جامعة بيرزيت
BIRZEIT UNIVERSITY

Faculty of Engineering and Technology
Master in Electrical Engineering

A Study of Technical, Economical and Environmental Viability of a Microgrid

دراسة فنية واقتصادية وبيئية لفاعلية الشبكات الصغيرة

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Supervisor:

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June 2019

الإهداء

إلى والدتي منبع الحب والحنان والعطاء الغير منقطع...

إلى والدي قدوتي الأولى ونبراسي الذي ينير الطريق...

إلى أخي الصديق الأوفى الأقرب الى القلب...

إلى رفيقة دربي الرافعة الحقيقية في الحياة...

وإلى كل من ساعد وساهم لكي يرى هذا العمل النور؛

لفلسطين الحبيبة أهدي هذا العمل.

وديع فرَاج

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List of Abbreviations:

Combined Heat Power	*CHP*
Depth of Discharge	*DOD*
Diesel Generator	*DG*
General Algebraic Modeling System	*GAMS*
Institute of Electrical and Electronics Engineers	*IEEE*
Microgrid	*MG*
Mixed Integer Linear Programming	*MILP*
PhotoVoltaic	*PV*
Maximum Power Point Tracking	*MPPT*
Renewable Energy Sources	*RES*
Wind Turbine	*WT*

Abstract

Due to environmental and economic reasons, the world is moving from bulk generation towards distributed generation. Microgrids are group of distributed energy resources, loads, and storage units that are controllable within clearly defined electrical boundaries. Microgrids have the potential to provide better power quality, reliability, voltage profile, and outage management. The thesis aims at modeling and optimizing the size and operation of a microgrid. The microgrid must be able to exploit available resources such as solar, wind and other renewable energy sources. Technical and economic constraints will be taken into consideration. Distributed generation, storage units, and load profiles were added to a typical microgrid. A mixed integer linear programming model is used to find the optimal size of the different components then GAMS modeling language was used to find the optimal size of the different components, and the optimal strategy to be followed. This will enable the exploring of different scenarios. These scenarios are based on different parameters such as load and supply profiles.

In addition, this thesis aims to provide a framework that can be used to optimize the size and operation of a micorgrid. Solar irradiance and wind profiles have been used from the weather station at Birzeit University. Therefore, the data represents typical profiles in Palestine. Yet, the framework can be used to study building a microgrid in any location in the world. This approach exploits the available renewable energy resources and hence it provides an environmental friendly solution. Additionally, the approach takes the technical and economical constraints into consideration. The results show that a mix of energy resources provides a good technical and economical solution.

المستخلص

ينتقل العالم تدريجياً من توليد الطاقة المركزي بموردٍ واحدٍ الى توليد الطاقة بأقسامٍ بموارد مختلفة "المولدات الموزعة" بسبب الأوضاع الإقتصادية والبيئية الحالية."المايكروغريد" عبارة عن مجموعة من موارد الطاقة والأحمال والتخزين الموزعة، والتي يمكن التحكم بها ولها حدود كهربائية محددة.

تمتلك "المايكروغريد" القدرة على توفير جودة أفضل للطاقة، و تزيد من قدرة الاعتماد على الطاقة، بالإضافة للتحسين من جودة الجهد الكهربائي،والعمل على توفير بديل أفضل عند انقطاع الطاقة. وبهذا الخصوص فإن هذه الأطروحة تهدف إلى تصميم " المياكروغريد " والاستفادة المثلى من حجمه وعمله.

إن من شأن "المايكروغريد" أن يتمكن من استغلال الموارد المتاحة مثل الطاقة الشمسية، وطاقة الرياح، وأنواع أخرى من مصادر الطاقة المتجددة. وللتنويه سوف يتم الأخذ بعين الاعتبار القيود و المعيقات الاقتصادية والتقنية، حيث سوف نقوم بإضافة مولدات كهربائية وبطاريات للتخزين، وطبيعة وشكل الأحمال إلى "مايكروغريد" نموذجي.

سوف نلجأ لاستخدام برنامج "GAMS" من أجل إيجاد الحجم الأمثل للمكونات المختلفة ومن ثم الإستراتيجية التي تلي ذلك. بهذه الطريقة سيتم البحث في سيناريوهات مختلفة، هذه السيناريوهات ستحفز وستعمل على قياس الكميات الكهربائية على غرار الأحمال وخصائص المصادر الكهربائية.

يهدف هذا البحث إلى إيجاد إطار عملٍ من شأنه أن يصل إلى التصميم الأفضل ل"مايكروغريد"، لقد استخدمنا الإشعاع الشمسي وملامح الرياح من محطة الطقس في جامعة بيرزيت. لذلك تمثل هذه البيانات ملفات تعريف نموذجية في فلسطين، مع ذلك يمكن استخدام الإطار لدراسة بناء "المايكروغريد" في أي مكان في العالم. يستغل هذا النهج موارد الطاقة المتجددة المتاحة وبالتالي يوفر حلاً صديقًا للبيئة، بالإضافة إلى ذلك يأخذ القيود التقنية والاقتصادية بعين الاعتبار. لقد أظهرت النتائج أن مزيجًا من موارد الطاقة يوفر حلاً تقنيًا واقتصاديًا جيدًا.

Chapter 1: Introduction

The energy demand is constantly increasing along with the depletion of fossil fuel. This is causing the world to move towards deploying more distributed generation and in particular renewable energy sources (RES). These energy sources provide economic and environmental benefits. The concept of microgrid (MG), which is based on renewable energy, introduces a promising alternative to centralized generation. Many factories, companies and customers are using, or planning to use, MGs to cover their power demand. The idea of having MGs in different areas in Palestine, an occupied country with nearly no power production, has a huge benefit to the Palestinian economy.

Energy demand has increased proportionally with the increase of the world's population energy demand. This is causing governments and power utilities to take into consideration renewable energy as a solution for future energy demands as it comes from resources that are constantly replenished and sustainable. In addition, renewable energy is much cheaper than conventional energy sources. Figure 1 below shows the production of renewable energy worldwide by the year 2018:

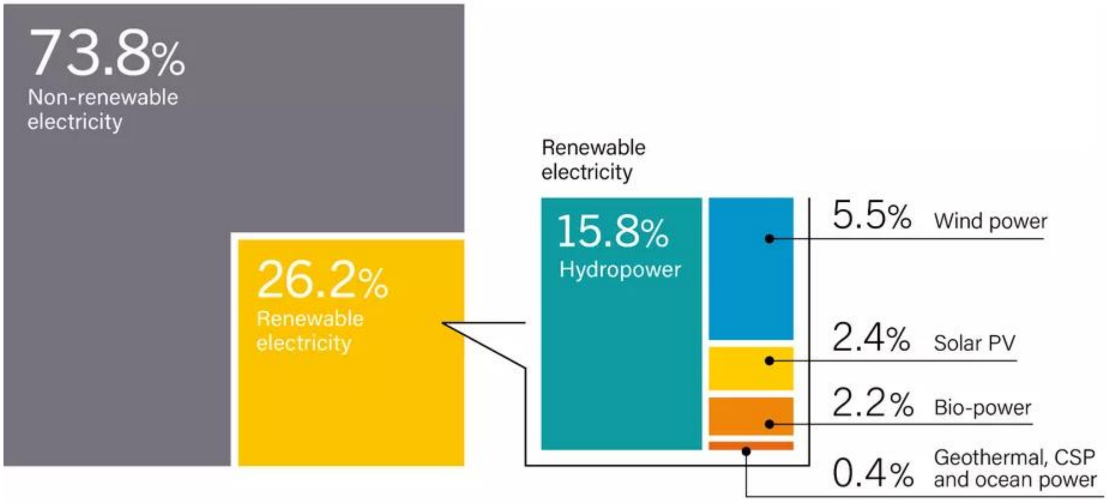

Figure 1 Renewable energy share of global electricity production [1]

RES in all countries has a huge impact on the number of jobs in the world. Figure 2 below shows the 2018 statistics for the number of jobs in the renewable energy industry worldwide:

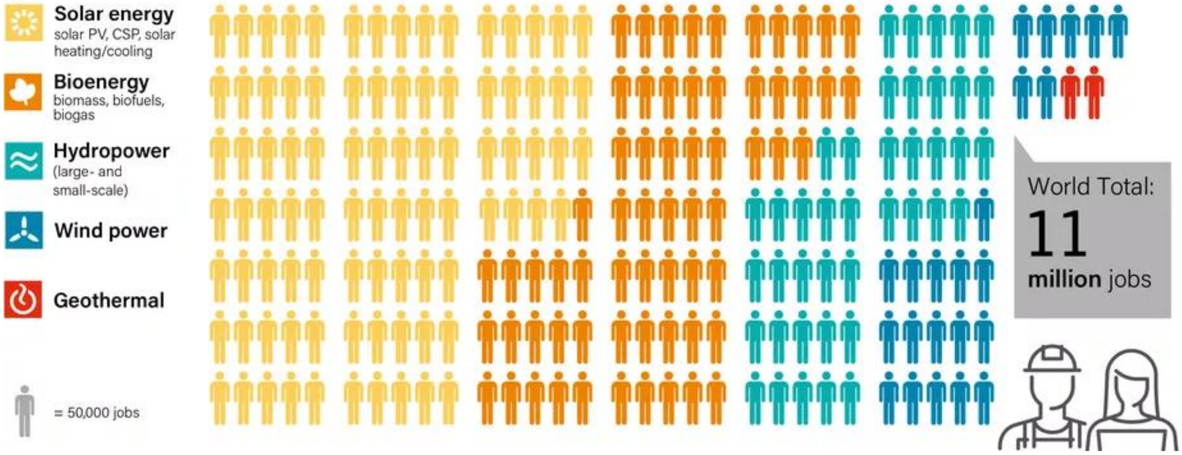

Figure 2 year 2018 jobs in renewable energy industry [1]

In addition, MGs are part of evolving electricity grids due to the potential to improve reliability, increase penetration rates for renewable generation and reduction of cost. MGs are defined as a cluster of small sources and storage systems that are controllable; MGs can be connected on the main grid or can be independent from it. In Palestine there are only few small power generation plants and the majority of the power is bought from the Israeli occupation or Jordan. Economically it is very important to involve MGs that are based on RES in power production. Of course, other countries relate to MGs both because of its economic benefit, and because MGs are considered more environmentally friendly. This work will take local and international locations to build a model for the optimal MG design.

In general, MGs have been developed and enhanced for the main following benefits:

- MGs can provide better reliability and power quality in cases of blackouts on the grid. MGs can also reduce the central generation reserve requirements [2, 3].
- MGs reduce voltage sags and support voltage [4].

- MGs have great environmental benefits when emission credits are considered.
- MGs are considered economic since they are localized. As such, some transmission infrastructure can be disregarded; in addition, combined heat power technology (CHP) can be applied in MGs to reduce energy consumption [5].
- MGs are one of the most important solutions for energy generation in far and remote areas with no utility service.

MGs mainly consist of power conversion equipment, energy resources, controllers, communication and management system and, of course, load/customer that the MG is implemented for. Figure 3 below shows the main components of MGs [6, 7]:

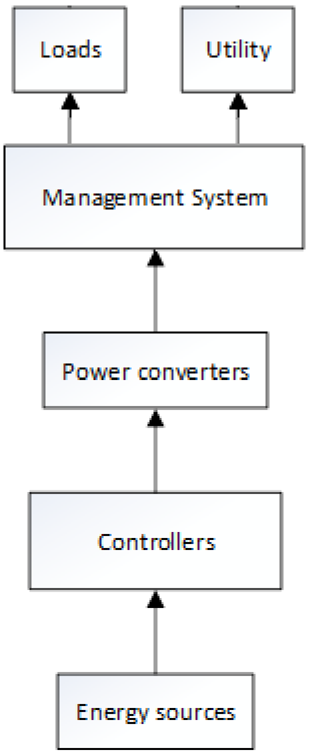

Figure 3 Microgrid key components

An example of a MG system is based on data from a weather station in Palestine. Yet this framework can be used to study building a MG in any location in the world. This work aims to model and optimize the operation of a MG-sized system to cover all the power demand serving the neighborhood. The MG will be based on different RES that are able to use local energy resources such as sun, wind and others.

The aim of this work is to address the optimal design for the MG that is needed to answer the autonomy of the neighborhood, and to clarify the economic and environmental benefits. In addition, the key problems that arise will be introduced. A mixed integer linear programming (MILP) model will be proposed to find the optimal sizes of the different components of the MG. Hence the thesis is organized as follows: Chapter 2 presents an overview on MGs and its components; in addition, it discusses the advantages and disadvantages of MGs and MG’s reliability. Chapter 2 also overviews the distributed generation and elaborates on the world energy production and energy sources such as photovoltaic (PV), wind turbine (WT), diesel generator (DG), storage and biomass. Chapter 3 explores the related work on MGs and similar studies. Chapter 4 details the modeling of the components and optimization problem. Chapter 5 presents the software tool and the load profile; in addition, this chapter includes case studies, results and discussion. Chapter 6 presents a final conclusion for this work.

Chapter 2: Microgrids Theory Components

2.1 Microgrids: An Overview

A MG is considered a small-scale power grid that has the ability to work independently or being connected with other small power grids. Any small power system that is considered a localized power station and has its own generation sources and storage or backup sources, with defied boundaries and constrains can be referred to as a MG. The definition and type referred to as a MG differs depending on whether the MG is connected to a grid or not. A MG is often supported by generators or WT system and solar system or all combined; if the MG is connected to the main grid it would provide backup power for the periods that has high demand.

MGs are defined in Cambridge dictionary as: “an electricity grid system of electricity wires for a small area not connected to a country's main electrical grid” [8]. While the American Department of Energy defines the MGs as: ‘‘a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid” [9].

Whenever a MG is implemented in an electrical distribution system, it must be well planned to avoid problems. The Institute of Electrical and Electronics Engineers (IEEE) Standard 1547 has been a foundational document about the interconnection of distributed energy resources, in addition IEEE 1547 provides functional technical requirements and specifications, also it provides flexible choices about operation mode, equipment that are in compliance with the standard [10].

IEEE 1547.4 covers key consideration for planning and operating MGs. This includes: impacts of voltage, frequency, power quality, inclusion of single point of common coupling and multiple PCCs, protection schemes and modifications, monitoring, information exchange and control. The standard discusses the normal operating modes of a MG. Strategies can be used to maintain operation of the system under parallel and island modes [11].

Since MGs are defined whether connected to the grid or not, in addition to the importance of size, MG’s can be classified into three main types [12]:

1. Remote MG: where the integrated level is low and the MG has no impact on the utility. The role of this type is to provide electricity as an independent system and this type is used for distant areas.
2. Complement MG: where the integrated level is middle and has little impact on the utility. The role of this type is to provide a complement power for important loads and this type is used where the large utility grid is mature and evolved.
3. Support MG: where the integrated level is high and the MG has a huge impact on the utility. The role of this type is to support the utility power system and this type is used where the renewable energy is rapidly developed.

In addition to what was mentioned above regarding MG types, different criteria must be speculated in order to define the category of the MG. Criteria such as whether the MG is connected to the grid or not; whether the generation is dispatchable or not; the voltage level of the MG; whether the MG is single phase or three phase; the size of the peak load; the size of the generation capacity; the number of customers, load management, metering and control.

2.2 Microgrids Components

The typical components of any MG can be classified as follows [13]:

1. Generation: in order to provide power to the load that is connected to the MG -whether it's connected to the grid or not- every MG must have a source of generation. The source of generation could be PV, WT, DG, biogas, biomass or any other generation source. The choice and percentage of penetration for each energy source depends on the availability for RES and other considerations such as cost of installation and power sell/buy costs.
2. Energy storage: Almost all MG's have energy storage systems that allow the power system to store the energy when it is producing above demand, and to return energy when the demand exceeds the supply.
3. Load Control: The ability to control loads relating to the optimization of the generation and storage resources, hence feeding the critical loads with power and disregarding the non-critical loads which can be automatically shut off to keep power flow for critical loads.

4. Utility Interconnection: An important design feature for a MG that has a connection with power grid. There are MGs that have a parallel operation with the utility system. On the other hand, there are islanded MGs with the option to be connected completely on a utility power system.
5. MG Control System: The control system in a MG connects all components together and has a critical role to maintain the balance of the generation and load. In advances, MG control systems are designed with software, sensors, metering and commutation paths for optimization and control.

Figure 4 below shows a possible configuration of MG:

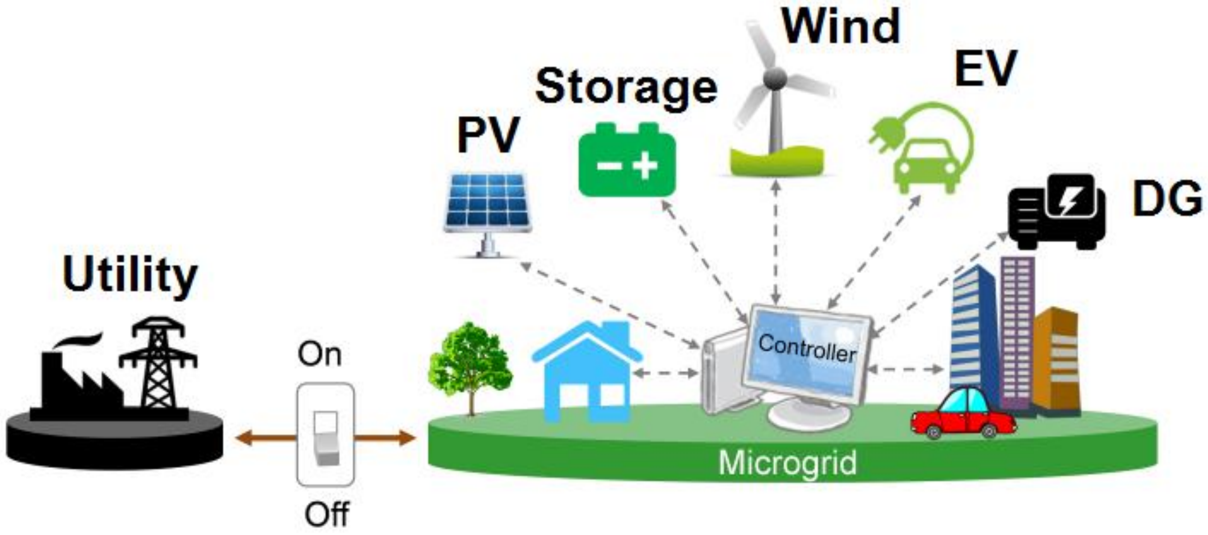

Figure 4 Possible configuration of MG [14]

2.3 Advantages and Technical Challenges of Microgrids

MGs are considered a hot topic to utilities, researchers and some governments since they can improve the efficiency of the utility power system. MGs also offer power disaster relief during disasters and crises. In addition, MGs are environmentally friendly, and they create jobs. The advantages of MGs can be noted as follows [2-4]:

1. Financial Benefits: MGs have financial benefits such as payback value since the RES have low operation cost in addition to the capital installation cost.
2. Reliability: MGs provide power from multiple resources so MGs can provide power even when extreme weather conditions cause power lines to fall down; hence enhancing reliability.
3. Faster construction: MGs are easy to install in remote areas without an existing power utility system, which makes MGs a faster solution for expanding a power system with the population growth in the world.
4. Grid connection/disconnection: The ability to connect and disconnect form utility system and operate independently.

5. Power enhancement: Reducing the demand on utility grid; and reducing voltage sags and supporting voltage.
6. Environmental benefits: MGs have great environmental benefits given that MGs use renewable energy generation technologies.

There are some technical challenges to be noted for MGs. The disadvantages can be summarized as follows [15]:

1. Complexity of design: The expanding number of distributed generation causes a more complicated design for MG.
2. Regulations: There are many laws in many countries that have the power generation centralized within utilities and have not caught up with the technology.
3. Storage challenge: MGs require battery storage which are expensive and require space and maintenance.
4. Resynchronization: The issue of resynchronization of MG to utility grid and vice versa.
5. Protection: The protection in MGs is very difficult since the MG is a combination of many RES, and other sources.

6. Power standards: MGs must always fall within voltage, frequency and power quality's acceptable limits.

2.4 Reliability of Microgrids

Reliability is the probability of a system performing its purpose for the intended period of time under specific operating conditions. In MGs, reliability analysis involves that MGs have different energy sources and backup systems which means that the system performing its purpose depends on many sources not a single point of failure.

The introduction of RES into the power system has a great attention because of the impact on improving reliability of any utility power system and due to the reduction of fuel cost, reduction of operation and maintenance costs and lowering harmful emissions. MGs have answered to the challenge of meeting the load requirements of people that live in remote areas in the most cost-effective way that cuts down all of the cost of extending the transmission and distribution lines to these remote areas. Additionally, it reduces the side effects of harmful gas emission from traditional power generation systems [16].

The complexity in modeling the RES is variable due to nature. Hence, the modeling for reliability studies is difficult and most MGs have a priority order for the loads that must be considered in order to maintain the electrical supply to these sensitive loads in case of insufficient generation.

There are several techniques in order to evaluate the reliability at customer point in the MG and these methods can be concluded in the following [17]:

1. Analytical methods: which consider the topology of the network in addition to the failure and repair rates of the components in the network.
2. Simulation methods: which takes into consideration the chronology of variation of RES in addition to the priority order of the loads.
3. Hybrid methods: which includes both analytical and simulation techniques to evaluate the reliability at customers points in a MG containing WT and PV generation and prioritized loads.

The outputs of the RES depend on different factors such as weather and geographical location which must be noted in order to study reliability for PV or wind. In addition, RES have their own failure rates and repair time. Models including all of what has been mentioned must be used in order to introduce the models for reliability studies.

2.5 Photovoltaic System

Solar power generation is one of the most rapidly growing sources of renewable energy-electricity. It has several advantages over other forms of electricity generations including the elimination of CO2 and greenhouse gases that are inherent to the use of fossil fuels. Clearly, emissions of CO2 and greenhouse gases tend to cause harm to the ozone layer and cause global warming. The photo-voltaic (PV) systems are also guided by electrical codes and standards.

To generate power, the PV array produces power when exposed to sunlight. As PV array is connected to many components, it conducts, converts, stores, distributes and controls the power out of the PV array. Clearly, the components depend on the chosen PV system. After determining what type of PV system should be used, sizing becomes critical. The size of the array, battery bank, and other major components must be carefully calculated.

Sizing is an important part of planning any PV system, but it is particularly stringent for PV systems like stand-alone systems. Standalone systems have batteries that are used to store excess energy generated during the daytime to be used at night. The storage capacity of these batteries is critical in the design in order to provide a reliable system with certain number of autonomy days, and it ensures system availability and reliability [18].

There are several PV systems types; they all have their advantages and disadvantages where the PV system type is chosen depending on the function that the system will perform. The types of PV systems include:

1. Interactive PV Systems (Grid-tied): Interactive systems generate solar power and route it to loads and to the power grid. Grid tied systems require few simple calculations and have wide variance in component sizing and no protection.

2. Standalone Systems (Off-grid): Stand-alone PV systems are independent from the power grid, where the system includes storage and is sized in a way which is directly proportional to the load requirements. Hence the design is to power up specific on-site loads.
3. Hybrid Systems: Hybrid systems combine multiple energy sources of power such as PV and wind. Hybrid systems include storage and they do not depend on the utility as a source of power.

There are specific components used in the PV system that depend on the function and operation desired, which means they depend on the type of PV system used and what is required for the system. These specific components are:

- Power generator: This is the PV array to be used.
- Power conditioning equipment: inverters, control and protection equipment.
- Power storage: batteries.
- Cables.
- Control system.

The Figures below (5 & 6) show standalone PV system and hybrid PV system components and connectivity:

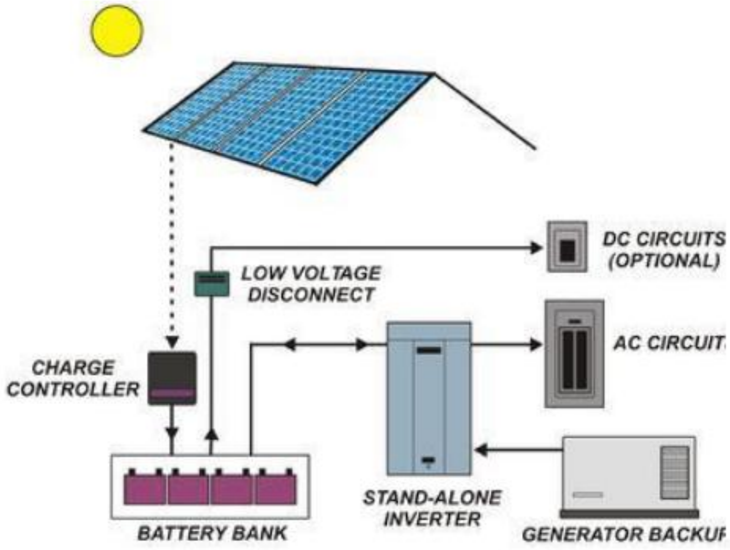

Figure 5 Standalone PV system [19]

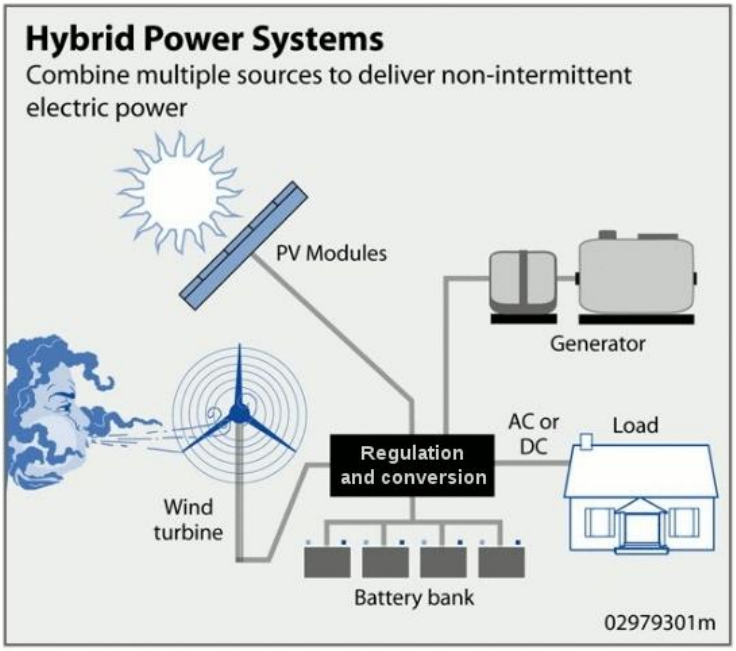

Figure 6 Hybrid PV power system [20]

Photovoltaic Sizing

Sizing is very important for electrical systems that include PV as a source of energy. The type of PV system must be defined at first, and then the size of array, battery bank, controls and other major components must be carefully calculated in order to meet the load requirements.

The sizing of a PV system depends on the type of system chosen. Below are some parameters that are very important in sizing a PV system:

- The power requirements from load profile.
- Critical design parameters that are based on monthly load and insolation.
- The size and configuration of the backup batteries that are based on system requirements.
- The size and configuration of the arrays that are based on system requirements.

For the system at hand, and since it will contain additional energy resource, hybrid PV system sizing is considered in the following steps:

- First: backup battery banks can be sized for shorter time periods than for stand-alone PV systems since there are other energy resources.
- Second: the array is sized to power up only parts of the load.
- Finally: In hybrid systems, the PV sizing calculations doesn’t require the worst-case load; the average load profile can be used instead in addition to insolation values.

2.6 Batteries

An electric battery is an electrochemical device that converts the stored chemical energy to electrical energy. It contains one or more cells that consist of anode and cathode.

Electrical storage batteries are divided into two types: primary batteries and secondary batteries.

Primary Batteries

The primary batteries can store and deliver electrical energy, but they cannot be recharged. This means that they cannot be used in PV system.

Secondary Batteries

The secondary batteries can store and deliver the electrical energy. These types of batteries are rechargeable by passing the current in opposite direction.

Batteries Comparison

The PV batteries differ from other types of batteries in that they are required to have deep discharge capability without being affected. During the life time of a PV standalone or hybrid system (which is estimated at 20-25 years), the batteries usually need to be replaced at one point in time. This depends on the technology used to build the PV battery, and in order to be able to manage the available battery capacity and estimate the time of battery replacement.

There are several types of secondary batteries that are used in PV systems, where the mostly used types are:

- Lead-acid battery.
- Nickel–metal hydride battery.
- Nickel–cadmium battery.
- Lithium-ion battery.

Batteries are chosen depending on several specifications such as the battery’s capacity, power ratings, depth of discharge (DoD), efficiency, cost and number of cycles. The top two choices for PV systems are the lithium ion and lead acid batteries [21]. A comparison between the two batteries is shown below:

Table I: Performance analysis of batteries [22]

Item	***Lead Acid***	***Lithium-Ion***
Operating temperature	18C to 45C	20C TO 65C
Environment	Damaging	Damaging
Safety transportation	Not good	Good
Cycles at 80% DOD	450	1000
High Current Discharge	Not advisable	Sustainable
Usage Life	2-3 Years	5-6 Years
Performance	Average	Good
Recyclability	Good	Poor
Size	Average	Small

The voltage of any battery is the nominal voltage of the battery cells which depends on the active chemicals that are used in the cell. The voltage of the cell measured at any time varies with load, internal impedance of the cell, usage life, operating temperature, and state of charge [23].

Batteries are also compared in extreme operation conditions such as high temperatures and excessive charging and discharging. The less resilient battery types in extreme condition will be harmed. This is looked at from a cost related point of view considering operating temperature and number of cycles. Table 2 below shows a cost comparison between the two types of batteries; lead acid and lithium-ion:

Table II: Cost comparison between lead acid & lithium-ion [24]

Item	***Flooded Lead Acid***	***Lithium-Ion***
Initial cost per capacity ($/ kWh)	131	530
Cost per Life Cycle ($/ kWh)	0.17$	0.19$
Regular Maintenance	Yes	No

2.7 Wind Turbines

WTs operate on a simple principle; the energy which is carried in the wind turns the blades that are on the WT around a rotor. The rotor is connected to the main shaft, which spins a generator to create electricity. New WTs models are divided into two main categories: the vertical-axis design and the horizontal-axis variety. Horizontal-axis WTs typically have either two or three blades. These three-bladed WTs are operated "upwind," with the blades facing into the wind.

The Components of WT system are:

- Foundation.
- Tower.
- Nacelle.
- Hub and rotor.
- Gear box.
- Generator.
- Yaw & Pitch.
- Braking.
- Power electronics and cooling.

The wind power equation is expressed as the following:

$$P = \frac{1}{2} x\ \rho \text{ x A x E x } v^3 \qquad (1)$$

Where,

P	Power in Watts
ρ	Air Density in Kg/m³
A	Rotor Swept Area in m
V	Wind Speed in m/s
E	Efficiency in percent

Figure 7 below demonstrates the characteristics of the power curve for the WTs models used in this work:

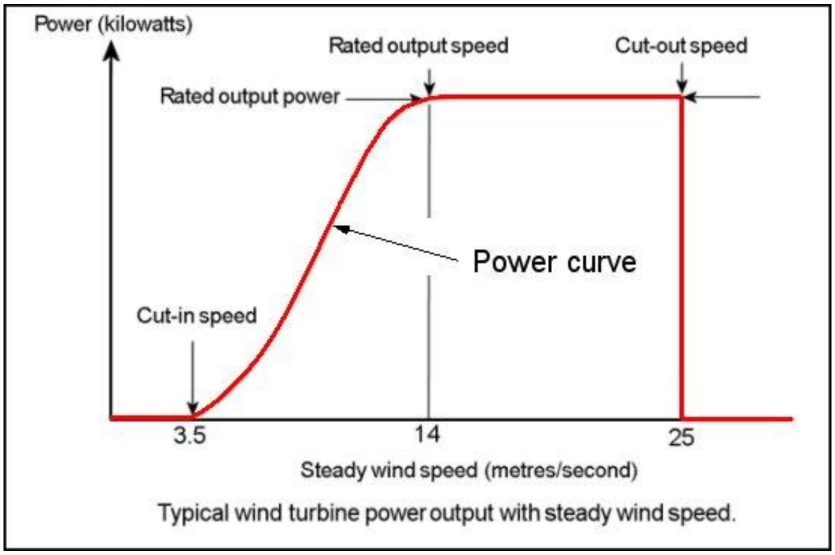

Figure 7 Power curve for Wind Turbine [25]

As shown in Figure 7, at low speed, typically less than 3 m/s, there is insufficient torque exerted by the wind; this is called the cut-in speed. Next to that the relationship between speed and power is proportional till it reaches rated output speed, and at this point the plant gives rated output power. After this point at 14 m/s any increase of the speed will not cause a rise in output power. This occurs as a result of torque control by simply adjusting the blade angle [26].

If the speed still increases and achieves a constant toque it would be too harsh for the turbine in terms of structure either dynamically or statically. Beyond the speed of 25 m/s the rotor will fail. It is necessary to insert a braking system in order to avoid high speeds and to bring the rotor to standstill.

Wind Turbines Utility Scale

Utility-scale turbines range in capacity from 100 kilowatts up to a number of megawatts. Larger WTs are linked together to form wind farms and are more cost effective, and thus provide bulk power to the electrical grid. Offshore WTs are much bigger; they can produce more energy with the additional benefit of not having the same transportation challenges of the land WTs installation, since the offshore WTs can be transported on big ships instead of transporting them on streets [27].

Single Small Turbine

These are turbines that produce less than 100 kilowatts. Single small turbines are used for homes, telecommunication dishes. Sometimes single small turbines are connected with a solar system, backup batteries and a DG. This combination of different resources for the power system is called the hybrid system, which is mainly used in far and off-grid locations that have no transmission lines or any connection to the utility [28].

2.8 Diesel Generators

A DG consists of the diesel engine with an electric generator that are combined together in order to generate electrical energy. DGs are mostly used in places that have no connection to the utility, or it is used as backup or emergency supply if the utility power fails to supply the load. DGs can be used for complex applications such as supporting the power grid.

Diesel Generator Sizing

Proper sizing of DGs is very critical to overcome shortage of power. Hence sizing depends on the type of appliances and the load that will be powered from the generator [29]. Generating models and sets are chosen depending on the load to be supplied; by taking into consideration the electrical load's characteristics such as kW, kVA, kVAR, harmonic content, non-linear loads and surge currents. The expected way of operation and duty time as well as environmental conditions must also be considered. The capital cost is the primary concern for backup generators, where the typical operating cost of DGs depends on fuel consumption [30].

Synchronization is the method to connect generators electrically together. It involves matching voltage, frequency and phase before connecting the generator to the system. As for load sharing for parallel running generators it can be accomplished by using droop speed control that is controlled by the frequency at the generator. This is because it keeps adjusting the engine fuel control to shift load to and from the remaining power sources.

Diesel Generator in Island Mode

The island mode in DG is when the DG is operating with no connectivity to the utility. For example, if an islanded power plant is needed as a main power source for an isolated neighborhood. It will have a number of generators; some are rated to carry the required load and one or more for load rising or backup.

DGs can be operated in island mode in combination with renewable energy such as solar power or wind power. This combination could be applied by maximizing the utilization of renewable energy and minimizing the diesel fuel consumption.

A combination of a solar power system with a diesel engine generator is shown in Figure 8 below, where the system has a controller to measure the power produced by each source as a percentage of the demand in order to switch between the two sources at a certain threshold.

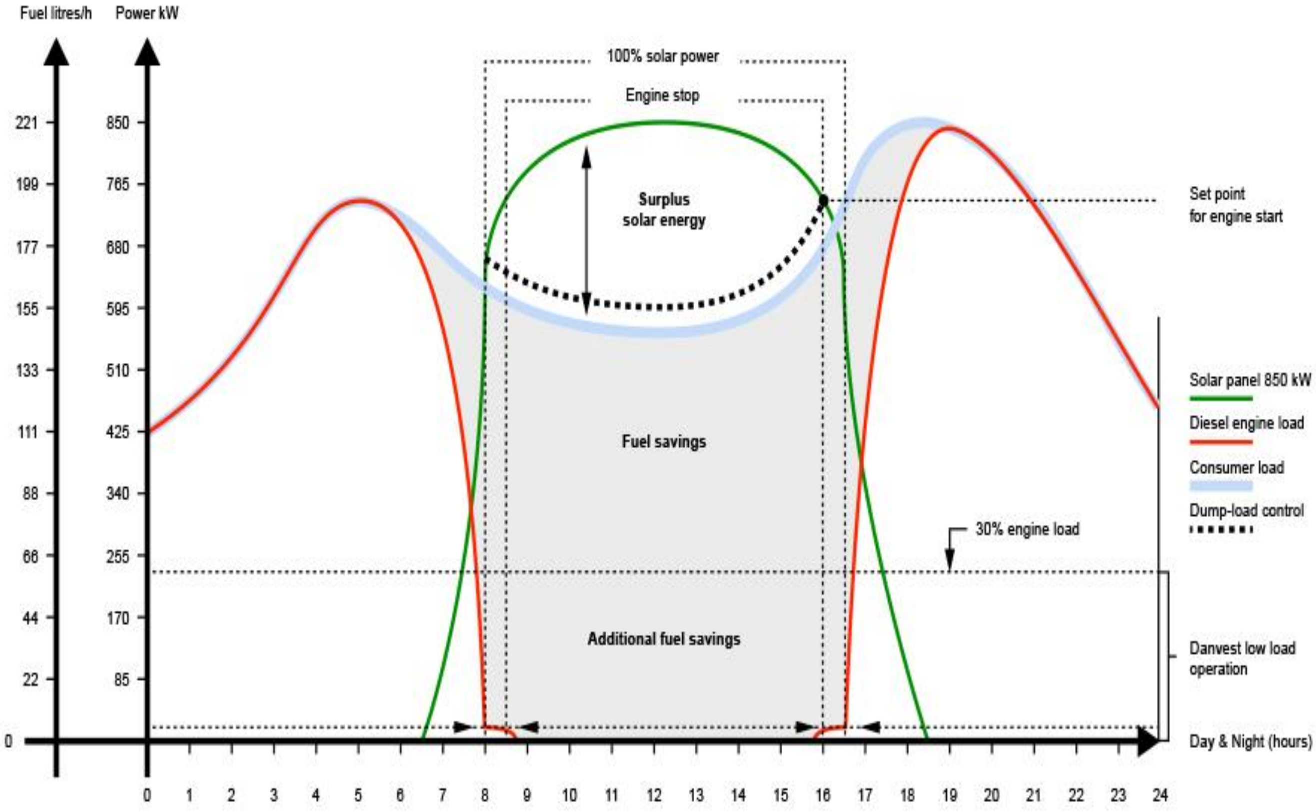

Figure 8 Combination between PV and diesel generator [31]

Chapter 3: Literature Review

MGs are described as a small local energy network. MGs include loads, control system and several energy resources, such as PV cells, generators, WTs and batteries. MGs can be applied for single consumer, community MG with multiple consumers; and utility MG with supply resources on utility side with consumer utility objectives [32].

MGs can provide reliability and better power quality and they also support voltage and reduce voltage sags [33]. Of course, MGs based on renewable energy have environmental benefits since they decrease the dependency on energy sources that have harmful emissions such as oil. In addition, there are many economic benefits for using MGs such as having a local MG which produces power and then selling the excess of it in a short payback period.

Different studies classify MGs into two main groups: system design and operation planning. System design involves the selection and sizing of the energy resources with minimum cost taking into consideration environmental affects, hence the investment cost must be minimized [34, 35]. The design in system design group of MGs is based on the hourly energy demand profile with dynamic nature and is critical for the voltage levels; the reliability of the system and power flow [36]. The selection technique is based on a number of constrains such as maintenance cost, weather conditions and energy loads.

Operation planning on the other hand targets short-term supply in case of power failures and disturbances or variability of RES. The performance of the MGs in operation planning group is outstanding. The optimal operation of MG includes two functions: supply side management where energy management decides to include energy resources and sells to the grid; while demand side management optimizes the generation through demand modification [37].

MGs can be designed as AC or DC or hybrid MGs. Since RES like solar PV are DC, where RES like wind generators are AC, a hybrid MG containing both the AC and DC sources would be more efficient than either DC or AC MG. A new configuration for future power systems which is the hybrid AC/DC gird for a high efficient connection of the inherent AC and DC sources and loads is presented in [38]. MG modular designs that is a based on PV system that shows information of solar irradiance on site, performance, observations and power quality is one of the approaches of designing a MG [39]. Another approach of designing a smart MG with storage can be done by simultaneously integrating the energy management and sizing a small MG with storage. Through this, the complexity of the resulting optimization problem is drawn and solved by using suitable optimization methods [40]. Figure 9 below shows AC couple system and DC/AC couple system:

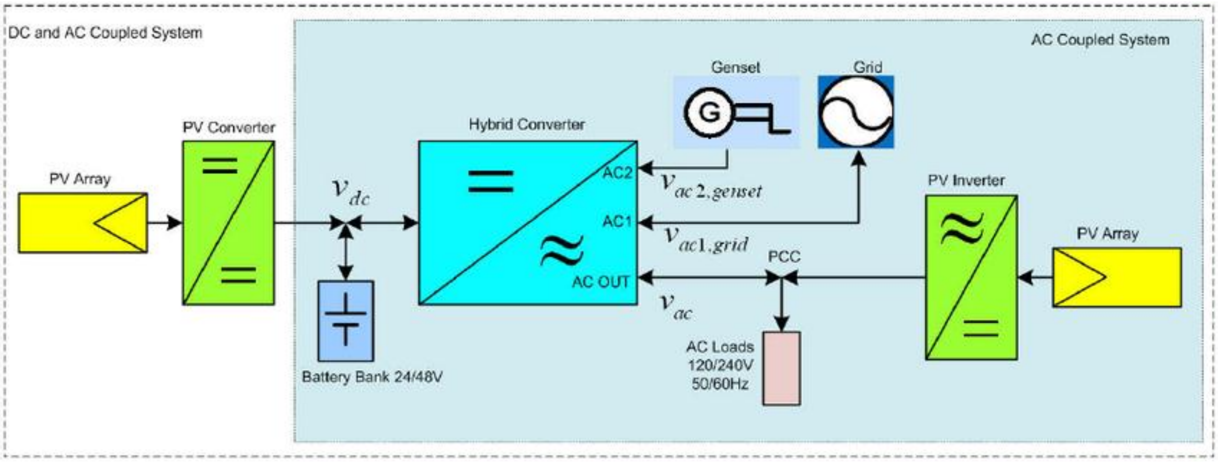

Figure 9 AC couple system and DC/AC couple system

One of the concerns regarding MGs is the reliability in islanded operation. A graph partitioning and integer programming integrated method for the optimal loop-based MG topology planning is presented in

[41]. While hybrid islanding detection based on the probability of islanding for MGs with multiple connection points that is calculated at the MG and side, and then sent to the control of the MG is proposed in [42]. Also, the probability of islanding for the MG values is processed by discrete wavelet transform by using an artificial neural network.

Many control systems and schemes are used and developed for MGs to optimize the system or to solve and troubleshoot different problems that arise depending on the system's topology and design. In the case of PV systems in autonomous MG, the traditional power system slows down the system's frequency response, and thus the control for the system. On the other hand, the autonomous renewable MG usually has much smaller inertia than a power system; the control system is fast and accurate to fight against uncertainties. Reducing the demand requirements on the control can be accomplished by increasing the inertia of the PV system through inertial emulation [43].

Adaptive sliding mode control is introduced in [44] to control a standalone single-phase MG system with hydro turbine generator, wind DC generator, solar photo-voltaic array and battery energy storage. For

DC MGs, three novel non-linear droop control techniques are proposed to overcome sensor calibration and cable resistance which affect load sharing and voltage regulation [45].

Many researches have worked on the optimal MG in technical, economic and environmental sense; Di Zhang's thesis [46] investigated several problems in the optimal design and scheduling of MG, along with concerns of cost. Similar mathematical models were developed in the thesis using mixed integer linear programming (MILP). The research, however, involved optimal scheduling of smart homes in order to study the electrical consumption. Peak demand reduction and cost savings were obtained via energy resources operation managements and energy consumptions.

Much more constrains were considered in Di Zhang's thesis [46] since the research included combined heat and power (CHP), thermal storage, demand, state of charge (SOC) and degradation cost. The research worked on optimal design and pricing in a MG, optimal energy consumption scheduling and operation management of smart homes, and optimal scheduling of electrical vehicle battery usage with degradation.

In this research CHP will not be considered, in addition to thermal storage and SOC. Although optimal design and pricing will be calculated and simulated in this work, scheduling and operation management will not be introduced since this research will focus on the optimal design of a MG in addition to cost minimization and environmental benefits.

An optimal size of PV/wind/diesel system with battery storage to an off-grid remote region was studied as a case study in Rafsanjan, Iran in [47]. The hybrid system must always satisfy the load at any given time. Of course, the system includes PV and WT which are dependent on the variation of the resources, and also the load demand fluctuates. Cost minimization was also considered in order to find the optimal size for the system.

The system was modeled and implemented in [47] on Matlab software. The optimization of PV/wind/diesel/battery-based hybrid system for a remote area was simulated, and it was found that using wind/diesel/battery is the optimal system which is the most cost-effective.

In this work similar approach is considered for the same PV/wind/diesel/battery-based hybrid system, but for a different region so the resources (wind and irradiance) that the WT and PV systems are dependent on will have different values. The results, therefore, will be different on what is the optimal system which is the most cost-effective. In addition, the bus in [47] is a DC bus; in this work, however, the bus will be an AC bus.

Chapter 4: Optimal Sizing of PV/WT MG Using Numerical Algorithm

4.1 Optimization

A solar PV and wind systems can’t produce energy continuously at all times. This is because these systems can generate power only if the weather is windy or if there is enough solar irradiation from the sun. Combining these two sources, therefore, will most definitely improve the total overall output power especially if they are tied to the power grid. The traditional sizing method for the hybrid solar PV and WT systems is based on availability of long-term weather data such as solar radiation and wind speed. In addition, the power requirements from the load profile are needed in order to have proper sizing for both the PV system and the WT system and to maximize the utilization of the renewable energy systems.

After the weather data is collected, the system will be modeled with different proposed scenarios; here the scenarios are based on cost, penetration percentage for each source. The scenarios must be optimized in order to find the optimal design in reliability and cost minimization terms. Figure 10 below shows the flowchart of the simulation process that is followed by uploading weather and load profiles:

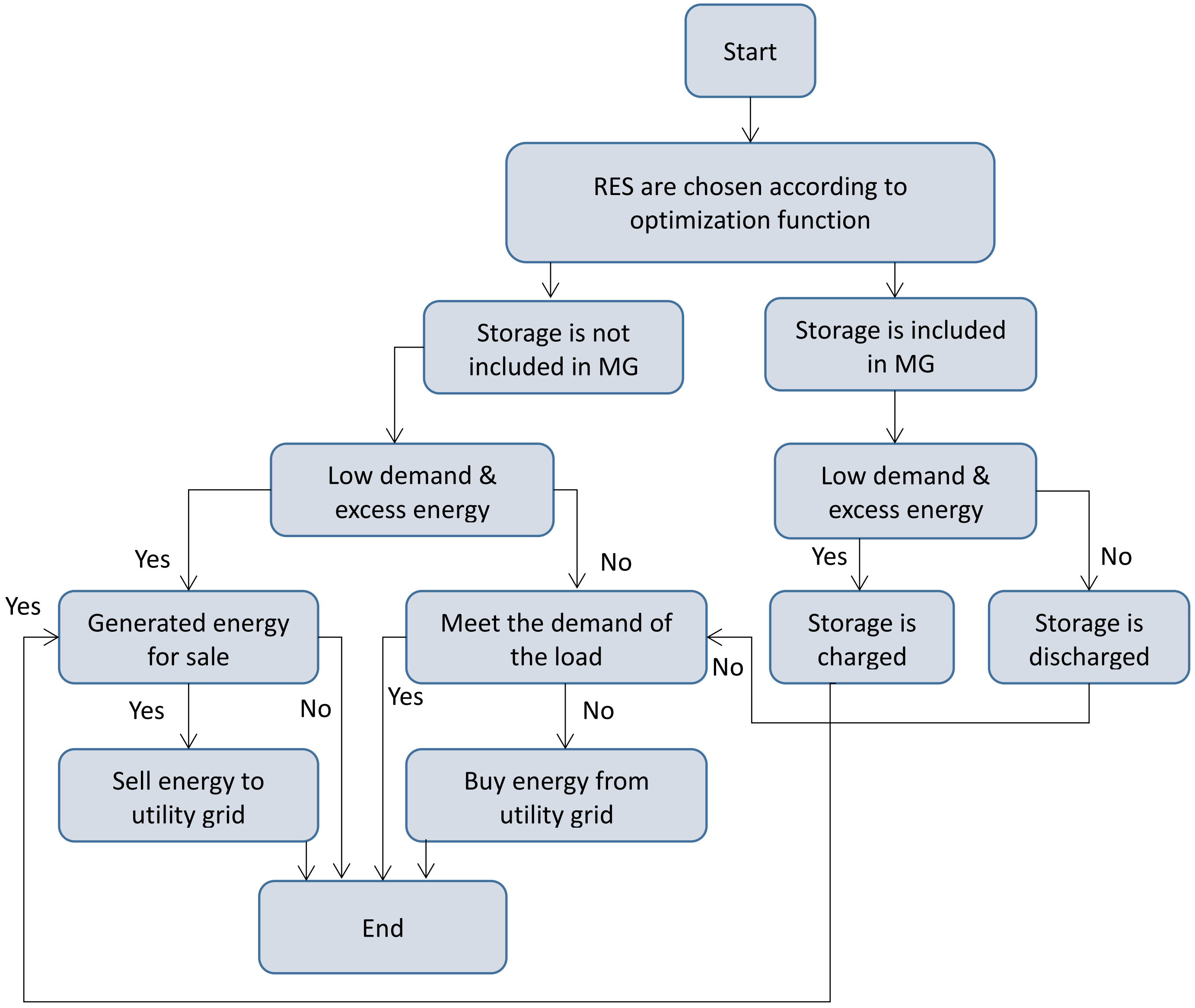

Figure 10 Simulation flow chart

4.2 Mathematical Modeling

A mathematical model for a MG is needed since the system must be analyzed in terms of power, load flow, voltage, current and fault. The MG will consist of a PV system, WT system and a DG.

The main objective is to minimize the cost of the MG system by finding the optimal design taking into consideration the load profile, weather forecast and cost of the installing the system. It is important to maximize the utilization of the RES in the system depending on demand and system reliability. The system will be optimized for 24 hours with different step sizes (i.e.., 10 minutes, 15 minutes, 1 hour…).

The common approach is to optimize the design by minimizing the total cost C_m:

Where C_m is:

$$C_m = CC_1 + CC_2 + CC_3 + OC_1 + OC_2 + OC_3 + TE + EC \qquad (2)$$

Where,

Cost minimized C_m includes the capital cost of all energy sources and the cost of each charge/discharge of electricity within the MG and utility, in addition to the cost of operation.

CC_1	Capital cost of PV system
CC_2	Capital cost of WT system
CC_3	Capital cost of DG
OC_1	Operation cost of PV system
OC_2	Operation cost of WT system
OC_3	Operation cost of DG
TE	Transferred electricity cost within MG
EC	Electricity cost from and to utility

The total cost minimization may result in an unfair cost distribution between RES. It is necessary to note that each renewable energy source has its own benefits and performance in the MG which might be critical to the design.

The output power of PV system, WT system and DG over a period of 24 hours cannot exceed their installed capacity hence:

$$PV_O - PV_C \leq 0 \qquad (3)$$

$$WT_O - WT_C \leq 0 \quad (4)$$

$$DG_O - DG_C \leq 0 \quad (5)$$

Where,

PV_O	Output power of PV in 24 hour
WT_O	Output power of WT in 24 hour
DG_O	Output power of DG in 24 hour
PV_C	Installed electrical capacity of PV
WT_C	Installed electrical capacity of WT
DG_C	Installed electrical capacity of DG

Assuming that C_u is the cost of power from utility grid serving same load, the aim is to minimize the following:

$$Min\,\emptyset = C_u - C_m \quad (6)$$

The system configuration of the hybrid components will consist of PV, WT, DG and storage. The generation of power is determined with the characteristic of each component in addition to several constrains that are related to each source. In the MG the system produces power via the renewable energy resources, while the battery is used to store excess energy and to enhance the system reliability. Finally, if the renewable energy sources fail to satisfy the entire load, the DG kicks in and covers the remaining load.

MGs consist of several technologies for operation in MG such as distributed generation, distributed storage, interconnection switches, and control link, power link. The MG system configuration along with these technologies is shown in Figure 11 below:

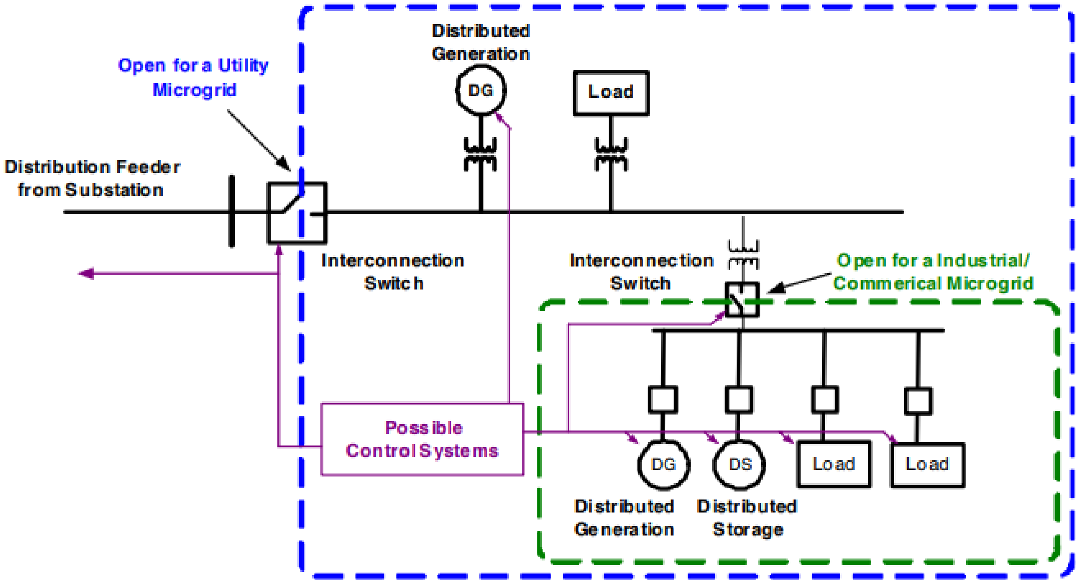

Figure 11 MG system configuration with technologies [11]

4.3 Modeling of Components

The system must be modeled in order to simulate and evaluate the MG; the modeling is related to cost and kW production. In addition, many constrains are involved in each source according to the characteristics of the source. In this section the modeling of PV system, WT, storage and DG will be elaborated into the final equations used in the design.

PV System

The output power of the PV system Ppv(t) is determined by the solar irradiance in specific time, in addition to the area of the PV panels and the overall efficiency of the DC/AC converter.

$$Ppv(t) = I(t) \times A \times \eta \qquad (7)$$

Where $I(t)$ denotes the solar irradiance in unit of time, A is the PV panel's area and η is the overall efficiency of the DC/AC converter. It is assumed the PV panels have Maximum Power Point Tracking (MPPT) system.

The capital daily PV generation cost per kWh is very important because it allows comparing the cost of solar energy to other energy sources costs depending on design choices, which will decide whether to buy or sell energy in the system. The daily PV generation cost per kW $\mathrm{PV}_{\mathrm{cost}}$ is modeled by the following equation:

$$\mathrm{PV}_{\mathrm{cost}} = \frac{Total\ cost}{Period} \qquad (8)$$

Where the total cost is the cost of a 1kW PV system and the period is considered to be the life time of the system which is 20 years. Total cost of 1kW PV panel is assumed to be 1400$ [48]. The efficiency of the system is taken into consideration, in addition, storage isn't considered in this part. Also the $\mathrm{PV}_{\mathrm{cost}}$ can change with the market's supply and demand on the PV systems. The $\mathrm{PV}_{\mathrm{cost}}$ is assumed to be the following:

$$\mathrm{PV}_{\mathrm{cost}} = \frac{1400}{20 * 365} = 0.19\$\ /kW - daily$$

Wind turbine

The output power of the WT system Pwt(t) is determined by the wind speed, hence if the wind speed exceeds the cut-in speed, the WT starts generating power. If the wind speed exceeds the rated speed of the WT, the generation of the output power from WT will be constant. Finally, if the wind speed exceeds the cut-off limit, the WT generator stops running in order to protect the generator. The power produced of WT Pwt(t) at time t is determined by the following [47]:

$$Pwt(t) = \begin{cases} 0 & \mathrm{V}(\mathrm{t}) \leq \mathrm{V}_{cut-in} \ \ or \ \ \mathrm{V}(\mathrm{t}) \geq \mathrm{V}_{cut-out} \\ \mathrm{P}_{rated} \times \frac{\mathrm{V}(\mathrm{t})-\mathrm{V}_{cut-in}}{\mathrm{V}_r-\mathrm{V}_{cut-in}} & \mathrm{V}_{cut-in} < \mathrm{V}(\mathrm{t}) < V_r \\ P_{rated} & V_r < \mathrm{V}(\mathrm{t}) < \mathrm{V}_{cut-out} \end{cases} \tag{9}$$

Where P_{rated} is the rated power of the WT, V_{cut-in} is the cut-in speed where the WT starts generating power, $\mathrm{V}_{cut-down}$ is the cut-down speed where the WT stops generating power, V_r is the rated speed of the WT and finally $\mathrm{V}(\mathrm{t})$ is the wind speed at time t.

From Figure 7 -Power curve for WT- the V_{cut-in} is 3.5m/s, the $\mathrm{V}_{cut-down}$ speed is 25m/s and V_r is 14m/s.

The capital daily wind generation cost per kWh is very important because it allows comparing the cost of wind energy to other energy sources costs depending on design choices, which will decide whether to buy or sell energy in the system. The daily wind generation cost per kW $\mathrm{Wind}_{\mathrm{cost}}$ is modeled by the following equation:

$$\text{Wind}_{\text{cost}} = \frac{Total\ cost}{Period} \qquad (10)$$

Where the total cost is the cost of a 1kW WT and the period is considered to be the life time of the system which is 20 years. Total cost of 1kW WT system is assumed to be 4000$ [49]. The efficiency of the system is taken into consideration, in addition, storage isn't considered in this part. Also the $\text{Wind}_{\text{cost}}$ can change with the market's supply and demand on the WT systems. The $\text{Wind}_{\text{cost}}$ is assumed to be the following:

$$\text{Wind}_{\text{cost}} = \frac{4000}{20 * 365} = 0.54\$\ per\ kW - daily$$

Diesel generation

As a backup for the system, the DG kicks in when insufficient power is generated by the renewable energy resources and the battery system energy is at the minimum level. Of course, the fuel consumption and the DG cost is calculated and modeled in order to compare the cost of DG energy to other energy sources costs depending on design choices, which will decide whether to buy or sell energy in the system.

The capital daily DG cost per kW $\mathrm{DG_{cost}}$ is modeled by the following equation:

$$\mathrm{DG_{cost}} = \frac{Total\ cost}{Period} \qquad (11)$$

Where the total cost is the cost of a 1kW DG and the period is considered to be the life time of the DG which is 20 years. Total cost of 1kW DG is assumed to be 200$ [50]. The efficiency of the DG is taken into consideration, in addition, storage isn't considered in this part. Also the $\mathrm{DG_{cost}}$ can change with the market's supply and demand on the DG. The $\mathrm{DG_{cost}}$ is assumed to be the following:

$$\mathrm{DG_{cost}} = \frac{200}{20 * 365} = 0.027\$\, per\ kW - daily$$

Unlike the WT and PV solar system which have only a capital daily cost per kWh, in DG the fuel consumption cost also must be determined in order for the total cost of the DG generation to be calculated. The total cost of the DG generation, therefore, is the fuel consumption cost in addition to the capital daily DG cost per kWh.

The fuel consumption cost will be calculated for 75% load of the rated power, the fuel consumption cost will be modeled by $DG_{run\text{-}cost}$ which is the DG running cost as the following:

$$DG_{run-cost} = \frac{Litter\ consumption \times cost}{DG\ power} \qquad (12)$$

Where the litter cost is the cost of the fuel consumption covering 75% load of the rated power and the DG power is the rated power of the DG. For 100kW DG, the DG litter consumption is assumed to be 21.95 litters, and the cost of 1 litter is 1.49$ [51]. The maintenance of the DG and the transportation cost of fuel are neglected, hence The $DG_{run\text{-}cost}$:

$$DG_{run-cost} = \frac{21.95 \times 1.49}{100} = \ 0.33\$\ per\ kWh$$

Battery (Storage)

Due to inconsistent behavior of renewable energy resources, a storage system is a must in hybrid MG system. The battery system’s capacity will be changing according to the changes in the behavior of the renewable energy sources. The storage system capital cost is calculated and modeled in order to compare the cost of storing or discharging storage energy to other energy sources costs depending on design choices, the daily battery cost $\text{Battery}_{\text{cost}}$ will be modeled by the following formula:

$$\text{Battery}_{\text{cost}} = \frac{Total\ cost}{Period} \qquad (13)$$

Where the total cost is the cost of 1kWh battery with inverter and the life time period is assumed to be 5 years, the cost of 1 kWh battery is assumed to be 670$ [52].

The $\text{Battery}_{\text{cost}}$ is:

$$\text{Battery}_{\text{cost}} = \frac{670}{5 * 365} = 0.37\$\ per\ kWh/daily$$

The energy of the battery system depends on the charge, discharge and efficiency. The energy of the battery $E_{\text{Battery}}(t)$ can be determined by the following function:

$$E_{Battery}(t) = E_{Battery}(t-1) - 0.9 \times E_{charge}(t) + 1.1 \times E_{discharge}(t) \qquad (14)$$

Where $E_{Battery}(t-1)$ is the energy at the battery at t-1, the energy charged quantity $E_{charge}(t)$ is energy charged to the battery multiplied by 0.9 due to losses and finally the discharged energy quantity $E_{discharge}(t)$ is the energy discharged from the battery multiplied by 1.1 due to losses.

System components

The system consists of WT, PV panels, DG, Storage (Battery) and load. All of these components are connected on the same AC bus as shown and elaborated in Figure 12 below:

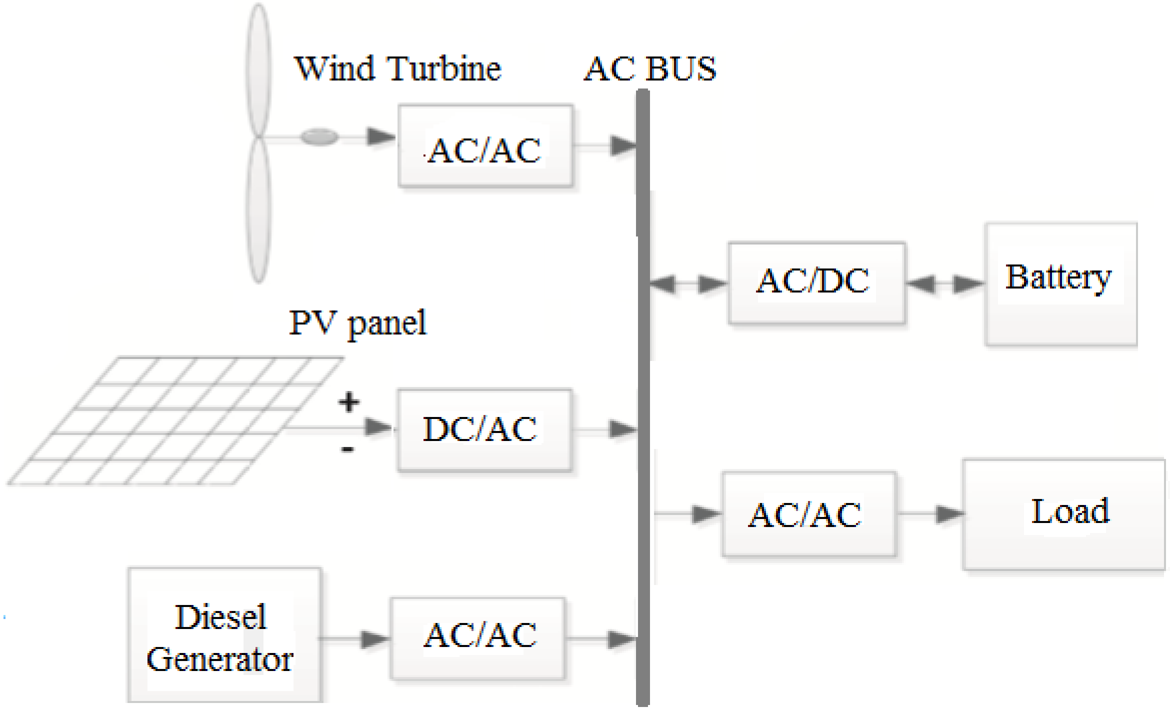

Figure 12 Schematic of hybrid system components connect on AC bus

Figure 12 shows how the system is built: system components are connected on the same bus; the system consists of WT, PV panels, DG, Storage (Battery) and load. Power converters are used for the conversation of power since the bus is AC bus.

The distance between each resource is considered to be very small hence losses are negligible and won’t be added in the calculations.

4.4 Optimization Problem

The objective function of the design is the function that will find the optimal design to minimize the amount of the total cost C_T. The function C_T consists of the cost of all sources and components in the system, where the cost as described in the previous section could be a running cost or a capital cost. In addition, several constrains must be noted in order to determine the amount of power generated or consumed; hence to determine the cost.

System constrains

There are many constrains to be taken into consideration. In the system at hand, voltage is taken into consideration as voltage must not be more than 420V and less than 370V [53]. In addition, the power generated must be equal to the power consumed in which the following power balance equation condition must be met:

$$0 = -P_{Grid}(t) + P_{Load}(t) + P_{charge}(t) - P_{discharge}(t) - P_{pv}(t) - P_{DG}(t) - P_{wt}(t) + P_{pv,sell}(t) + P_{wt,sell}(t) \tag{15}$$

Where -referring to equations 7, 9, 14-, P_{Load} is the power consumed by the load multiplied by 100000 to be at 100kW measurement range, P_{charge} is the power charged to the battery, $P_{discharge}$ is the power discharged from the battery, P_{pv} is the power generated and consumed from the PV system, P_{DG} is the power generated and consumed from the DG, P_{WT} is the power generated and consumed from the WT system, $P_{pv,sell}$ is the excess power generated and sold from the PV system, $P_{wt,sell}$ is the excess power generated and sold from the WT system. P_{Grid} is the power consumed from the grid. The power balance equation means that the total power generated and consumed and sold should equal to zero disregarding losses.

The maximum value of power for the wind turbine system

As discussed in equation (9), WT has to undergo a specific wind speed profile characteristic which is considered as a constrain for generation. WT, therefore, can generate at maximum power, or below or no power at all, depending on wind speed and power curve.

The value Pwt which is the power of WT system is limited in this work and must not exceed the maximum value Pwt_{max} which is fixed at 100kW; then Pwt is:

$$Pwt \leq Pwt_{max} \qquad (16)$$

Hence the power sold from WT, $P_{wt,sell}$ is:

$$P_{wt,sell} < Pwt \qquad (17)$$

The maximum value of power for the solar system

As shown in equation (7), the PV system has to undergo a specific solar irradiance profile characteristic, which is considered as a constrain for generation, in addition to PV panel area and efficiency. PV, therefore, can generate at maximum power, or below or no power at all, depending on all constrains mentioned above.

The value Ppv which is the power of PV system is limited in this work and must not exceed the maximum value Ppv_{max} which is fixed at 100kW; then Ppv is:

$$Ppv \leq Ppv_{max} \qquad (18)$$

Hence the power sold from PV $P_{pv,sell}$ is:

$$P_{pv,sell} < Ppv \qquad (19)$$

The maximum value of power for the battery (storage)

Referring to equation (14) the storage energy which is charged or discharged is limited due to efficiency and losses and is multiplied by a factor.

The size of the storage $\mathrm{Battery}_{\mathrm{size}}$ is also limited in this work and must not exceed the maximum value $\mathrm{Battery}_{\mathrm{max}}$ which is fixed at 100kW; then the $\mathrm{Battery}_{\mathrm{size}}$ is:

$$\mathrm{Battery}_{\mathrm{size}} < \mathrm{Battery}_{\mathrm{max}} \qquad (20)$$

Hence the values of power charged to the storage P_{charge} and power discharged from the storage $P_{discharge}$ are limited to $\mathrm{P}_{\mathrm{max}}$ of the battery:

$$P_{charge} < \mathrm{P}_{\mathrm{max}} \qquad (21)$$

$$P_{discharge} < \mathrm{P}_{\mathrm{max}} \qquad (22)$$

The maximum value of power for the diesel generator

The size of the DG; DG_{Size} is also limited in this work and must not exceed the maximum value $\mathrm{DG}_{\mathrm{max}}$ which is fixed at 100kW; then the DG_{Size} is:

$$DG_{Size} < \mathrm{DG}_{\mathrm{max}} \qquad (23)$$

Objective function

The optimization function is built to minimize the total cost. The total cost consists of: the cost of the PV system according to size, the cost of the WT system according to size, the cost of selling power generated from the PV system, the cost of selling power generated from the WT system, the cost of the DG according to size, the cost of running the DG, the cost of the storage system according to size, the cost of power that is bought from the grid. Referring to equations in chapter 4, the following optimization function is obtained:

$$Min \sum_{0}^{T} P_{Grid}(t) \times 0.00019 - P_{pv,sell}(t) \times 0.0001 - P_{wt,sell}(t) \times 0.0001 + P_{DG}(t) \times 0.00033 + P_{pv,size} \times 0.00019 + P_{wt,size} \times 0.00054 + DG_{Size} \times 0.000027 + \mathrm{Battery}_{\mathrm{size}} \times 0.00037 \qquad (24)$$

Where T is the number of steps (T=8760 for yearly simulation, T=24 for daily simulation), $P_{pv,size}$ is the size of the PV system multiplied by $\mathrm{PV}_{\mathrm{cost}}$ to find the cost, $P_{pv,sell}(t)$ is the power generated and sold from

PV system per unit time multiplied by $0.1\$/\mathrm{kWh}$ to find the cost, $P_{wt,size}$ is the size of the WT system multiplied by $\mathrm{Wind_{cost}}$ to find the cost, $P_{wt,sell}\ (t)$ is the power generated and sold from WT system per unit time multiplied by $0.1\$/\mathrm{kWh}$ to find the cost, $P_{DG}(t)$ is the power generated and consumed from DG per unit time multiplied by $DG_{run-cost}$ to find the cost, DG_{Size} is the size of the DG multiplied by $\mathrm{DG_{cost}}$ to find the cost, $\mathrm{Battery_{size}}$is the size of the storage system multiplied by $\mathrm{Battery_{cost}}$ to find the cost , $P_{Grid}(t)$ is the power consumed from the grid multiplied by 0.19$/kWh to find the cost. All of the parameters mentioned above are multiplied by factors which are calculated from equations 8 to 14 in order to determine the cost. As for the cost of selling power, it is assumed that power is sold at a rate of 0.1$/kWh. It is also assumed that power is bought at a rate of 0.19$/kWh. The overall aim of the function is to minimize the total cost; hence selling power decreases the output, while consuming power adds to the output of the total cost.

Chapter 5: Simulation Results and Evaluation

5.1 Software and Load Profile

The General Algebraic Modeling System (GAMS) is a high-level modeling system for optimization and mathematical programming. It consists of a language compiler and a stable of integrated high-performance solvers. GAMS is tailored for complex, large scale modeling applications, and has the function to build large maintainable models which can be adapted to handle different constrains. GAMS is specifically designed for modeling non-linear, linear and mixed integer optimization problems. In our case, GAMS is used for modeling and simulating linear optimization problem.

The modeling and simulation was compiled for a MG system that consists of DG, PV system, WT system, storage and load. All of the system components are connected to the same bus.

To explore the impact of different parameters, several case studies have been defined as follows:

Case study 1: in this case study the system consists of PV, Wind, Storage and DG. We simulated 24 hours with 1-hour time step, and we considered a high solar irradiation and moderate wind speed, actual data is used from the weather station in Birzeit University. In this case selling energy is permitted to the utility on cost rate mentioned in equation (24). In addition, there is disconnection from the main grid during the day from 5:00AM till 21:00PM (16 hours).

Case study 2: similar to case study 1, but in this case, there is no disconnection from the main grid during the day.

Case study 3: similar to case study 2, but in this case the wind profile is changed, and higher wind speeds are chosen (estimated data is used for high wind speed areas). There is disconnection from the main grid during the day from 5:00AM till 21:00PM (16 hours).

Case study 4: in this case study the system consists of PV, Wind, Storage and DG. We simulated 1year or 365 days with 1-hour step (8760 steps) and we considered a high solar irradiation and moderate wind speed, actual data is used from the weather station in Birzeit University. In this case there is no disconnection from the main grid, also selling energy is not allowed in this case.

Case study 5: similar to case study 4, but in this case, there is no disconnection from the main grid and selling energy is allowed in this case.

Case study 6: similar to case study 4, but in this case, there are some disconnections from the main grid during the year for a total of 27 hours on random days. In this case selling energy is permitted to the utility.

Figure 13 below shows a daily load profile which will be studied in some cases (1 to 3):

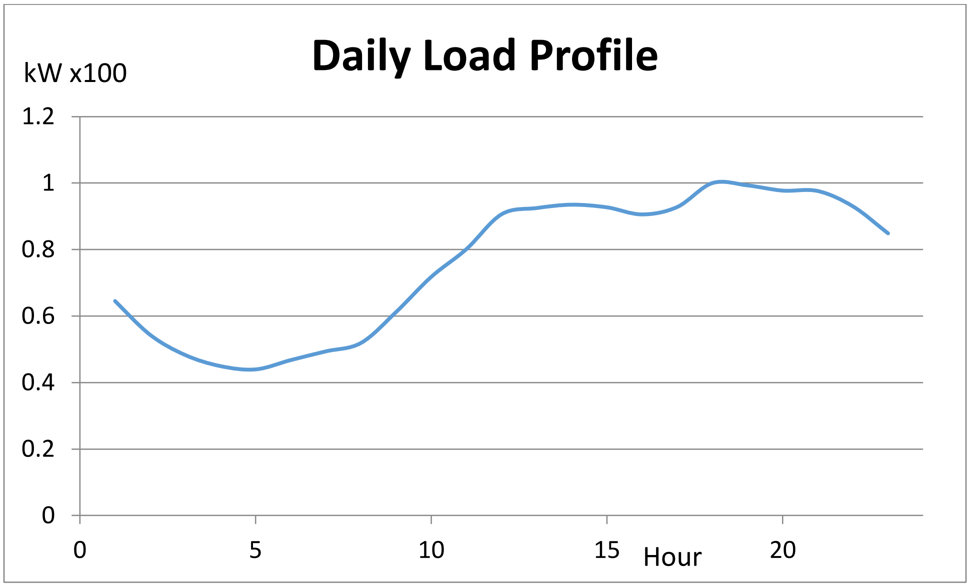

Figure 13 Load profile for 24 hours for case 1

5.2 Case Studies

Case study 1:

DG, PV system, WT system, storage and load are connected to the same bus; the simulation is performed at steps of one hour for 1 day (24 steps). In this case there is disconnection from the main grid during the day. Selling energy is permitted in this case.

The PV system to be used in the simulation will undergo the following characteristics of daily irradiance profile taken from Birzeit University weather station as shown in Figure 14:

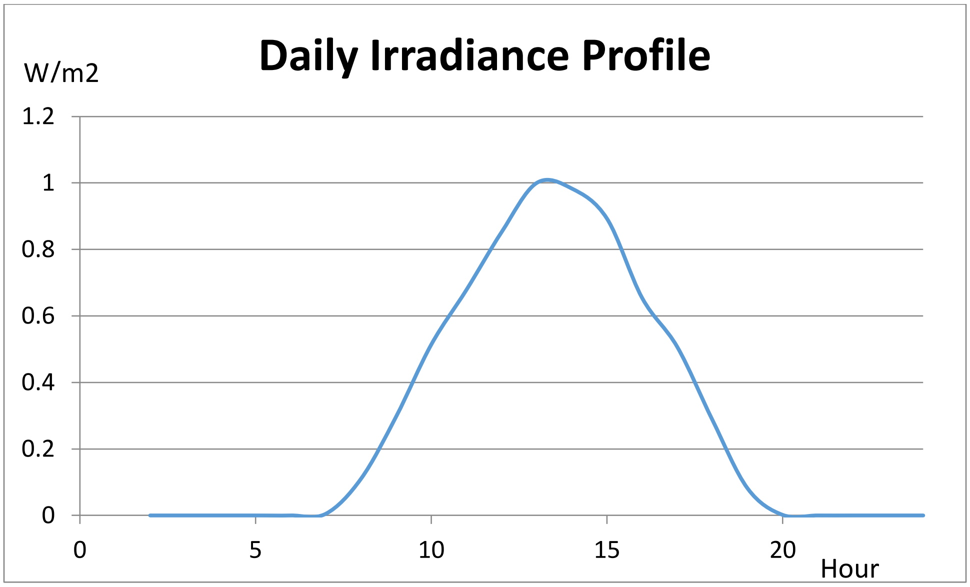

Figure 14 Solar irradiance profile for 24 hour period for case 1

The WT system to be used in the simulation will undergo the following characteristics of wind speed taken from Birzeit University weather station as shown in Figure 15:

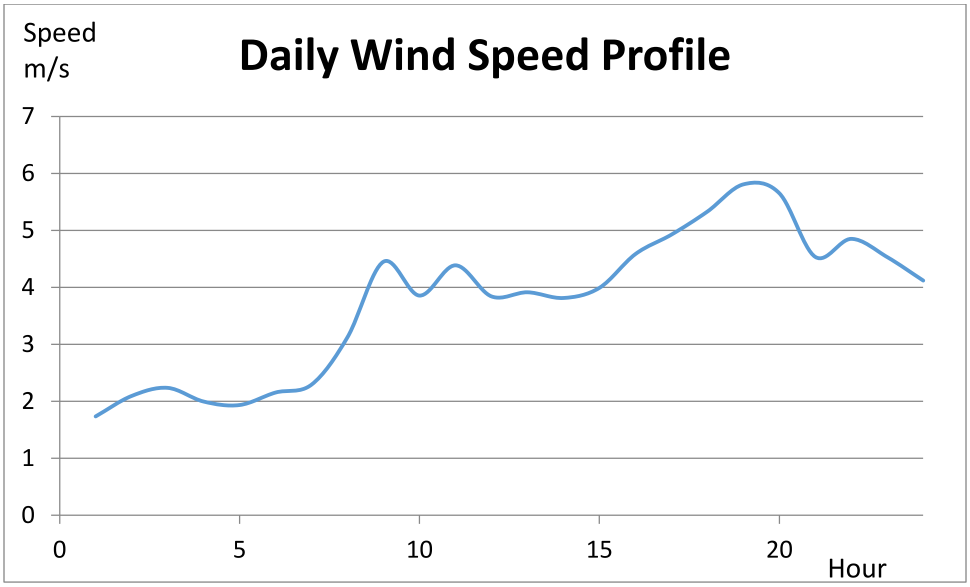

Figure 15 Wind speed profile for 24 hour period for case 1

The simulation was performed for 1 day on 1-hour step with the above data; the results for case 1 were as the following as shown in Figure 16:

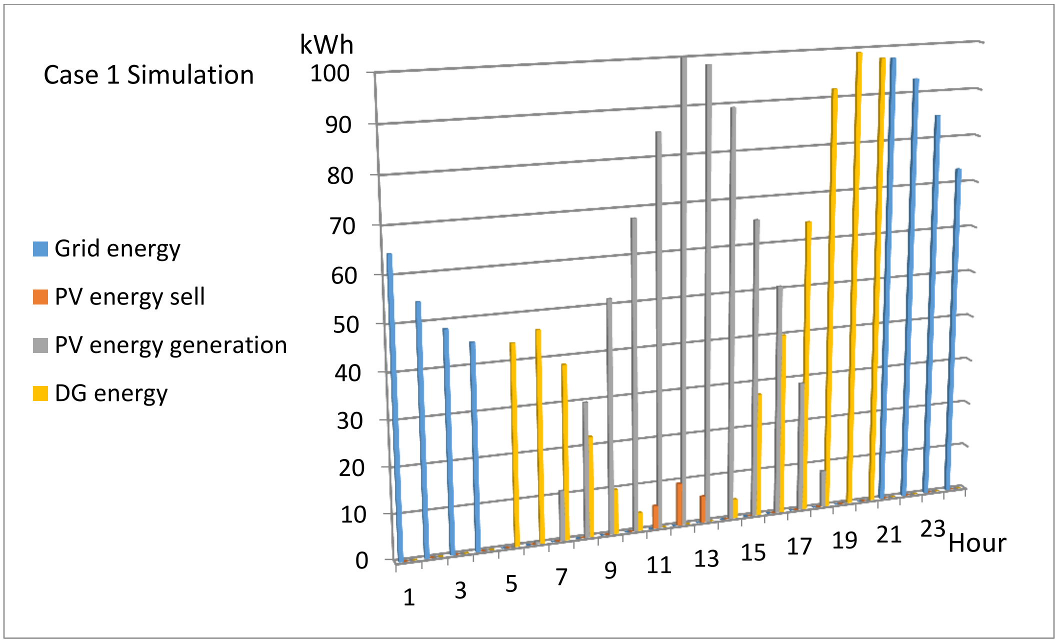

Figure 16 Case 1 simulation results

The simulation shows that the optimal design for this case is a MG with 99.14kW DG and a 100kW PV system, the optimal design doesn't include neither WT nor storage. Table 3 below shows simulation results and the total power sold or consumed per 24 hours:

Table III: Simulation results for case 1:

Hour	***Grid energy kWh***	***PV generation kWh***	***PV Sell kWh***	***DG kWh***
1	64.53	0	0	0
2	54.35	0	0	0
3	48.27	0	0	0
4	44.96	0	0	0
5	0	0	0	43.96
6	0	0.51	0	46.26
7	0	11.03	0	38.35
8	0	29.74	0	22.18
9	0	51.41	0	9.83
10	0	67.84	0	3.97
11	0	85.20	5.06	0
12	0	100.00	9.38	0
13	0	98.32	5.82	0
14	0	89.27	0	4.23
15	0	65.42	0	27.28
16	0	50.69	0	39.88
17	0	28.73	0	64.08
18	0	8.15	0	91.85
19	0	0.16	0	99.14
20	0	0	0	97.73
21	97.61	0	0	0
22	92.99	0	0	0
23	84.88	0	0	0
24	73.00	0	0	0
Sum	**560.59**	**686.49**	**20.26**	**588.74**

Case study 2:

Similar to case 1 setup, but in this case, there is no disconnection from the main grid during the day. Selling energy is permitted in this case. The daily load profile which will be studied in addition to the daily solar irradiance and the daily wind speed profiles in this case is exactly the same as in case 1.

The simulation was performed for 1 day on 1-hour step with the above data; the results for case 2 were as follows as shown in Figure 17:

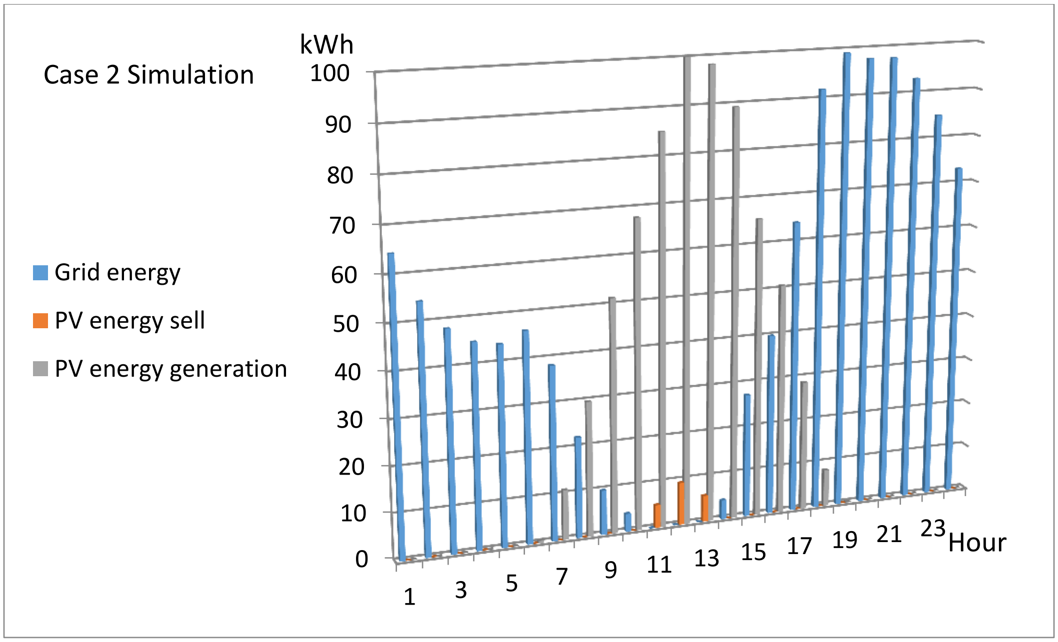

Figure 17 Case 2 simulation results

The simulation shows that the optimal design for this case is a MG with a connection to grid and a 100kW PV system. The optimal design doesn’t include neither WT, nor storage nor DG. Table 4 below shows simulation results and the total power sold or consumed per 24 hours:

Table IV: Simulation results for case 2:

Hour	***Grid energy kWh***	***PV generation kWh***	***PV Sell kWh***
1	64.53	0	0
2	54.35	0	0
3	48.27	0	0
4	44.96	0	0
5	43.96	0	0
6	46.26	0.51	0
7	38.35	11.03	0
8	22.18	29.74	0
9	9.83	51.41	0
10	3.97	67.84	0
11	0	85.20	5.06
12	0	100.00	9.38
13	0	98.32	5.82
14	4.23	89.27	0
15	27.28	65.42	0
16	39.88	50.69	0
17	64.08	28.73	0
18	91.85	8.15	0
19	99.14	0.16	0
20	97.73	0	0
21	97.61	0	0
22	92.99	0	0
23	84.88	0	0
24	73.00	0	0
Sum	**1149.33**	**686.49**	**20.26**

Case study 3:

Similar to case 1 setup, but in this case, there is no disconnection from the main grid during the day. Selling energy is permitted in this case. The daily load profile which will be studied in addition to the daily solar irradiance profile in this case is exactly the same as in case 1. As for the wind profile, it is changed from cases 1 as higher wind speeds are chosen.

The WT system to be used in the simulation will undergo the following characteristics of wind speed; estimated data is used for high wind speed areas to test the behavior of the system as shown in Figure 18:

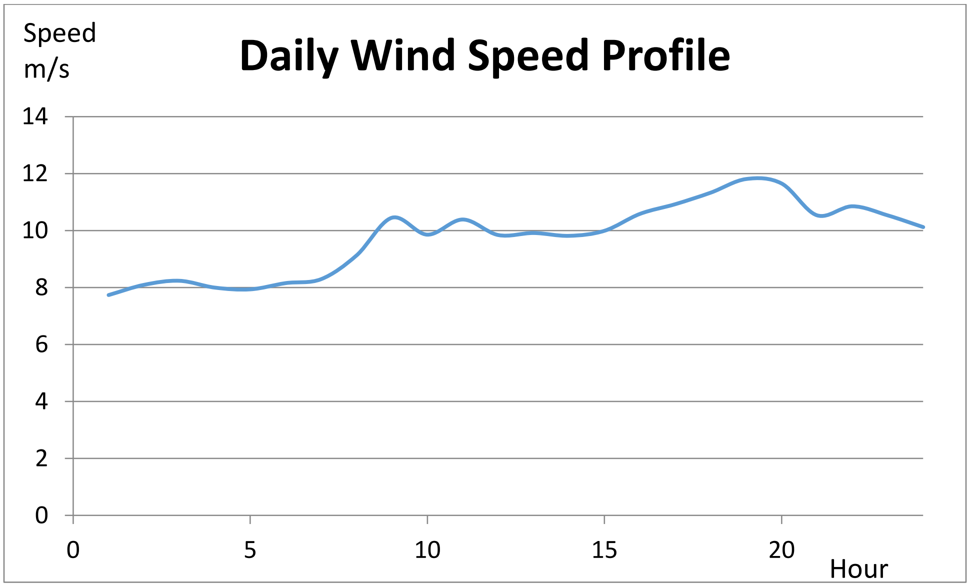

Figure 18 Wind speed profile for 24 hour period for case 3

The simulation was performed for 1 day on 1-hour step with the above data; the results for case 3 were as follows, as shown in Figure 19:

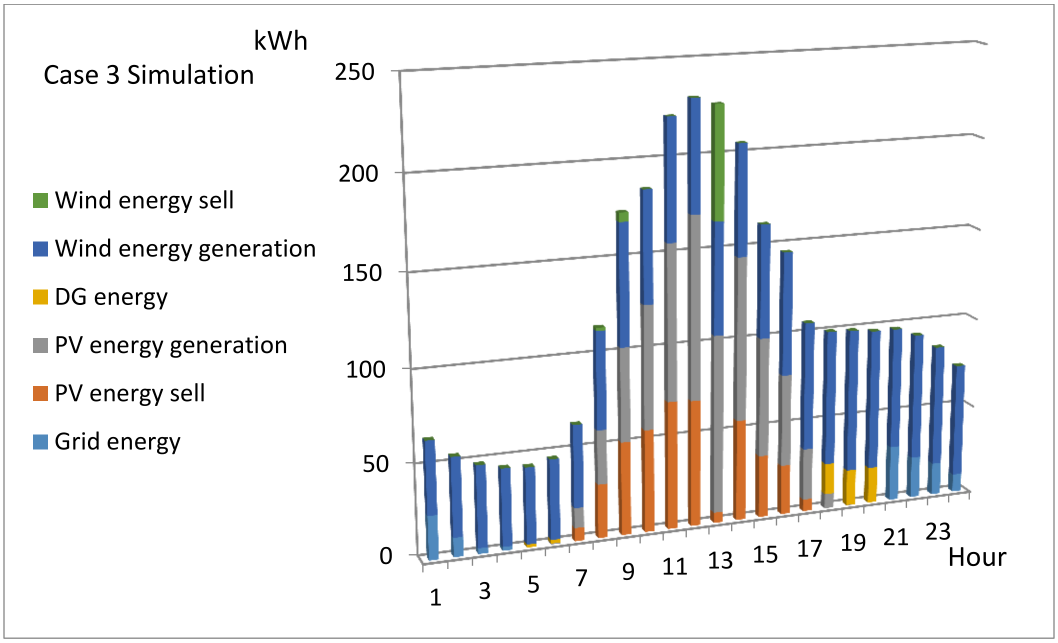

Figure 19 Case 3 simulation results

The simulation shows that the optimal design for this case is a MG with a connection to grid and a 20.1 kW DG, 100kW PV system, 100kW WT system. The optimal design doesn't include storage. Table 5 below shows simulation results and the total power sold or consumed per 24 hours:

Table V: Simulation results for case 3:

Hour	***Grid energy kWh***	***PV generation kWh***	***PV Sell kWh***	***DG kWh***	***Wind generation kWh***	***Wind Sell kWh***
1	75.64	0	0	0	40.34	0
2	54.35	0	0	0	43.76	0
3	48.27	0	0	0	45.11	0
4	139.96	0	0	0	42.83	0
5	0	0	0	1.72	42.25	0
6	0	0.51	0	1.92	44.33	0
7	0	11.03	7.31	0	45.66	0
8	0	29.74	29.74	0	53.58	1.66
9	0	51.41	51.41	0	66.19	4.95
10	0	67.84	56.57	0	60.53	0
11	0	85.20	70.65	0	65.59	0
12	0	100.00	69.78	0	60.40	0
13	0	98.32	5.82	0	61.09	61.09
14	0	89.27	55.90	0	60.13	0
15	0	65.42	34.54	0	61.82	0
16	0	50.69	27.59	0	67.47	0
17	0	28.73	6.63	0	70.71	0
18	0	8.15	0	17.29	74.56	0
19	0	0.16	0	20.03	79.11	0
20	0	0	0	20.10	77.64	0
21	45.64	0	0	0	67.00	0
22	43.02	0	0	0	70.01	0
23	42.95	0	0	0	66.96	0
24	39.98	0	0	0	63.05	0
Sum	**121.5**	**686.49**	**146.2**	**61.1**	**1430.1**	**67.7**

Case study 4:

DG, PV system, WT system, storage and load are connected to the same bus; the simulation is performed as steps of one hour for 365 days (8760 steps) so this case is simulated for one year. In this case there is no disconnection from the main grid. Additionally, selling energy is not allowed.

The yearly load profile which will be studied in this case has the following shape, shown in Figure 20:

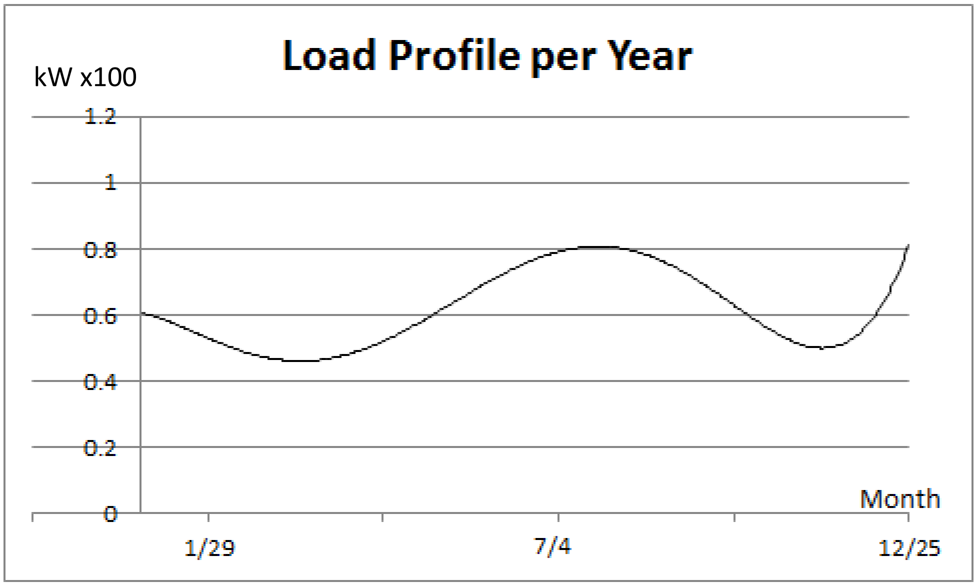

Figure 20 Load profile per 8760 hours for case 4

The PV system to be used in the simulation will undergo the following characteristics of yearly irradiance profile taken from Birzeit University weather station as shown in Figure 21:

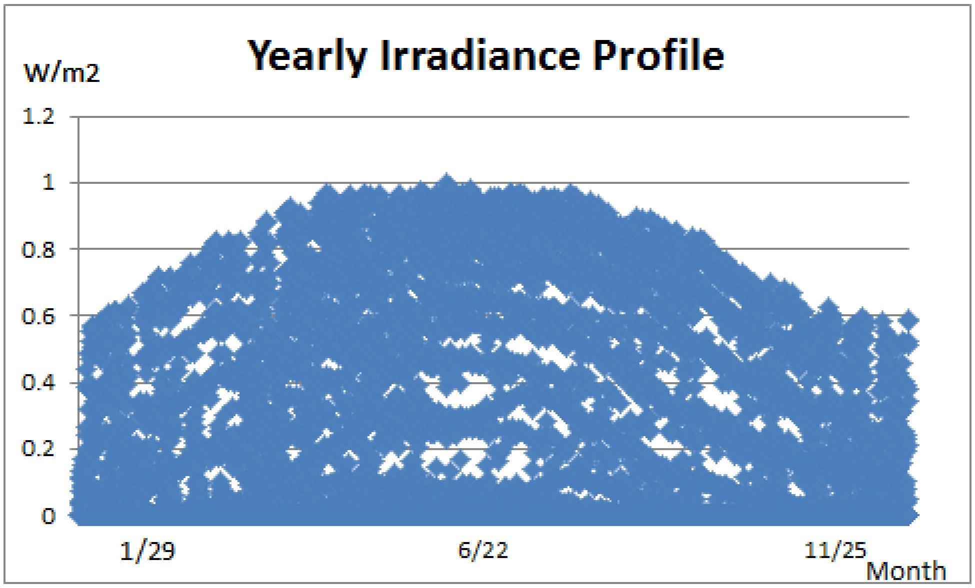

Figure 21 Irradiance profile for 8760 hours for case 4

The WT system to be used in the simulation will undergo the following characteristics of wind speed taken from Birzeit University weather station as shown in Figure 22:

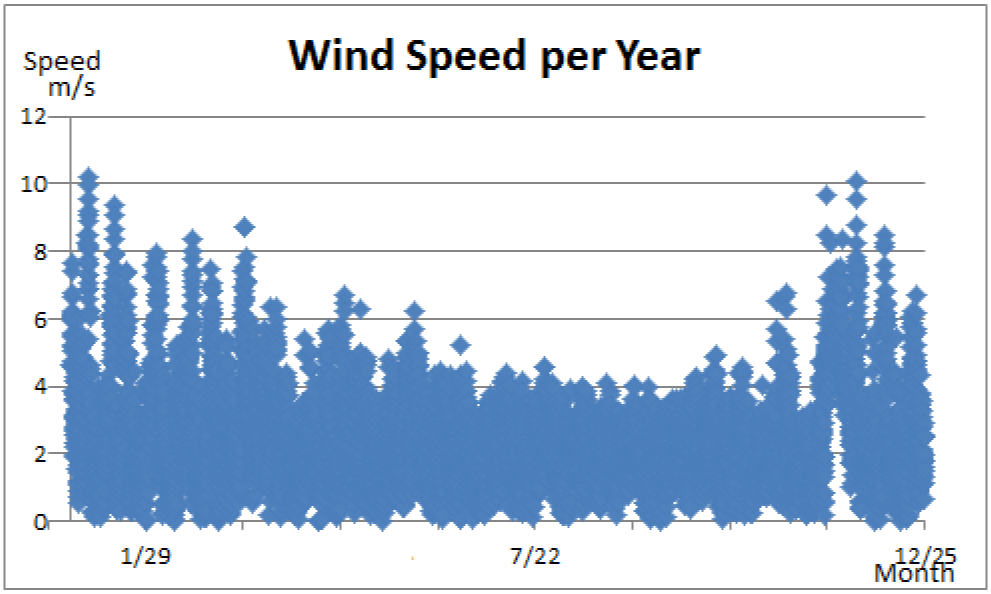

Figure 22 Wind speed profile for 8760 hours for case 4

The simulation was performed for 1 year on 1-hour step with the above data; the results for case 4 were as follows, shown in Figure 23:

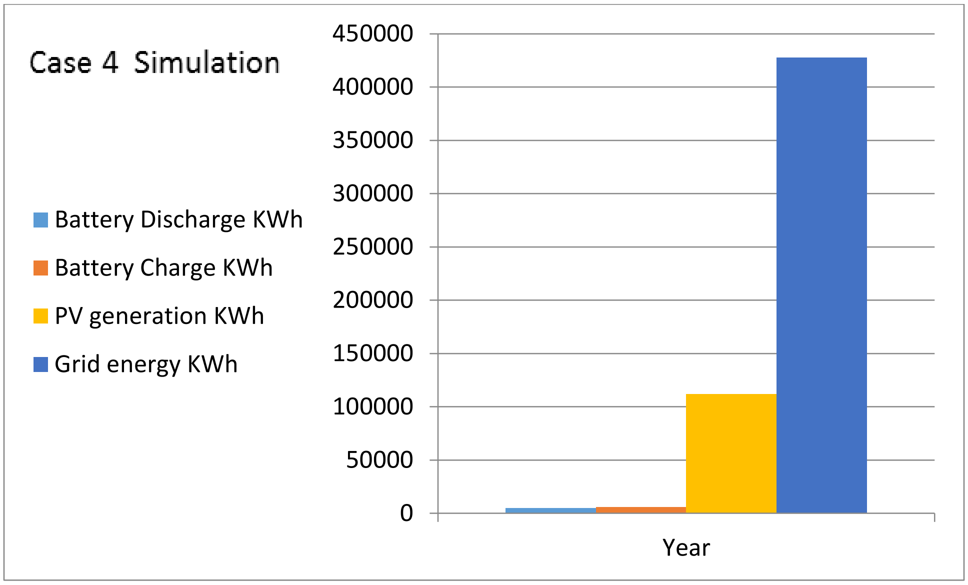

Figure 23 Case 4 simulation results

The simulation was performed for one year on 1-hour step (total 8760 steps) with the above data; the simulation shows that the optimal design for this case is a MG with a connection to grid and a 9.6kWh storage, 65.1kW PV system. The optimal design doesn't include neither WT nor DG.

Case study 5:

Similar to case 4, but in this case selling energy is allowed in this case. The daily load profile which will be studied in addition to the daily solar irradiance and the daily wind speed profiles in this case is exactly the same as in case 4.

The simulation was performed for 1 year on 1-hour step with the above data; the results for case 5 were as follows, shown in Figure 24:

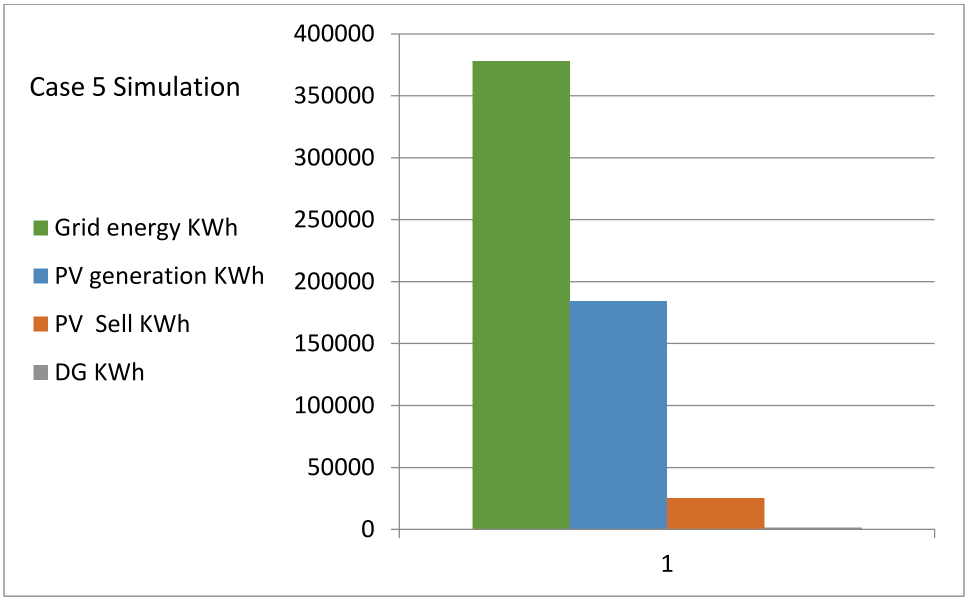

Figure 24 Case 5 simulation results

The simulation was performed for one year on 1-hour step (total 8760 steps) with the above data; the simulation shows that the optimal design for this case is a MG with a connection to grid and a 76.4kW DG, 100kW PV system. The optimal design doesn’t include neither WT nor storage.

Case study 6:

Similar to case 4, but in this case, there are some disconnections from the main grid and selling energy is allowed. The daily load profile which will be studied in addition to the daily solar irradiance and the daily wind speed profiles in this case is exactly the same as in case 4.

The simulation was performed for 1 year on 1-hour step with the above data; the results for case 6 were as follows, as shown in Figure 25:

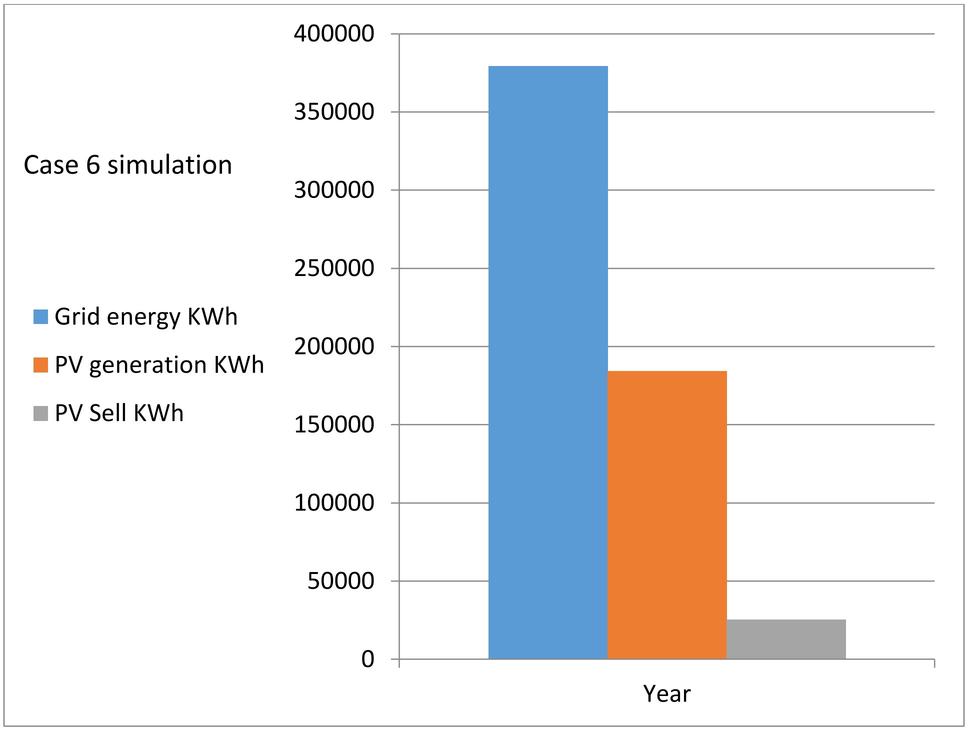

Figure 25 Case 6 simulation results

The simulation was performed for one year on 1-hour step (total 8760 steps) with the above data; the simulation shows that the optimal design for this case is a MG with a connection to grid and 100kW PV system, the optimal design doesn't include neither WT nor storage nor DG.

5.3 Results Discussion

GAMS modeling language was used to simulate different scenarios in order to measure the electrical quantities. The size of each source was an output of the simulation based on the conditions that the MG is built in (such as weather, local costs of resources and power demand). The scenarios were developed to elaborate every case possible in order to find the optimal design for a MG. The mathematical model and code were built so it can find the optimal size for any mix of energy sources. Therefore, the input for any resource can be simulated for a different period of time.

In case 1 and case 2 a DG, PV system, WT system, storage and load are connected to the same bus; the simulation was performed at steps of one hour for 1 day (24 steps) for the same load on both cases. This scenario was built with disconnection allowed from the main grid during the day at one case, and not allowed at the other case.

The Figures 26 & 27 below show the result of the simulation for case 1 and for case 2 as a percentage of penetration for each source selected as an optimal design:

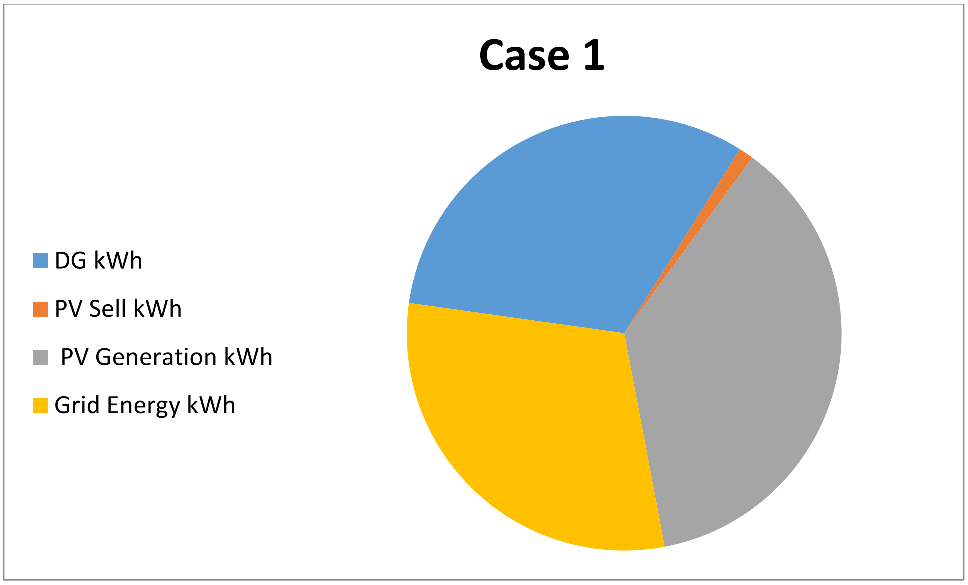

Figure 26 Case 1 Penetration for each source

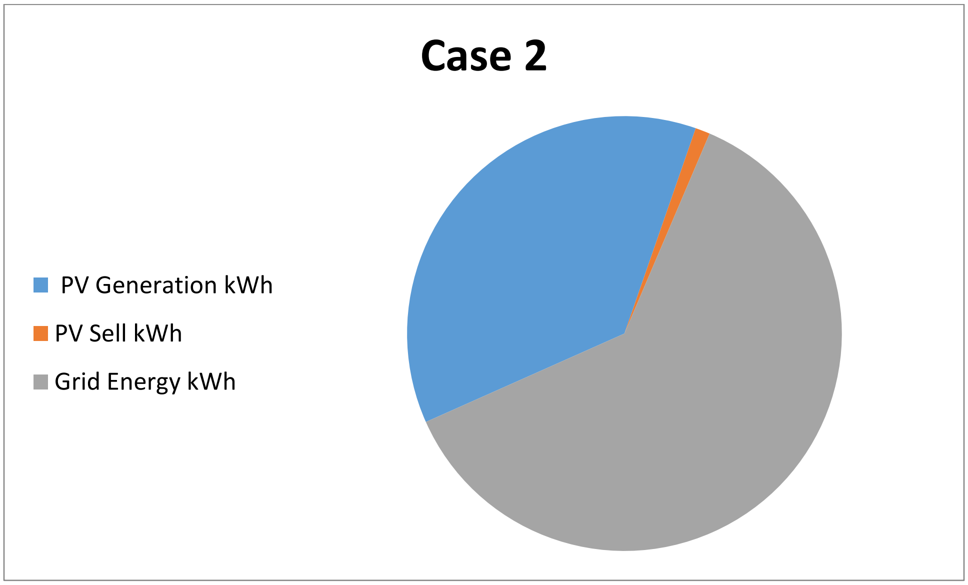

Figure 27 Case 2 Penetration for each source

As shown from Figures 26 & 27, in case 1 the optimal design for the MG was a 99.14kW DG and a 100kW PV system. The optimal design for this case did not include neither WT nor storage. Since disconnection was allowed in this case, it was cheaper to have DG in the design which will produce 588.74kWh instead of getting the same amount of power from grid as what happened in case 2 but at a higher cost. Both cases sold generated power from PV system at the same rate; it is noted that during the period 11:00 AM to 13:00 PM the power flow were positive which means the system was selling power to the utility; hence the power consumption was less than the power produced. The only difference between the two cases is that the optimal design for MG is a design with a DG if disconnection from the grid was allowed. The technical design for case 1 and case 2 including PV system must have a 100kW PV system and a 100kW DG.

Figure 28 below shows the result of the simulation for case 3 as a percentage of penetration for each source selected as an optimal design:

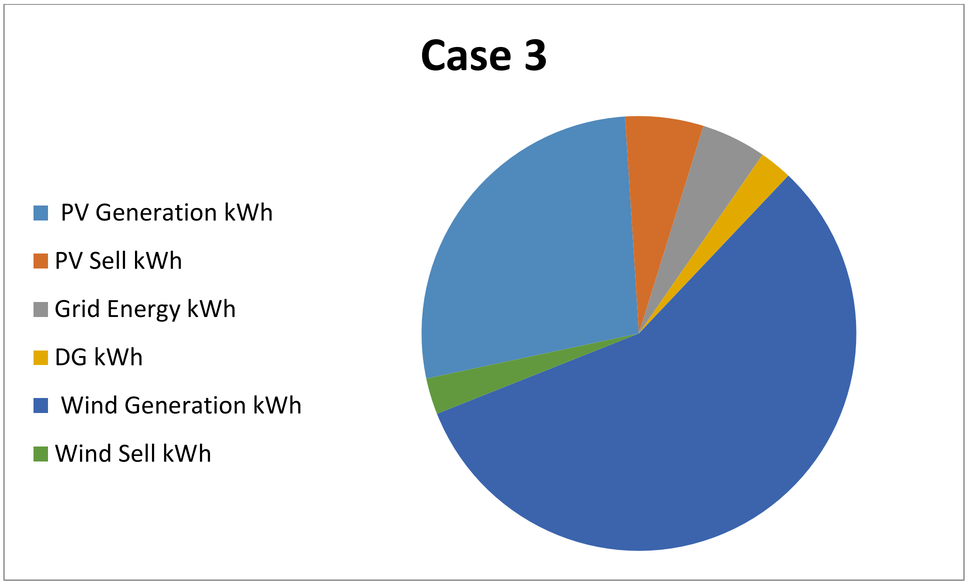

Figure 28 Case 3 Penetration for each source

As for case 3 which had the same daily solar irradiance profile as case 1 but wind profile was changed from case 1 (higher wind speeds are chosen for locations that have up to 12 m/s wind speed). The simulation was performed at steps of one hour for 1 day (24 steps). In this case there is disconnection from the main grid during the day. For this case the optimal design was a MG with a connection to grid and a 20.1 kW DG, 100kW PV system, 100kW WT system. There was no need for storage in this case since wind generation was activated at all hours of the day. A small DG was chosen for this design since WTs is able to generate 1430.1kWh per 24 hours. PV and wind excess energy was sold. A technical design for 100kW WT system and PV system is used for this case.

Case 4 included DG, PV system, WT system, storage and load which were connected to the same bus. The simulation was performed as steps of one hour for 365 days (8760 steps) so this case was simulated for one year. New yearly load profile, yearly solar irradiance profile, yearly wind speed profile were simulated for cases 4 to 6 in order to build new scenarios.

Figure 29 below shows the result of the simulation for case 4 as a percentage of penetration for each source selected as an optimal design:

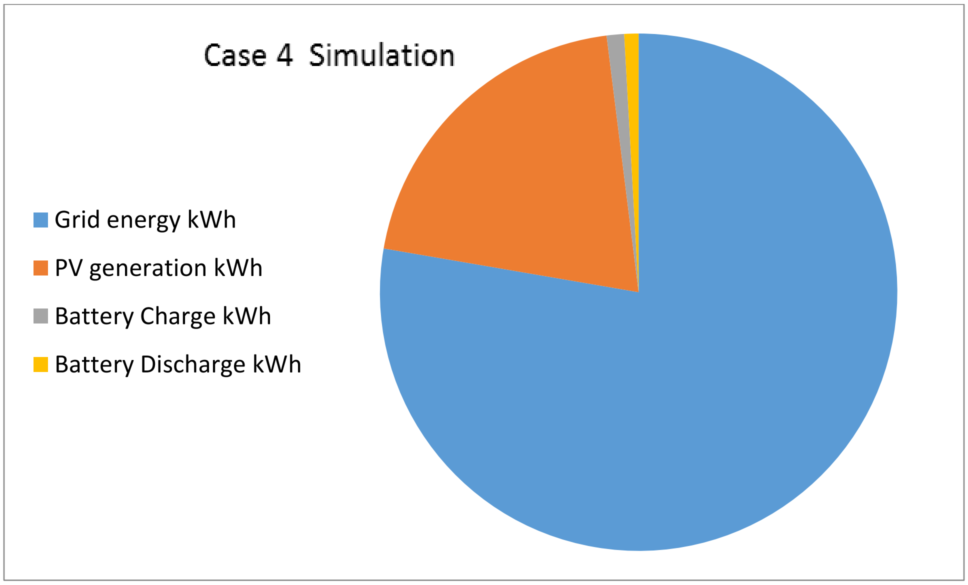

Figure 29 Case 4 Penetration for each source

In case 4 there was no disconnection from the main grid, also selling energy was not allowed. The simulation showed that the optimal design for this case is a MG with a connection to grid and a 9.6kWh storage, 65.1kW PV system. Since there was no disconnection from the grid, the optimal design was only by adding a PV system which will contribute in power. The storage system is small although it helps with increasing reliability if the grid power fails. The technical design for this case is for a PV system that can provide 65.1kW and a 9.6kWh storage system.

Figure 30 below show the result of the simulation for case 5 as a percentage of penetration for each source selected as an optimal design:

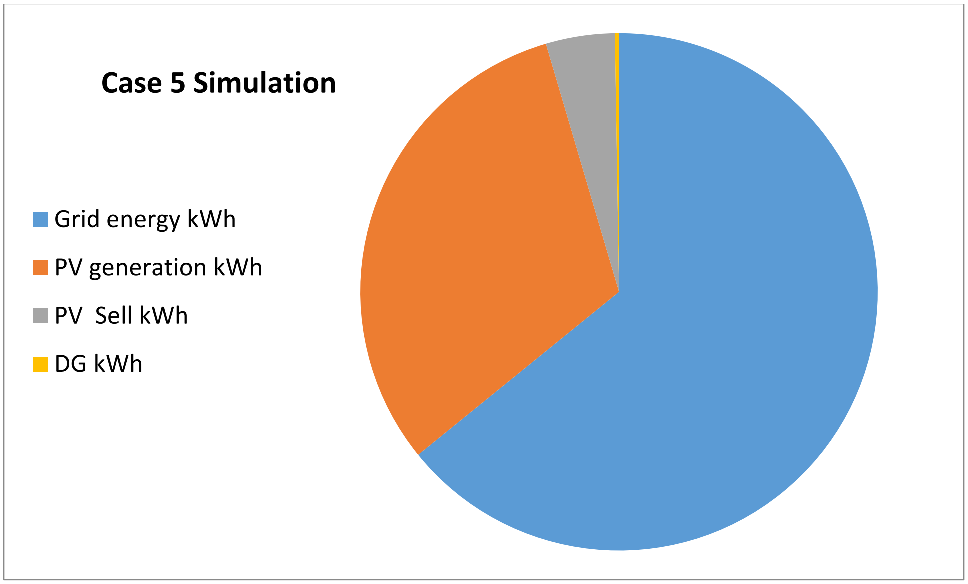

Figure 30 Case 5 Penetration for each source

Case 5 had the same yearly load profile, yearly solar irradiance profile and yearly wind speed profile as in case 4. It was simulated also as steps of one hour for 365 days (8760 steps), and therefore this case was simulated for one year. In this case there was no disconnection from the main grid and selling energy was allowed. The optimal design for this case is a MG with a connection to grid and a 76.4kW DG, 100kW PV system. Hence a larger PV system was required in this case, which will have an income since a total PV energy of amount 25349.5kWh will be sold in a year. A large DG is required in this case even though the total yearly contribution of power is low. However, adding another source (back up DG) enhances reliability. The optimal design did not include neither storage nor WT since wind profile was not at high values and the wind speed was moderate.

Finally, case 6 had the same yearly load profile; yearly solar irradiance profile and yearly wind speed profile as in case 4. It was simulated as steps of one hour for 365 days (8760 steps), and therefore simulated for one year. In this case there were some disconnections from the main grid and selling energy was allowed.

Figure 31 below show the result of the simulation for case 6 as a percentage of penetration for each source selected as an optimal design:

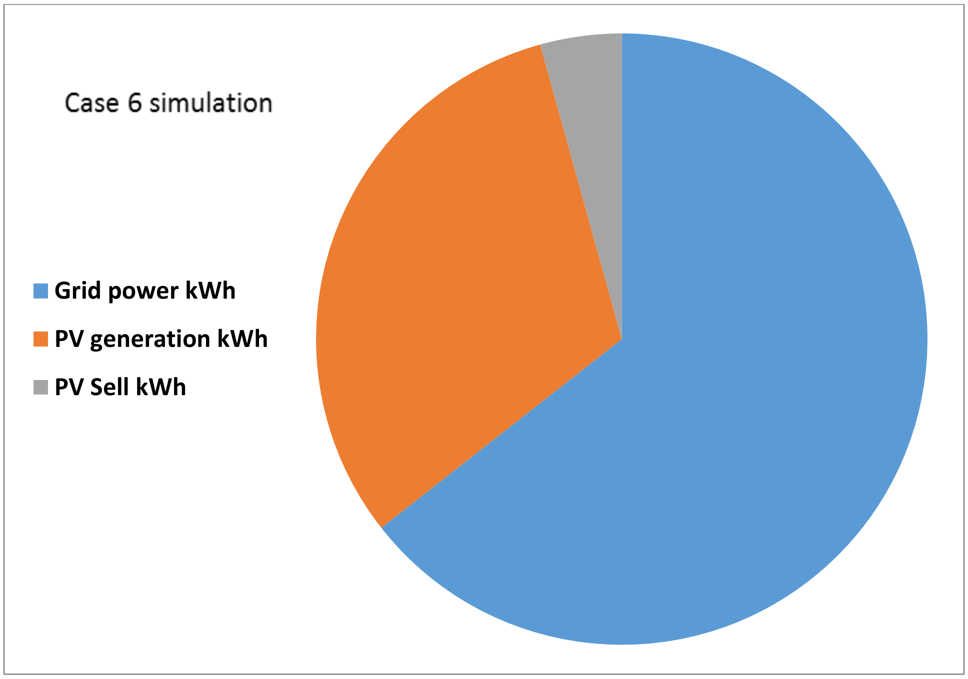

Figure 31 Case 6 Penetration for each source

For case 6 the optimal design is a MG with a connection to grid and 100kW PV system. Since disconnection was allowed in this case, it was beneficial to have only a PV system which can generate power and the excess power can be sold in night time, and where low solar irradiance power can be consumed from grid. The technical design is built for 100kW PV system. The optimal design does not include neither WT nor storage nor DG, this is because the MG is connected to the grid and the optimization is to minimize the cost. Additionally, wind profile was not at high values and the wind speed was moderate. Reliability, in this case, is better than case 5 since there are three sources.

Chapter 6: Conclusion and Recommendation for Future Work

Renewable energy sources are becoming an interesting choice for countries and power utilities due to large energy demand worldwide, along with the depletion of fossil fuels. MGs are based on several RES and sometimes have DG, storage, and can be connected to the grid. This work aimed to obtain the optimal design of a MG since MGs can be an alternative to centralized generation of power.

The optimization function was based on the minimization of cost and choosing the best resource that is economically beneficial. Energy resources were modeled mathematically depending on the characteristics of each source. PV systems depend on solar irradiation; WTs depends on wind speeds; DGs depends on DG cost and running cost of a DG; and finally, storage cost depends on the battery cost. The life time of each resource was discussed and estimated based on several researches that involve each of the energy sources. The optimization function aims to find the best economical design of MG.

This work introduced a framework to find the optimal design for a MG disregarding the input shape or behavior. The provided model can be used in any geographical location by providing the characteristics of the source in the area to be studied. The work introduced the definition of MG; its advantages and disadvantages. Additionally, the work introduced the term reliability in MGs and how it relates to RES and to the cases discussed. System components were overviewed technically, and the behavior of each resource was explained in detail.

This work has included DG, PV system, storage, and WTs and grid connectivity on an AC bus. Mathematical models were derived for each component and the model was built in relation to the cost. The optimization function was to minimize the total cost of MG. Constrains were added to each component and the simulation code was built in order to accept any input energy source. Several cases were simulated and analyzed; an expected behavior was noted from the results which conclude that the simulation process relates to the theory of the optimization.

For future work, voltage profile, losses and control must be included in the design. Voltage profile assures voltage levels at load in case of different buses, also losses must be taken into consideration. Control techniques in MGs are developing quickly; control can be performed on load side wherever there is a critical load that is considered priority or over source side where it is better to sell energy and gain money rather than consuming it.

References

[1] REN21, “RENEWABLES 2019 GLOBAL STATUS REPORT,” RENEWABLES 2019 GLOBAL STATUS REPORT. [Online]. Available: http://www.ren21.net/gsr-2019/. [Accessed: 04-Aug-2019].

[2] N. D. Hatziargyriou, A. G. Anastasiadis, A. G. Tsikalakis, and J. Vasiljevska, “Quantification of economic, environmental and operational benefits due to significant penetration of Microgrids in a typical LV and MV Greek network,” European Transactions on Electrical Power, vol. 21, no. 2, pp. 1217–1237, 2011.

[3] D. T. Ton and M. A. Smith, “The U.S. Department of Energys Microgrid Initiative,” The Electricity Journal, vol. 25, no. 8, pp. 84–94, 2012.

[4] A. G. Tsikalakis and N. D. Hatziargyriou, “Centralized Control for Optimizing Microgrids Operation,” IEEE Transactions on Energy Conversion, vol. 23, no. 1, pp. 241–248, 2008.

[5] C. Marnay, G. Venkataramanan, M. Stadler, A. Siddiqui, R. Firestone, and B. Chandran, “Optimal Technology Selection and Operation of Microgrids in Commercial Buildings,” 2007 IEEE Power Engineering Society General Meeting, 2007.

[6] Z. Sun and X.-Y. Zhang, “Advances on Distributed Generation Technology,” Energy Procedia, vol. 17, pp. 32–38, 2012.

[7] S. J. Mu, M. Huang, J. J. Yang, J. Yu, T. H. Li, and J. S. Hu, “Overview of Communication and Control Techniques in the Microgrid,” Applied Mechanics and Materials, vol. 71-78, pp. 2382–2388, 2011.

[8] “MICROGRID: meaning in the Cambridge English Dictionary,” Cambridge Dictionary. [Online]. Available: https://dictionary.cambridge.org/dictionary/english/microgrid. [Accessed: 05-Aug-2019].

[9] D. T. Ton and M. A. Smith, “The U.S. Department of Energys Microgrid Initiative,” The Electricity Journal, vol. 25, no. 8, pp. 84–94, 2012.

[10] T. Basso, “IEEE 1547 and 2030 Standards for Distributed Energy Resources Interconnection and Interoperability with the Electricity Grid,” Jan. 2014.

[11] B. Kroposki, T. Basso, and R. Deblasio, “Microgrid standards and technologies,” 2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008.

[12] Slideshare.net. (2019). Micro-Grid in India. [online] Available at: https://www.slideshare.net/sanjeevirny/microgrid-27610344 [Accessed 19 Apr. 2019].

[13] Guarnieri, M., Bovo, A., Giovannelli, A. and Mattavelli, P. (2018). A Real Multitechnology Microgrid in Venice: A Design Review. IEEE Industrial Electronics Magazine, 12(3), pp.19-31.

[14] Building-microgrid.lbl.gov. (2019). About Microgrids | Building Microgrid. [online] Available at: https://building-microgrid.lbl.gov/about-microgrids [Accessed 25 Jul. 2019].

[15] B. S. Hartono, Budiyanto, and R. Setiabudy, “Review of microgrid technology,” 2013 International Conference on QiR, 2013.

[16] T. Adefarati, R. Bansal and J. Justo, "Reliability and economic evaluation of a microgrid power system", Energy Procedia, vol. 142, pp. 43-48, 2017.

[17] O. A. Ansari, N. Safari, and C. Y. Chung, “Reliability assessment of microgrid with renewable generation and prioritized loads,” 2016 IEEE Green Energy and Systems Conference (IGSEC), 2016.

[18] "Solar Electricity", Fsec.ucf.edu, 2019. [Online]. Available: http://www.fsec.ucf.edu/en/consumer/solar_electricity. [Accessed: 27-Apr- 2019].

[19] "aladdinsolar.com", Aladdinsolar.com, 2019. [Online]. Available: http://www.aladdinsolar.com/pvsystems.html. [Accessed: 27- Apr- 2019].

[20] "Hybrid Wind and Solar Electric Systems", Energy.gov, 2019. [Online]. Available: https://energy.gov/energysaver/buying-and-making-electricity/hybrid-wind-and-solar-electric-systems. [Accessed: 27- Apr- 2019].

[21] "What is the Best Battery for Solar Storage in 2019? | EnergySage", Energysage.com, 2019. [Online]. Available: https://www.energysage.com/solar/solar-energy-storage/what-are-the-best-batteries-for-solar-panels. [Accessed: 27- Apr- 2019].

[22] S. M. A. S. Bukhari, J. Maqsood, M. Q. Baig, S. Ashraf, and T. A. Khan, “Comparison of Characteristics -- Lead Acid, Nickel Based, Lead Crystal and Lithium Based Batteries,” 2015 17th UKSim-AMSS International Conference on Modelling and Simulation (UKSim), 2015.

[23] Battery Performance Characteristics - How to specify and test a battery", Mpoweruk.com, 2019. [Online]. Available: https://mpoweruk.com/performance.htm. [Accessed: 27- Apr- 2019].

[24] Off grid solar: a handbook for photovoltaics with lead-acid or lithium-ion batteries. San Francisco, CA: Joseph P. OConnor, 2016.

[25] "Wind turbine power curve definitions", Wind-power-program.com, 2019. [Online]. Available: http://www.wind-power-program.com/popups/powercurve.htm. [Accessed: 27- Apr- 2019].

[26] "Wind turbine power curves.", Wind-power-program.com, 2019. [Online]. Available: http://www.wind-power-program.com/turbine_characteristics.htm. [Accessed: 27- Apr- 2019].

[27] M. R. Milligan, “Wind Energy,” Modelling utility-scale wind power plants, vol. 3, no. 4, pp. 167–206 , 2000.

[28] Forsyth, National Renewable Energy Laboratory (U.S.) “Windpower,” in An introduction to the small wind turbine project, 1997.

[29] T. Khatib, A. Mohamed, K. Sopian, and M. Mahmoud, “Optimal sizing of building integrated hybrid PV/diesel generator system for zero load rejection for Malaysia,” Energy and Buildings, vol. 43, no. 12, pp. 3430–3435, 2011.

[30] "Industrial Diesel Generators: New & Used Generator Sets - We Buy/Sell", Dieselserviceandsupply.com, 2019. [Online]. Available: http://Dieselserviceandsupply.com. [Accessed: 27- Apr- 2019].

[31] "Danvest Energy A/S - Wind Diesel Systems, Solar Diesel Systems", Danvest.com, 2019. [Online]. Available: http://www.danvest.com/how-does-it-work.pp. [Accessed: 27- Apr- 2019].

[32] E. Shaffer, P. Roege, and T. Zheleva, “Advanced Microgrid Concepts and Technologies Workshop,” 2013.

[33] A. G. Tsikalakis and N. D. Hatziargyriou, “Centralized control for optimizing microgrids operation,” 2011 IEEE Power and Energy Society General Meeting, 2011.

[34] S. Choi, S. Park, D.-J. Kang, S.-J. Han, and H.-M. Kim, “A microgrid energy management system for inducing optimal demand response,” 2011 IEEE International Conference on Smart Grid Communications (SmartGridComm), 2011.

[35] T. Logenthiran, D. Srinivasan, A. M. Khambadkone, and T. S. Raj, “Optimal sizing of Distributed Energy Resources for integrated microgrids using Evolutionary Strategy,” 2012 IEEE Congress on Evolutionary Computation, 2012.

[36] N. Lin, B. Zhou, and X. Wang, “Optimal placement of distributed generators in micro-grid,” 2011 International Conference on Consumer Electronics, Communications and Networks (CECNet), 2011.

[37] H. Meidani and R. Ghanem, "Multiscale Markov models with random transitions for energy demand management", Energy and Buildings, vol. 61, pp. 267-274, 2013.

[38] A. Arteconi, N. Hewitt and F. Polonara, "Domestic demand-side management (DSM): Role of heat pumps and thermal energy storage (TES) systems", Applied Thermal Engineering, vol. 51, no. 1-2, pp. 155-165, 2013.

[39] S. Vega Cotto and W. Lee, "Microgrid Modular Design for Tribal Healthcare Facilities: Kayenta Health Center PV System Case Study", IEEE Transactions on Industry Applications, vol. 53, no. 6, pp. 5121-5129, 2017.

[40] R. Rigo-Mariani, B. Sareni, and X. Roboam, “Integrated Optimal Design of a Smart Microgrid With Storage,” IEEE Transactions on Smart Grid, vol. 8, no. 4, pp. 1762–1770, 2017.

[41] L. Che, X. Zhang, M. Shahidehpour, A. Alabdulwahab and Y. Al-Turki, "Optimal Planning of Loop-Based Microgrid Topology", IEEE Transactions on Smart Grid, vol. 8, no. 4, pp. 1771-1781, 2017.

[42] S. Kermany, M. Joorabian, S. Deilami and M. Masoum, "Hybrid Islanding Detection in Microgrid With Multiple Connection Points to Smart Grids Using Fuzzy-Neural Network", IEEE Transactions on Power Systems, vol. 32, no. 4, pp. 2640-2651, 2017. Available: 10.1109/tpwrs.2016.2617344.

[43] W. Im, C. Wang, W. Liu, L. Liu and J. Kim, "Distributed virtual inertia based control of multiple photovoltaic systems in autonomous microgrid", IEEE/CAA Journal of Automatica Sinica, vol. 4, no. 3, pp. 512-519, 2017.

[44] U. K. Kalla, B. Singh, S. S. Murthy, C. Jain, and K. Kant, “Adaptive Sliding Mode Control of Standalone Single-Phase Microgrid Using Hydro, Wind, and Solar PV Array-Based Generation,” IEEE Transactions on Smart Grid, vol. 9, no. 6, pp. 6806–6814, 2018.

[45] P. Prabhakaran, Y. Goyal and V. Agarwal, "Novel Nonlinear Droop Control Techniques to Overcome the Load Sharing and Voltage Regulation Issues in DC Microgrid", IEEE Transactions on Power Electronics, vol. 33, no. 5, pp. 4477-4487, 2018.

[46] D. Zhang, “Optimal design and planning of energy microgrids,” University College London, 2014.

[47] A. Maleki and A. Askarzadeh, “Optimal sizing of a PV/wind/diesel system with battery storage for electrification to an off-grid remote region: A case study of Rafsanjan, Iran,” Sustainable Energy Technologies and Assessments, vol. 7, pp. 147–153, 2014.

[48] Infinite Energy. (2019). 100kW Solar System | Commercial Solar | Infinite Energy. [online] Available at: https://www.infiniteenergy.com.au/commercial-solar-system-size-comparison/100kw [Accessed 19 Apr. 2019].

[49] "Wind Energy Cost", Conserve Energy Future, 2019. [Online]. Available: https://www.conserve-energy-future.com/windenergycost.php. [Accessed: 19- Apr- 2019].

[50] "Perkins 100 kW Diesel Generator", Centralmainediesel.com, 2019. [Online]. Available: http://www.centralmainediesel.com/order/09152.asp?page=9152. [Accessed: 20- Apr- 2019].

[51] "Approximate Diesel Generator Fuel Consumption Chart", Dieselserviceandsupply.com, 2019. [Online]. Available: https://www.dieselserviceandsupply.com/Diesel_Fuel_Consumption.asp. [Accessed: 20- Apr- 2019].

[52] "How Many Batteries Do You Need?", SolarQuotes, 2019. [Online]. Available: https://www.solarquotes.com.au/battery-storage/sizing/. [Accessed: 20- Apr- 2019].

[53] Voltage Disturbance. [Online]. Available: http://voltage-disturbance.com/voltage-quality/voltage-tolerance-standard-ansi-c84-1/. [Accessed: 05-Aug-2019].