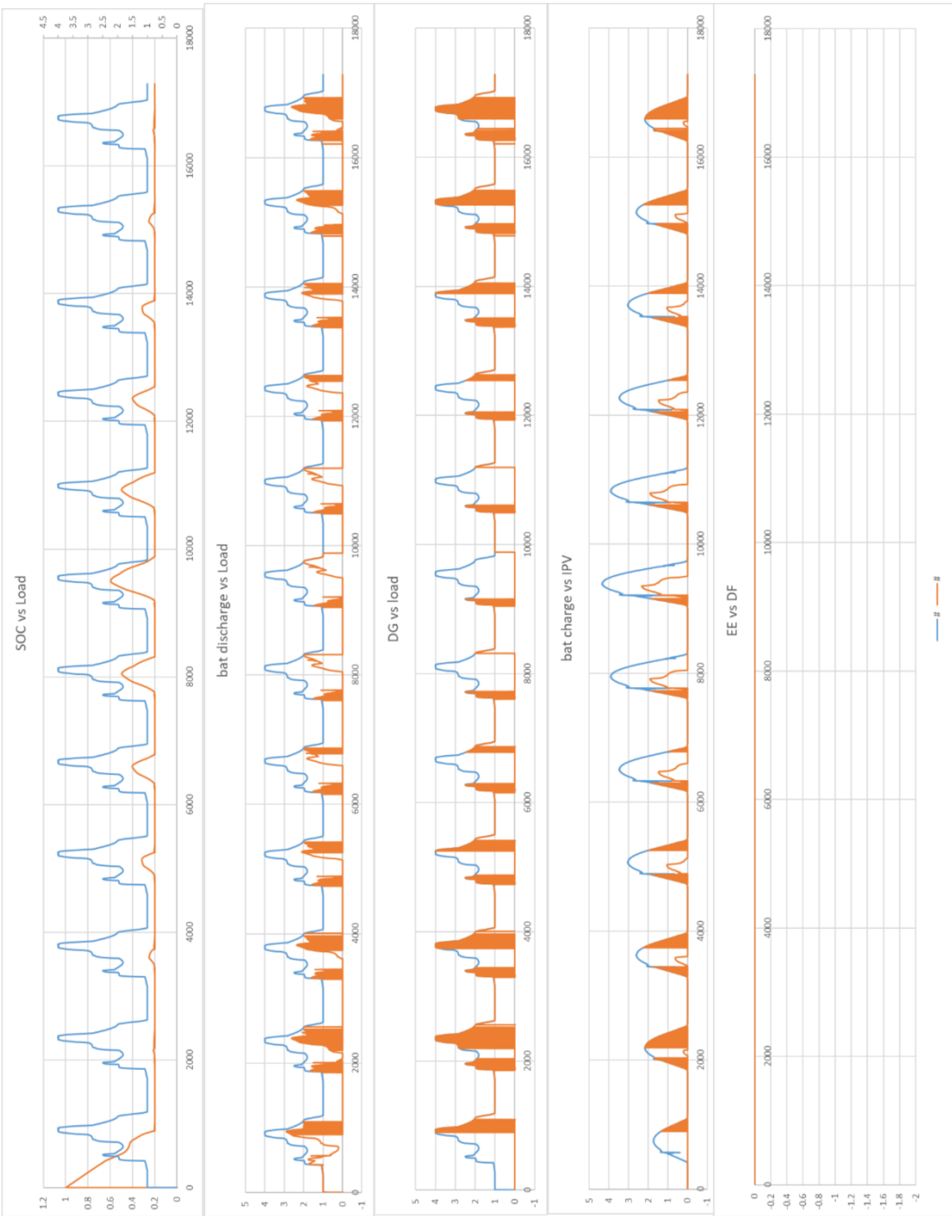


Fig.25

Intuitive Method dispatch simulation of the Load Following size based strategy (Int-SLF)

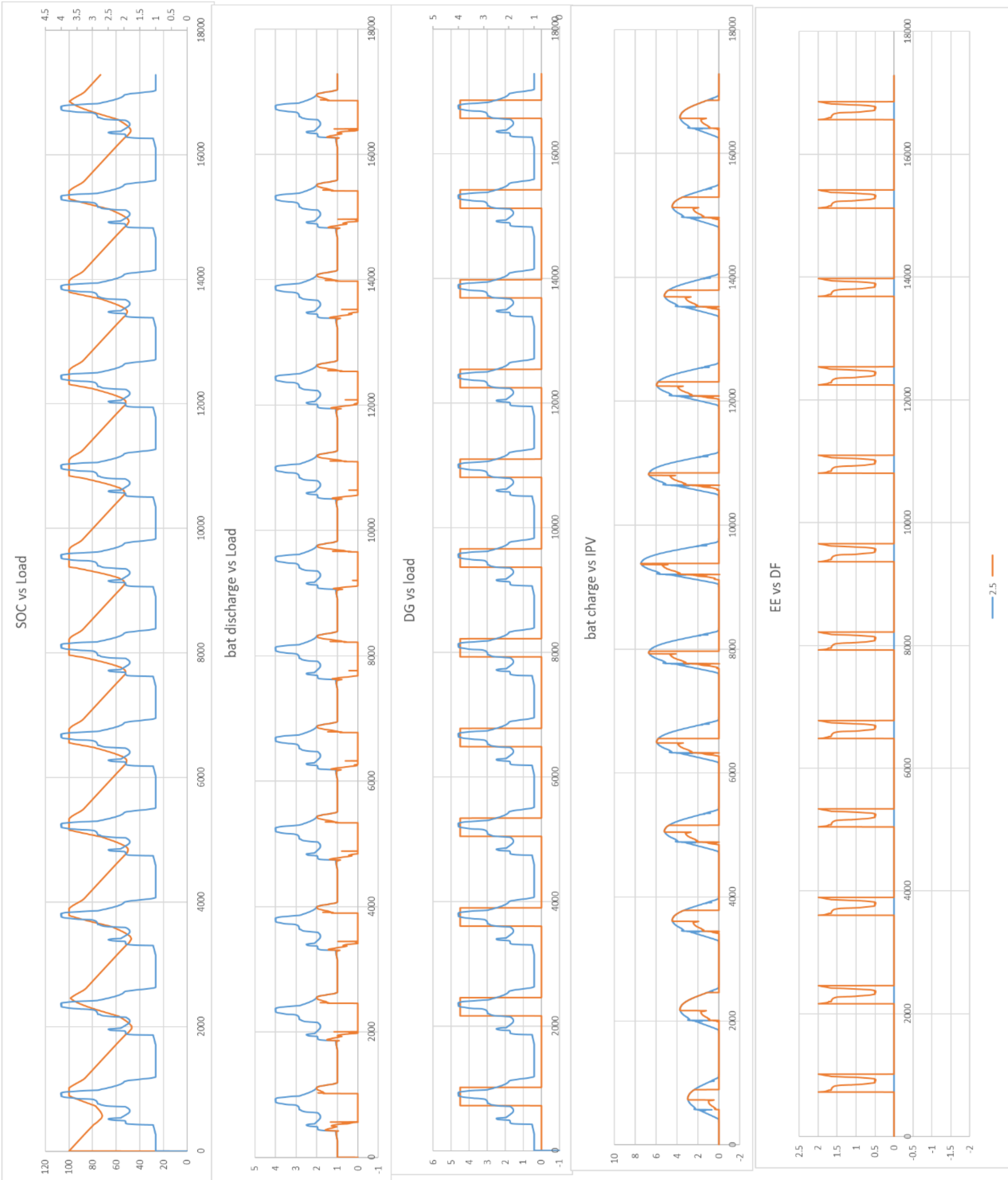


Fig.26

divided load supplying time between PV, DG, and battery system(Int-SLF)

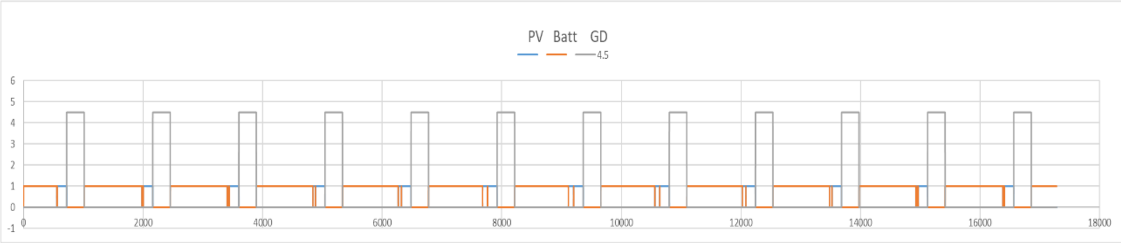


Fig.27

Intuitive Method dispatch simulation of Intuitive Method size based strategy (Int-SInt)

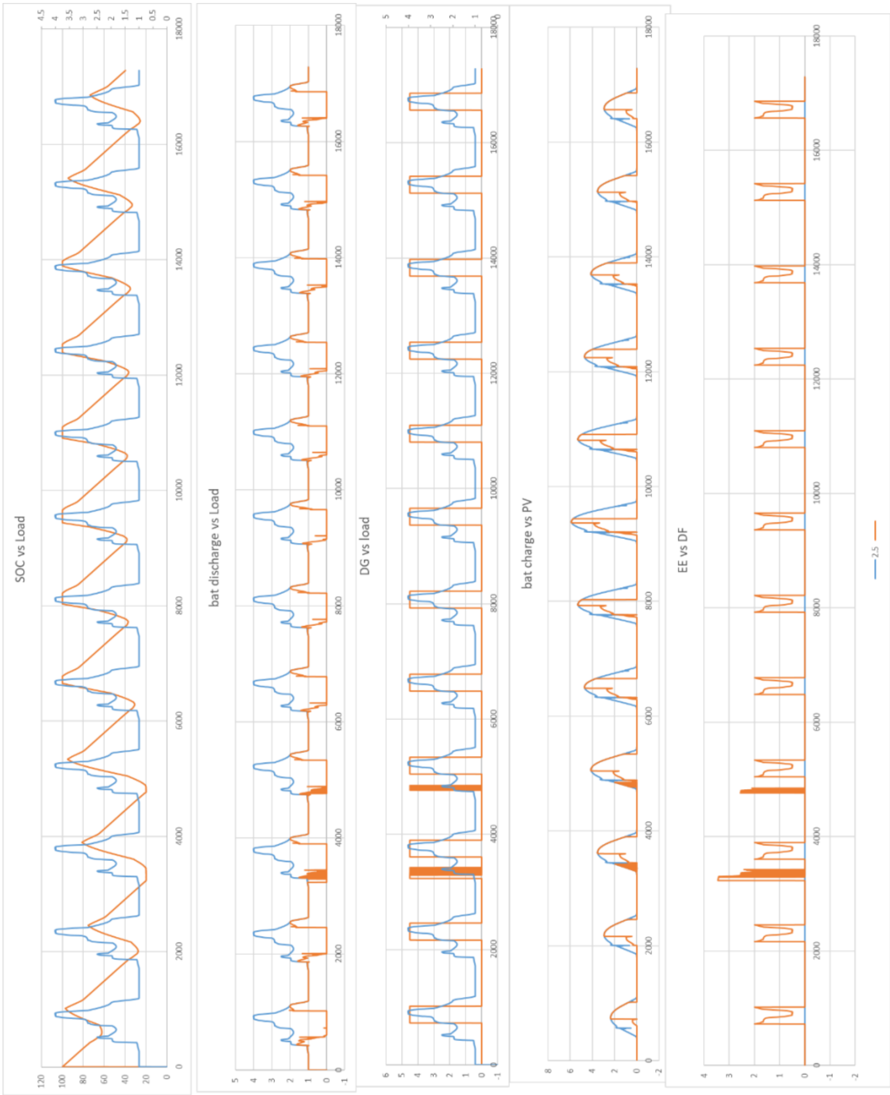


Fig.28

divided load supplying time between PV, DG, and battery system

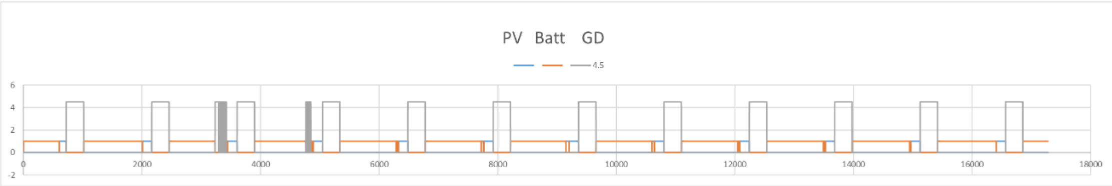


Fig.29

Intuitive Method dispatch simulation of Cycle Charge size based strategy (Int-SCC)

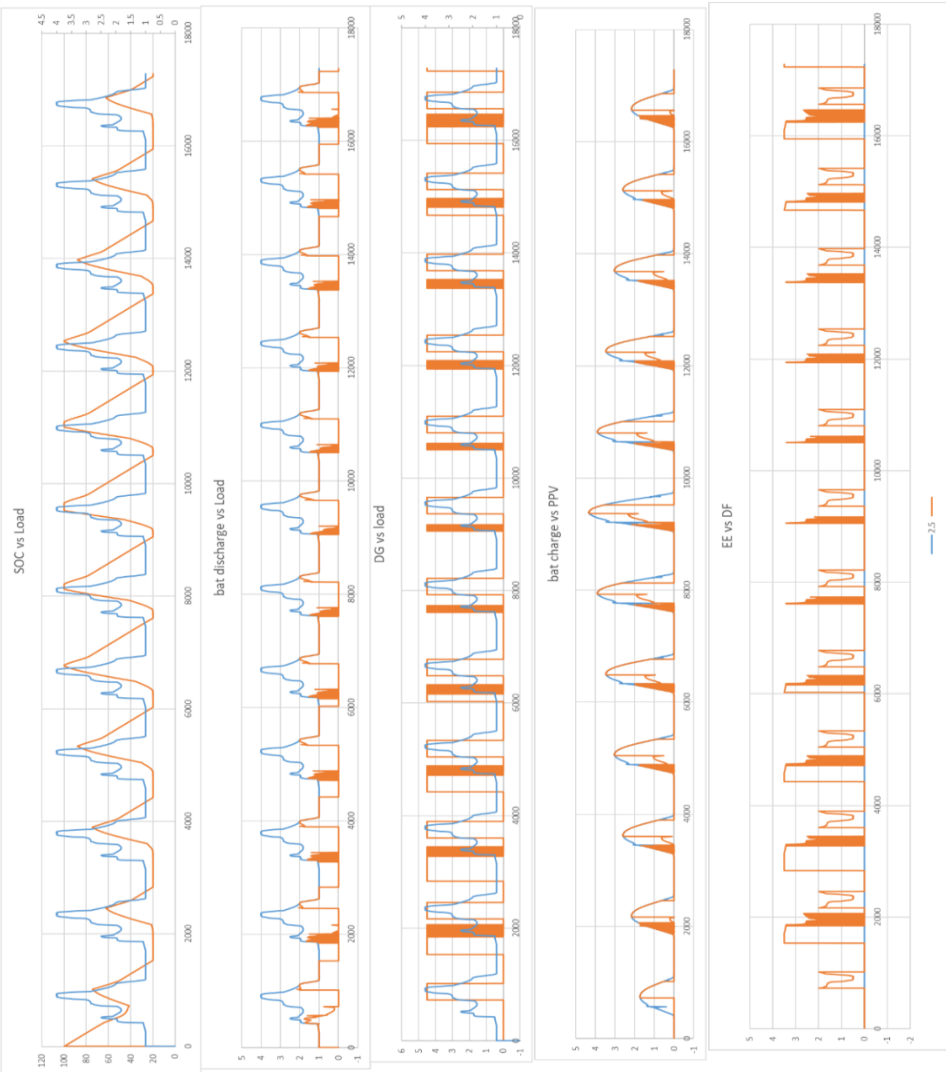


Fig.30

divided load supplying time between PV, DG, and battery system(Int-SCC)

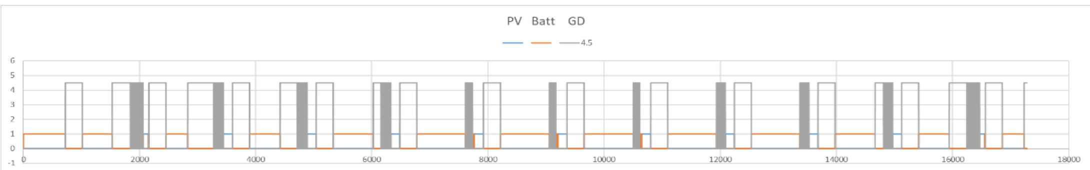


Fig.31

Cycle Charge dispatch simulation of the load following size based strategy (CC-SI)

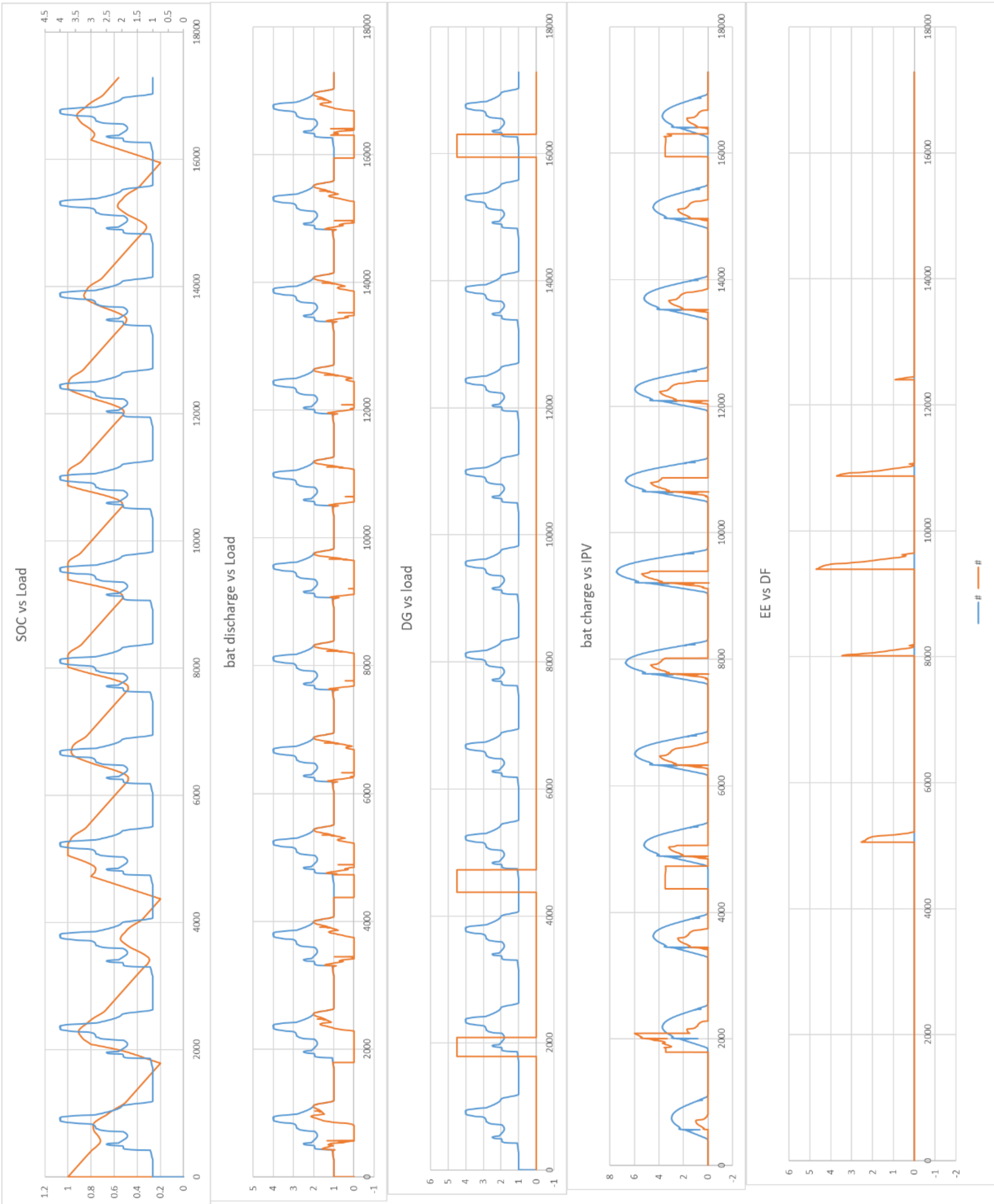


Fig.32

Cycle Charge dispatch simulation of the Intuitive method size (CC-SInt)

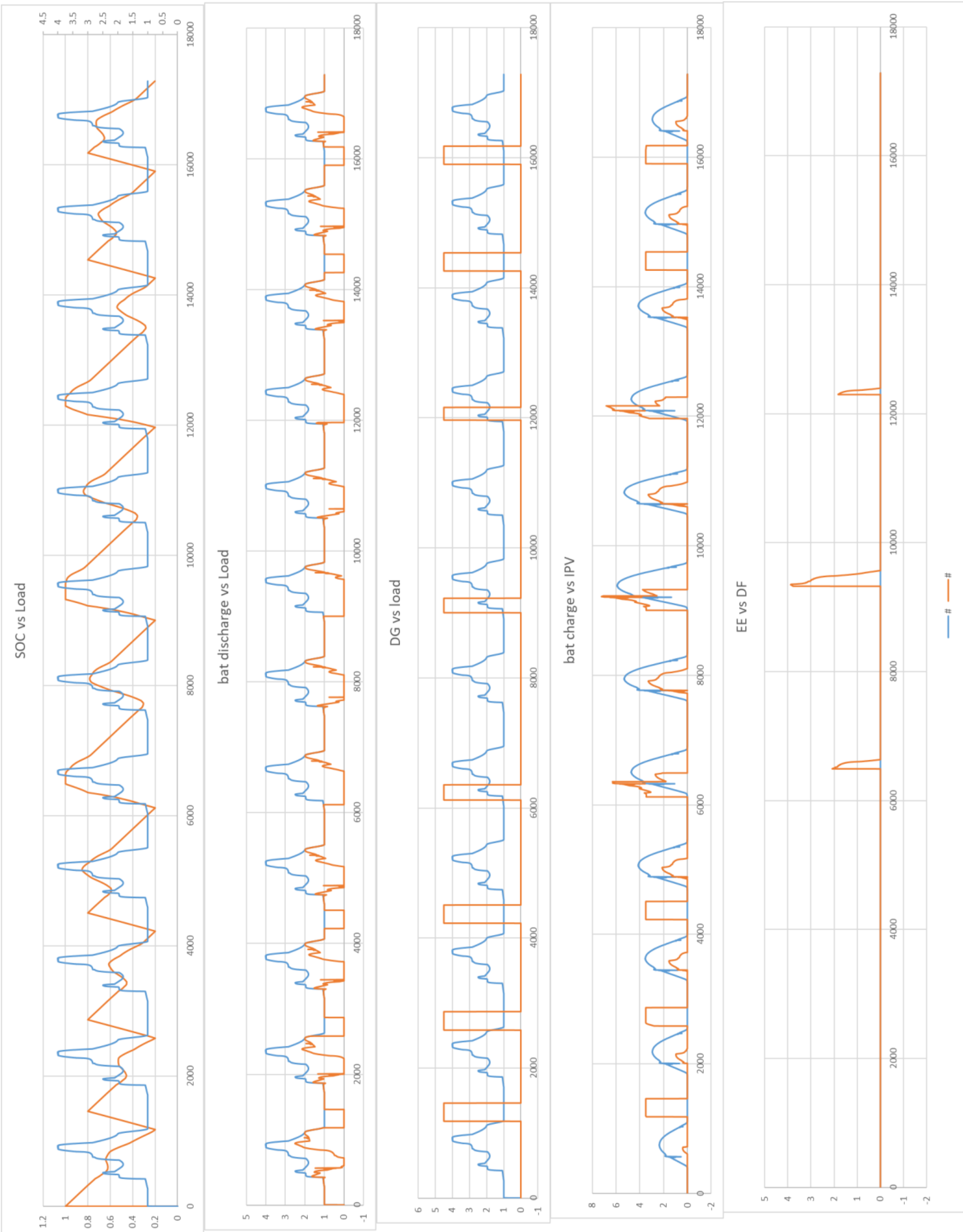
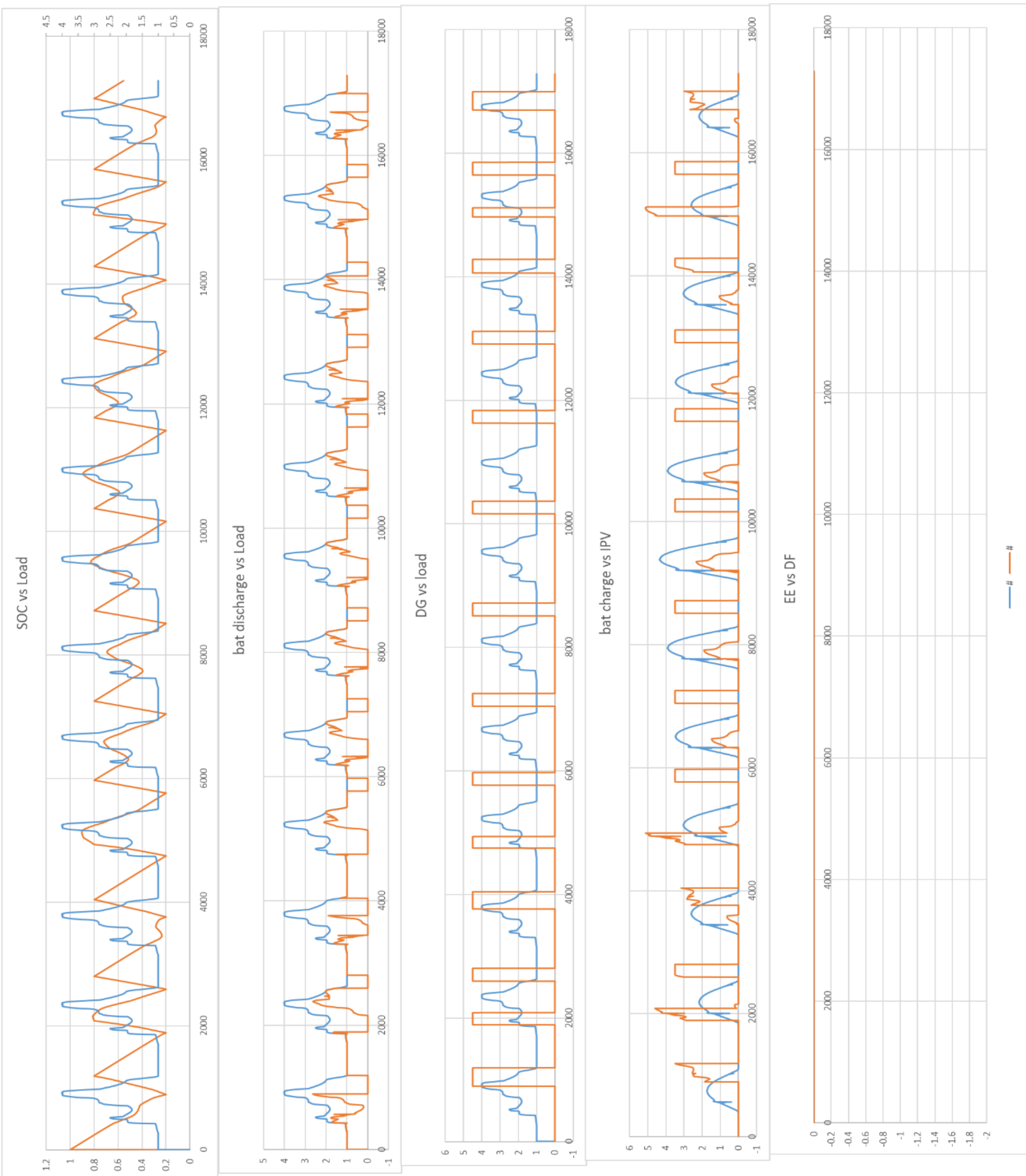


Fig.33

Cycle Charge dispatch simulation of the Cycle Charge size based strategy (CC-SInt)



جــامعـــــة النجاح الوطنية

كليـــة الدراســـــات العليـــا

نمذجة الخوارزميات التشغيلية لأنظمة الخلايا الكهروضوئية الهجينة مع مولدات الديزل

إعداد

أمجد محمد عبدالفتاح عداربة

إشراف

د. تامر الخطيب

قدمت هذه الرسالة استكمالا لمتطلبات الحصول على درجه الماجستير في هندسة الطاقة النظيفة وترشيد الإستهلاك، من كلية الدراسات العليا، في جامعة النجاح الوطنية، نابلس– فلسطين.

2022

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الملخص

إن العالم اليوم يواجه حالة من الزيادة المتسارعة على طلب الكهرباء، في ظل أن توسيع البنية التحتية للشبكة الكهربائية يستهلك مبالغ باهظة الثمن خاصة في المناطق الريفي، مما جعل النظام الهجين (الخلايا الكهروضوئية/مولد الديزل/ البطاريات) يُقدم كحل للمشكلة، بل وإعتباره الحل المثالي، وذلك نظراً لموثوقيته العالية و توليده لطاقة ذات تكلفة منخفضة مقارنةً بمصادر الطاقة التقليدية الأخرى. وقد هدفت هذه الاطروحة الى للحصول على أفضل حجم وإستراتيجية تَحكُّم وفقًا لمتطلبات وإهتمامات ظروف التشغيل المختلفة لهذه الأنظمة، وذلك عن طريق دراسة ومحاكاة وتلخيص ثلاثة طرق تَحكُّم مع إستراتيجيات التحجيم الخاصة بها للنظم الهجينة (خلايا الكهروضوئية/مولد الديزل/ البطاريات)، ومن خلال هذه الدراسة تبيين لنا أن الطريقة المثلى للتحكم بالأنظمة الهجينة هي إتباع استراتيجية تحكم دورة الشحنة مع حجم الاستراتيجية البديهية، وبذات الوقت يمكن أيضاً الحصول على إستراتيجية تحكم وحجم مثالية لكل متطلب من متطلبات ظروف التشغيل التالية: (تقليل حجم البطارية والخلايا الكهروضوئية، تقليل الوقت الذي تكون فيه البطاريات في حالة الشحنة الدنيا، تقليل دقائق عمل مولد الديزل، الحد من التبديل المتكرر بين مولد الديزل والبطاريات، زيادة تغذية الطاقة من مصادر متجددة، وتقليل الوقود المستهلك وتقليل نسبة الطاقة الزائدة غير المستخدمة).

وقد كانت تائج المقارنة بين الاستراتيجيات المختلفة هي كما يلي:

- أظهرت طريقة المحاكاة البديهية أن 59٪ من الطاقة المستهلكة جاءت من المصادر المتجددة بينما 41٪ تم توليدها من مولدات الديزل. 2800 دقيقة من وقت المحاكاة ، كانت البطاريات عند أدنى قيمة لحالة الشحن. 24٪ من الطاقة المولدة تعتبر طاقة زائدة للنظام، تم استهلاك 328 لترًا من الوقود
- أظهرت محاكاة دورة الشحن أن 90٪ من الطاقة المستهلكة جاءت من المصادر المتجددة بينما تم توليد 10٪ فقط من مولد الديزل. 26 دقيقة فقط من وقت المحاكاة ، كانت البطاريات عند الحد الأدنى لقيمة حالة الشحن ،35٪ من الطاقة المولدة تعتبر طاقة زائدة للنظام ، م استهلاك 156 لترًا من الوقود
- الحمل التالي أظهرت المحاكاة أن 73٪ من الطاقة المستهلكة جاءت من العوامل المتجددة بينما تم توليد 27٪ من مولدات الديزل. 708 دقيقة من وقت المحاكاة ، كانت البطاريات عند أدنى قيمة لحالة الشحن ،71٪ من الطاقة المولدة تعتبر طاقة زائدة للنظام وتم استهلاك 226 لترًا من الوقود.

كلمات مفتاحية: الأنظمة الهجينة، نمذجة الأنظمة، مولد ديزل، الطاقة الكهروضوئية، طرق التحكم، طاقة متجددة، تخزين الطاقة، حالة الشحن.