Master of Science Thesis

AC/DC AND HYBRID MICROGRID COMPARISON FOR A WATERPUMP SYSTEM

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AC/DC AND HYBRID MICROGRID COMPARISON FOR A WATERPUMP SYSTEM

By

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LIST OF ABBREVIATIONS

DC	: Direct Current
AC	: Alternative Current
PV	: Photovoltaic
PWM	: Pulse Width Modulation
RES	: Renewable Energy Source
DER	: Distributed Energy Resource
IEEE	: International Electrical and Electronic Engineers
IEC	: International Electro technical Commission
HOMER	: Hybrid Optimization Model for Electric Renewables
NREL	: National Renewable Energy Laboratory
WT	: Wind Turbine
WTS	: Wind Turbine Systems
VSC	: Voltage Source Converter
VSI	: Voltage Source Inverter
CCS	: Current Control Strategy
TW	: Tera Watt
HPGS	: Hybrid Power Generation System
CO_2	: Carbon dioxide
MPC	: Model Predictive Control
MILP	: Mixed Integer Linear Programming
DFIG	: Doubly Fed Induction Generator
PMSG	: Permanent Magnet Synchronous Generator
VFC	: Variable Frequency Control
IM	: Induction Motor
MV	: Medium Voltage
MPPT	: Maximum Power Point Tracking
COE	: Cost of Energy
NPC	: Net Present Cost
CRF	: Capital Recovery Factor

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ACKNOWLEDGMENT

This thesis presents the result of my master graduation project, conducted at Rijkswaterstaat (Ministry of Infrastructure and the Environment) in Delft. It is the final part of my studies at Delft University of Technology, completing my Master of Science in Electrical Engineering. I had the opportunity to research the energy efficiency AC/DC and hybrid micro grids in a water-pump system (Gemaal Kreekrak) to pump the water from one site to other site.

At the end of my thesis, I would like to thank all those people who made this work possible and unforgettable experience for me.

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ABSTRACT

In this thesis, the main objective is to argue and address the best fitting micro grid electric distribution system for a typical water-pump systems whereby the primary energy sources is renewable. So far, the grid whose main sources were wind, fossil fuel and solar energy has achieved the energy supply for the pump located at 51° 26' 58" N and 4° 13' 41" E. Seasonal changes were taken into consideration when carrying out the analyzes in the study from both perspectives; the load side and the energy sources. Energy efficiency is analyzed and compared across multiple types of micro grid distribution systems, and the raw data are processed by HOMER program and the results are deduced as such.

The study consists of various grid configurations. Each grid configuration (AC, DC and hybrid AC/DC) is also analyzed by assuming that all three main energy sources are connected to the micro grid.

The system performance is also analyzed with 50% load increase in the AC-DC hybrid network. Besides, each grid configuration was re-analyzed using multiple types wind turbine and PV panels and the results were depicted. In Rilland-Netherlands, which was the selected pilot area, solar energy technologies are not utilized sufficiently because the solar energy potential is low. Therefore, most of the energy is supplied by wind power generation systems. For this region, energy surplus produced could be stored in batteries. However, this is not an option due to the cost and technical constraints.

According to the analysis results obtained via the HOMER program, the most appropriate solution is to use a hybrid micro grid whose energy source is renewable and it is Grid-Connected. In this regard, the Grid/PV/wind renewable hybrid in a hybrid AC/DC micro-grid system is the most suitable one for the selected pilot area Rilland-Netherlands.

Keywords: AC, DC, Hybrid AC/DC micro-grid, PV, Wind, Productivity analysis, Energy production

CHAPTER I. INTRODUCTION

The Kreekraksluizen-complex is located in the Scheldt-Rhine connection and is part of the Rotterdam-Antwerp shipping corridor. This corridor is intensively navigated by commercial shipping and is of great economic importance.

The Kreekrak locks, in combination with the pumping station, form a retaining watershed between the Zoommeer Lake and the Antwerp Canal House (primary water defense). The Kreekrak pumping station, form a retaining watershed between the Zoommeer Lake and the Antwerp Canal building (primary water defense).

Within the drainage of water function, the pumping station has the following two functions:

1. To keep the salty water at a certain distance by maintaining a freshwater bubble on the Antwerp Canal;
2. Drainage of water in the context of the calamity regulation.

In this chapter, the problem is described in a detailed manner. In Section 1.1, the problem definition is depicted. In Section 1.2, the purpose of the thesis is described. Following, the method is described in Section 1.3. Finally, the organization of thesis is presented In Section 1.4.

1.1 Problem Definition

Rijkswaterstaat, the provinces and the water boards together consume approximately 176.8 GWh/year to manage the Dutch water system. This is about the equivalent of electricity consumption of 50,500 households (3,500kWh per household).

Rijkswaterstaat uses 31.5 GWh (18%) annually, the provinces consume 4.7 GWh (3 %) and the water boards 140.6 GWh (79 %). The water boards are by far the largest energy consumers in Dutch water management. Most of the energy (94%) consumed by the water pumping systems [1].

According to climate agreement, Rijkswaterstaat wants to be energy-neutral by 2030. That means generating as much energy as consuming. Rijkswaterstaat also want to be fully air-condition-neutral by 2030, or just no CO_2 emissions and greenhouse gases, not even by chain partners [2].

The precondition for this study is to improve energy efficiency with minimal adjustments within the water-pumping system. The energy efficiency analysis is done with existing water pumping system components. Minimum 90% of the energy consumption by the water-pumping system Kreekrak will be supplied by renewable energy sources such as solar and wind energy. The rest of energy consumption will be supplied by utility grid.

Rijkswaterstaat considered generating the energy for the drainage in combination of the wind energy and solar energy. This study focuses to determine the most suitable micro-grid type based on energy efficiency for the water pumping system.

1.2. Purpose of the Thesis (Objective)

High-level RESs integration into the grid, the system creates instability and affects system dynamics [3]. Voltage source converters (VSCs) are used in the grid connection of the RESs. VSCs interfacing with RESs lack the performance required to provide frequency and voltage control of an AC system. Therefore, they cannot contribute to the development of system stability [4]. The loads in the system are powered by AC and/or DC power. Since a PV panel is known to generate DC power, a DC-to-AC converter is needed for an AC load. However, the cascade power electronics structure and application problems in a DC micro-grid continue. Energy losses and high costs in both DC and AC micro-grids reveal the necessity of investigating three types of networks [5], [6].

In this study, the most suitable micro-grid type, concerning energy efficiency and economic benefits will be determined for the water pump system that are an AC load. The components sizing and emission will be calculated. The recommended AC, DC or Hybrid AC/DC micro-grids will provide the whole or all 90% or more energy from the Solar and Wind systems to ensure the running of the water pump.

1.4. Method

The five sub-questions described in the previous section give a brief overview of the structure of this research. In this section, the method used in this research is described in detail. First, a literature study was executed regarding the water pumping systems including its sub-elements, different micro-grid topologies including its sub-elements (solar arrays, wind turbines, power converters)[7],[8], [9].

The main task is to find the best choice out of three micro-grid types with different energy sources (solar panel, wind turbine and utility grid), these micro-grid types are compared and the best suitable type is chosen. Further two cases are defined with different system components such as solar panel, wind turbine and converter.

HOMER (NREL, US) program was used to simulate system operation and to calculate technical-economic parameters for each configuration. The HOMER program is a computer model that enables the design of power systems and the comparison of power generation technologies and applications. The American National Renewable Energy Laboratory (NREL) developed it. HOMER calculates the physical behavior and whole life cost of a power system, and this includes the creation and operation of components throughout the life of the system. The program offers the possibility to compare the design options based on technical and economic values. It also helps to understand the uncertainties in input data or the effect of changes on system design. The program requires input values such as technology options, component costs, and resource compliance, and by using all of this data, it lists system combinations that can be applied to different system configurations according to system costs [10].

1.5. Organization of Thesis

Except this chapter, the thesis consists of five chapters, excluding references and annexes. A summary of these sections is given below.

In chapter II, brief information about energy concept, past, and future is given. It explains how the need for the RESs occurred, what the RESs were and what areas could be used. Problems related to network integration of RESs, the solution methods in the literature about these problems are explained. Literature summary of the study was given, and the expected result and purpose were explained.

In Chapter III, information about current and proposed system components is provided. The utility gird, transformer, variable frequency controller, induction motor, PV panel and wind turbine are described.

In Chapter IV, renewable energy sources in Rilland, Netherlands and the load profile are analyzed. The annual average solar energy density, wind speed distribution and the load profile are calculated.

In Chapter V, micro-grid comparison studies are conducted. In HOMER software, the proposed micro-grids: AC micro-grids, DC micro-grids and Hybrid micro-grids are simulated for water-pump system. For variable load, solar energy and wind energy different analysis are performed. The advantages and disadvantages of the systems proposed are revealed by graphical analysis.

In Section VI, the results of the proposed methods are given by making a general evaluation. According to the results, suggestions were made for future works.

CHAPTER II. LITERATURE STUDY

The literature study is presented in this chapter. The purposes of this chapter is to give the necessary background to address the research questions. The development of the energy consumption, production and distribution systems is reviewed. The background of the energy is shortly discussed in Section 2.1. The micro-grids and their sub-systems are reviewed in Section 2.2. Lastly, in Section 2.3 the optimization studies with HOMER are described.

2.1. Background

The energy demand towards 2030 will increase by around 50-55%. Renewable energy will be an essential alternative to meet this energy demand [11]. In this context, the depletion of the primary energy sources of fossil origin and concerns about global warming are increasingly increasing the importance of alternative energy sources.

Increasing energy needs may cause interruptions that are due to economic and/or physical reasons such as the loss of power in the case of long distances, the lack of sufficient energy despite the increasing energy need and the unbalanced power distribution, etc. Therefore, a more intensive analysis is needed to ensure network safety. In this context, Distributed Energy Resources (DERs) has been used. Problems that may occur during network connections of the DERs are problematic for the plant, system, and consumer unless they are analyzed in detail [12].

DERs can reduce the electrical and physical distances between the load and the resources, as well as improve the reactive power to increase the mains voltage and power quality. They can eliminate the need for energy in distribution and transmission lines and reduce line losses. However, when the Voltage Source Inverter (VSI) is checked, it is different when it is compared to the single DER connected to the network and the multiple DERs connected to the network. The Current Control Strategy (CCS) can control single DER. The multi-DERs network requires to be regulated faster since it has more than one power generation characteristic and capacities [13], [14]. During DERs working; may cause problems such as over and under voltage, surge voltage change, unstable network frequency and voltage [15]. Therefore, it is difficult to meet the high-precision real-time control requirement in load fluctuations.

Renewable energy is seen as an analytical solution method in meeting the energy needs of the world in the future. For example, renewable energy studies in Europe starting in the 1970s have now led to the acquisition of 30-60% of energy in countries such as Denmark, Portugal and Spain [16]. Also, according to US data, while the share of renewable energy in total energy is given as 10% in 2011, it is seen that comprehensive work has been done to reach this rate up to 80% by 2050 [17]. However, most of the renewable energy technologies are dependent on weather conditions, and this creates problems in the integration of the network system. In this context, more work is needed to meet energy needs.

2.2. Micro Grids

Consumption habits of users vary depending on time in daily, monthly and annual processes. Due to these differences, demand may be too low for sometimes when it is above average and at times, it may be high enough to force the capacity of the network. The micro-grids are structures that contain a group of loads fed by one or more distributed energy sources and part of the MV (Medium Voltage)/LV (Low voltage) distribution system [18].

The benefits of micro-grids to nature and the economy, and the acceptability of grid power in the industry because of these benefits depend primarily on the characteristics of controllers and properties of controllers. Control and participation of distributed energy resources (DER) to traditional power systems is essential due to load characteristics and power quality problems [19].

The objectives of the micro-grids are to meet the demanded power and to keep the power quality at the best level. However, the active and reactive power changes of the DERs and the voltage fluctuations due to non-linear loads impair the stability of the network. Wang, Blaabjerg [20] the AC micro-grid, modeled in Matlab/Simulink environment with loads and production units. The harmonic problems/distortions that may occur during the operation of the system with the simulation operation performed have been determined, and it has been shown that the solutions provided can be used in the micro-grid integration and good results can be obtained. Diaz, Gonzalez-Moran [21] in his study, with the help of the theory of bifurcation frequency/voltage variation in the power system, or in other words the attenuation/reduction coefficients (droop coefficient) has determined. Then, he investigated the effect of the selected coefficient for micro-grid stability and reserve amount to be kept in island mode. A switch-based controller based on sliding mode control has been developed to prevent changes in the case of failures of the DERs producing in them, or a new unit is added [22]. This controller is built into the DER and it offers a convenient application.

2.2.1 Renewable Energy Sources

Approximately 80% of the electrical energy consumed in the world is currently based on fossil-based energy sources and nuclear sources; the remaining 20% is obtained from the RESs [23]. Due to ease of use and cleanliness, the share of alternative energy in energy consumption is increasing with each passing year compared to other energy sources.

Solar energy, one of the alternative energy sources, is the result of fusion events occurring in the sun. The radiation resulting from these fusion events is called solar energy. Approximately half of the sunlight reaches the earth by passing the atmosphere layer covering the earth's surface. Increased warmth on earth by solar energy makes it possible to sustain life. Due to temperature changes on the surface of the earth, wind formation and/or ocean stream occur. The amount of solar energy is about 1370 W/m^2 outside the atmosphere and can range from 0 to 1100 W/m^2 inner atmosphere. In this context, even a small portion of the amount of energy that can reach the earth can be said to be much more than the amount of energy consumed. The literature shows that after the 1970s, work on obtaining electricity from solar energy increased. Solar energy systems, or photovoltaic (PV) systems, which are an environmentally friendly technology, have shown a decrease in cost with the advancement of technology and have established itself as a new energy source [24].

Wind energy systems, another alternative energy source, are based on the electrical energy obtained from the kinetic power of the wind and energy production depends on the wind speed. The turbine is connected to a high tower in order to be more utilized from the kinetic power of the wind. Wind is a non-continuous source, but wind turbines are a reliable technology. Wind turbine systems have undergone significant changes and transformations. Although, in the 1980s, a wind turbine of 50 kW was considered too large and today wind turbines have a capacity of 2-3 MW and 10 MW turbines whose design has been studied. The reasons for this development include lower energy cost and performance improvement regarding network connection [11].

Another source among RESs is hydroelectric energy. This energy type uses the flow power of water. It is a kind of energy without harmful greenhouse gas emissions. Hydroelectric energy is generated by the transmission of kinetic energy generated by the flow of water to the turbines via channels. Especially in places where the height and water flow rate is high, it is of great advantage to make hydroelectric generation [25].

Another source found among RESs is a geothermal energy source. This type of energy, which serves different purposes such as heating, cooling, electricity generation and mineral production, also helps the tourism sector with the help of hot springs. It has a vital role among the clean energy sources in our country [26].

RESs include many other energy sources such as biomass, hydrogen, wave energy, etc. If one considers the economic, social and commercial developments in the world, RESs will all have a significant share in the future [27]. The literature calls RESs as distributed energy resources (DER) in network integration [28].

Geothermal energy is the type of energy obtained directly or indirectly in geothermal sources.

2.2.2 Distributed Energy Sources

The voltage control is applied to the DER inverters when there is no main network to provide voltage reference to the network to which they are connected. In this respect, it is better to apply them to specific powerful DER inverters in terms of energy continuity. Voltage control algorithms with constant amplitude and frequency reference values for inverter output amplitude are typical inverter control techniques applied to the primary source inverter in single master applications [29]. However, the use of a drop-based voltage control technique that does not require communication in multiple main source applications such as micro-grids is widely used [31].

The fact that the density of DERs with variable output in micro-grids makes it necessary to create different energy management mechanisms. The established management scenarios are made separately for the network connected situation for the independent operating state in which the micro-grid provides its voltage and frequency stability. From the studies [32], the energy management mechanism for an independent droop-controlled micro-grid provided an optimal solution for determining the output power of DER units by minimizing the cost of fuel. At the same time, stability has been shown to improve energy quality and system performance. A new double-layer control system [33], which can be used in both island mode and grid-connected operation of the micro-grid, has also been developed. The first of these layers is planning to take advantage of the renewable system based on the estimation data, and the second provides power flow and voltage regulation by using real-time data. In island mode, the primary objective is to ensure energy balance. Considering the change in the operating conditions, both high energy density batteries and ultra-power capacitors with high power density are used in the composite storage system developed by [34] and it is envisaged that the energy management mechanism and power are distributed appropriately between these energy storage systems. While providing energy/power management in Colson, Nehrir [35] constraints and objectives are determined and optimum solutions have been introduced by using particle swarm and ant colony optimization methods that provide faster solutions than traditional calculation methods.

In recent years, modern loads (such as LED, power electronics) have been widely used in commercial establishments, dwellings, and the provision of energy supplies for these high-tech products through the DC distribution system connected to the micro-grid is discussed in another topic. On this subject [36] a hybrid AC-DC micro-grid has been designed to minimize transducer losses. AC loads to AC grid, DC loads are connected to DC grid and the developed algorithm can provide regular energy flow (between AC-DC) and system stability. It is envisaged that the excess energy produced from DC output sources such as PV and solid fuel cells is carried to other units with high quality and high-efficiency DC distribution line [37].

In the DC micro-grid structure designed for rural areas where electrical energy cannot reach, instant power sharing can be made with distributed control of the network voltage and the available (obtainable) energy amount can be determined [38]. The losses resulting from distributed storage of energy from the PV systems assumed to be installed in each house are minimized.

Today, it is seen that the response of micro-grid to different loads and energy management are the key issues and the studies conducted in this area are seen to be intense. In Kanchev, Lu [39] and Kanchev presented a dynamic programming-based energy management mechanism to minimize the operating costs and CO_2 emission by taking the household user micro-grid as a multi-purpose optimization problem, which can also generate energy from the PV system and at the same time have a battery unit. An optimization-based approach to reducing the weight of conventional fuel-based units in the micro-grid is presented in [40] to make the best use of the energy storage system and DER. Gazijahani, Hosseinzadeh [41] also proposed the scenario-based day ahead power scheduling model taking into account the stochastic nature of the DERs within the micro-grid and the unpredictable energy demand. However, none of those above mentioned energy management studies have addressed the impact of demand response and the use of electric vehicles on micro-grid operation.

Abedini, Moradi [42], PV from DER, wind, diesel generator as a source of energy, and at the same time using a fixed battery is a hybrid micro-grid to perform the optimal design and economic conditions in order to ensure the operation of an optimization-based strategy has developed and presented in the study. Numerous studies have been conducted in order to improve system performance, efficiency, and sustainability by integrating the demand response program into the energy management system and to integrate large-scale renewable resources into the micro-grid.

2.2.3. Control and Energy Management Systems

To this end, Solanki, Raghurajan [43] aimed to reduce the fluctuations in the estimation of output power intermittent energy sources and variable demand by developing a model predictive control (MPC) based microprocessor energy management mechanism. They have also integrated an artificial neural network-based model into the energy management strategy to determine the ability of controllable loads to reduce load curves and energy consumption. On the other hand, the effect of the electric vehicle as a response to demand was not investigated by the effect of peak clipping on the control axioms and the stochastic structure of the energy storage system was neglected.

In Lopez, Martin [44], presented a decentralized optimal energy management strategy for a micro-grid using AC systems, programmable sources, and electric vehicle battery as a storage unit. Besides, the price-based demand response program was taken into account in order to ensure economic and efficient operation in the micro-grid and to shape the demand.

[45] Also proposed a robust two-step co-ordination strategy to prevent the occurrence of mismatches by correctly performing control/coordination of programmable AC-DC production sources within the micro-grid. In the first phase, demand response application was realized by considering day ahead market pricing. In the second stage, as mentioned, micro-turbine and so on power outlets of distributed systems are set. However, in the study, direct load control and integration of the electric vehicle, which are more effective than the pricing-based demand response, were not taken into consideration.

In [46] distributed energy systems have defined a central controller for the micro-grid with domestic, commercial, industrial users. Then, by applying the demand response, two different market policies have been adopted, and results are investigated whereby the effect of micro-network operation cost is minimum, and the controller gain is maximized.

In Bui, Hussain [47], energy management based on multi-collector (aggregator - load collector, energy storage system collector and central collector, etc.) in order to evaluate all possible strategies in multiple (AC-DC) micro-grids strategy and to perform micro-operation with the most appropriate method. Besides, mixed integer linear programming (MILP) was used to minimize operation cost by implementing a system of demand response. The mathematical modeling of a micro-grid using energy from renewable energy sources by high rates was obtained by using MILP and the response of demand and the effects of charge-discharge strategies developed on the energy storage system to the commercial operation were investigated.

2.2.4. System Load Water Pump

When we look at water pumps; in their study; Jin and Jiang [48] developed the control algorithm for water pump by converting the variable DC energy obtained from the PV system into DC-AC energy with DC-DC and complementary PWM, respectively. They stated that the experimental results were satisfactory. Palma-Behnke, Benavides [49] in their study, have designed an AC micro-grid structure from PV, wind and other DERs. This network structure (running) loads (water pump etc.) with the proposed energy management system optimizing water pump activation as a flexible load, especially in periods of excess energy, water supply has been managed efficiently. In a similar study, the same results were reported [19].

In Hammad's [50] study, water pumping economy with different methods are discussed. The methods examined are; diesel production system (DPS), photovoltaic production system (PVPS), mechanical wind pumping system (MWPS) and electrical wind pumping system (EWPS). The results obtained showed lower costs for both photovoltaic and wind systems compared to the diesel generator and showed that they were economical.

In Gopal, Mohanraj [52] research on renewable energy sources and water pumping systems (RESWPS) has been reviewed. The reported studies were divided into five main groups as follows: (i) solar photovoltaic water pumping systems (SPWPS), (ii) solar water pumping systems (STWPS), (iii) wind energy water pumping systems (WEWPSs), (iv) biomass water pumping systems (BWPS) and (v) hybrid renewable energy water pumping systems (HREWPSs). More than 100 articles on RESWPSs have been briefly reviewed. This study concluded that renewable energy sources (RES) play an essential role in reducing the consumption of conventional energy sources and the environmental impact for water pumping applications.

In addition to these studies, many studies have been conducted to control systems, energy management, power quality improvement and so on [52], [53], [54], [55]. AC, DC and Hybrid microcirculation structures are few and insufficient. Although there are different areas of study, there is no energy, power analysis study comparing AC, DC and Hybrid micro-grids on water pumps. This study stands out with this aspect.

2.3. Optimization Studies with HOMER

Himri Y., et al. conducted a techno-economic evaluation of hybrid energy systems without a grid connection in a region in the south-west of Algeria. For this study, they used the HOMER program to assess the production of energy, life cycle costs and the reduction of GHG emissions. As a result, Himri Y., Stambouli, Draoui and Himri S. found that the current diesel power plant is the only suitable solution for the diesel fuel price range used in the simulation for wind speeds of less than 5.00 m/s. They found that the wind-diesel hybrid energy system is a more suitable solution in a case where diesel price is 0.162 $/L or more and wind speed is 5.48 m/s or more [56].

Dalton, Lockington, and Baldock introduced an analysis of the technical and financial feasibility of the system configurations consisting of only renewable energy systems, only city network and together with city network and renewable energy systems, for a large-scale hotel with grid connection. Dalton, Lockington, and Baldock determined the net present cost (NPC), a renewable fraction (RF) and payback time as the evaluation criteria and benefited from the HOMER program as an evaluation program. The results They found the potential essentially for renewable energy systems to provide considerable power for a large-scale hotel with utility electricity, a renewable energy for wind energy conversion systems are applicable instead of photovoltaic systems for large-scale grid-connected applications and energy system technology and hydrogen fuel cells and storage of hydrogen is not particularly economical in network-linked configurations [57].

Henryson and Svensson have provided ways to meet the power and energy demands for the Swedish Antarctic Research Program (SWEDARP) as much as possible by renewable energy resources under strict environmental legislation. Henryson and Svensson aimed at the design of a new power system that would provide 1 kW of electrical power for the continuous monitoring and collection of research data. Henryson and Svensson's thesis is based on the technical realization and economic feasibility study. In Henryson and Svensson's thesis, the results are based on analysis and computer simulations (HOMER), where each primary system element is expected to work under severe climatic conditions in Wasa station in Antarctica. Henryson and Svensson concluded that wind power in terms of primary energy source in Antarctica has outstanding potential and that a system of three wind turbines of 3 kW each and a total battery capacity of 2,000-2,0800 Ah are the optimum system [58].

Hansen and Bower explored the distributed power generation technologies available in rural areas of India and modeled their economic performance. Hansen and Bower also compared the costs of hybrid distributed electricity generation systems with grid connection for village-level applications in remote areas. The inputs modeled in the operation of Hansen and Bower depend on demand, fuel availability, costs, and local operating conditions in the Kachchh district of Gujarat, India. Hansen and Bower found that, if local energy sources (wind, solar, biomass) were sufficient, hybrid energy systems could provide economical electricity in rural areas [59].

CHAPTER III. THE WATER PUPMING SYSTEM COMPONENTS

This chapter aims to give an introduction to the system and its components. First, the current system components are described in section 3.1. The proposed system components are explained in section 3.2. Lastly, in Section 3.3 the method for micro-grid comparison studies HOMER is explained.

Water pumping systems are facilities including pumps and equipment for pumping fluids from one place to another. They are used for a variety of infrastructure systems, such as the supply of water to canals, the drainage of low-lying land, and the removal of sewage to processing sites. The main function of Kreekrak water pumping system is to keep the salty water at a certain distance from the equipment of the pumping systems. This is will be done when fresh water is pumped into the channel. At this manner, fresh water will keep salty water at a certain distance [60], [61], [62], [63].

3.1. Current System Components

The present system is connected to the existing 10 kV grids at two points. The water-pumping system consists of four main units, see Figure 3.1. These four units are briefly explained below:

1. AC Motors: Consists of four induction motors.
2. Variable Frequency Converter (VFC): There are 4 VFCs.
3. Transformer: There are four transformers.
4. Mains: Show the medium voltage network.

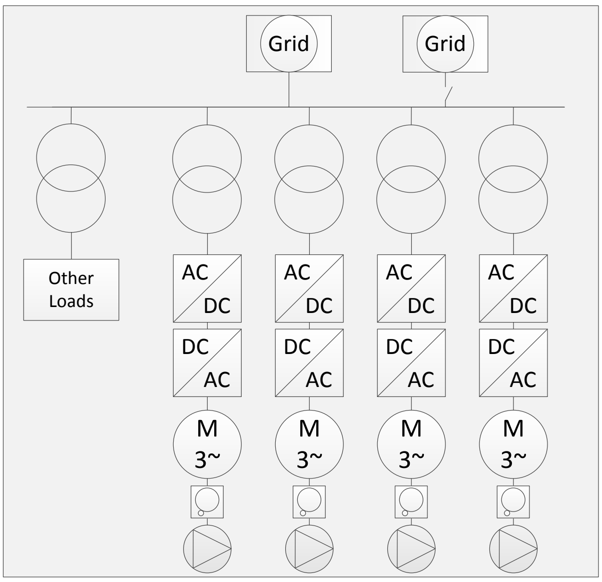


Figure 3. 1 Current System Components.

3.1.1. Grid

The water pump system is connected to the MV network system. The nominal voltage of this grid is 10 kV. The system will automatically use the RESs during a power failure. Here, the utility grid serves as storage when the RESs generate excess energy that means that the grid supplies energy from the RESs. The PV system will generate electricity as long as it is sunlight. In addition, wind turbines will generate energy as long as there is enough wind. If there is no energy or sufficient energy from the PV or wind turbine, the gird will supply the energy demand of the system.

3.1.2. Transformers

The transformer is an electrical device that transmits electric energy to two or more circuits using electromagnetic induction and it is used to lower/increase the voltage and electric current. The transformer voltage used in this study reduces the voltage from 10 kV to 690 V. The parameters of the transformer are given in Table 3.1[65].

Table 3. 1 Transformer specification.

Parameters	**Values**
Manufacturer	Schneider
Type	Giethars
Material	Aluminium
Rated power	400kVA
Circuit	Dyn 5
Primary voltage	10 kV
Secondary voltage	0.69 kV
Uk	6%
Power factor	0.87
Frequency	50Hz
No-load losses	705W
Load losses at 120°C	3590W

3.1.3. Converter Topologies

Electrical systems may be DC and/or AC. In this context, systems need to be transformed into each other. In this study, the VFC is the device that can set the desired frequency to control the speed of the IM and controls the speed of the water pump. There are four possible transducer types. These:

- DC-DC Converter
- DC-AC Converter
- AC-DC Converter
- AC-AC Converter

The parameters of VFC are given in Table 3.2. VFC power loss varies significantly with the switching frequency used, as well as the load and output frequency [65].

Table 3. 2 Variable frequency converter specification.

Parameters	Values
Manufacturer	Vacon
Type	NXP03856A0N0SSO
Connection voltage	3AC/690V
Frequency	50Hz
Rated power	355kW
Nominal output current	385A

3.1.4. AC Motors

Nowadays, induction motors (IM) have been widely used in the industry for such reasons, low cost, and low maintenance and robust. In this study, a 4-pole IM is used for the water-pumping system. This engine is used to convert electrical energy into mechanical energy. The parameters of the induction motor are given in Table 3.3 [66].

Table 3. 3 Induction motor specification.

Parameters	Values
Manufacturer	Siemens
Type	1LA83554PM84-Z
Rated power	358kW
Current	385
Cos Φ	0.87
Rated voltage U D/Y	400/690 VD/Y 50Hz

In this system, the IM has two different rotational speeds with a maximum power of 314 kW; the speed of the motors is 77.5 rpm. During normal operation, at a power output of 196.8 kW, the motors are 65 rpm.

AC motors are considered as load in this thesis and these motors are powered by AC power. Water pump system used for pumping water was used for two time intervals. The first time interval during the week is night. During this time, the pumping engines spend energy from 11.00 pm to 07.00 am. The second time interval during the weekend is daytime, and it consumes energy from morning 9:00 am until 22:00.

If the system can only operate in renewable energy sources, the water pump will only work during the day. During the night wind energy system will be used, and the water pump will not work if there is not enough energy. In the worst case, the system will use energy from one of the grids.

3.2. Proposed System Components

The proposed system is connected to the existing 10 kV system at two points. This system consists of seven main units; see Figure 3.2. These four units are briefly explained below:

1. AC Motors: Consists of four induction motors.
2. Variable Frequency Converter (VFC): There are four VFCs.
3. Transformer: There are four transformers.
4. Mains: Show the medium voltage grid.
5. Wind Turbine
6. Solar Panels
7. Inverter

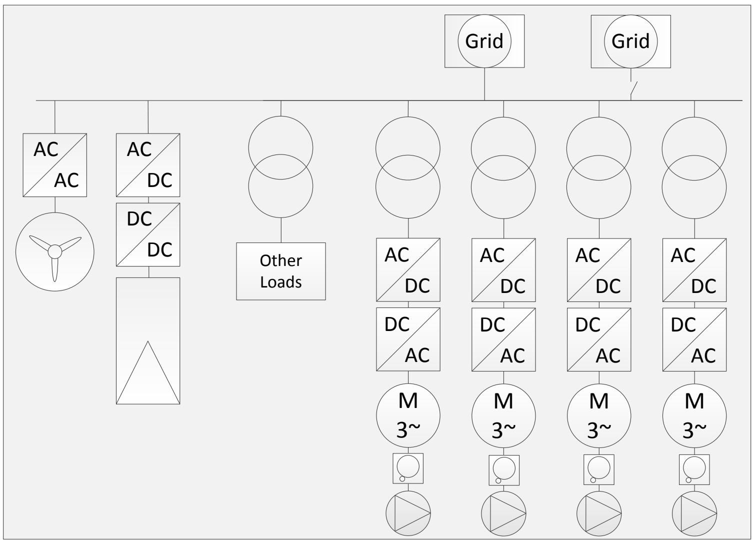


Figure 3. 2 Proposed System Components.

3.2.1 PV Panel

Solar energy is one of the most crucial RESs due to quite abundant, relatively reliable and not limited to a geographical region. This is likely to make it the most important source of power for future power grids. The decreasing cost of solar technology day after day and the high penetration of solar powered systems bring technical difficulties to all energy systems. In order to adequately address these issues, the technological aspects of solar energy should be investigated in more detail. Therefore, the fundamentals of solar energy technology will be discussed in this chapter [67],[68].

In this study, in case-I Centsys 200W and in case-II Canadian Solar 200W PV Panel are used. The mechanical data of these panels and additional information are taken from the Solar Panel Technical Data datasheet [90], [91].

3.2.2 Wind Turbine

The wind energy source is an essential and growing RES for electrical power systems. Wind turbine systems (WTS) and components have proliferated in the last two decades [71].

During the past 30 years, the dimensions of the wind turbines have increased by about 10-12 times. Besides, the capacity has reached 100 megawatts from the order of 100 kW and in the near future, it is expected to be in the order of 10-12 MW. In this context, the energy cost generated by a medium-sized wind turbine in right wind conditions (wind speed 7-8 m/s and above) is estimated to be around 2.5-3 cents/kWh in the future [13]. Currently, 5 and 7.5 MW turbines are in the market as commercial products, and the development and production processes of 8 or 10 MW turbines continue [72].

In this study, in case-I Fuhrlander 250kW and case-II Enercon E33 330kW wind turbine are used. The mechanical data of these wind turbines and additional information are taken from [73],[74].

3.2.3 Inverters

The inverters used in the integration of PV systems into the grid are an essential factor in the energy conversion of solar energy. PV inverters convert the DC energy generated by PV energy systems into the required AC energy during connection to the power grid [75].

In this study, in case-I CPS SC100KT 100kW and in case-II ABB 175kW converter are used. The information are taken from [76],[77].

3.3. Method Used for Micro-grid Comparison Studies

The micro-grid concept includes the transmission and distribution network using DERs effectively[78],[79],[80],[81]. The micro-grid defined by CERTS (Consortium of Electrical Reliability Technology Solutions of the USA) is a load set, storage and a power system that includes many DERs [82]. Depending on the status of the connection of the micro-grids to the main grid, they are named in two ways: On-Grid/Grid-Connected and Off-Grid/Islanded mode. There are three types of micro-grids in the literature. These are briefly described [83].

3.3.1 Homer Software

HOMER Software [10] (**H**ybrid **O**ptimization **M**odel for **E**lectric **R**enewables) is a computer model developed by the US National Renewable Energy Laboratory to facilitate the comparison of power generation technologies in a wide range of applications and to assist the design of micro energy systems. HOMER models the life cycle cost of an energy system, which is the sum of the operating cost of the energy system during the lifetime and the installation. HOMER allows the designer to compare a wide range of design options concerning technical and economic values. In addition, HOMER enables the understanding and measurement of the effects of changes and uncertainties in inputs belong to the energy system. HOMER primarily performs three tasks: Simulation, Optimization and Precision analysis.

Simulation

The main benefit of the HOMER program is the ability to simulate long-term studies of power systems. Upper stages of optimization and precision analysis are based on this simulation method. The simulation process serves two purposes. First, the program first determines the feasibility-applicability- of the system. In this case, the systems that produce the energy sufficient to cover the load by providing the conditions imposed by the user are selected as applicable by the program. Secondly, the cost of living in the system mentioned earlier is estimated. This cost statement is a convenient tool to compare the economy of various system configurations. This comparison is the source of the optimization process of the HOMER program.

The program finds out how the system works by simulating it for a year and agrees that the same essential results (fuel consumption, over- or under-power generation, etc...) will be valid for each year throughout the life of the project. Time-dependent changes such as load value development or component degradation due to aging are not taken into account.

Optimization
Simulation process models a specific system configuration, while optimization determines the best possible system. In the optimization stage, the HOMER program lists the components and the components, which are different from the numbers or sizes of these components according to the SM values, and the system with the lowest value is selected as the Optimum System (OS).

The optimization process aims to determine the optimum value of the decision-making variables that interest the user. The user who builds the system on these variables can control the system. For example,

- PV panel size,
- Number of wind turbines,
- Generator size, number,
- The size of AC-DC rectifier/converter elements,
- Hydrogen tank capacity,
- Fuel cell, electrolyzer size

Precision Analysis
In the precision analysis, HOMER performs multiple optimizations by using different input assumptions. This analysis shows how sensitive the output results are to the change in input data. In the precision analysis, the user can enter a series of different values for a single input component, and these values are called precision values. As an example, network power fee, fuel cost, PV panel life, interest rate, hourly electric load or renewable source data as variables can be used as a precision variable.

The user can perform any desired amount of precision analysis for the desired components, and each combination of these sensitive component values creates a separate sensitive situation. For example, if the mains power price is six, the interest rate is four; this result in 24 different precision states and the HOMER program performs a separate optimization process for each sensitive situation and presents the results in tabular or graphical format. Thus, an energy planner can decide which technology or combinations will provide optimum conditions under different conditions, a market analyst can decide at what price values or under what conditions a product (such as fuel cell) can compete with alternatives or politicians can decide with which emission penalties the economy will lead to cleaner technology.

3.3.2 Homer Software Economic Modeling

In this study, HOMER software used for system optimization and cost estimation offers the possibility to use many configurations for calculation. For any load requirement, the HOMER program address the questions about whether the number of turbines is sufficient or not, what a new turbine, diesel generator, or the addition of a solar panel would produce and what combination would cost the least. One of the advantages of this software is to make calculations based on hourly basis. In this study, system components, energy sources and loads are modeled for a single year hour by hour. The energy flow and cost for a given clock is constant. This type of modeling is ideal for demonstrating the intermittent power generation of renewable energy sources.

Modeling requires input values such as technology options, component costs, and resource compliance, and the program uses all of these data to simulate different system configurations and lists the suitable combinations based on net cost (system cost). Net cost is also referred to as the cost of living and covers the entire cost of installing and operating components throughout the project period.

The HOMER program assumes that all price increases will be the same rate during the life of the project. With this assumption, the inflation value is subtracted from the analysis by using the real (inflation-compliant) interest rate instead of the nominal interest rate in the current time reduction of future cash flows. Therefore, the real interest rate, which is the difference between the nominal interest rate and the inflation rate, is entered as data. All the costs in question here are the actual costs and are expressed in US dollars ($).

To calculate the scrap costs of equipment used at the end of the project, HOMER uses the following equation.

$$S = C_{rep}\frac{R_{rem}}{R_{comp}} \tag{1}$$

Where S is the value of the scrap, C_{rep} is the replacement cost of the equipment, R_{rem} the remaining life of the equipment, R_{comp} the life of the equipment. For example, if the PV life used in a system with a life of 20 years is taken as 20 years, the cost of PV scrap at the end of the project will be zero since it has no remaining life. On the other hand, when a PV system with a 30-year life cycle is used, a 20-year project will cost 1/3 of the replacement cost.

3.3.3 Modeling System Components

HOMER models PV panels as components that generate DC electricity about the global solar radiation rate independently of its voltage and temperature. HOMER expresses the power output of the PV panels with the following formula.

$$P_{PV} = f_{PV}Y_{PV}\left(\frac{I_T}{I_S}\right) \tag{2}$$

Here, the f_{PV} value is derating factor and applied to calculate the output power of the PV to take into account the losses and generally was chosen 100% or less. The determined plate values of PV panels correspond to one kW/m2 solar radiation under test conditions. Harsh environmental conditions, different operating voltages, dust, and pollution of the panels can cause the PV systems to generate power below their output power. The f_{PV} value takes into account these losses. Return to the above formula; Y_{PV} PV panel capacity, I_T, global radiation level per panel and I_S is the standard amount of radiation used in the calculation of the capacity of PV modules whose value is one kW/m2.

HOMER models wind turbines as a device that converts wind kinetic energy into AC or DC electrical energy according to a specific power curve. HOMER recognizes that the wind turbine power curve is applied to a standard air density of 1,225 kg/m3 (corresponding to standard temperature and pressure values).

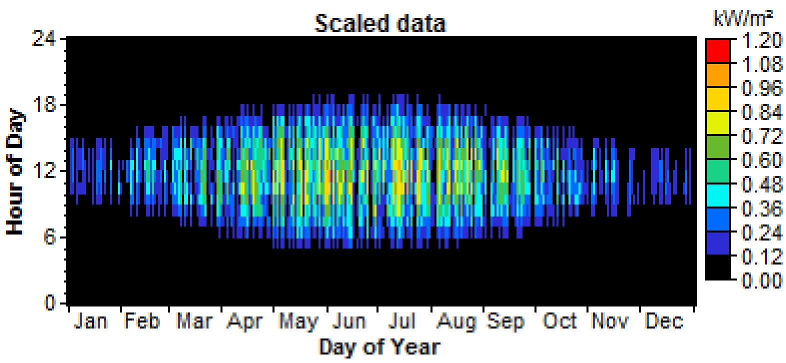
In HOMER, the term load refers to an electrical or thermal energy demand. Feeding loads are the reason for the presence of micro-energy systems, so the modeling of a micro-energy system begins with the modeling of the load or loads that the system must supply. HOMER models three different load types. The primary load specifies the electrical need to be supplied according to a particular program. The deferrable load refers to the need for electricity that can be provided at any time during a given period. Thermal load indicates the need for heat.

CHAPTER IV. ENERGY SOURCES AND LOAD PROFILE

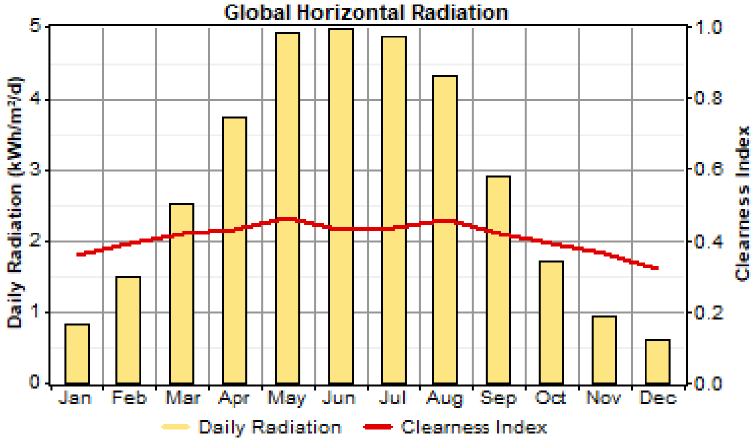
A typical hybrid system combines two or more energy sources with the aim to achieve an efficient system. In this study, the hybrid system combines the solar, wind and utility grid with load. In this chapter, the renewable energy sources in Rilland Netherlands and the load profile are discussed. The solar source in Rilland Netherlands is discussed in section 4.1. The wind source in Rilland Netherlands is discussed in section 4.2. The load profile used in this study is described in section 4.3.

4.1. Solar Energy Source in Rilland Netherlands

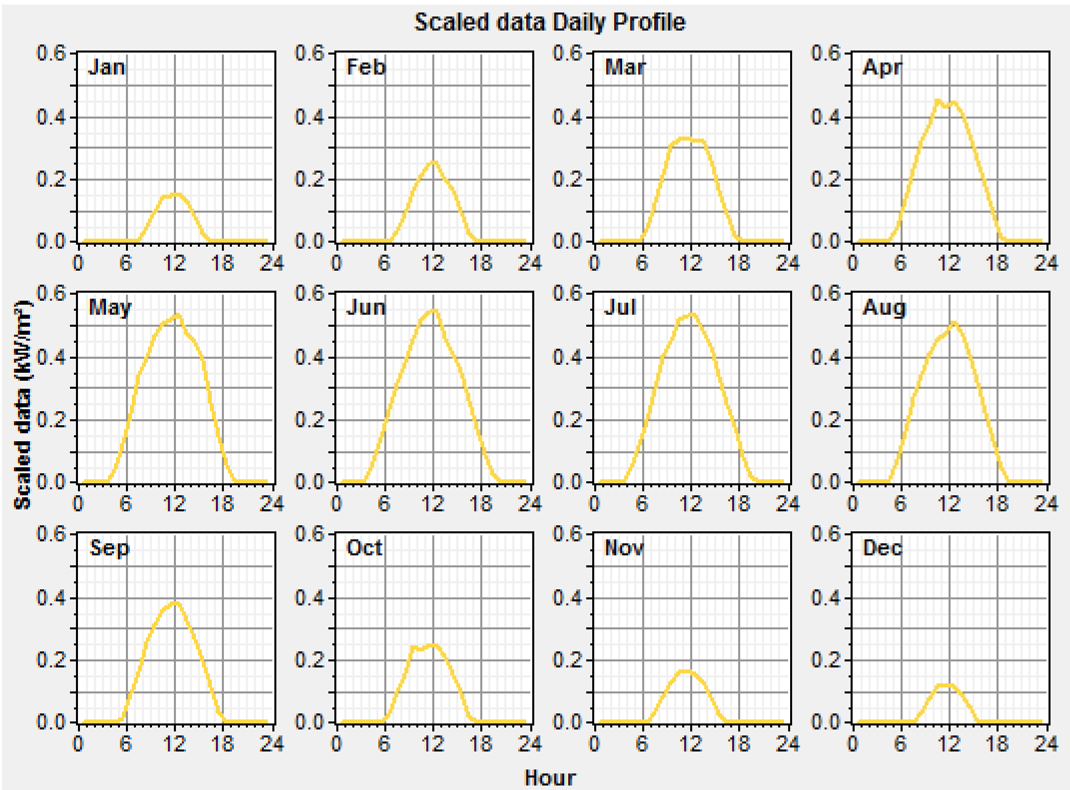
The solar radiation data of the region, which was provided by HOMER software, varies in the range of 0.61–4.96 kWh/m^2/day. It is shown in Figure 4.1 (a), (b) and (c). It is easily seen that from Figure 4.1 that the most and least solar global irradiance is observed in June and December, respectively. The scaled annual average of the solar radiation is estimated to be 2.819 kWh/m^2/day. According to the latitude of the place that has been chosen, the HOMER software can generate the clearness index from the solar radiation data obtained from HOMER software [84]. In HOMER Software, the hourly solar radiation data was generated using the monthly solar data by means of the Graham algorithm [85]. In this context, if the solar radiation data are not available, clearness index can also be used to obtain the solar radiation data. Eventually, either the clearness index or the solar radiation data can be used to represent the solar resource input as long as the data of latitude is available to the HOMER software.



(a)



(b)

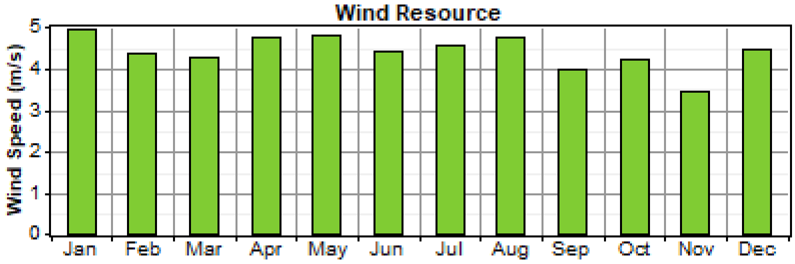


(c)

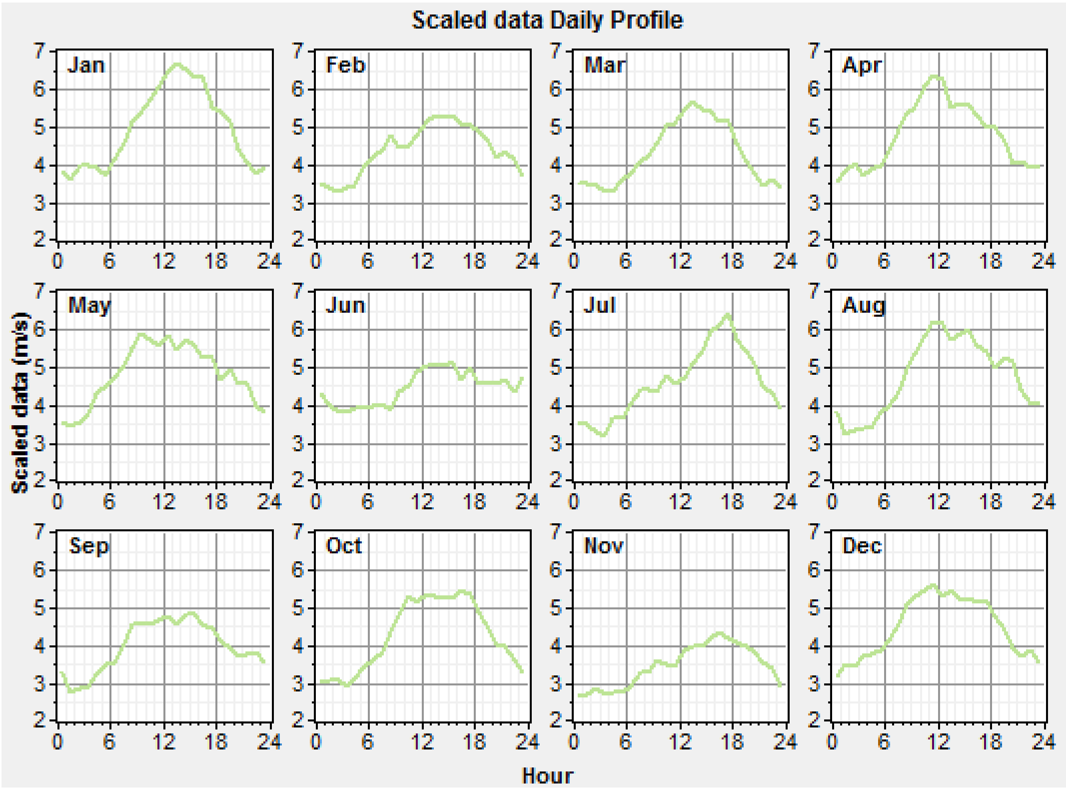
Figure 4. 1 The average solar energy density; (a) hourly (b) monthly (c) daily.

4.2. Wind Energy Sources in Rilland Netherlands

The hourly wind speed data of the region which is measured at the height of 10 m were provided by Koninklijk Nederlands Meteorologisch Instituut [86]. Annually wind speed distribution profile is shown in Figure 4.2 (a) and (b). According to the wind speed data, it is highlighted that wind speed distribution ranges between 3.43 and 4.93 m/s, while the regional average wind speed is about 4.42 m/s. Moreover, it is clear that the highest and lowest wind speed values occur in January and November, respectively.



(a)



(b)

Figure 4. 2 The wind speed distribution profile of the region; (a) monthly, (b) daily.

Furthermore, Curve Fitting Toolbox in MATLAB calculates Weibull shape factor called as k describes the breadth of the distribution of wind speed over the year and then it is considered as 1.96 in the HOMER software. The wind speed probability density function of the .region is shown in Figure 4.3.

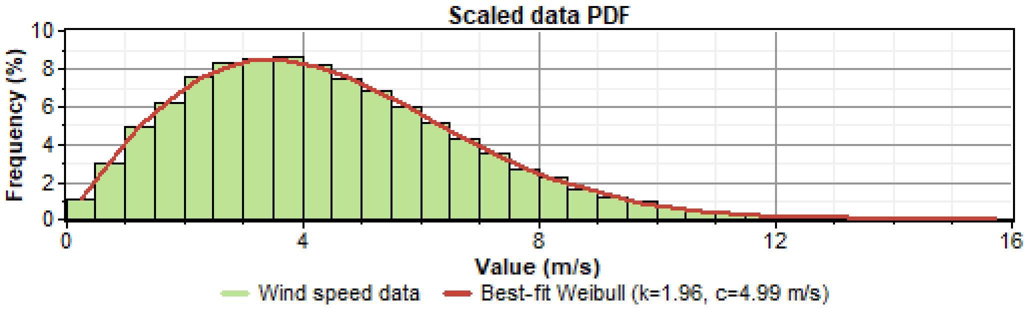


Figure 4. 3 The wind speed probability density function of the region.

4.3. Load Profile of the Water-pump system

The latitude and longitude coordinates of the location where the pump is located are 51° 26' 58" N and 4° 13' 41" E. Energy requirement of the pump is currently supplied by electricity. Load data used in this study was obtained from Coördinatie Bureau Energie (CBE) [87].

Rijkswaterstaat. According to the load data, the average daily energy demand of the campus is about 1767 kWh. HOMER simulates the operation of a system by making energy balance calculations for each hour in a year. If the hourly load profiles are not available for a whole year, so HOMER is used to synthesize the load profiles (with randomness) by entering the values for a typical day. Load data is expressed as time series. When there is missing data, HOMER calculates the randomly incomplete data set using the curve fitting method [88]. Either day-to-day randomness or time step-to-time-step randomness is taken as 5% in the study. According to the load data, the minimum load demand occurs 09:00. Load profile of the pump is shown in Figure 4.4.

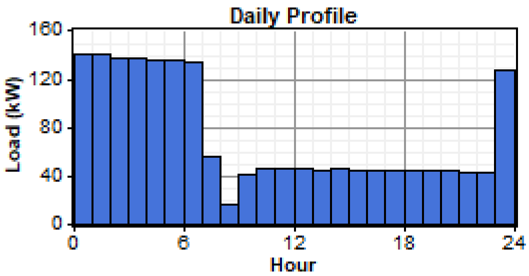
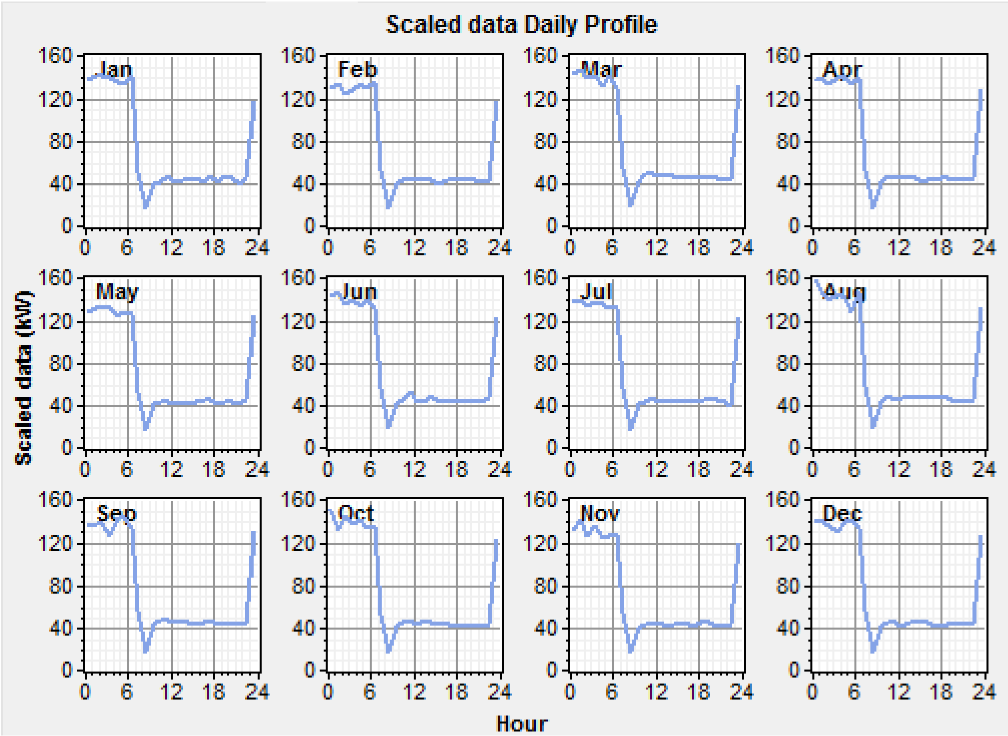
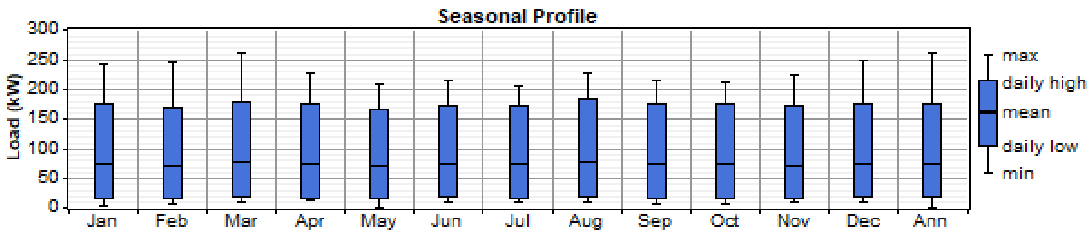


Figure 4. 4 Daily load profile of the pump.

For March, maximum value of the load demand is 265 kWh, which occurs between 00:00 and 03:00. Seasonal load profile of the pump is demonstrated in Figure 4.5 (a) and (b). Load requirements further vary through each month. This is shown in Figure 4.5 generated by the HOMER software.



(a)



(b)

Figure 4. 5 Seasonal load profile of the pump; (a) daily (b) monthly.

It is regarded that, since the coldest months are December, January, and February, the load requirement is high for these months. Random variability factors known as day-to-day variability and time step to time step variability are entered to the HOMER software in order to make the synthetic load data more realistic. Both of them are supposed to be around 2%. Regarding all assumptions, the regional energy demand, by means of HOMER simulation software, is calculated to be about 1767 kWh/day.

CHAPTER V. CASE STUDY

Three types of micro-grids are compared in this chapter. For each type of micro-grid, two cases are proposed with different RES's components. Each option is independently analyzed and the unit energy cost is calculated. Additionally, the emission of the each option is compared to the only grid connected water-pumping system. First, the proposed system components (PV panels, wind turbines and converters) are described in section 5.1. Finally, the operational characteristics are discussed in section 5.2.

5.1. Systems Components

In this study, PV power system, wind power system and the utility grid supply the energy requirement of the water-pumping system. The proposed hybrid renewable system is grid connected and it consists PV panel, wind turbine and converter. The amount of the energy from PV panel and wind turbine is based on the potential of solar and wind energy sources respectively.

In order to obtain optimum solutions, a value range is specified as a parameter for each component. In following section for both cases, these components are defined.

5.1.1. PV Panel

In such a hybrid system, solar energy, one of the most significant renewable energy sources in the region, is surely considered as one of the basic load suppliers. Because PV panels have less efficiency, the designed PV array size is chosen between 0-800kW. It should be noted that this PV array can only generate electricity at the day time period from 6 a.m. to 6 p.m. Otherwise, at night period after 6 p.m, there is no electricity generation and thus the output power of the solar energy is 0 W. In this period, either the WTs or the utility grid will take over the task.

In the Case-I, for economic analysis, the following assumptions are made by regarding the specifications of PV module available in the reference:

- The cost of each kW of PV module is $6000.
- The cost of replacement is $5000.
- Operating and maintenance cost is assumed to be zero since it is negligibly small [89].

In the Case-II, for economic analysis, the following assumptions are made by regarding the specifications of PV module available in the reference:

- The cost of each kW of PV module is $7200.
- The cost of replacement is $6000.
- Operating and maintenance cost is assumed to be zero since it is negligibly small [90].

5.1.2. Wind Turbine

In the hybrid system, wind energy like solar energy is also one of the abundant renewable energy sources. Therefore, is regarded as one of the basic load suppliers. In order to extract the usable energy form from wind energy, devices such as WTs are required and utilized.

In the case-I, WT is chosen as Fuhrlander 250kW with output power capacity 250 kW and a lifetime of 20 years. Additionally, the initial cost of the WT is $170,000, while its replacement cost equals to $150,000 and operating and maintenance cost of the described WT is $5000 per year. In the HOMER software, for economic analysis, the number of the WT varies in the range of 0–10 to determine the most feasible configuration of the hybrid system [91].

In the case-II, WT is chosen as Emerson E33with output power capacity 330 kW and a lifetime of 25 years. Additionally, the initial cost of the WT is $570,000, while its replacement cost equals to $550,000 and operating and maintenance cost of the described WT is $5000 per year. In the HOMER software, for economic analysis, the number of the WT varies in the range of 0–10 to determine the most feasible configuration of the hybrid system [92].

5.1.3. Converter

When there is an AC load demanded and WTs or PV panels in the hybrid system are generating direct current (DC) power, the generated DC power first would be converted to AC by using inverters. Then, it would be ready to supply the AC load demand. It will fully supply both the PV power and the excess power of the WT, which will remain after supplying the load demand.

In case-I, the rated power of the inverter is 100 kW. The inverter has an efficiency of 90%. Furthermore, the initial cost of the inverter is considered to be $1100, which is the same as the replacement cost. In addition, there is no operating and maintenance cost estimated. In order to obtain the optimum solutions the size of the converter varies in the range of 0–700kW with an increment of 25kW [93].

In case-II, rated power of the inverter is 175 kW. The inverter has an efficiency of 90%. The initial cost of the inverter is considered to be $1500, which is the same as the replacement cost. In addition, there is no operating and maintenance cost estimated. The size of the converter varies in the range of 0–700kW with an increment of 25kW [94].

5.1.4. Grid

A grid is used as a backup power component or excess power absorber. The grid supplies power when there is not enough power from the RES to provide the load demand. In this case the purchase price is 0.15$/kWh. When there is surplus power from the RES, then the grid will consumes this power. In addition, the retail price is 0.09$/kWh.

In case-I, the sale capacity of the grid is about 50kW. Purchase capacity of the grid varies 0-500kW an increment with 50kW in order to obtain optimum solutions.

In case-II, the sale capacity of the grid is about 55kW. Purchase capacity of the grid varies 0-550kW an increment with 55kW in order to obtain optimum solutions.

5.2. Operational Characteristics

Levelized cost of energy: HOMER defines the levelized cost of energy (COE) as the average cost/kWh of useful electrical energy produced by the system. The equation for the COE is as follows:

$$\mathrm{COE} = \frac{\mathrm{C_{ann,tot}}}{\mathrm{E_{prim,AC}} + \mathrm{E_{prim,DC}} + \mathrm{E_{grid,sales}}} \tag{3}$$

Where,

$C_{ann,tot}$ is total annualized cost [\$/year],
$E_{prim,AC}$ is AC primary load served [kWh/year],
$E_{prim,DC}$ is DC primary load served [kWh/year],
$E_{grid,sales}$ is total grid sales [kWh/year].

The total annualized cost is the sum of the annualized costs of each system component plus the other annualized cost. It is an important value because HOMER uses it to calculate both the levelized cost of energy and the total net present cost [88], [95], [96].

Net present cost (NPC): The present value of the cost of installing and operating the system over the lifetime of the project is also referred as lifecycle cost. The total net present cost is HOMER's main economic output. All systems are ranked according to net present cost and all other economic outputs are calculated for finding the net present cost. The net present cost is calculated according to the following equation[88],[95],[96]:

$$\mathrm{C_{NPC}} = \frac{\mathrm{C_{ann,tot}}}{\mathrm{CRF(i,R_{proj})}} \tag{4}$$

Where,

$C_{ann,tot}$ is total annualized cost [\$/year],
CRF is capital recovery factor,
i = real interest rate [%],
R_{proj} is project lifetime [year].

The capital recovery factor (CRF) is a ratio used to calculate the present value of an annuity (a series of equal annual cash flows). The equation for the capital recovery factor is

$$\mathrm{CRF}(\mathrm{i}, \mathrm{N}) = \frac{\mathrm{i}(1+\mathrm{i})^{\mathrm{N}}}{(1+\mathrm{i})^{\mathrm{N}-1}} \quad (5)$$

Where

i is real interest rate [%]

N is number of years.

The designed system will consider the following principles:

- For following data there is no public source [Rijkswaterstaat]:
  - For the utility grid connection, the purchase price is 0.15$/kWh and the retail price is 0.09$/kWh.
  - No cost subsidy available from Dutch government is considered.
  - Renewable fraction of the hybrid power system is assumed at least 90%.
  - The operating reserve of hourly load is 10%. Meanwhile, the operating reserves of renewable output are 25% for solar output power and 40% for wind output power. It should be noted that operating reserve means safety margin that enables the reliable power supply despite the variability of the electricity load, solar power supply and wind power supply.

- Following data is from data sheets of the components:
  - The micro-grid is grid connected.
  - The annual real interest rate is taken as 4% for Netherlands.
  - The project lifetime is considered to be 25 years.
  - Two different hybrid energy system configurations are presented in this study:
    - Case-I: Centsys 200W PV Panel, Fuhrlander 250kW wind turbine and CPS SC100KT 100kW converter
    - Case-II: Canadian Solar 200W PV Panel, Enercon E33 330kW wind turbine and ABB 175kW converter

5.2.1. AC Micro-Grids

In AC micro-grid two cases are analyzed with different components. All energy sources are connected to the AC bus and the PV power generation system has its own controller and converter.

5.2.1.1. Case-I

Figure 5. 1 shows the block diagram of the hybrid system in case of an AC micro-grid.

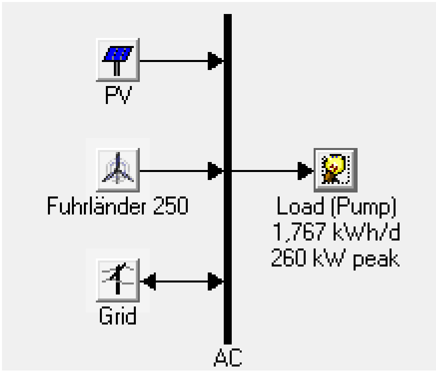


Figure 5. 1 Block diagram of AC micro-grid case-I.

In Table 4.1, when the average solar radiation (2.819 kWh/m2/day) and the average wind speed (4.42 m/s) at the location, the optimal hybrid power generation system is combination of Grid/Wind/PV, as indicated in Table 4.1. For the average wind speed, the optimal hybrid power generation system consists of a 100kW PV power generation system, seven pieces of 250kW wind turbines and 200 kW from utility grid. For this option, AC micro-grid, the unit energy cost is $ 0.343/kWh.

Moreover, Table 5. 1 shows the excellent hybrid power generation system options based on the variation of wind speed and solar radiation.

Table 5. 1 Optimum HPGS options AC micro-grid case-I.

Solar (kWh/m²/d)	Wind (m/s)				PV (kW)	FL250	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
2.819	4.420				100	7	200	$ 1,910,000	71,901	$ 2,829,130	0.343	0.90	0.00
2.819	5.000					6	200	$ 1,020,000	53,614	$ 1,705,368	0.207	0.92	0.00
2.819	6.000					4	200	$ 680,000	31,328	$ 1,080,475	0.131	0.92	0.00
2.819	7.000					3	200	$ 510,000	18,753	$ 749,729	0.091	0.93	0.00
4.000	4.420				100	7	200	$ 1,910,000	71,138	$ 2,819,380	0.342	0.91	0.00
4.000	5.000					6	200	$ 1,020,000	53,614	$ 1,705,368	0.207	0.92	0.00
4.000	6.000					4	200	$ 680,000	31,328	$ 1,080,475	0.131	0.92	0.00
4.000	7.000					3	200	$ 510,000	18,753	$ 749,729	0.091	0.93	0.00
5.000	4.420				100	7	200	$ 1,910,000	70,807	$ 2,815,149	0.342	0.91	0.00
5.000	5.000					6	200	$ 1,020,000	53,614	$ 1,705,368	0.207	0.92	0.00
5.000	6.000					4	200	$ 680,000	31,328	$ 1,080,475	0.131	0.92	0.00
5.000	7.000					3	200	$ 510,000	18,753	$ 749,729	0.091	0.93	0.00
6.000	4.420				100	7	200	$ 1,910,000	70,552	$ 2,811,889	0.341	0.91	0.00
6.000	5.000					6	200	$ 1,020,000	53,614	$ 1,705,368	0.207	0.92	0.00
6.000	6.000					4	200	$ 680,000	31,328	$ 1,080,475	0.131	0.92	0.00
6.000	7.000					3	200	$ 510,000	18,753	$ 749,729	0.091	0.93	0.00

AC micro-grid generates in total 2656923 kWh/year, 96,520 kWh/year of the power is produced by PV power generation system, 2,302,248 kWh/year from the wind power generation system and the remaining 258,155 kWh/year supplied by utility grid. In Figure 5. 2 the monthly power produced by the components of the optimal hybrid power generation system is shown.

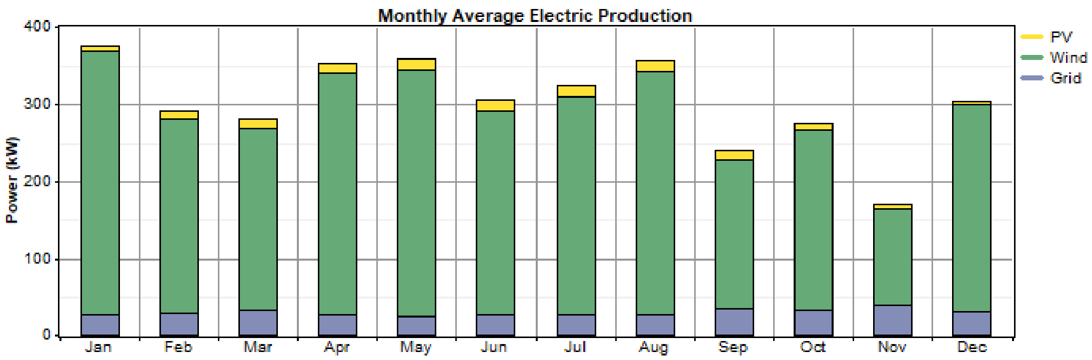


Figure 5. 2 Monthly power generation by AC micro-grid components case-I.

The change in unit energy cost according to solar radiation and wind speed data is depicted in Figure 5. 3. Figure 5. 3 is investigated in detail, wind speed of 5 m/s and above and all the solar radiation data of the maximum power generation system Grid/Wind is seen. Moreover, when wind speed is less than 5 m/s and in all solar radiation data, it is seen that the optimum power generation system is Grid/Wind/PV. If the wind speed data increases from 5 m/s to 6 m/s; the unit energy costs also decreased inversely from $ 0.207/kWh to $ 0.131/kWh. The wind speed of 6 m/s and above the unit energy cost of $ 0.091/kWh value is reached.

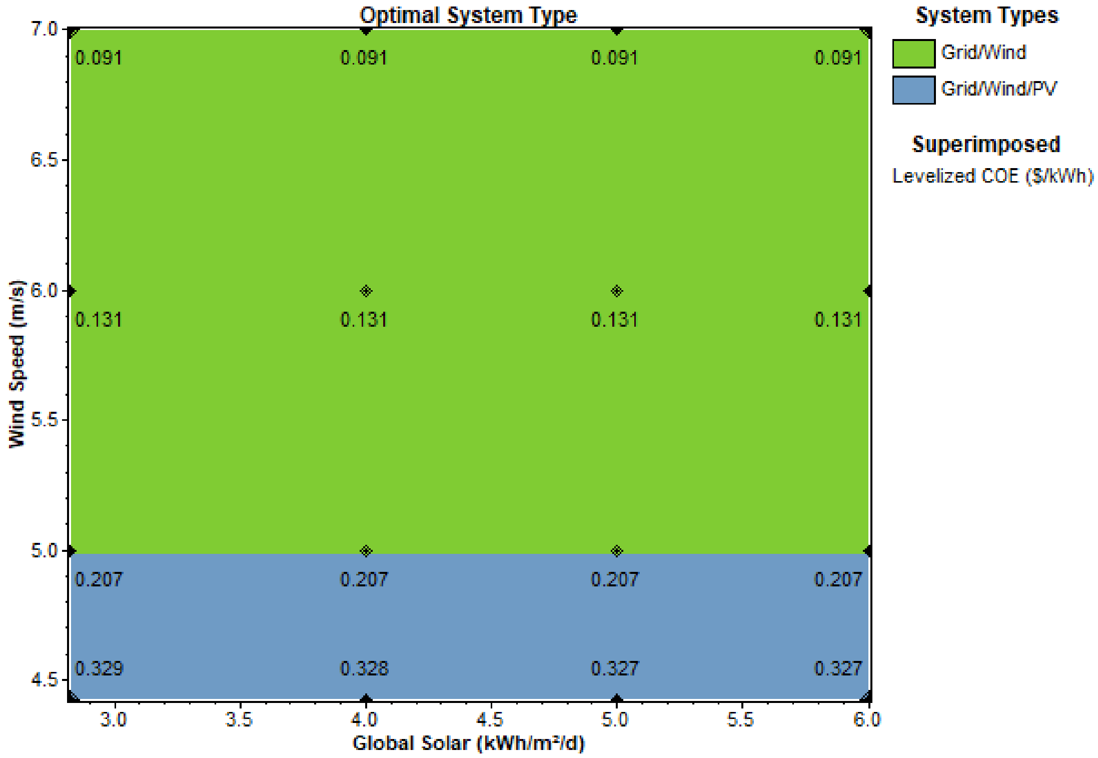


Figure 5. 3 Unit energy cost changes in case-I AC micro-grid.

When 90% of the total energy is generated from renewable energy sources, the emissions is significantly minimized by optimal Grid/Wind/PV hybrid AC/DC micro-grid. In numerical terms, emission values are reduced down to 130.487 kg/year for CO2, 277 kg/year for NO and 566 kg/year for SO2. The source that contributes to the formation of these values is the utility grid. Table 5. 2 shows the emission values of the Grid/Wind/PV hybrid power generation system.

Table 5. 2 The emission generated by AC micro-grid case-I.

Pollutant	Emissions (kg/yr)
Carbon dioxide	-130,487
Carbon monoxide	0
Unburned hydrocarbons	0
Particulate matter	0
Sulfur dioxide	-566
Nitrogen oxides	-277

5.2.1.2. Case-II

Figure 5. 4 shows the block diagram of the AC micro-grid of case-II.

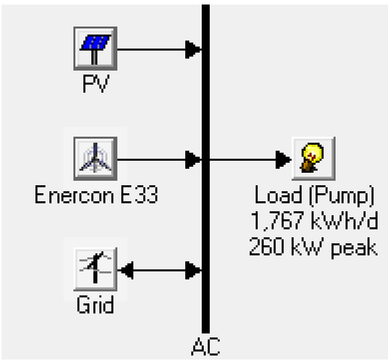


Figure 5. 4 Block diagram of AC micro-grid case-II.

The calculated average solar radiation is 2.819 kWh/m2/day and the average wind speed is 4.42 m/s at the location where the pump is used. It is seen that the optimal hybrid power generation system is Grid/Wind, see Table 5. 3. In this table is also seen that for the average solar radiation and wind speed the optimal hybrid power generation system consists of five pieces of Enercon E33 model 330 kW wind power generation system and 220kW from the utility grid. The unit energy cost is 0.498$/kWh for the AC micro-gird.

Additionally, based on the variation of wind speed and solar radiation is for this case the best hybrid power generation system options shown in Table 5. 3.

Table 5. 3 Optimum HPGS options AC micro-grid case-II.

Solar (kWh/m²/d)	Wind (m/s)	PV (kW)	E33	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
2.819	4.420		5	220	$ 2,850,000	98,295	$ 4,106,545	0.498	0.91	0.00
2.819	5.000		4	220	$ 2,280,000	74,973	$ 3,238,408	0.393	0.92	0.00
2.819	6.000		3	220	$ 1,710,000	49,660	$ 2,344,822	0.284	0.94	0.00
2.819	7.000		2	220	$ 1,140,000	28,300	$ 1,501,772	0.182	0.93	0.00
4.000	4.420		5	220	$ 2,850,000	98,295	$ 4,106,545	0.498	0.91	0.00
4.000	5.000		4	220	$ 2,280,000	74,973	$ 3,238,408	0.393	0.92	0.00
4.000	6.000	50	2	220	$ 1,500,000	38,506	$ 1,992,236	0.242	0.90	0.00
4.000	7.000		2	220	$ 1,140,000	28,300	$ 1,501,772	0.182	0.93	0.00
5.000	4.420		5	220	$ 2,850,000	98,295	$ 4,106,545	0.498	0.91	0.00
5.000	5.000		4	220	$ 2,280,000	74,973	$ 3,238,408	0.393	0.92	0.00
5.000	6.000	50	2	220	$ 1,500,000	38,323	$ 1,989,903	0.241	0.90	0.00
5.000	7.000		2	220	$ 1,140,000	28,300	$ 1,501,772	0.182	0.93	0.00
6.000	4.420		5	220	$ 2,850,000	98,295	$ 4,106,545	0.498	0.91	0.00
6.000	5.000		4	220	$ 2,280,000	74,973	$ 3,238,408	0.393	0.92	0.00
6.000	6.000	50	2	220	$ 1,500,000	38,183	$ 1,988,106	0.241	0.90	0.00
6.000	7.000		2	220	$ 1,140,000	28,300	$ 1,501,772	0.182	0.93	0.00

Figure 5. 5 shows the monthly changes for power produced by the optimal hybrid power generation system components. In the AC micro-gird, the wind power generation system generates 2,512,727 kWh/year and the remaining 246,220 kWh/year comes from the utility grid. It is clearly seen that the PV power generation system does not generate energy due to the low potential value of solar radiation.

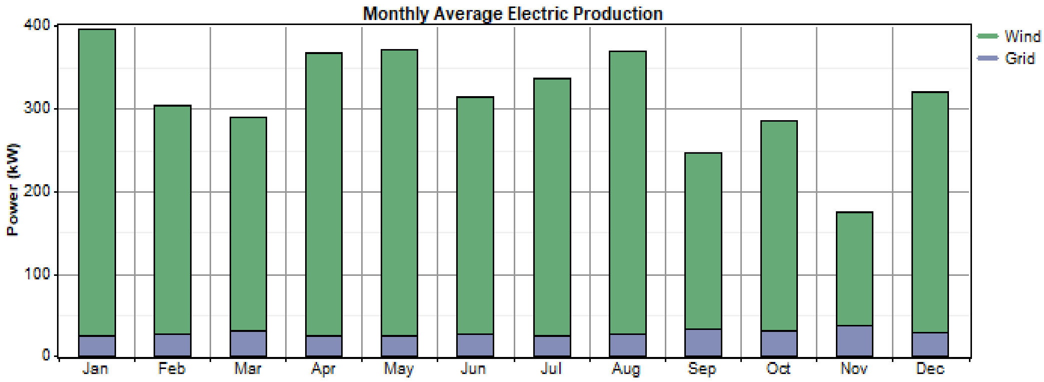


Figure 5. 5 Monthly power generation by AC micro-grid components case-II.

The change in unit energy cost according to solar radiation and wind speed data is seen in Figure 5. 6. If we carefully look at Figure 5. 6 in detail when wind speed is between 5.5 and 6 m/s and solar radiation is between 4 kWh/m2/d and 6 kWh/m2/d, the optimum power generation system is Grid/Wind/PV. Moreover, the wind power and all solar radiation show that the optimum power generation system is Grid/Wind.

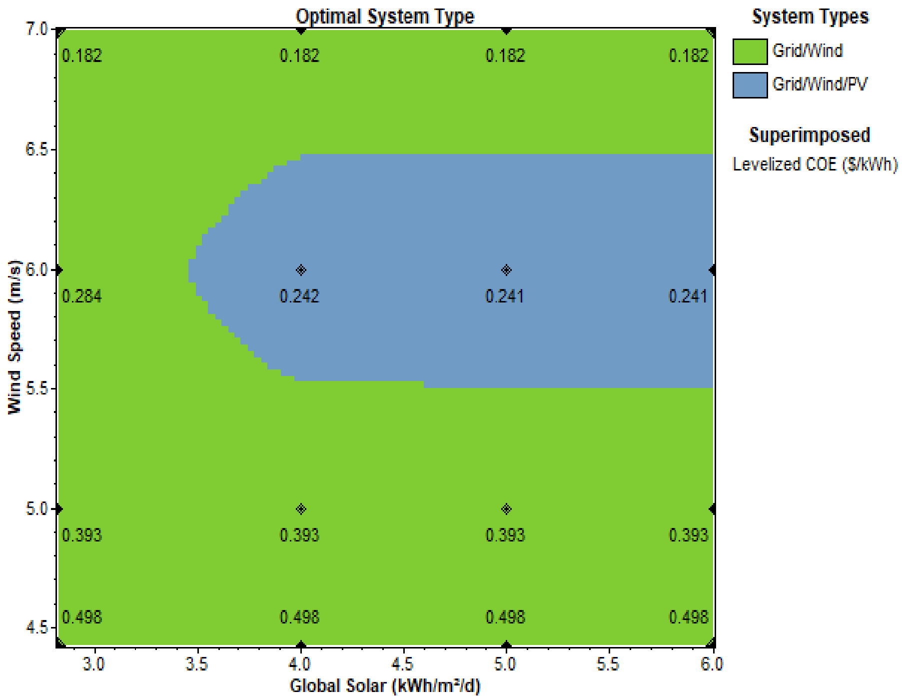


Figure 5. 6 Unit energy cost changes in case-II AC micro-grid.

In this option when 91% of the total energy is generated from renewable energy sources, the emissions are significantly minimized by optimal Grid/Wind AC micro-grid. In numerical terms, emission values are reduced down to 152.581 kg/year for CO_2, 324 kg/year for NO and 662 kg/year for SO_2. Table 5. 4 shows the emission values generated by the Grid/Wind hybrid power generation system.

Table 5. 4 The emission generated by AC micro-grid case-II.

Pollutant	Emissions (kg/yr)
Carbon dioxide	-152,581
Carbon monoxide	0
Unburned hydrocarbons	0
Particulate matter	0
Sulfur dioxide	-662
Nitrogen oxides	-324

5.2.2. DC Micro-Grids

In DC micro-grid, all energy sources are connected to the DC bus and the PV power generation system has its own controller. Here, the energy requirement of the pump is converted by an inverter from the DC bus to AC. The inverter is an additional cost element, which negatively affects the unit energy cost. Again, the same components are used as mentioned earlier in this chapter to assay the cases.

5.2.2.1. Case-I

Figure 5. 7 shows the block diagram of the DC micro-grid of case-I.

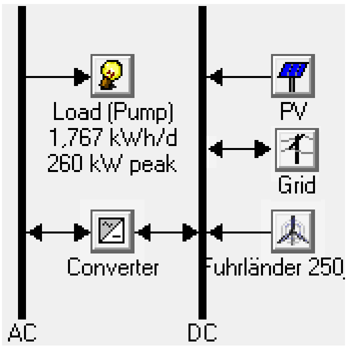


Figure 5. 7 Block diagram of DC micro-grid case-I.

For the average solar radiation (2.819 kWh/m2/day) and wind speed (4.42 m/s), it is seen that the optimal hybrid power generation system is Grid/Wind/PV, see Table 4.5. In this table is also seen that for average solar radiation and wind speed the optimal hybrid power generation system consists of a 100kW PV power generation system, seven pieces of 250kW wind turbines and 200 kW from utility grid. For this option, DC micro-grid, the unit energy cost is 0.332$/kWh.

Moreover, based on the variation of wind speed and solar radiation is for this case the best hybrid power generation system options are shown in Table 5. 5

Table 5. 5 Optimum HPGS options DC micro-grid case-I.

Solar (kWh/m²/d)	Wind (m/s)	PV (kW)	FL250	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
2.819	4.420	100	7	300	200	$ 1,793,300	73,583	$ 2,733,942	0.332	0.90	0.00
2.819	5.000		6	300	200	$ 1,023,300	55,223	$ 1,729,231	0.210	0.91	0.00
2.819	6.000		4	300	200	$ 683,300	33,141	$ 1,106,954	0.134	0.92	0.00
2.819	7.000		3	300	200	$ 513,300	20,475	$ 775,043	0.094	0.93	0.00
4.000	4.420	100	7	300	200	$ 1,793,300	72,838	$ 2,724,412	0.331	0.90	0.00
4.000	5.000		6	300	200	$ 1,023,300	55,223	$ 1,729,231	0.210	0.91	0.00
4.000	6.000		4	300	200	$ 683,300	33,141	$ 1,106,954	0.134	0.92	0.00
4.000	7.000		3	300	200	$ 513,300	20,475	$ 775,043	0.094	0.93	0.00
5.000	4.420	100	7	300	200	$ 1,793,300	72,513	$ 2,720,258	0.330	0.90	0.00
5.000	5.000		6	300	200	$ 1,023,300	55,223	$ 1,729,231	0.210	0.91	0.00
5.000	6.000		4	300	200	$ 683,300	33,141	$ 1,106,954	0.134	0.92	0.00
5.000	7.000		3	300	200	$ 513,300	20,475	$ 775,043	0.094	0.93	0.00
6.000	4.420	100	7	300	200	$ 1,793,300	72,266	$ 2,717,107	0.330	0.90	0.00
6.000	5.000		6	300	200	$ 1,023,300	55,223	$ 1,729,231	0.210	0.91	0.00
6.000	6.000		4	300	200	$ 683,300	33,141	$ 1,106,954	0.134	0.92	0.00
6.000	7.000		3	300	200	$ 513,300	20,475	$ 775,043	0.094	0.93	0.00

In the DC micro-gird case-I, PV power generation system produced 96,520 kWh/year, the wind power generation system generates 2,302,248 kWh/year and the remaining 258,155 kWh/year comes from the utility grid. The optimum hybrid power generation system generated monthly power is shown in Figure 5. 8.

Compare to AC micro-grid case-I, the DC micro-grid does not contribute any changes in power generation. Only the additional converter cost appears and the electrical losses are increased. There is no change in the monthly power production.

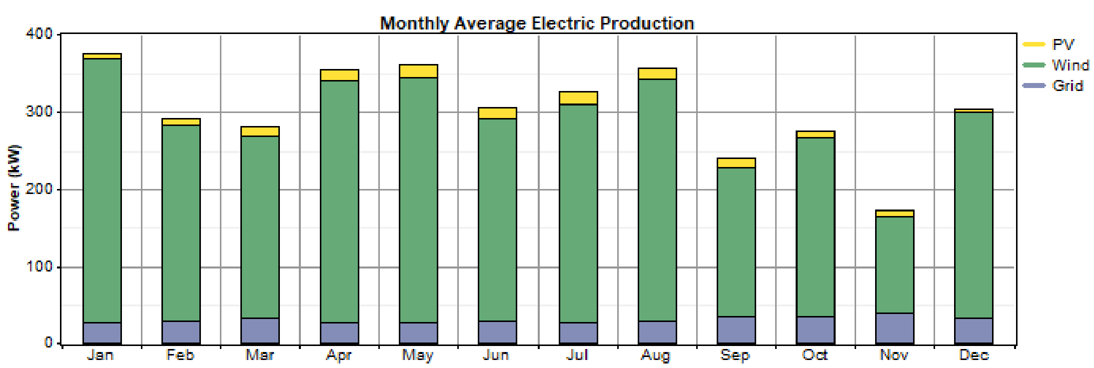


Figure 5. 8 Monthly power generation by DC micro-grid components case-I.

The change in unit energy cost according to solar radiation and wind speed data is seen in Figure 5. 9. If we look closer at the Figure 5. 9, when the wind speed is equal or larger than 5 m/s the optimum power generation system is Grid/Wind for all values of solar radiation. Moreover, the optimum power generation system is Grid/Wind/PV when the wind speed is less than 5 m/s for all values solar radiation.
If the wind speed increases from 5 m/s to 6 m/s; unit energy costs also decreased inversely from 0.210 $/kWh to 0.134$/kWh. On the other hand, the wind speed is equal or larger than 6 m/s the unit energy cost is decreased to 0.094 $/kWh.

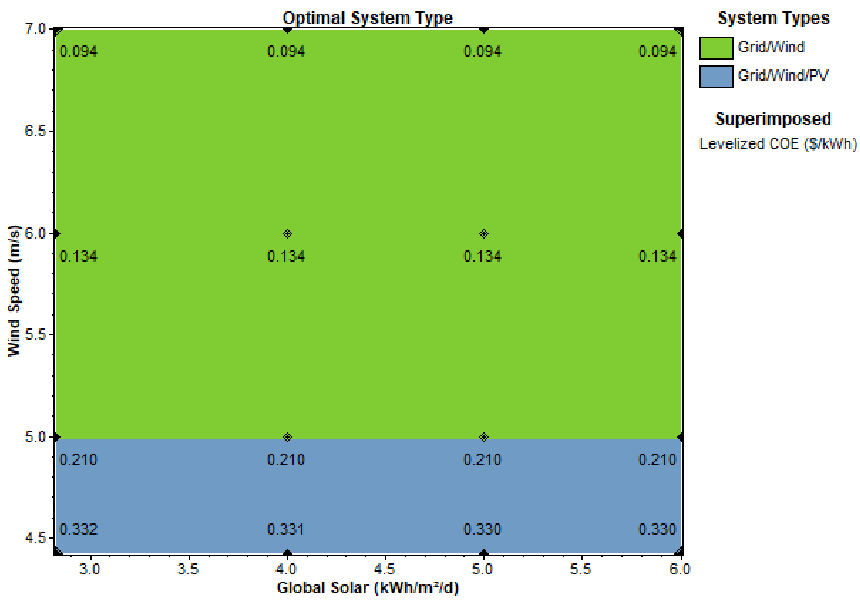


Figure 5. 9 Unit energy cost changes in case-I DC micro-grid.

In this DC micro-grid the emissions are significantly minimized by optimal Grid/Wind AC micro-grid when 90% of the total energy is generated from renewable energy sources. In numerical terms, emissions are reduced down to 114,972 kg/year for CO2, 498 kg/year for NO, and 244 kg/year for SO2. The source that contributes to the formation of these values is the grid. Table 5. 6 shows the emission values of the Grid/Wind/PV hybrid power generation system.

Table 5. 6 The emission generated by DC micro-grid case-I.

Pollutant	Emissions (kg/yr)
Carbon dioxide	-114,972
Carbon monoxide	0
Unburned hydrocarbons	0
Particulate matter	0
Sulfur dioxide	-498
Nitrogen oxides	-244

5.2.2.2. Case-II

Figure 5. 10 shows the block diagram of the DC micro-grid of case-II.

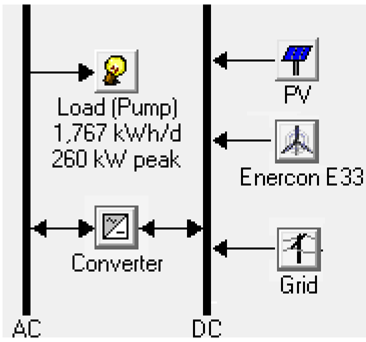


Figure 5. 10 Block diagram of DC micro-grid case-II.

In Table 5. 7, when the average solar radiation (2.819 kWh/m2/day) and the average wind speed (4.42 m/s) at the location, the optimal hybrid power generation system is combination of Grid/Wind. For the average wind speed, the optimal hybrid power generation system consists of five pieces of Enercon E33 model wind turbine, a 175kW converter and a supply of 220kW from utility grid. In the DC micro-gird, for the average wind speed the unit energy cost is 0.498$/kWh.

For this option, based on the variation of wind speed and solar radiation is the best hybrid power generation system options shown in Table 5. 7

Table 5. 7 Optimum HPGS options DC micro-grid case-II.

Solar (kWh/m²/d)	Wind (m/s)	PV (kW)	E33	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
2.819	4.420		5	175	220	$ 2,851,750	98,336	$ 4,108,810	0.498	0.91	0.00
2.819	5.000		4	175	220	$ 2,281,750	75,013	$ 3,240,673	0.393	0.92	0.00
2.819	6.000		3	175	220	$ 1,711,750	49,700	$ 2,347,087	0.285	0.94	0.00
2.819	7.000		2	175	220	$ 1,141,750	28,341	$ 1,504,037	0.182	0.93	0.00
4.000	4.420		5	175	220	$ 2,851,750	98,336	$ 4,108,810	0.498	0.91	0.00
4.000	5.000		4	175	220	$ 2,281,750	75,013	$ 3,240,673	0.393	0.92	0.00
4.000	6.000		3	175	220	$ 1,711,750	49,700	$ 2,347,087	0.285	0.94	0.00
4.000	7.000		2	175	220	$ 1,141,750	28,341	$ 1,504,037	0.182	0.93	0.00
5.000	4.420		5	175	220	$ 2,851,750	98,336	$ 4,108,810	0.498	0.91	0.00
5.000	5.000		4	175	220	$ 2,281,750	75,013	$ 3,240,673	0.393	0.92	0.00
5.000	6.000		3	175	220	$ 1,711,750	49,700	$ 2,347,087	0.285	0.94	0.00
5.000	7.000		2	175	220	$ 1,141,750	28,341	$ 1,504,037	0.182	0.93	0.00
6.000	4.420		5	175	220	$ 2,851,750	98,336	$ 4,108,810	0.498	0.91	0.00
6.000	5.000		4	175	220	$ 2,281,750	75,013	$ 3,240,673	0.393	0.92	0.00
6.000	6.000		3	175	220	$ 1,711,750	49,700	$ 2,347,087	0.285	0.94	0.00
6.000	7.000		2	175	220	$ 1,141,750	28,341	$ 1,504,037	0.182	0.93	0.00

In the DC micro-gird case-II, the wind power generation system generates 2,512,727 kWh/year and the remaining 246,220 kWh/year is generated by the utility grid. The optimum hybrid power generation system generated monthly power is shown in Figure 5. 11. Additionally Figure 5. 11 clearly shows that the PV power generation system does not generate energy due to the low potential value of solar radiation.

Compared to AC micro-grid case-II, this DC micro-grid does not contribute any changes in power generation. Only the additional converter cost appears and the electrical losses are increased. There is no change in the monthly power production.

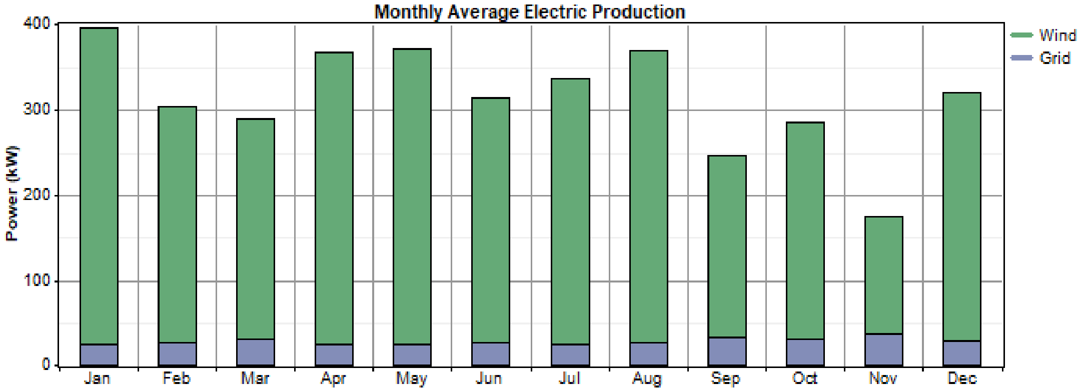


Figure 5. 11 Monthly power generation by DC micro-grid components case-II.

The change in unit energy cost by solar radiation and wind speed is shown in Figure 5. 12. The optimum power generation system is Grid/Wind for all wind speeds and for all solar radiation values. When the wind speed increased; the unit energy costs is decreased.

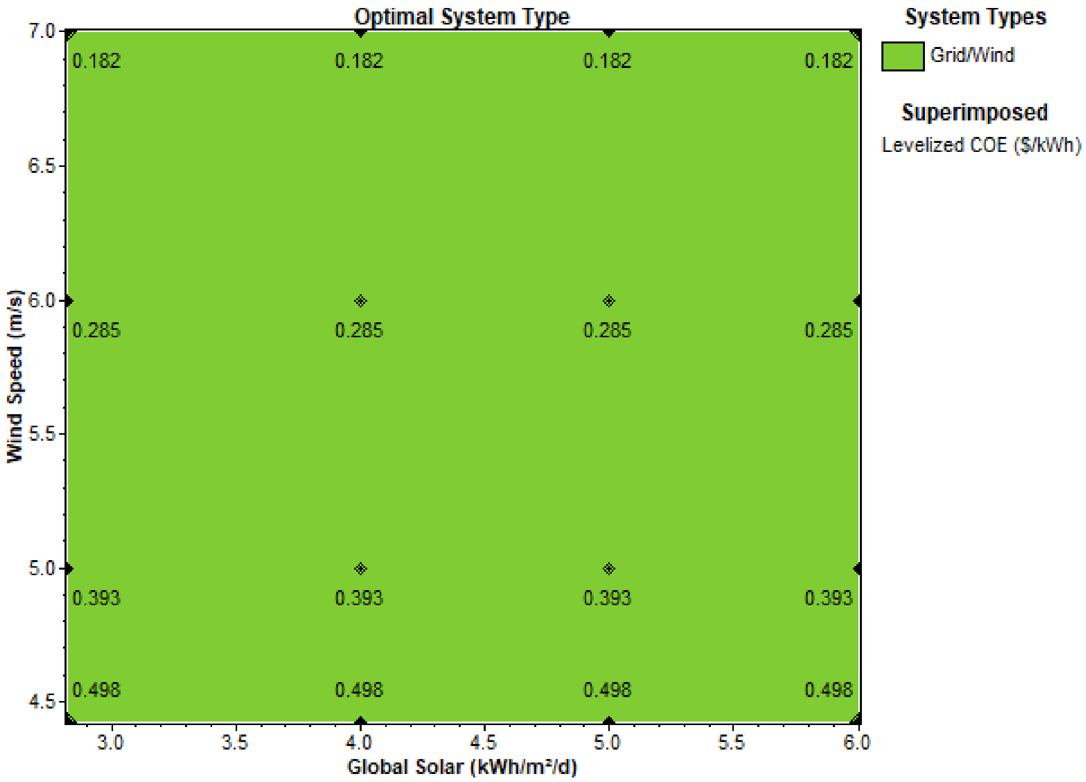


Figure 5. 12 Unit energy cost changes in case-II DC micro-grid

If 91% of the total energy is generated from renewable energy sources, the emissions are significantly minimized by optimal Grid/Wind DC micro-grid. In numerical terms, emission values are reduced down to 152.581 kg/year for CO2, 324 kg/year NO and 662 kg/year SO2. The source that contributes to the formation of these values is the utility grid. Table 5. 8 shows the emission values generated by the Grid/Wind hybrid power generation system.

Table 5. 8 The emission generated by DC micro-grid case-II.

Pollutant	Emissions (kg/yr)
Carbon dioxide	-152,581
Carbon monoxide	0
Unburned hydrocarbons	0
Particulate matter	0
Sulfur dioxide	-662
Nitrogen oxides	-324

5.2.3. Hybrid AC/DC Micro-Grids

Only the PV power generation system is connected the DC bus. The energy from the PV panels is converted from the DC bus to AC by an inverter. The inverter is an additional cost element. The wind power generation system and the utility grid are connected to the AC bus and directly supply the load.

5.2.3.1. Case-I

Figure 5. 13 shows the block diagram of the hybrid AC/DC micro-grid.

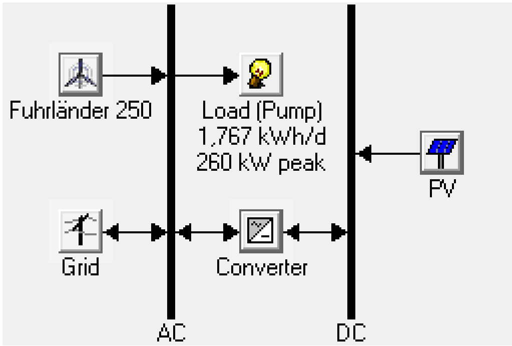


Figure 5. 13 Block diagram of hybrid AC/DC micro-grid case-I.

Table 5. 9 shows the optimum hybrid power generation system options by changing the wind speed and solar radiation. When the average solar radiation of the location of the pump is 2.819 kWh/m2/ day and the wind speed is 4.42 m/s, it is seen that the optimal hybrid power generation system, which supply the energy requirement of the pump, is Grid/Wind/PV.

For the average wind speed and solar radiation, the optimal hybrid power generation system consists of 100 kW PV power generation system, seven 250 kW wind power generation systems, 100kW converter and 200kW from the utility grid. In addition, the unit energy cost is 0.329 $/kWh.

Table 5. 9 Optimum HPGS options hybrid AC/DC micro-grid case-I.

Solar (kWh/m²/d)	Wind (m/s)	PV (kW)	FL250	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
2.819	4.420	100	7	100	200	$ 1,791,100	72,142	$ 2,713,319	0.329	0.90	0.00
2.819	5.000		6		200	$ 1,020,000	53,614	$ 1,705,368	0.207	0.92	0.00
2.819	6.000		4		200	$ 680,000	31,328	$ 1,080,475	0.131	0.92	0.00
2.819	7.000		3		200	$ 510,000	18,753	$ 749,729	0.091	0.93	0.00
4.000	4.420	100	7	100	200	$ 1,791,100	71,431	$ 2,704,234	0.328	0.91	0.00
4.000	5.000		6		200	$ 1,020,000	53,614	$ 1,705,368	0.207	0.92	0.00
4.000	6.000		4		200	$ 680,000	31,328	$ 1,080,475	0.131	0.92	0.00
4.000	7.000		3		200	$ 510,000	18,753	$ 749,729	0.091	0.93	0.00
5.000	4.420	100	7	100	200	$ 1,791,100	71,122	$ 2,700,278	0.328	0.91	0.00
5.000	5.000		6		200	$ 1,020,000	53,614	$ 1,705,368	0.207	0.92	0.00
5.000	6.000		4		200	$ 680,000	31,328	$ 1,080,475	0.131	0.92	0.00
5.000	7.000		3		200	$ 510,000	18,753	$ 749,729	0.091	0.93	0.00
6.000	4.420	100	7	100	200	$ 1,791,100	70,884	$ 2,697,233	0.327	0.91	0.00
6.000	5.000		6		200	$ 1,020,000	53,614	$ 1,705,368	0.207	0.92	0.00
6.000	6.000		4		200	$ 680,000	31,328	$ 1,080,475	0.131	0.92	0.00
6.000	7.000		3		200	$ 510,000	18,753	$ 749,729	0.091	0.93	0.00

In the AC/DC hybrid micro-gird case-I, PV power generation system produced 96,520 kWh/year, the wind power generation system generates 2,302,248 kWh/year and the remaining 258,155 kWh/year comes from the utility grid. Figure 5. 13 shows the monthly changes in the amount of power generated by the optimal hybrid power generation system components. Compare to wind energy the solar energy is very low, that is because of low solar radiation.

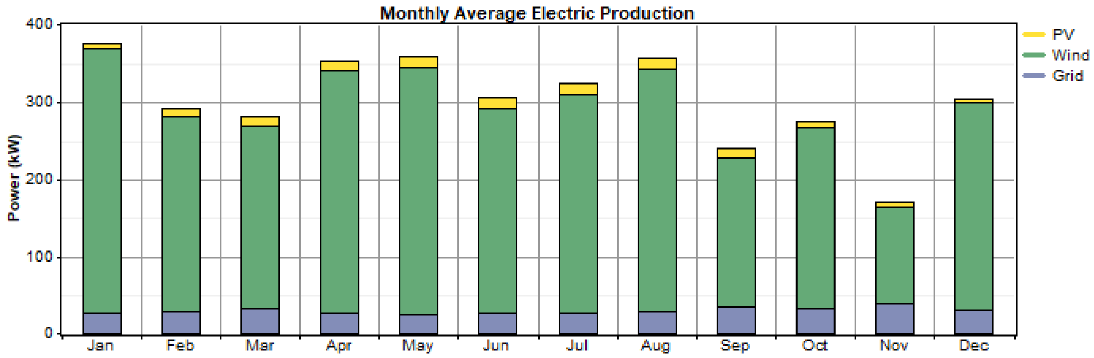


Figure 5. 14 Monthly power generation by hybrid AC/DC micro-grid components case-I.

The change in unit energy cost according to solar radiation and wind speed is given in Figure 5. 15. When the wind speed is equal or larger than 5 m/s the optimum power generation system is the combination of Grid/Wind for all solar radiation. If the wind speed increases from 5 m/s to 6 m/s; unit energy costs also decreased from 0.207 $/kWh to 0.131$/kWh. On the other hand, when the wind speed is equal or larger than 6 m/s the unit energy cost will be 0.091 $/kWh.

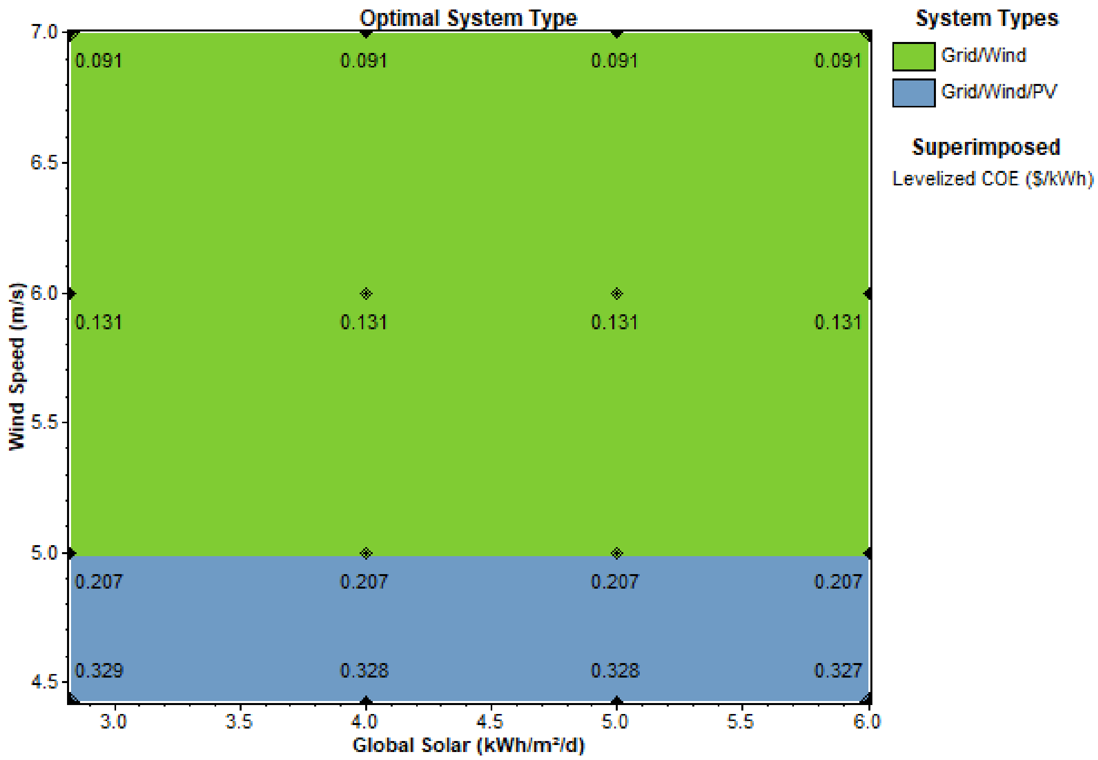


Figure 5. 15 Unit energy cost changes in case-I hybrid AC/DC micro-grid.

Emissions are significantly minimized by optimal Grid/Wind/PV hybrid power generation system when 90% of total energy is generated from the renewable energy sources. In numerical terms, emission values are reduced down to 128,385 kg/year for CO2, 272 kg/year for NO and 557 kg/year for SO2. The source contributing to these values is the utility grid. Table 5. 10 shows the emission values generated by the Grid/Wind/PV hybrid power generation system.

Table 5. 10 The emission generated by hybrid AC/DC micro-grid case-I.

Pollutant	Emissions (kg/yr.)
Carbon dioxide	-128,385
Carbon monoxide	0
Unburned hydrocarbons	0
Particulate matter	0
Sulfur dioxide	-557
Nitrogen oxides	-272

5.2.3.2. Case –II

Figure 5. 16 shows the block diagram of AC-DC Hybrid micro-grid.

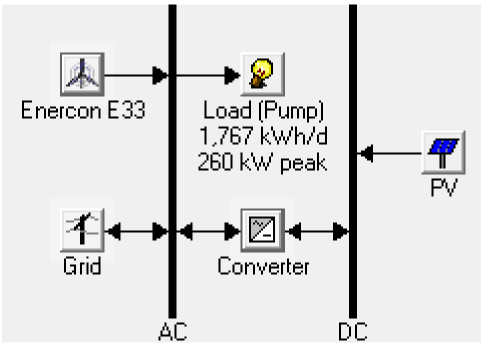


Figure 5. 16 Block diagram of AC-DC Hybrid micro grid of Case-II.

Table 5. 11 shows the optimum hybrid power generation system options obtained according to the changes in wind speed and solar radiation. For the average solar radiation and wind speed, the optimal hybrid power generation is a combination of Grid/Wind. This optimal hybrid power generation system consists five Enercon E33 330 kW wind power generation system and a 220 kW utility grid. The unit energy cost of the hybrid power generation system at average wind and solar radiation is 0.501 $/kWh.

Table 5. 11 Optimum HPGS options hybrid AC/DC micro-grid case-II.

Solar (kWh/m²/d)	Wind (m/s)	PV (kW)	E33	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
2.819	4.420		5		220	$ 2,850,000	100,151	$ 4,130,266	0.501	0.91	0.00
2.819	5.000		4		220	$ 2,280,000	77,018	$ 3,264,553	0.396	0.92	0.00
2.819	6.000	100	2	175	220	$ 1,741,500	43,339	$ 2,295,514	0.278	0.90	0.00
2.819	7.000		2		220	$ 1,140,000	30,707	$ 1,532,540	0.186	0.93	0.00
4.000	4.420		5		220	$ 2,850,000	100,151	$ 4,130,266	0.501	0.91	0.00
4.000	5.000	100	3	175	220	$ 2,311,500	65,714	$ 3,151,542	0.382	0.90	0.00
4.000	6.000	100	2	175	220	$ 1,741,500	42,726	$ 2,287,684	0.277	0.91	0.00
4.000	7.000		2		220	$ 1,140,000	30,707	$ 1,532,540	0.186	0.93	0.00
5.000	4.420		5		220	$ 2,850,000	100,151	$ 4,130,266	0.501	0.91	0.00
5.000	5.000	100	3	175	220	$ 2,311,500	65,403	$ 3,147,576	0.382	0.90	0.00
5.000	6.000	100	2	175	220	$ 1,741,500	42,454	$ 2,284,208	0.277	0.91	0.00
5.000	7.000		2		220	$ 1,140,000	30,707	$ 1,532,540	0.186	0.93	0.00
6.000	4.420		5		220	$ 2,850,000	100,151	$ 4,130,266	0.501	0.91	0.00
6.000	5.000	100	3	175	220	$ 2,311,500	65,172	$ 3,144,611	0.381	0.90	0.00
6.000	6.000	100	2	175	220	$ 1,741,500	42,252	$ 2,281,621	0.277	0.91	0.00
6.000	7.000		2		220	$ 1,140,000	30,707	$ 1,532,540	0.186	0.93	0.00

The energy production with the optimum hybrid power generation system is shown in Figure 5. 17. In this AC/DC hybrid micro-gird case-II, the wind power generation system generates 2,512,727 kWh/year and the remaining 246,220kWh/year is generated by the utility grid. The production of the PV power generation system has not been realized due to the low value of solar energy.

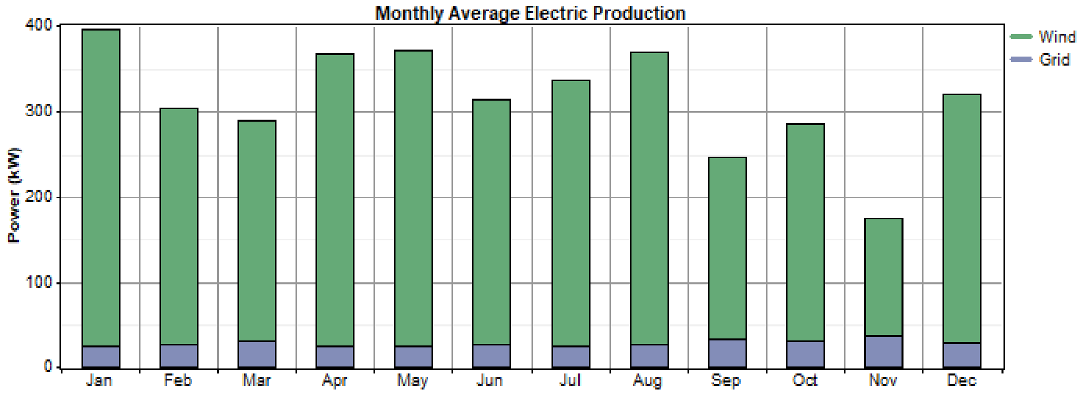


Figure 5. 17 Monthly power generation by hybrid AC/DC micro-grid components case-II.

The change in unit energy cost by solar radiation and wind speed variation is seen in Figure 5. 18. In Figure 5. 18, the optimum power generation system is a combination of Grid/Wind at the average value of the wind speed and solar radiation. Moreover, when wind speed is between 5 m/s and 6.1 and the solar radiation is between 4 kWh/m2/d and 6 kWh/m2/d, then the optimum power generation system is Grid/Wind/PV.

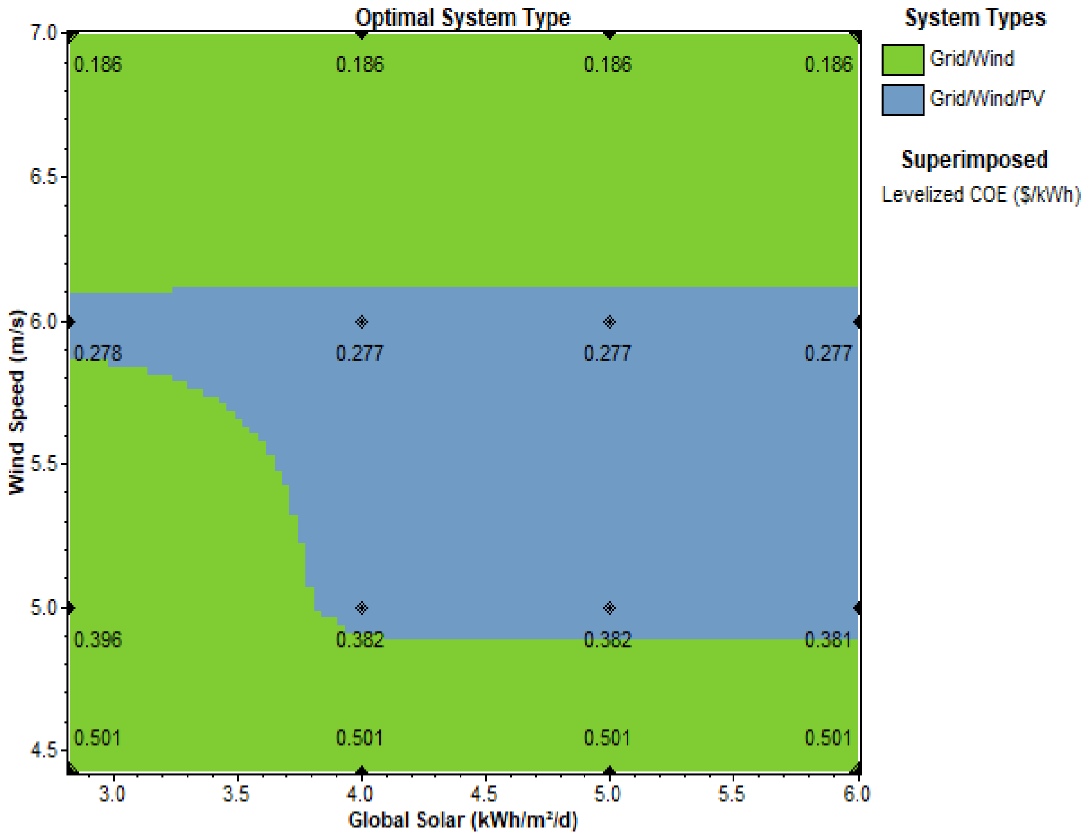


Figure 5. 18 Unit energy cost changes in case-II hybrid AC/DC micro-grid.

Emissions from the system when only the utility grid is active are considerably minimized by optimal Grid/Wind hybrid power generation where the renewable energy rate is 91%. In numerical terms, emission values are reduced down to 129,126 kg/year for CO_2, 274 kg/year for NO and 560 kg/year for SO_2. The source contributing to these values is the utility grid.

Table 5. 12 shows the emission values generated by the Grid/Wind hybrid power generation system.

Table 5. 12 The emission generated by hybrid AC/DC micro-grid case-II.

Pollutant	Emissions (kg/yr.)
Carbon dioxyde	-129,126
Carbon monoxyde	0
Unburned hydrocarbonés	0
Particulate matter	0
Sulfur dioxide	-560
Nitrogen oxides	-274

5.2.4. Load Increased Hybrid AC-DC Micro-Grids

The amount of energy required by the water-pump system is increased by 50%. The daily energy is increased to 2.7 MW and the peak power is calculated as 391kW. In this configuration is only a PV power generation system connected to DC bus. The energy from the PV panels is converted from the DC bus to AC by a converter. The wind power generation system and the utility grid are connected to the AC bus and directly supply the load.

5.2.4.1. Case-I

Figure 5. 19 shows the block diagram of the hybrid AC/DC micro-grid where the load is increased with 50%.

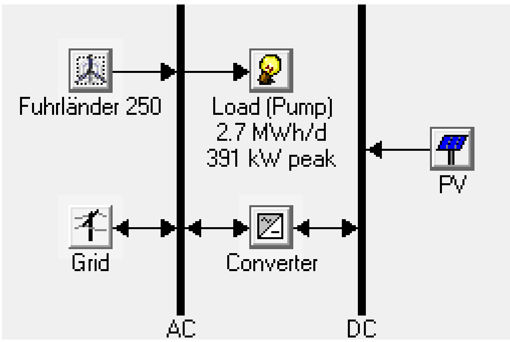


Figure 5. 19 Block diagram hybrid AC/DC micro-grid 150% load Case-I.

Table 5. 13 shows the optimum hybrid power generation system options based on the variation of wind speed and solar radiation. When the average solar radiation of the location of the pump is 2.819 kWh/m2/ day and the wind speed is 4.42 m/s, then the optimal hybrid power generation system which supply the energy demand of the water-pump system is Grid/Wind/PV.

Under these conditions, the optimal hybrid power generation system consists of 600 kW PV power generation system, nine 250 kW wind power generation systems, 300kW converter and 300kW from the utility grid. The unit energy cost is 0.552$/kWh for the AC/DC hybrid micro-gird with load increase.

Table 5. 13 Optimum HPGS options hybrid AC/DC micro-grid 150% load Case-I.

Solar (kWh/m²/d)	Wind (m/s)	PV (kW)	FL250	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
2.819	4.420	600	9	200	300	$ 5,132,200	132,130	$ 6,821,269	0.552	0.90	0.00
2.819	5.000		8		300	$ 1,360,000	84,760	$ 2,443,523	0.198	0.90	0.00
2.819	6.000		5		300	$ 850,000	53,290	$ 1,531,224	0.124	0.91	0.00
2.819	7.000		4		300	$ 680,000	38,338	$ 1,170,082	0.095	0.92	0.00
4.000	4.420	400	9	200	300	$ 3,932,200	119,392	$ 5,458,424	0.442	0.90	0.00
4.000	5.000		8		300	$ 1,360,000	84,760	$ 2,443,523	0.198	0.90	0.00
4.000	6.000		5		300	$ 850,000	53,290	$ 1,531,224	0.124	0.91	0.00
4.000	7.000		4		300	$ 680,000	38,338	$ 1,170,082	0.095	0.92	0.00
5.000	4.420	400	9	200	300	$ 3,932,200	118,796	$ 5,450,808	0.441	0.90	0.00
5.000	5.000		8		300	$ 1,360,000	84,760	$ 2,443,523	0.198	0.90	0.00
5.000	6.000		5		300	$ 850,000	53,290	$ 1,531,224	0.124	0.91	0.00
5.000	7.000		4		300	$ 680,000	38,338	$ 1,170,082	0.095	0.92	0.00
6.000	4.420	400	9	200	300	$ 3,932,200	118,389	$ 5,445,614	0.441	0.90	0.00
6.000	5.000		8		300	$ 1,360,000	84,760	$ 2,443,523	0.198	0.90	0.00
6.000	6.000		5		300	$ 850,000	53,290	$ 1,531,224	0.124	0.91	0.00
6.000	7.000		4		300	$ 680,000	38,338	$ 1,170,082	0.095	0.92	0.00

When the load is increased with 50%, the PV power generation system generates 579,123 kWh/year, the wind power generation system generates 2,960,035 kWh/year and the remaining 381,301 kWh/year is generated by the utility grid. Figure 5. 20shows the monthly changes in the amount of power produced by the optimal hybrid power generation system components.

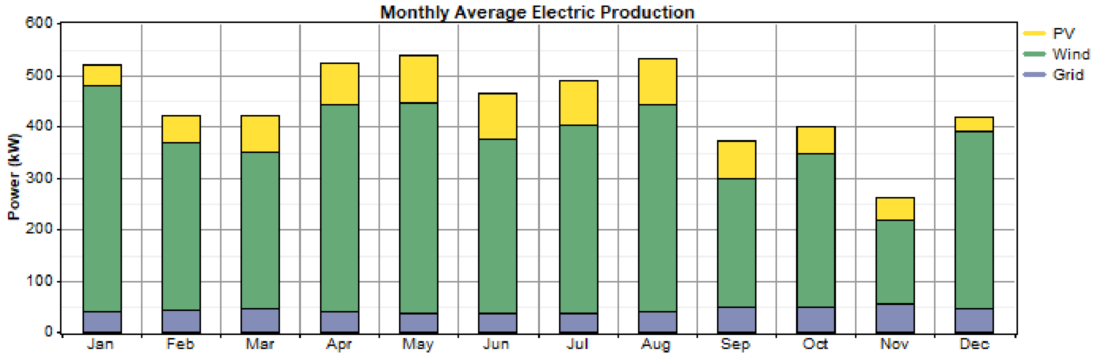


Figure 5. 20 Monthly power generation by hybrid AC/DC micro-grid components 150% load Case-I.

The change in unit energy cost according to solar radiation and wind speed is perceived in Figure 5. 21. If we take a closer look at Figure 5. 21, for the wind speed equal of larger than 5 m/s the optimum power generation system is Grid/Wind for all solar radiation values. Furthermore, when the wind speed is less than 5 m/s the optimum power generation system is Grid/Wind/PV for all solar radiation values.

When the wind speed increases from 5 m/s to 6 m/s; then the unit energy cost decreased from $ 0.198/kWh to $ 0.124/kWh. For the wind speed, which is larger than 6 m/s, the unit energy cost is $ 0.095/kWh.

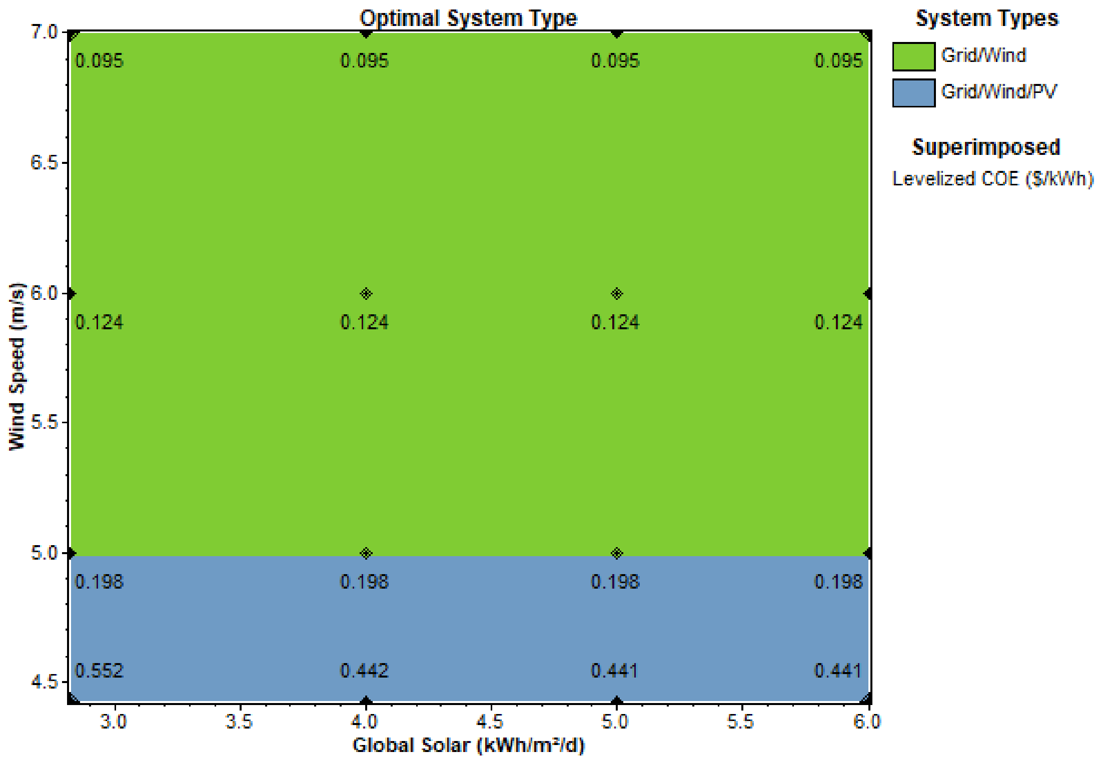


Figure 5. 21 Unit energy cost changes in hybrid AC/DC micro-grid 150% load Case-I.

Emissions compared to the system that only the grid is connected are significantly minimized by optimal Grid/Wind/PV hybrid power generation system when 90% of energy is generated by renewable energy sources. In numerical terms, the emission values are reduced down to 81,444 kg/year for CO2, 173 kg/year for NO and 353 kg/year for SO2. The utility grid contributes to these emission values. Table 5. 14 shows the emission values generated by the Grid/Wind/PV hybrid power generation system.

Table 5. 14 The emission generated by the Grid/Wind HPGS 150% load Case-I.

Pollutant	Emissions (kg/yr.)
Carbon dioxide	-81,444
Carbon monoxide	0
Unburned hydrocarbons	0
Particulate matter	0
Sulfur dioxide	-353
Nitrogen oxides	-173

5.2.4.2. Case-II

Figure 5. 22 shows a block diagram of the Hybrid AC/DC micro-grid where the load is increased with 50%.

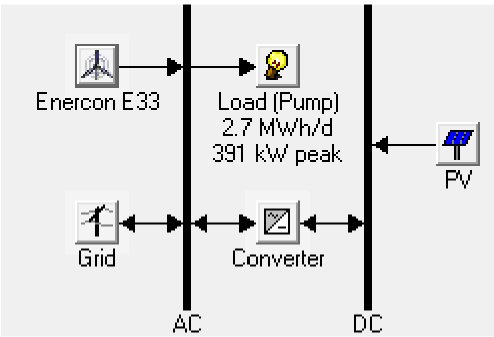


Figure 5. 22 Block diagram hybrid AC/DC micro-grid 150% load Case-II.

Table 5. 15 shows the optimum hybrid power generation system options according to the changes in wind speed and solar radiation. For the average solar radiation (2.819 kWh/m2/day) and the wind speed (4.42 m/s), the optimal hybrid power generation system is Grid/Wind. The optimal hybrid power generation system consists seven Enercon E33 330kW wind power generation system and a 330kW utility grid. The unit energy cost of the hybrid power generation system is 0.480$/kWh.

Table 5. 15 Optimum HPGS options hybrid AC/DC micro-grid 150% load Case-II.

Solar (kWh/m²/d)	Wind (m/s)					PV (kW)	E33	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
2.819	4.420						7		330	$ 3,990,000	151,870	$ 5,931,411	0.480	0.90	0.00
2.819	5.000						5		330	$ 2,850,000	110,574	$ 4,263,509	0.345	0.90	0.00
2.819	6.000						4		330	$ 2,280,000	82,647	$ 3,336,500	0.270	0.93	0.00
2.819	7.000						3		330	$ 1,710,000	58,624	$ 2,459,417	0.199	0.93	0.00
4.000	4.420						7		330	$ 3,990,000	151,870	$ 5,931,411	0.480	0.90	0.00
4.000	5.000						5		330	$ 2,850,000	110,574	$ 4,263,509	0.345	0.90	0.00
4.000	6.000						4		330	$ 2,280,000	82,647	$ 3,336,500	0.270	0.93	0.00
4.000	7.000						3		330	$ 1,710,000	58,624	$ 2,459,417	0.199	0.93	0.00
5.000	4.420						7		330	$ 3,990,000	151,870	$ 5,931,411	0.480	0.90	0.00
5.000	5.000						5		330	$ 2,850,000	110,574	$ 4,263,509	0.345	0.90	0.00
5.000	6.000						4		330	$ 2,280,000	82,647	$ 3,336,500	0.270	0.93	0.00
5.000	7.000						3		330	$ 1,710,000	58,624	$ 2,459,417	0.199	0.93	0.00
6.000	4.420						7		330	$ 3,990,000	151,870	$ 5,931,411	0.480	0.90	0.00
6.000	5.000						5		330	$ 2,850,000	110,574	$ 4,263,509	0.345	0.90	0.00
6.000	6.000						4		330	$ 2,280,000	82,647	$ 3,336,500	0.270	0.93	0.00
6.000	7.000						3		330	$ 1,710,000	58,624	$ 2,459,417	0.199	0.93	0.00

In this case, the wind power generation system generates 3,517,810 kWh/year and the remaining 378,378kWh/year is generated by the utility grid. Due to the low value of solar energy, power generation from the PV power generation system has not been realized. Figure 5. 23 shows the monthly changes in power production by the optimal hybrid power generation system components.

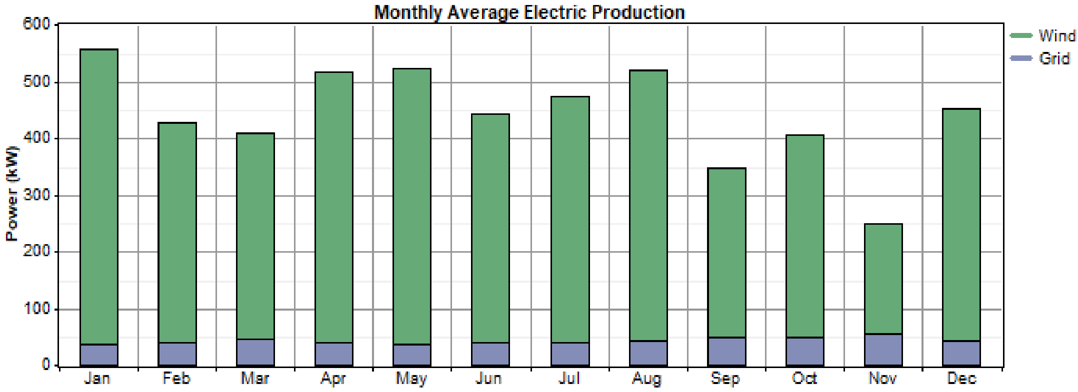


Figure 5. 23 Monthly power generation by hybrid AC/DC micro-grid components 150% load Case-II.

The change in unit energy cost according to solar radiation and wind speed is shown in Figure 5. 24. In Figure 5. 24, the optimum power generation system is combination of Grid/Wind at all wind speeds and for all solar radiations.

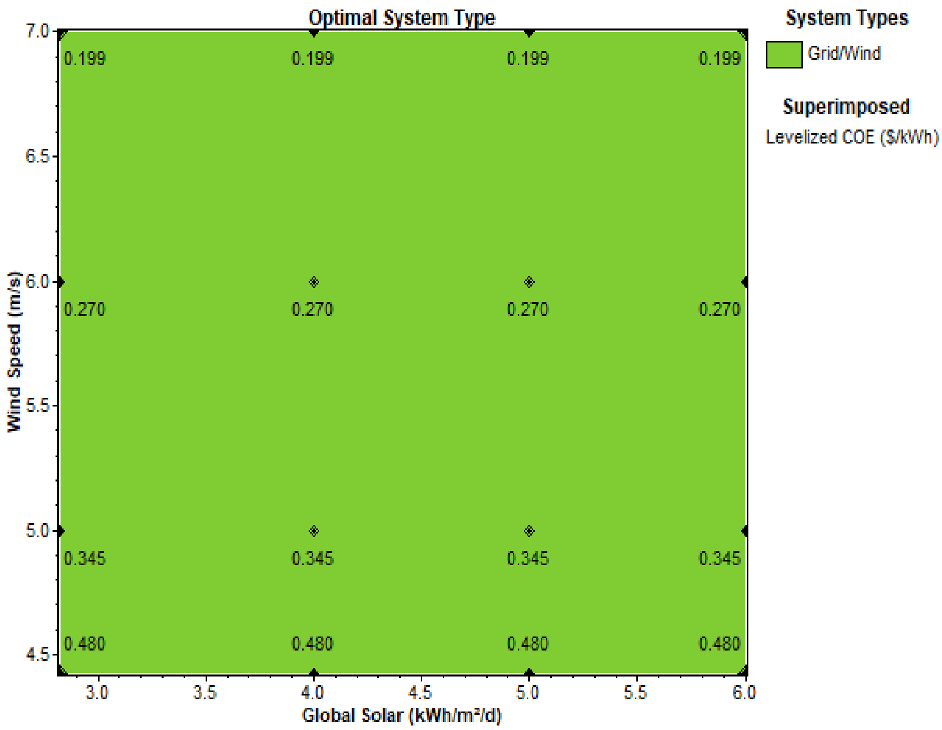


Figure 5. 24 Unit energy cost changes in hybrid AC/DC micro-grid 150% load Case-II.

Emission is significantly minimized by optimal Grid/Wind hybrid power generation system when 90 % of the energy is generated by renewable energy sources. In numerical terms, emission values are reduced down to 54.689 kg/year for CO2, 116 kg/year for NO and 237 kg/year for SO2. The source contributing to these values is the utility grid. Table 5. 16 shows the emission values of the Grid/Wind hybrid power generation system.

Table 5. 16 The emission generated by the Grid/Wind HPGS 150% load Case-II.

Pollutant	**Emissions (kg/yr.)**
Carbon dioxide	-54,689
Carbon monoxide	0
Unburned hydrocarbons	0
Particulate matter	0
Sulfur dioxide	-237
Nitrogen oxides	-116

CHAPTER VI. CONCLUSION AND FUTURE WORK

The water-pumping system is an essential chain component of the water management system and played an important role for the economy in Netherlands [97].

These systems must work continuously; therefore, the continuity of the energy is essential for the water-pumping systems. The energy consumption of these systems is high. Due to high-energy consumption, the efficiency of the energy usage is crucial. First the research question are presented and subsequently answered in Section 6.1 during this research, many possibilities for future research were identified. These possibilities are discussed in Section 6.2

6.1. Conclusions

Within the scope of this study, it is planned to supply at least 90% of the energy requirement of the pump from renewable energy sources. The energy requirement of the pump located at the latitude and longitude coordinates 51° 26' 58" N and 4° 13' 41" E will be supplied by the utility grid, wind, and solar energy sources. Seasonal changes are taken into consideration for both the load side and the energy sources in the analysis.

Two different hybrid system configurations (Case-I and II) were created and their performance was evaluated in four primary cases. The analysis consists of four necessary conditions,

- All energy sources are connected to the AC micro-grid to supply the energy requirement of the load (pumping system)
- The energy supply of the load (pumping system) by connecting all energy sources to the DC micro-grid
- The energy supply of the load (pumping system) by connecting all energy sources to hybrid AC/DC micro-grid
- The energy requirement of the load (pumping system) is ensured if all energy sources are connected to the hybrid AC/DC micro-grid and the load is increased by 50%.

The most advantageous of these four necessary conditions is the hybrid AC/DC micro-grid. In the case, where all energy sources are connected to the AC bus, an additional cost is generated by adding a converter to convert the DC power from the PV power generation system into the AC power. In the case where all energy sources are connected to the DC bus, there is a need for a converter to convert the AC power to the DC power in order to meet the energy requirement of the load (pump), and this creates an additional cost. When hybrid AC/DC micro-grid is used, unnecessary expenses such as converters are eliminated.

The energy consumption of the water-pumping system is supplied by three micro-grids types. For each case (I and II) different components are used such as solar panels, wind turbines and converters. The energy consumption of the water-pump has been analyzed regarding four essential conditions. These options and characteristics of the optimal hybrid energy system obtained in each case are given in detail in Table-1. When Table-1 is sifted through, hybrid AC-DC micro-grid in case-I is the situation, which has the lowest unit cost.

After the analysis, Grid/PV/Wind hybrid renewable energy system is the optimum energy system to supply the energy consumption of the water-pump system. The optimal option of the Grid/PV/Wind hybrid power generation system consists of a 100kW PV power generation system, a 7x250 kW wind power generation system, a 200kW utility grid and a 100kW converter.

The initial cost, operating and maintenance cost and the net current price of the optimal hybrid system was calculated to be 1,791,100 $/yr, 72,142 $/yr and 2,713,319 $/yr, respectively. The renewable rate of the system is 90% and the unit energy cost is 0.329 $/kWh.

The optimal hybrid power generation system generates in total 2570055 kWh/year. PV power generation system produces 96,520 kWh/year. The wind power generation system generates 2,302,248 kWh/year. The utility grid supplies 258,155 kWh/year. The low value of the part provided by the PV power generation system is due to the low-level of the solar energy potential.

This optimum energy system is calculated at the location where the average wind speed is 4.42 m/s and the average solar radiation is 2.819 kWh/m2/day. In addition, the unit energy cost is 0.329$/kWh. Moreover, when the wind speed increases from 5 m/s to 6 m/s; unit energy costs decreased from $ 0.207/kWh to $ 0.131/kWh. If the wind speed is equal to or larger than 6 m/s, the unit energy cost reaches $ 0.091/kWh.

When the load is increased with 50%; in case–I, the unit energy cost is also increased with almost 60%. In Case-II, the unit energy cost is decreased approximately with 4.5%. It is clearly seen that the unit energy cost in case-II is cheaper than in case-I, roughly 13%.

Emissions from the system where only the utility grid is connected are significantly minimized by optimal Grid/Wind/PV hybrid power generation in the case of 90% of the renewable energy rate. In numerical terms, emission values are reduced down to 128,385 kg/year for CO_2, 272 kg/year for NO and 557 kg/year for SO_2. The source contributing to these values is the utility grid.

Table 6. 1 Optimal options and features for each situation

SITUATION	CASES	PV (kW)	WT (kW)	Conv. (kW)	Grid (kW)	Initial Capital ($)	Operating Cost ($/yr)	Net Present Cost ($)	CoE ($/kWh)	Hybrid Ren. Ener. Types
(ONLY AC BUS)	CASE-1	100	7x250	-	200	1,910,000	71,901	2,829,130	0.343	Grid/PV/Wind
	CASE-2	-	5x330	-	220	2,850,000	98,295	4,106,545	0.498	Grid/Wind
(ONLY DC BUS)	CASE-1	100	7x250	300	200	1,793,300	73,583	2,733,942	0.332	Grid/PV/Wind
	CASE-2		5x330	175	220	2,851,750	98,336	4,108,810	0.499	Grid/Wind
(AC-DC HYBRID BUS)	CASE-1	100	7x250	100	200	1,791,100	72,142	2,713,319	0.329	Grid/PV/Wind
	CASE-2	-	5x330	-	220	2,850,000	100,151	4,130,266	0.501	Grid/Wind
(%50 LOAD INCREASE)	CASE-1	600	9x250	300	300	5,132,200	132,130	6,821,2619	0.552	Grid/PV/Wind
	CASE-2	-	7x330	-	330	3,990,000	151,870	5,931,411	0.480	Grid/Wind

In Rilland Netherlands, solar energy cannot be utilized sufficiently because the potential of solar energy is low. Therefore, the most of the consumed energy is supplied by the wind power generation systems.

Renewable energy sources connected to the grid is the most applicable solution in today's conditions. In addition, the analysis results confirm that the Grid/PV/Wind renewable hybrid energy system is the most suitable system for the selected pilot area.

6.2. Future Works

In order to shed light on future studies, the following points are listed below:

- For a DC load, water-pumping system can be determined concerning energy efficiency and economic benefits the most suitable micro-grid type.
- The study can be repeated by replacing only renewable energy sources (biomass, hydroelectric, fuel cell, flywheel systems, etc.) at the same location. In this case, the optimal hybrid systems can be determined by comparing with each other. For example, if there are animal farms in the same location or the vicinity, energy production can be realized by evaluating the animal wastes in the farms, which the farm owners have difficulty in eliminating. In this respect, feasibility studies of PV/Wind/Biomass hybrid energy system can be realized.
- The optimum hybrid energy system can be designed by combining the most appropriate sources by identifying the potential of the renewable energy sources of the pilot region. In this case, proper planning can reduce the unit cost.
- Grid-independent systems may be recommended for the pilot zone, but the current load is in the kW system range. Storage is quite difficult and troublesome in cases where the load is large. However, as independent network small power systems can be installed in the pilot area. PV/Wind/Battery, Wind/Battery, PV/Battery systems can be used, as an example to supply the energy needs of small load systems.

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