Chapter

Optimization of Renewable Energy-Based Smart Micro-Grid System

Marwa Mohsen Ibrahim Abd El-Rahman

Abstract

Optimization of renewable energy-based micro-grids is presently attracting significant consideration. Hence the main objective of this chapter is to evaluate the technical and economic performance of a micro-grid (MG) comparing between two operation modes; stand-alone (off-grid), and grid connected (on-grid). The micro-grid system (MGS) suggested components are; PV panels, wind turbine(s) inverter, and control unit in case of grid connected. In the stand alone mode diesel generator and short term storage are added to the renewable generators. To investigate the performance of the MGS; technically, detailed models for each component will be presented then the complete MGS model is developed. Another objective of this study is the economical evaluation of MGS by comparing the system net present cost (NPC) and cost of generated electricity for the two modes of operation; off-grid and on-grid.

Keywords: renewable energy, smart grids, micro-grid, on/off grid, simulation, MATLAB software, optimization

1. Introduction

Renewable energy (*RE*) industry is growing rapidly with rising concerns about oil depletion and climate change. *RE* is seen by many as part of the appropriate response to these concerns and some national governments have put programs in place to support the wider use of sustainable energy systems [1]. Rapid increases in energy demand and energy deficiency are two contradicting facts that face developing countries at the present and expectedly in the future. Compared to fossil fuel energy generation and nuclear power stations, *RE* is considered the safest benign energy generation sources. *RE* sources are offering the suitable solution for such situations, as have been the answer for remote, isolated dwelling electrification, substituting or integrated with diesel fueled generators. The well-known RE sources are; solar, wind, hydropower, biomass and geothermal. Renewable energy technologies revolve these sources into utilizable forms of energy not only electricity but also heat, chemicals, or mechanical power. Even if fossil fuels supplies are unlimited, it is better to use renewable energy sources as they are clean technologies. Burning fossil fuels causes pollutant emissions and greenhouse gases contributing to global warming [2]. Renewable energy education is a relatively new field and previously it formed a minor part of traditional engineering courses. Modern renewable energy education includes a study of the technology, resources, systems design, economics, industry structure and policies in an integrated package.

Renewable energy and micro-grid had emerged from the development of new grid technology referred as smart grids [3]. Smart grids are computer controlled micro-grids. “renewable energy sources”; often referred to as distributed energy resources (DERs), while “smart-grids” refers to the whole electrical energy distribution networks from electricity generation to its transmission and storage with the capability to react to dynamic changes on energy distribution and load regulation [4]. A different review on smart grid concepts was described by Di Santo et al., who defined smart grid as; “a generation, transmission, and distribution system set with a two-way communication system controlled by the grid operator” [5]. In their study, the key element was the contact between the grid operator, electric utility, and consumers. In this review the authors categorized smart grid components as: smart homes, smart consumption, smart consumption, and smart distribution. A number of studies discussed socio-economic and socio-technical aspects symbolizing [6, 7].

1.1 Definition of smart grid

A smart grid can be defined as an electric system that uses information, two-way, cyber-secure communication technologies, and computational intelligence in an integrated fashion across electricity generation, transmission, substations, distribution and consumption to achieve a system that is clean, safe, secure, reliable, resilient, efficient, and sustainable [8]. This definition covers the entire spectrum of the energy system from the generation to the end points of consumption of the electricity. **Figure 1** illustrates different components of smart grid [9]. The ultimate smart grid is a vision, and it will require cost justification at every step before implementation, then testing and verification before extensive deployment.

Worldwide researches are going on micro-grids, there application and control to overcome the weaknesses of the centralized power grids [5]. Additionally the utilization of local sources of energy to provide local loads helps decreasing energy losses in transmission and distribution.

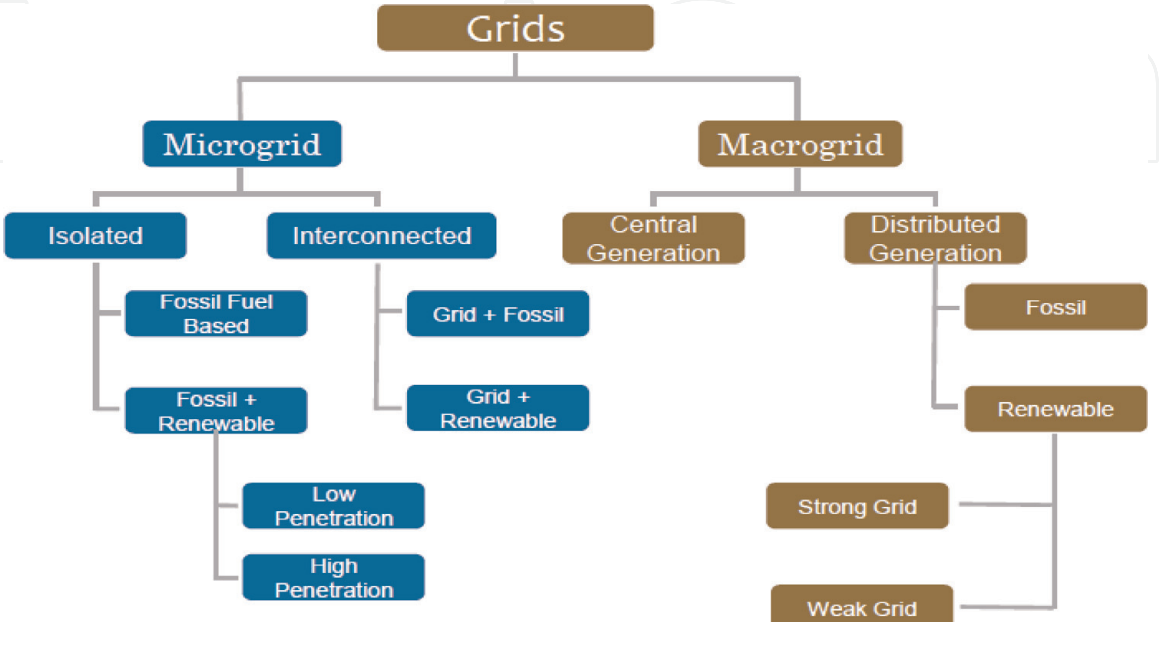


Figure 1.
Components of smart grid [9].

The conception of micro-grid (MG) for integrating distributed generation (DG) system is rapidly becoming important for reliable and sustainable renewable energy development. In ideal situation, it also allows for incorporating energy storage systems (ESSs), which are used to optimize energy consumption. Further, MG development in modern power sector had brought another emerging idea called smart grid [10].

Micro-grid can be defined as follows: an integrated energy system intelligently organizing interconnected loads and distributed energy resources and capable of operating in parallel with, or separately, from the existing utility's grid [11]. A description of possible micro-grid architecture is shown in **Figure 2**. Power electronic components are the base for flexible operation. The connection point to utility grid is called point of common coupling (PCC).

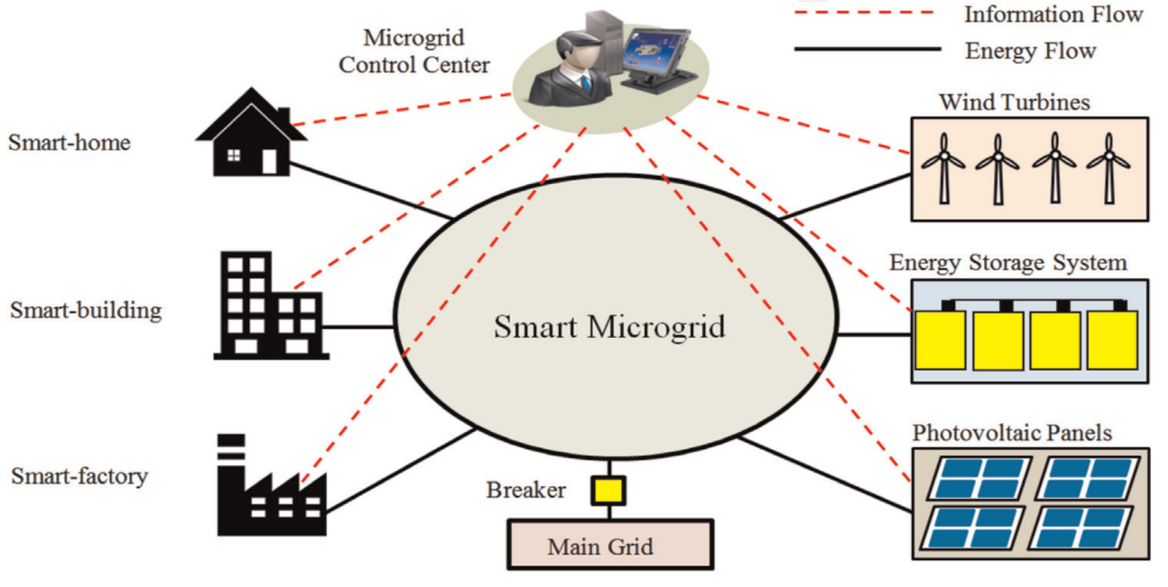


Figure 2.
Micro-grid architecture overview [12].

Energy Resources (30-40%)	Switchgear Protection & Transformers (20%)	SG Communications & Controls (10-20%)	Site Engineering & Construction (30%)	Operations & Markets
Energy storage; controllable loads; DG; renewable generation; CHP	Switchgear utility interconnection (incl. low-cost switches, interconnection study, protection schemes, and protection studies)	Standards & protocols; Control & protection technologies; Real-time signals (openADR); Local SCADA access; Power electronics (Smart Inverters, DC bus)	A&E (System design and analysis); System integration, testing, & validation	O&M; Market (utility) acceptance

Table 1.
Micro-grid major cost items [13].

Benefit	Customer	Utility	Society
Reduced Electricity cost & Fuel Cost	×		
Sales excess power to grid	×	×	
Remote monitoring and control	×	×	
Energy efficiency	×	×	
Reduced transmission & distribution losses		×	×
Reduced system congestion cost		×	
Reactive power & voltage control	×	×	
Peak shaving	×	×	
Increase use of renewable		×	×
Reduced SO2, Nox, CO2 emissions		×	×
Layered grid architecture		×	×
Automatic load management	×	×	
Load & resource profile		×	

Table 2.
Micro-grid benefits [14].

There are various requirements to support the micro-grid operation. Micro-grid is either used as a replacement for petrol generator to provide onsite energy generation or incorporated with the electricity grid. MG components propose the means for local control of electricity from both supply and utilization sides. **Table 1** shows the cost of its major parts as a percentage of the total cost.

1.2 Benefits and barriers of micro-grid

Benefits of micro-grid are shown in **Table 2**. The common technical barriers are problems concerning, dual-mode switching from grid-connected to off-grid mode, power quality and control, and protection issues. These issues are still a subject of research. Regulatory barriers are related to rules of power trading between micro-grid and the main network. The main financial barrier is the high replacement costs of the micro-grid components. Last of all, stakeholder barriers take in issues with differing self-interest and the expertise to manage operations.

2. Micro-grid system components

Being as intelligent and flexible as they are, the integration of micro-grids in power networks is currently getting great attention. Micro-grid system would comprise one or more of the following resources:

2.1 Distributed energy resources

2.1.1 Solar energy

The sun is ultimately the source of all energy supplies, excluding nuclear energy generation. Solar-electric power can be produced by power plants using the sun's heat or direct electricity generation using photovoltaic technology, which is more practical for urban use. Solar energy resources are:

- solar thermal conversion;
- low and medium temperature conversion;

- high temperature conversion-concentrated solar power (CSP);
- optical efficiency;
- combined optical and thermal efficiency; and
- solar electrical conversion (photovoltaic systems).

As a case study, Egypt lies in the Sun Belt area, with the following related data:

- direct normal irradiation ranges between 2000 kWh/m^2/year at the North and 3200 kWh/m^2/year at the South with very short cloudy times;
- the sunshine duration ranges between 9 and 11 hour/day from North to South; and
- potential capacity 73,656 TWh/year [15].

2.1.2 Wind energy

Egypt has become the leader of wind power in the Middle East and Africa through the past few years. Red Sea coast and Suez Gulf area are gifted with high rated wind speed (about 10 m/s) [16]. Hence, the area is considered suitable for constructing large wind projects. Wind power provides the major share of renewable energy generation in Egypt. Egyptian Wind Atlas exposed the huge potential of the Red Sea region in matter of wind energy where mountain chains on the coasts create a natural corridor that enhances the stability of winds. The Gulf of Suez west coasts have the benefit of being next to where electricity is most demanded. Wind generation equipment is divided into three general categories [17]:

- Utility-scale—corresponds to large turbines (250 kW to 2 MW).
- Industrial-scale—corresponds to medium sized turbines (50–250 kW).
- Residential-scale—corresponds to micro and small turbines (400 W to 50 kW).

In addition to solar and wind energies, other sources such as biomass, geothermal, hydro and bio-fuel can be incorporated.

2.2 Energy storage

Storage systems are vital to any micro-grid since they allow the balancing of electrical fluctuation and support the load required by the user. In isolated micro-grids, batteries are the mostly used as they are still considered the most economic electric storage technology [18]. Although energy storage technology has developed extremely in the past years, it still expected to continue developing. A tendency of reducing costs of battery technologies as lithium-ion and flow battery suggests that these technologies will be more applied. There is a relationship between energy storage and emissions. Energy storage is not 100% efficient which may cause extra emissions [19]. Even though batteries exist longer than pumped storage, costs have generally been too expensive for utility scale applications. **Figure 3** illustrates classification of energy storage technologies while **Figure 4** presents benefits of energy

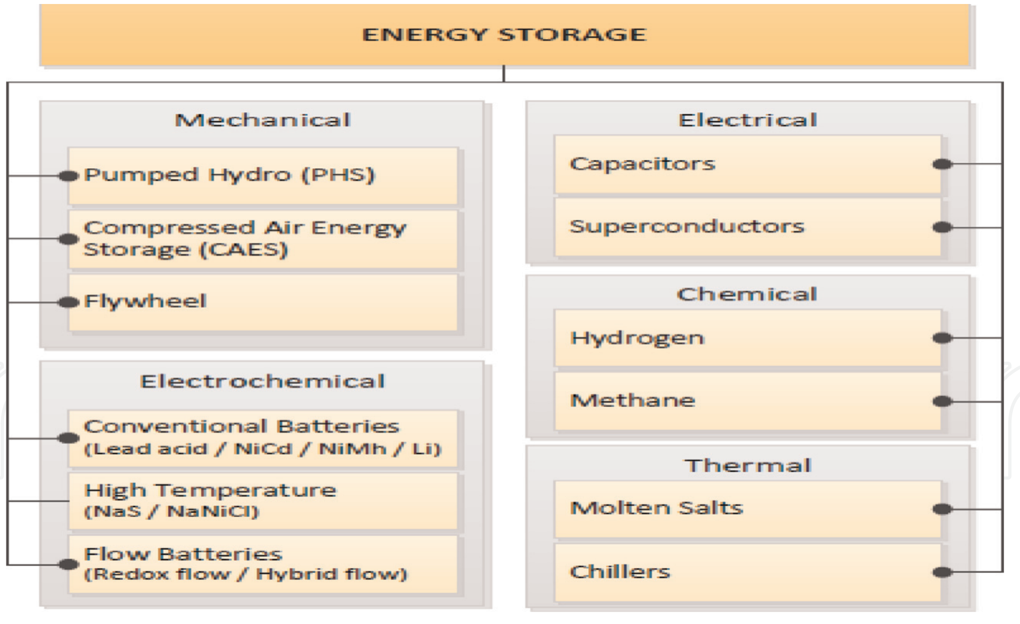


Figure 3.
Classification of energy storage technologies [20].

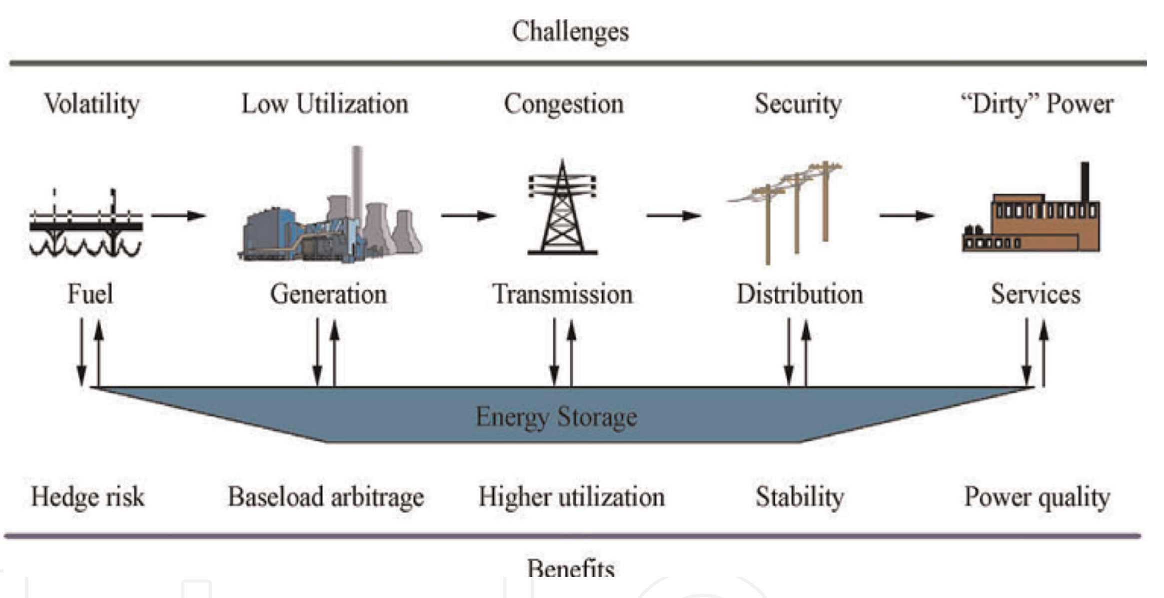


Figure 4.
Benefits of energy storage [21].

storage system. Costs of electricity of different energy storage technologies are shown in **Figure 5**.

2.3 Electric load

Construction of micro-grid and sizing of their energy components depends principally on the required load pattern to be supplied. Load may be domestic industrial or commercial demand.

2.4 Micro-grid control system (power management system)

Micro-grid control system (MCS) is the crucial component that enables the incorporation and optimization of energy to reduce the overall micro-grid energy cost [23]. The MCS provides an easy solution to combine conventional and renewable energy sources with energy storage to reach optimal operation minimizing the

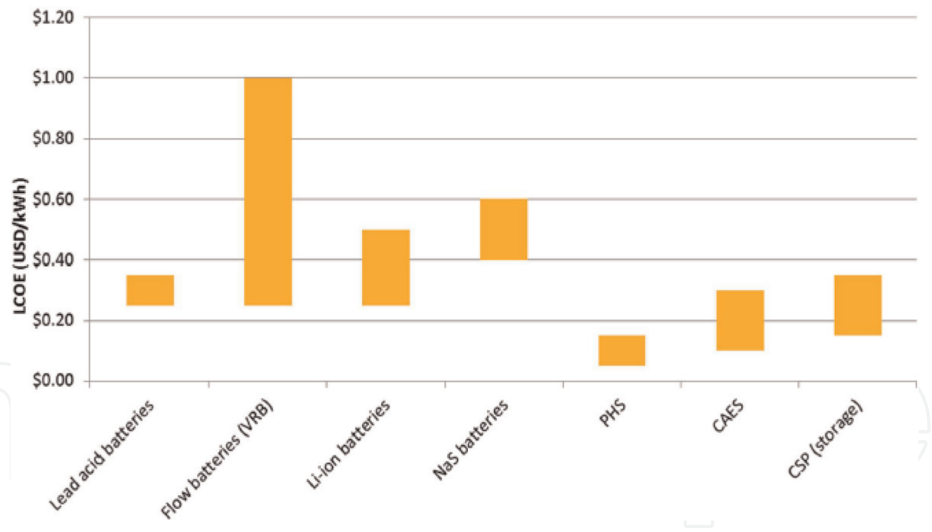


Figure 5.
Energy storage technologies levelized cost of electricity (LCOE) [22].

total cost and cost of energy (COE). Modern systems often merge software with control systems, such as smart meters, that can make the grid operation efficient and reliable.

3. Micro-grid modeling using MATLAB/SIMULINK

This section discusses the detailed modeling of micro-grid components and micro-grid system. Typical power sources, loads, and transmission lines have been modeled individually and tested well in MATLAB/SIMULINK. Actually, SIMULINK is a graphical programming environment for modeling, simulating and analyzing multi-domain dynamical systems [24, 25]. MATLAB/SIMULINK software package is used in the current study to model the MG components and investigate the operation of the MG system. List of PV, WT, DG models, short-term storage models, load models, utility grid model, and transmission line models is programmed and exhibited in the following [26].

3.1 Photovoltaic cell modeling (PV)

Solar PV panel power output varies with change in the sun direction, following changes in solar radiation amount and temperatures differences. As, the PV cell efficiency is low it is popular to activate the module at the peak power point so, the maximum power be capable of delivered to the load under changing temperature and irradiance circumstances. For reaching the maximum power from the solar PV module, a maximum power point tracker (MPPT) which helps in saving cost of the PV system. Prior to modeling a generalized PV array system a PV model is constructed using MATLAB/SIMULINK to show and verify the nonlinear I-V and P-V output characteristics of PV module. The basic model comprises a photocurrent source, a single diode junction and a series resistance and a shunt resistance [27]. The output-terminal current I is specified by Eq. (1) equipped the light-generated current I_{ph}, less than the diode current I_D and the shunt-leakage current I_{sh}.

$$I = I_{ph} - I_D - I_{sh} \tag{1}$$

The series resistance R_s represents the interior resistance to the present flow and shunt resistance R_{sh} is inversely associated with the outflow current to the bottom.

In a great PV cell, R_{sh} = 1 (no leakage to ground) and R_s = 0 (no series loss). The PV cell adaptation efficiency is receptive to little differences in R_s, however is insensible to deviations in R_{sh}. A tiny increase in Rs will reduce the PV output significantly. Within the equivalent circuit, the current delivered to the external load equals this I_{ph} generated by the illumination, less than the diode current I_D and as well the current of ground shunt I_{sh}. The open circuit voltage U_{oc} of the cell is found when the load current is zero, i.e., when I = 0, and is obtained from Eq. (2).

$$U_{oc} = U + IR_s \tag{2}$$

where U is the PV cell terminal voltage [27]. **Figure 6** illustrates the corresponding MATLAB/SIMULINK model of the PV array. I-V and P-V output curves with difference in radiation of PV array are exhibited in **Figure 7**.

3.2 Wind turbine modeling (WT)

Classically, a wind turbine combines of a rotor with three-blades, drive train and generator. Pitch angle is controlled so as to limit the generator output power to its face value for high wind speeds. The power produced by the rotor is obtained by Eqs. (3) and (4) [28]:

$$P = \frac{1}{2}\, Cp\,(\lambda, \beta)\, \rho\, AV^3 \tag{3}$$

where P: extracted power by rotor blades (W); ρ: air density (kg/m^3); A: turbine swept area (m^2); V: wind speed (m/s); Cp (λ, β): turbine power coefficient (max

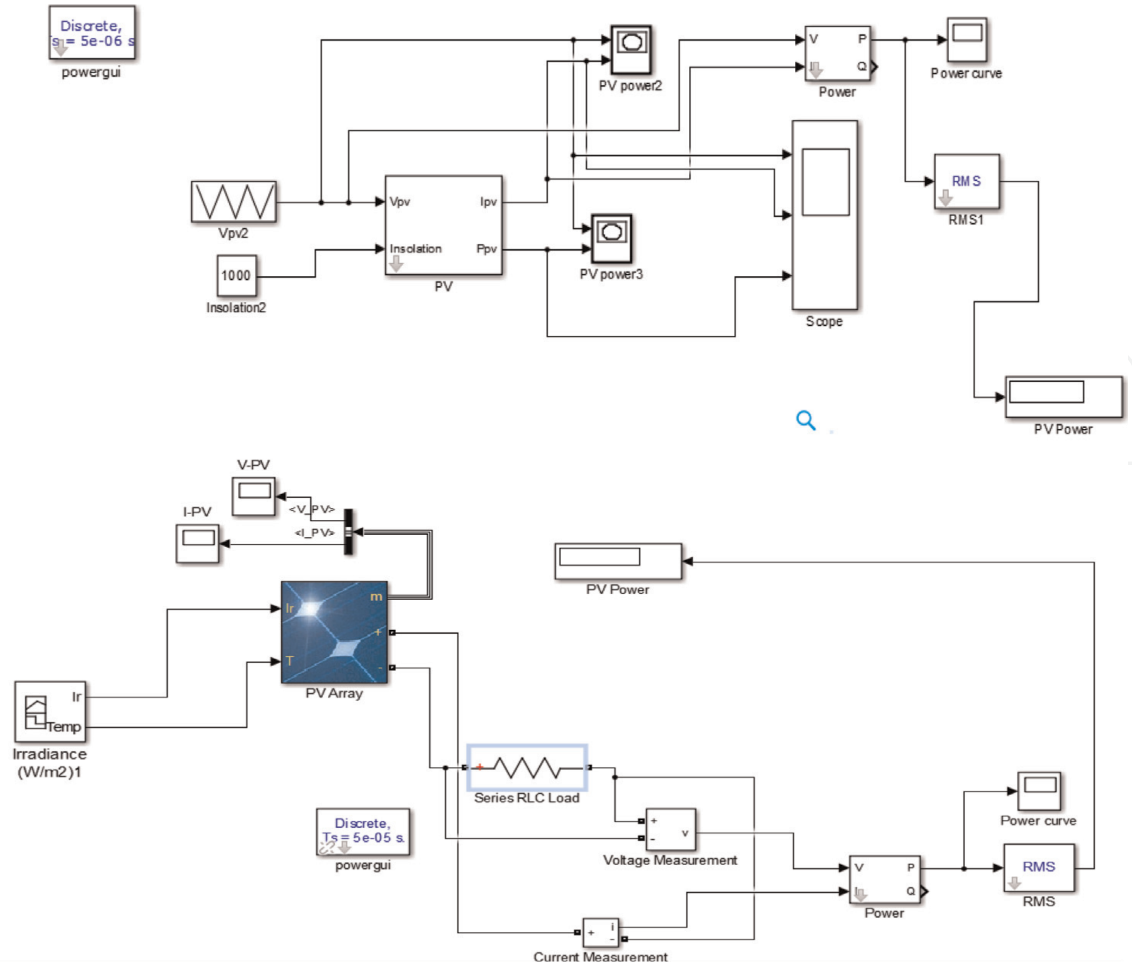


Figure 6.
Modeling of the PV array [26].

value: 59.26%, Betz Law); λ: tip speed ratio (rotor blade tip speed to wind speed); β: blade pitch angle (deg).

$$P = Ta * \omega r \tag{4}$$

T_a is the aerodynamic torque applied to rotor and ω_r the rotor rotational speed. SIMULINK model of a fixed wind turbine is shown in **Figure 8**. **Figure 9** illustrates

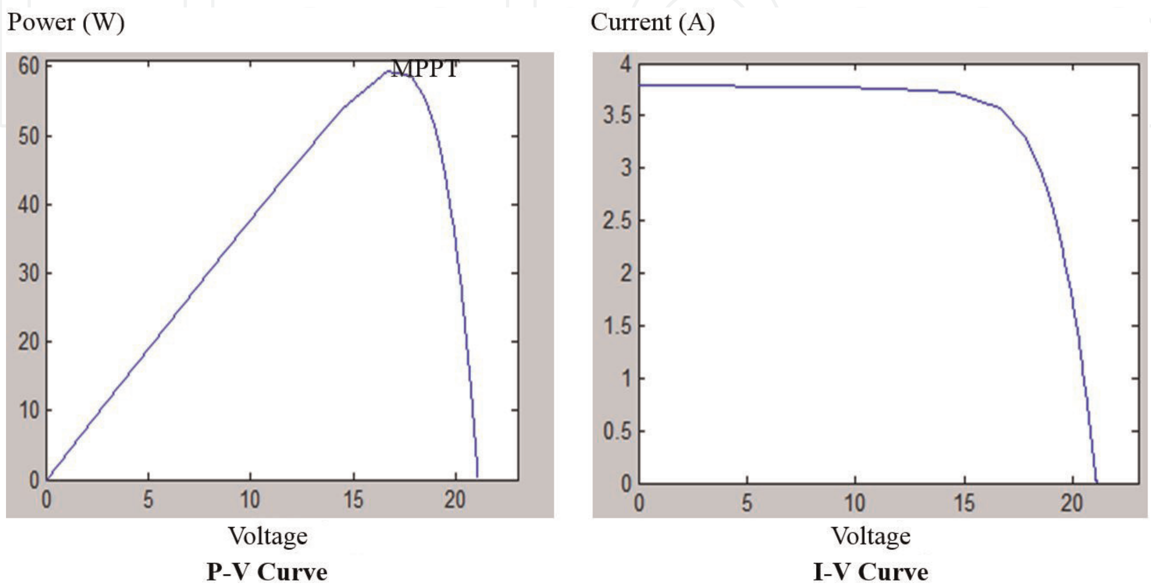


Figure 7.
P-V and I-V output curves of PV array [26].

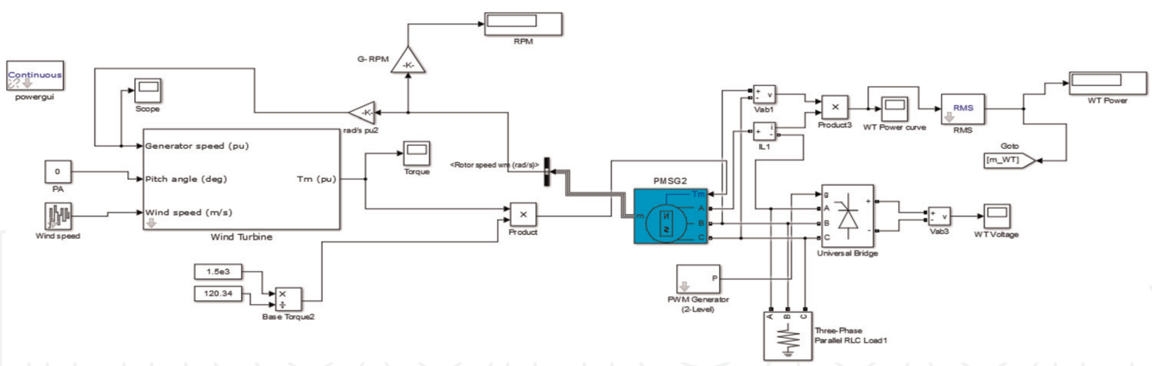


Figure 8.
Modeling of the fixed wind turbine speed [26].

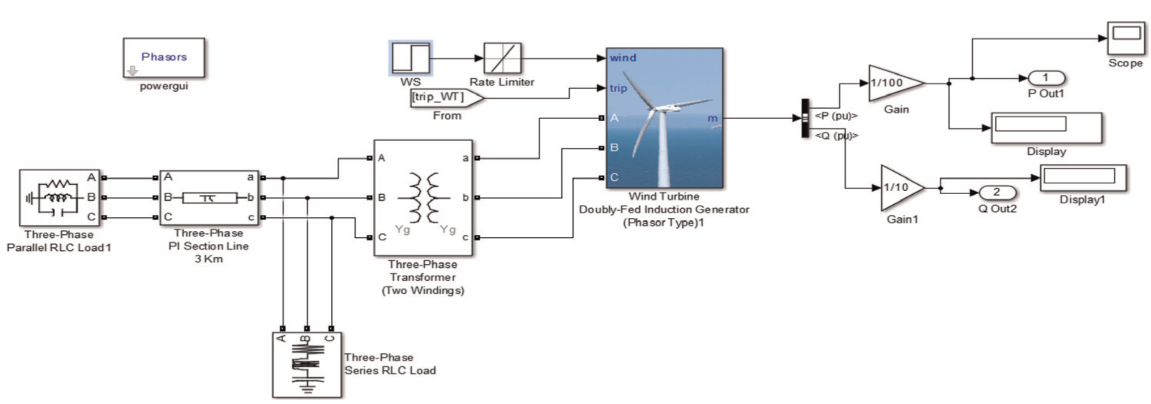


Figure 9.
Description of DFIG WT modeling [26].

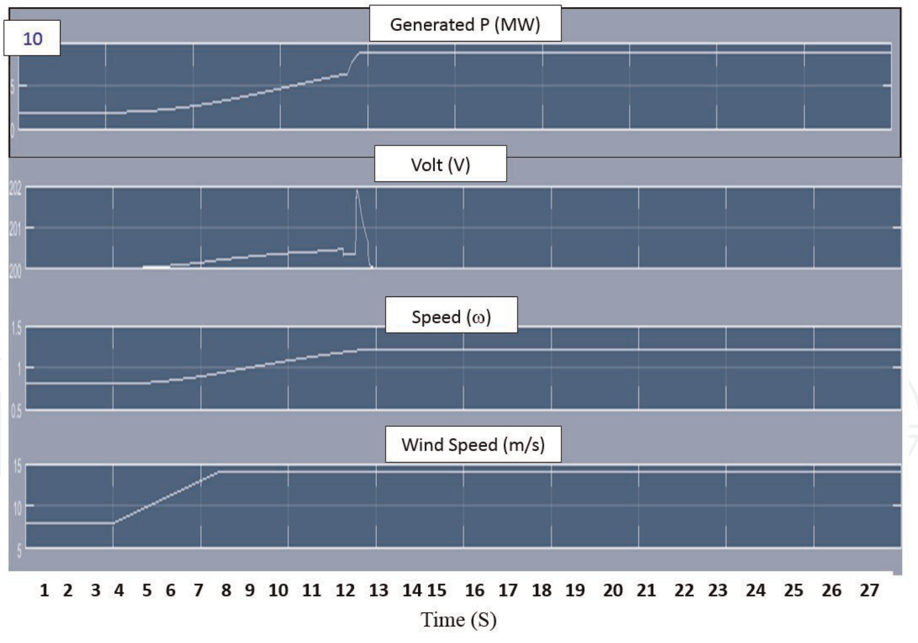


Figure 10.
Output curves of WT modeling [26].

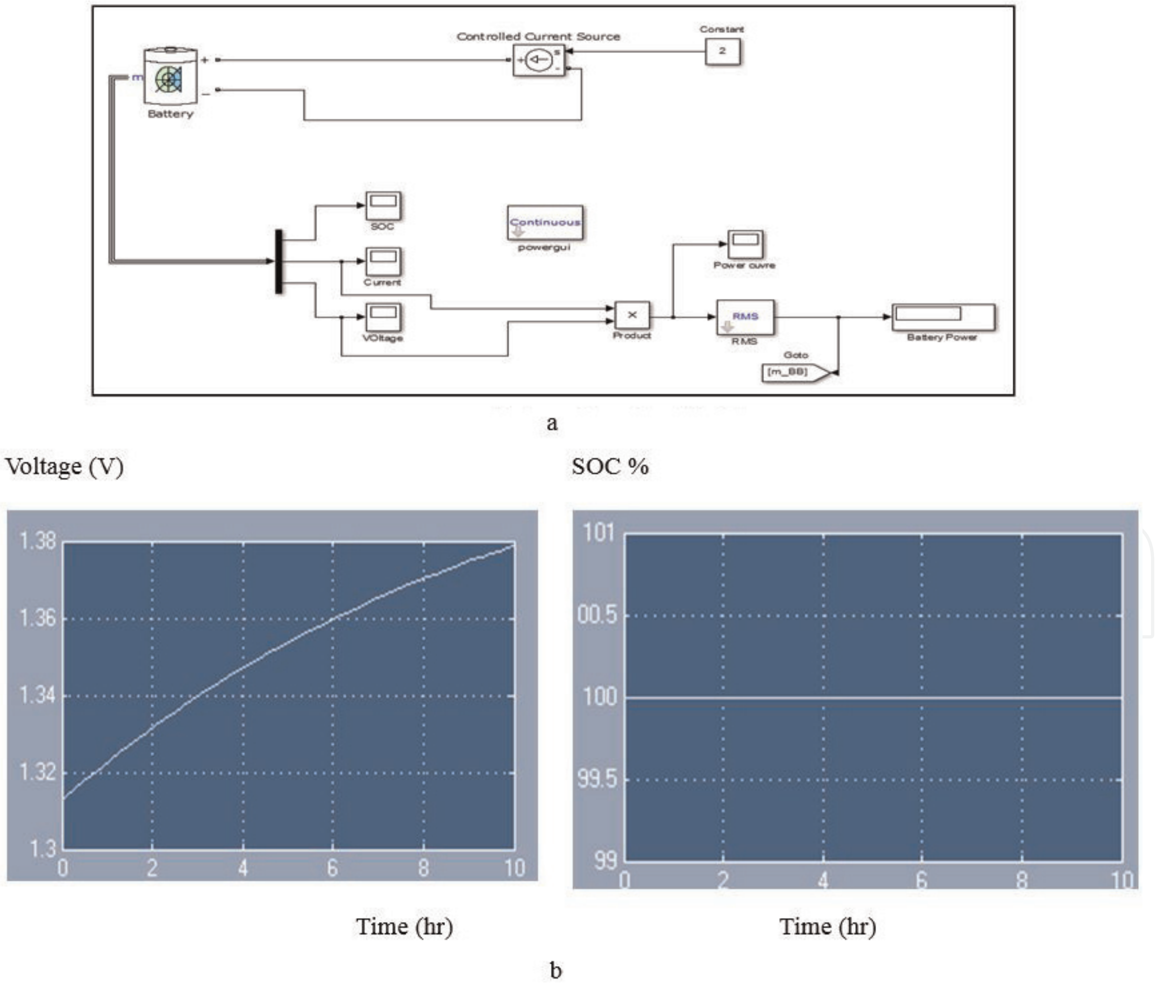


Figure 11.
Battery charging modeling and output curves [26]. (a) Battery charging modeling and (b) battery charging output curves.

variable WT speed as doubly-fed induction turbine generator (DFIG) and **Figure 10** presents WT output curves [26].

3.3 Short-term storage modeling (batteries)

The required electricity fluctuates according to the day and year time. Since the traditional power grid is not able to store up electricity, the mismatch between supply and demand is more likely observed. The battery model block in SIMULINK is utilized to simulate battery performance and obtain the results. To prevent the battery from overcharging or discharging, the state-of-charge (SOC) of the battery is no >100% (fully charged) and no <0% (empty condition) in SIMULINK model. Battery equation modeling is shown in next figure and equation since SOC is defined as [28]:

$$\text{SOC} = 100\left(1 - \frac{\int_0^t i dt}{Q}\right) \tag{5}$$

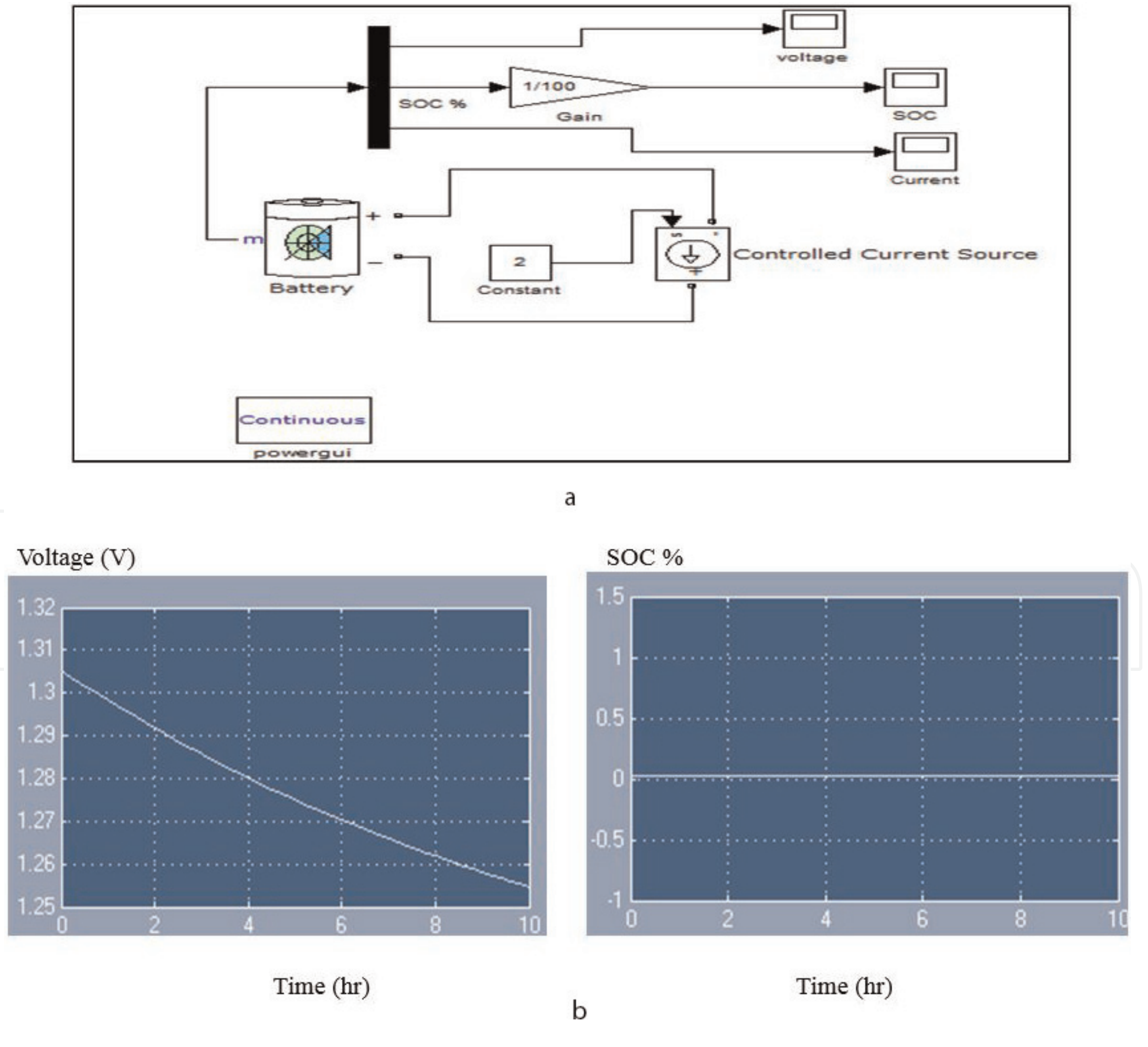


Figure 12.
Battery discharging modeling and output curves [26]. (a) Battery discharging modeling and (b) battery discharging outputs curves.

Figure 11 illustrates a comprehensive modeling of charge battery, (SOC and voltage curves) in MATLAB/SIMULINK while discharge battery modeling (SOC and voltage curves) are shown in **Figure 12**.

3.4 Diesel generator modeling

Diesel engines, developed over 100 years ago, have gained widespread acceptance in nearly each sector of the economy. Owing to their high potency and consistency they are used on several scales, starting from little units of 1 kW to massive many tens of MW power plants [29]. As a result of changes in load demands by the customers, it is important that the diesel engine has a feature of quick dynamic response. The power output of the engine and also the generator needs to be varied with the dynamic load so as to satisfy the customer demands. A diesel generator consists of a diesel engine with an electrical power generator. A diesel generator is chosen to be included within the micro-grid; its power capability would be higher than battery and PV and can support the grid. Emergency standby diesel generators are widely employed to support crucial loads when national grids occasionally fall.

In this micro-grid model, generator gives the reference signal in the micro-grid and manages the voltage and frequency using the diesel engine governor [30]. Diesel generator converts fuel energy (diesel or bio-diesel) into mechanical energy via an internal combustion engine, and next into electric energy by way of an

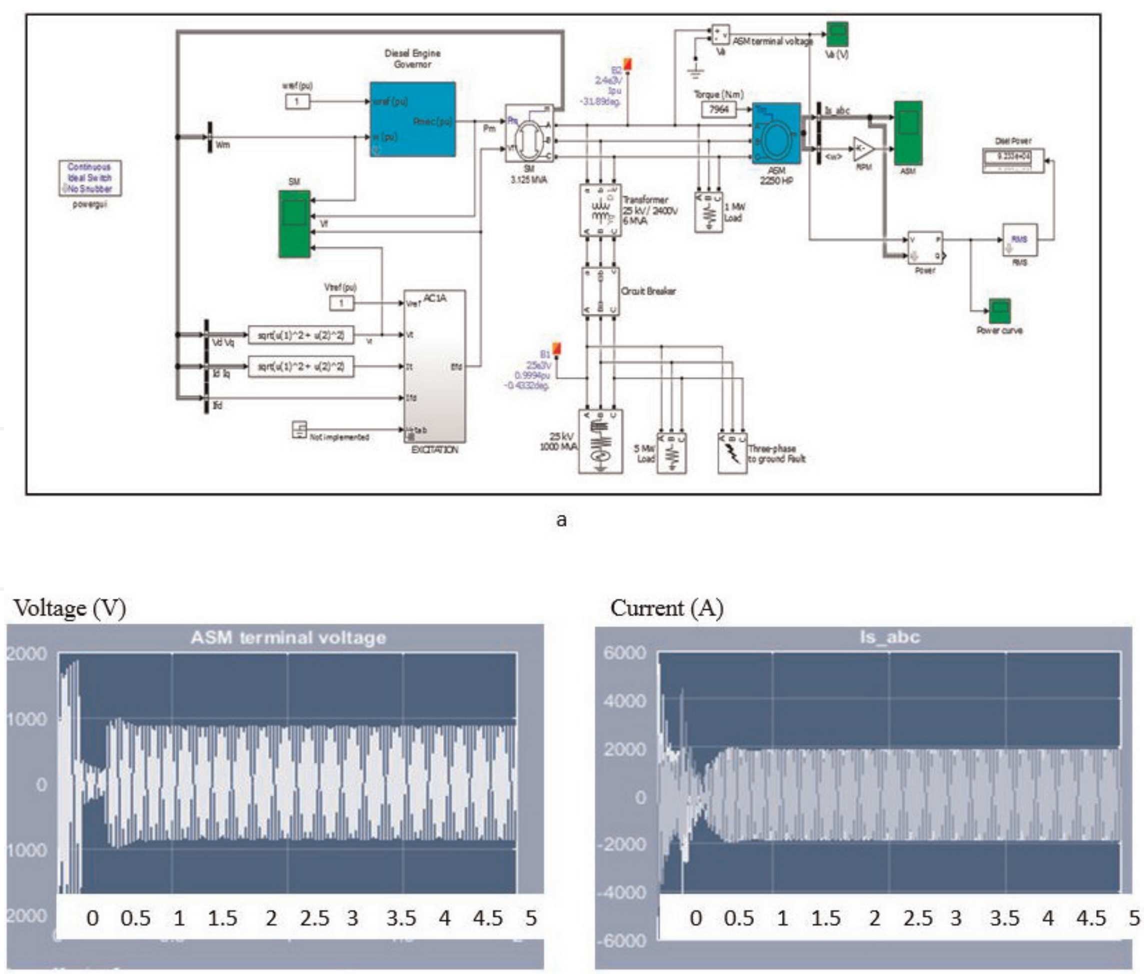


Figure 13.
Model of emergency diesel generator and output curves [26]. (a) Emergency diesel generator and asynchronous motor model and (b) output curves of emergency diesel generator model.

electric machine operating. **Figure 13** presents model of diesel engine and output power curve in MATLAB/SIMULINK [26].

3.5 Inverter controller

Power inverter is a mechanism that changes the dc sources to ac sources. Inverters are utilized in an extensive variety of applications, beginning from small switched power supplies for a computer to big electric utility applications to

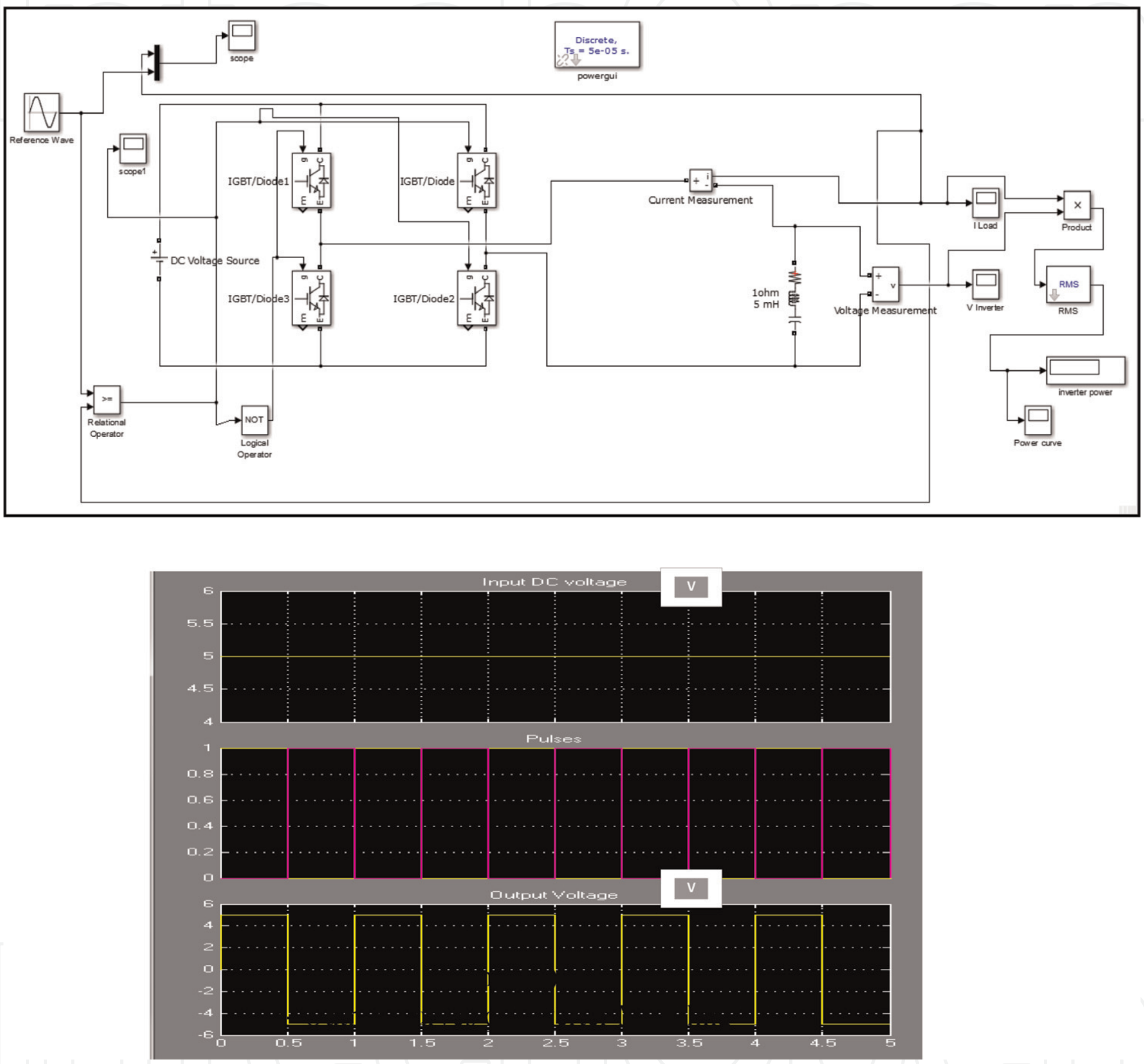
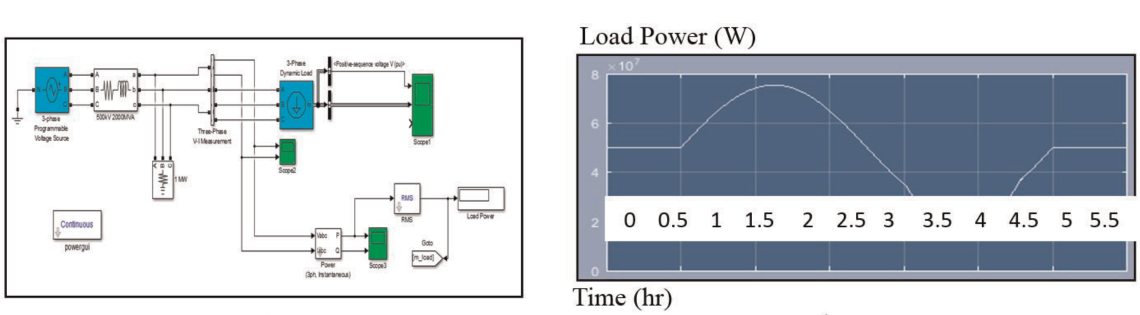


Figure 14.
Inverter modeling and output curves [26]. (a) Inverter modeling and (b) output curves of inverter modeling.



a b

Figure 15.
Three phase load model and output power curve [26]. (a) Three phase load model and (b) output load power curve.

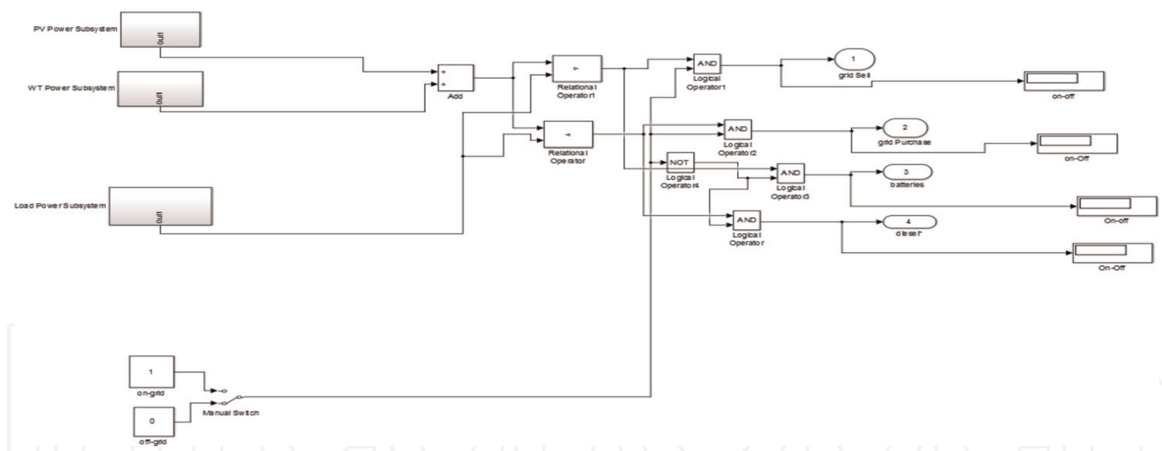


Figure 16.
Micro-grid control modeling in MATLAB/SIMULINK (on/off-grid mode) [26].

transport bulk power. **Figure 14** illustrates a model of inverter (a) and output power curve (b). Power inverters produce one of three special kinds of output wave [31]; square wave, modified sine wave and pure sine wave, each of them represent different quality of power output.

3.6 Electric load modeling

Figure 15 describes three phase load model and output power curve [26].

To work the micro-grid in grid-connected or off-grid way, a simple control logic circuit is intended in MATLAB/SIMULINK in **Figure 16**. In the on-grid system, when power output from renewable larger than load power, surplus power sent to grid sell block and when renewable output less than load power, grid purchase block used. In the off-grid system, when power output from renewable greater than load power, batteries are set in charging mode to store excess energy, and when renewable output less than load power, diesel generator used to cover this shortage.

4. Optimization of micro-grid system

The main goal of this study is to reach the optimal sizes of micro-grid components; including energy storage, investigating technical and economic performance, taking into consideration the environmental impacts. To evaluate system economy two criteria are used; the net present cost and the cost of generated electricity. The sustainability of supplying the load is an indicator of the system technical performance measured by the percentage of power shortage.

Hybrid energy systems lead to the improvement of system efficiency, power reliability, and reduction of energy storage size in case of off-grid applications. A review of the current situation of the simulation, optimization, and control technologies for the off-grid hybrid energy systems with battery storage was presented in [32]. A methodology for the design of smart grid hybrid power generation systems was presented by Hernández-Torres et al. [33]. The methodology was divided into two-level hierarchical techniques using the net energy concept and taking into consideration; technical, economical, societal and environmental aspects. The planned methodology consisted of two phases: a classic optimization process using levelized costs minimization and an analytical hierarchy process implementation for decision making problems. Technical—economical parameters were estimated using specific software as quantitative parameters. A hybrid genetic

DOI: http://dx.doi.org/10.5772/intechopen.87093

algorithm was used for the optimization of system components sizing [34]; PV-array, wind turbine, battery capacity and inverter that provide least system cost. Then, an iterative method for selecting the optimal inverter size of the proposed system is described.

Two alternative advanced methodologies were presented in [35, 36] to incorporate the uncertainties associated with renewable energy resources and load in sizing a building integrated hybrid energy system with minimum to maximum renewable energy fraction. Dynamic "multi-objective particle swarm" optimization algorithm, simulation module, and sampling average technique were used for hybrid energy system design through a multi-objective optimization model. The aim of this study was to minimize total net present cost as well as minimize cost of energy, maximize renewable energy ratio, and reduce fuel emission all together under a conditioned level of loss of load probability. Two studies of the micro-grid effect on the decreasing of cost through improving the reliability of small scale distributed generators using different optimization techniques were exhibited [37, 38].

Among the expanding PV technological and economic development, there is a prospective for mass-scale operation of grid-connected and off-grid power systems. The challenge arises in analyzing the economic projection on compound hybrid systems utilizing PV. A new metric levelized cost of delivery was investigated to estimate the levelized cost of electricity for using Photovoltaic in the smart grid system [39]. Another review [40] on up-to-date levelized cost of electricity calculation methods for PV system was described, highlighting the possible shortcoming of existing methods.

Borhanazad et al., [41] optimized the utilization of local renewable energy for on-grid application. HOMER, PV system, Hybrid 2, Sketch-up, and MATLAB software were used but HOMER is the simplest software. Based on the load profiles and the availability of water resources the simulation results showed the largest capacity produced the lowest energy cost, maximum reduction of carbon dioxide emission, and high renewable energy fraction. The optimization model included built-in individual models for: hybrid system, Loss of Power Supply Probability and Levelized Cost of Energy. The huge number of small-scale micro-grid parts with

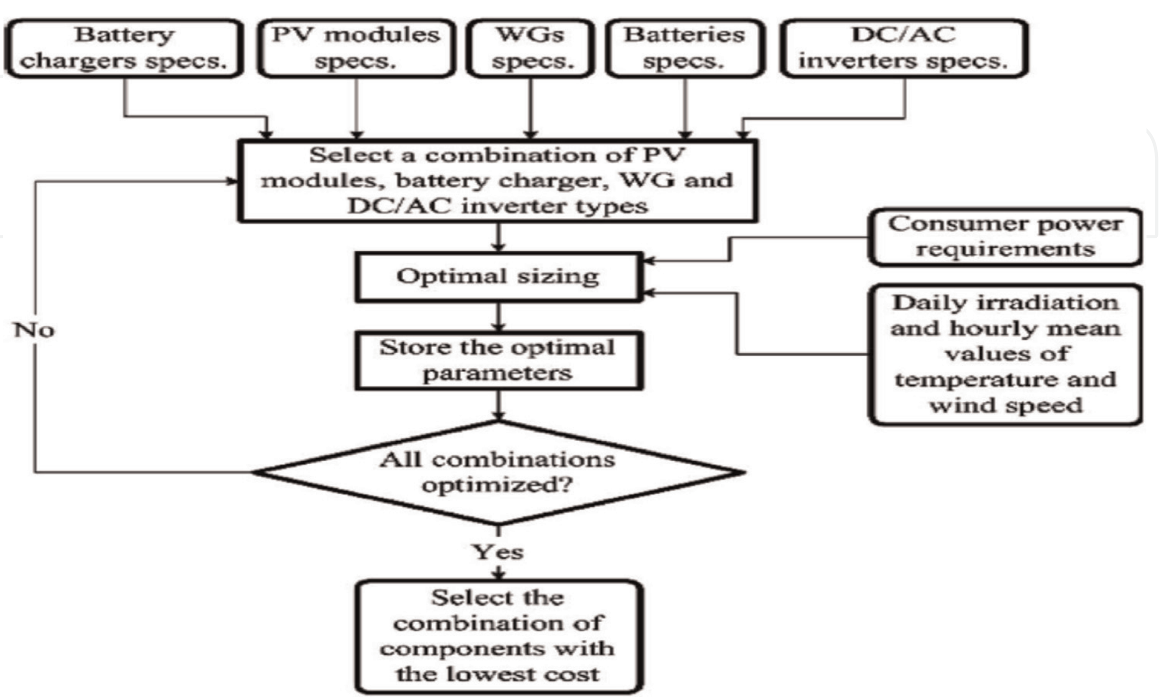


Figure 17.
Flowchart of the proposed optimization methodology [43].

their own characteristics is a large challenge for micro-grid modeling and setting up. Furthermore, in case of renewable energy, the power output might be irregular and nondispatchable. In order to investigate the economic performance and environmental impact of renewable energy-based micro-grid.

HOMER software package was developed by National Renewable Energy Laboratory is used to simulate the performance of a micro-grid system (MGS) to achieve the optimal configuration of the system supplying a predefined load. HOMER models both physical behavior of the power system's and its lifecycle cost. It allows the comparison a lot of different design options based on their technical and economic characteristics. It also assists quantifying the effects of uncertainty or changes in the inputs.

HOMER performs three functions [42]: simulation, optimization, and sensitivity analysis. In the simulation, HOMER models the performance of a MGS configuration every hour of the year to estimate its technical feasibility and lifetime cost. In the optimization, HOMER simulates various system configurations in search of the system that meets the technical constrains at minimum net present cost as the objective function. Sensitivity analysis algorithm allows the study of the effect of changing the parameter value on the optimal solution. **Figure 17** shows optimization process flow chart of micro-grid system [43].

4.1 Optimization model

Micro-power system optimization objective is minimizing both net present cost and cost of produced energy, under the conditions of specified ethics of allowable capacity shortage and definite renewable fraction percentage. This requires deciding different component sizes, site meteorological data, and the system mode of operation (Off/On) grid. The objective of optimizing micro-power system is to minimize the net present cost, minimizing the cost of produced energy at the same time. The optimization model can be created as follows [26].

4.1.1 Objective function

$$\text{Minimize z} = \sum \text{Net Present Costs (NPC)} \tag{6}$$

The net present cost (NPC) is the summation of:

- Capital cost = {PV module price × no of PV module + WT. price × no of WT + B. price × no of batteries + price + DG price (if used) + extension of grid cost (if the system is grid connected)}.
- Replacement cost = {Unit replacement cost (if any) × no of units}.
- Operation and maintenance Cost = {Unit O&M cost × no of units}.
- Fuel cost = {Consumed fuel (Liter) × Price liter}.

$$\text{Salvage value} = \left\{\text{Unit replacement cost} \times \frac{unitresduallifetime}{unitlifetime}\right\}.$$

$$\text{NPC} = \left\{\text{CC} + \sum_{i=1}^{N} \frac{(RC + O \wedge MC + FC - SV)}{(1+i)^N}\right\} \tag{7}$$

where CC, capital cost; RC, replacement cost; O&MC, operating and maintenance cost; FC, fuel cost; SV, salvage value; i, interest rate; and N, number of years (project life time).

4.1.2 Design constraints

- Maximum allowable shortage/year
- Minimum renewable fraction
- Wind and solar percentage of renewable fraction (wind-solar)
- Annual real interest rate

4.1.3 Decision variables

- Photovoltaic (module power, number of modules), solar radiation on site
- Wind turbine (turbine power, number of turbines), wind speed at the site
- Battery bank (battery Ah, number of batteries)
- Diesel generator (power in kW)
- Converter (rated power)
- Mode of application (Off/ON grid connected)

4.2 Simulation approach

Although the system reliability was assumed to be 85–90% no shortage was detected in some cases. The optimization software enables changing the variables of the hybrid system model in terms of sizing and operation. In such a method the life cycle cost of the hybrid systems regarding the demand necessities are reduced. In this approach the renewable energy sources (wind and solar) plus the energy stored in the battery are used to cover the demand. If used, the diesel generator is switched on as a back-up (off-grid system) source when the battery is discharged to a predefined level. For every hour the simulation process compares the needed energy demand and the delivered energy, and in relation to the difference, a choice to run the diesel generator or to charge the battery or discharge it will be taken. The use of renewable energy to supply load has priority over using batteries or diesel generator. The extra energy is utilized to charge batteries. Different configurations of WT/PV/Grid for on-grid system and WT/PV/DG/B for off-grid system are considered.

If the hourly simulated required demand is higher than the supplied energy and the battery had reached the minimum charge level (DOD), the diesel generator is switched on. Different configurations of WT/PV for on-grid system and WT/PV/DG/B for off-grid system are considered. Different wind turbine and photovoltaic models are used. The complete experiments will achieve for both on and off grid cases.

4.3 Optimization results

Several simulation runs were executed using HOMER, varying the parameters that have a significant effect on the optimization results. In addition to those input parameters, different prices of diesel oil have been used for sensitivity analysis. The output of the simulation is a list of feasible combinations of PV, wind-turbine, backup generator, converter, and battery, hybrid system components. The optimization results are shown in any of two shapes; a general form in which the top-ordered system configurations are stated along with their net present cost and a classified form where only the least-cost system configuration is regarded as for every system type. Total net present cost is applied to signify the life-cycle cost of a system. The discount rate and the project life span should defined by the user.

The NPC consists of construction cost initially, replacement-maintenance-fuel costs of each component, adding the cost of purchasing power from the national grid and various costs such as penalties effecting from pollutant emissions issues.

4.4 Sensitivity analysis

Sensitivity analysis was applied to estimate the effect of change of wind speed and solar radiation. It is expected when solar radiation and wind speed raise (renewable contribution), the NPC and COE will decrease. The effect of changing in solar radiation, wind speed, diesel price, grid price, PV efficiency and inflation rate are declared. **Figure 18** illustrates a sample of optimal system graph [43].

The pervious figure shows that:

- Wind/D/Battery system is optimal feasible solution for load probability in the range (45–120 kWh/d) and annual average wind speed in the range (5–7 m/s).

- PV/D/Battery system is optimal feasible solution for load probability in the range (5–40 kWh/d) and annual average wind speed <4.5 m/s.

- Wind/PV/D/Battery system is optimal feasible solution for load probability (<2 kWh/d) and annual average wind speed (>4 m/s).

- D/Battery system is the optimal feasible solution for load probability in the range (40–45 kWh/d) and annual average wind speed (<4.5 m/s).

- Diesel system is the optimal feasible solution for load probability (45:120 kWh/d) and annual average wind speed in the range (3–5.5 m/s).

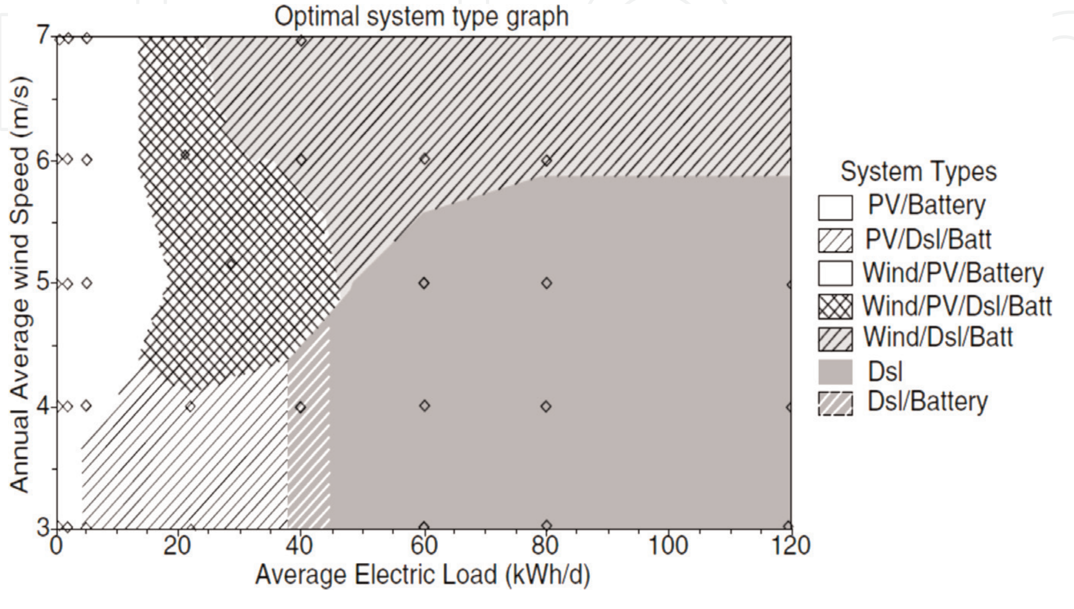


Figure 18.
Sample of optimal system graph [43].

4.5 Break-even analysis

Break even analysis is performed to estimate the distance between site location and the electricity grid for which the cost of installing renewable energy micro-grid is equivalent to the cost of extending electricity. If comparing cost of energy of off-grid system with the cost of extending the grid, it could be seen as the break-even is 18.4 km. This means that if the proposed site for installing the micro-grid is >18.4 km, then it is more economical to install the micro-grid. Obviously if WT and PV outputs are higher, then RES could break even with grid extension at shorter distance.

5. Emissions of CO_2 in micro-grid planning

The growing awareness of the high level of carbon and other greenhouse gases (GHS) emissions makes the concept of renewable energy-based micro-grids more attractive. It is vital now to rely on renewable energy sources to supply as much as possible energy demand, saving the limited fuel resource reducing greenhouse gases emissions [44]. A number of researches are performed to develop the feasibility of renewable energy generation. Reduction of pollutant emissions are anticipated using micro-grids as an alternative of conventional energy systems. The estimated off-grid system emissions are shown in **Table 3** [43]. These data is utilized to calculate the cost of CO_2 emissions.

In preceding simulation results, the emission penalties; according to updated Egyptian climate-change plan, have not been considered. The price of one ton of carbon dioxide is in the range \$60–\$80 by 2018 per ton of carbon [45]. The emissions cost appears adding to the operating and maintenance costs.

Emissions (kg/year)	Pollutant
21,956	Carbon dioxide
54.2	Carbon monoxide
6	Unburned hydrocarbons
4.09	Particular matter
44.1	Sulfur dioxide
484	Nitrogen oxides

Table 3.
Emissions produced from the optimum off-grid system [43].

6. Future work

- Further analysis can be performed on different developed Micro-grid models, including other components such as; biomass generators, thermal load, and other storage technologies, e.g., fuel cells and pumped hydro evaluating their performance.

- Investigation of super-capacitor battery performance as a new storage technology, upon its availability.

- To encourage the contribution of nongovernmental organizations, private sectors, and international companies to participate in the efforts of RE applications and REMG. This requires fulfilling the signed purchase power agreement (PPA), through regular payments and ability of transferring their revenues of selling electricity to dollar.

Author details

Marwa Mohsen Ibrahim Abd El-Rahman
Department of Mechanical Engineering, National Research Centre (NRC), Egypt

*Address all correspondence to: yara_mh2003@yahoo.com

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