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Optimization of Hybrid Renewable Electrical Energy System for a Port Terminal

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A dissertation submitted to

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in fulfillment of the requirements for the degree of

Master of Science in Engineering in Electricity Engineering

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COLLEGE OF AGRICULTURE, ENGINEERING, AND SCIENCE

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DETAILS OF CONTRIBUTION TO PUBLICATIONS that form part and/or include research presented in this thesis (include publications in preparation, submitted, *in the press,* and published and give details of the contributions of each author to the experimental work and writing of each publication)

Paper in preparation 1 - Optimization of Hybrid Renewable Electrical Energy System for A Port Terminal

Publication 2

Publication 3

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Abstract

The port terminals in South Africa currently face significant challenges linked to electricity constraints and security. South Africa is predominantly reliant on coal-generated electricity from the local utility for the provision of base-load electricity to power operations, and municipal distribution systems in many areas. A reduction in power in the latter part of 2015 has resulted in the curtailment of load shedding that is continuing to date, 2019. This risk is not mitigated, it is ongoing.

Port terminals in South Africa rely on the throughput of the vessels to ensure that freight is moved speedily. The aspects of port operations that are generally considered in measuring port performance and efficiency are berth productivity measured in moves or volumes per ship working hour also known as across the shipping rate, cargo dwell times, crane moves per hour, ship turnaround time with less focus or no energy management. The port operations are dependent on the throughput of the operation. The energy consumed for port operations is thus independent and is difficult to control in any sort of energy management plan. Coupling this with the time of use tariffs and demand penalties, the need for an adaptable hybrid system can alleviate some stresses and contribute positively to an energy management plan.

This study aims to determine that the distributed generation and storage performed by a variety of small, grid-connected referred to as distributed energy resources mitigate the energy cost issues in the port environment and reduction of Green House Gases (GHG) emissions. Distributed resources can help reduce the capacity problems to which an aging or overstressed grid is liable. The study is contributing to reducing dependence on major power plants supply and redirecting the source of supply to renewable technologies. This results in eliminating the need to erect new big power generation and deferral of new capacity. It also demonstrates that PV Solar and Wind Turbine Generation can reduce environmental impacts and gas greenhouse gas emissions. Compared to the coal power plants, distributed generators units are renewable or low emission generator-based sources.

The Homer Grid simulation tool suggest distributed generation to be the solution for the port i.e., the hybrid supply that includes the integration of photovoltaic generation, wind power generation, battery energy storage system (BESS) into the electricity Municipal Grid. Both Matlab and HOMER Grid optimizations tools are used to outline different options for reducing electricity costs. These tools compare the costs and savings and uses a powerful optimization to find the system that maximizes savings. We used these tools to analyze the distributed generation grid potential, peak renewables penetration, ratio of renewable sources to total energy, and grid stability. The tools present different study cases with optimal results.

The outcome shows a decrease in the cost of energy in the long term and can contribute towards the better energy management of the port.

Acknowledgment

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Acronyms

1. A	-	Amperage
2. AC	-	Alternative Current
3. AVGn	-	Average Wind Speed, km/h
4. BAT	-	Battery Voltage
5. BESS	-	Battery Energy Storage System
6. BTU	-	Moist Enthalpy Btu/lb
7. CO_2	-	Carbon Dioxide
8. DA	-	Density Altitude / Cloud Base
9. DC	-	Direct Current
10. DEG	-	Direction Degrees °
11. DER	-	Distributed Energy Resource
12. DER-CAM	-	Distributed Energy Resources Customer Adoption Model
13. DERs	-	Distributed Energy Resources
14. DEVn	-	Wind Standard Deviation %
15. DEW	-	Dewpoint °C
16. DG	-	Distributed Generation
17. DI	-	Discomfort Index
18. DIR	-	Compass Wind Direction
19. EMS	-	Energy Management System
20. ENP	-	Excess Network Percentage
21. ENTH	-	Moist Enthalpy kJ/kg
22. ESS	-	Energy Storage Systems
23. GHG	-	Green House Gas
24. GHI	-	Global Horizontal Irradiation/Irradiance
25. GTI	-	Grid-Tied Inverter
26. Homer	-	Hybrid Optimization of Multiple Energy Resources
27. HUM	-	Humidity
28. iHOGA	-	improved Hybrid Optimization by Genetic Algorithms
29. IPP	-	Independent Power Producer
30. IRP	-	Integrated Resource Plan
31. kW	-	Kilowatts
32. kWh	-	Kilowatts per Hours
33. LCOE	-	Levelized Cost of Electricity
34. MCDA	-	Multi-Criteria Decision Analysis
35. MNn	-	Minimum Wind Speed, km/h

36. MXn - Maximum Wind Speed, m/s (n = channels 1-3)
37. NAC - Network Access Charge
38. NMD - Notifies Maximum Demand
39. NOx - Nitrogen Oxides
40. NPC - Net Present Cost
41. NPV - Net Present Values
42. NRS - National Regulatory Services
43. O_3 - Ozone
44. OPEN - Open Platform for Energy Networks
45. PF - Power Factor
46. POD - Point of Delivery
47. PRESS - Pressure hPa (QNH)
48. PV - Photovoltaic
49. RAD - Relative Air Density
50. RAIN - Rainfall
51. RES - Renewable Energy Sources
52. RMG - Rail Mounted Gantry
53. ROI - Return on Investment
54. RPP - Renewable Power Plants
55. RTG - Rubber Tyre Gantry
56. SIG - Modem Signal Strength
57. SO_2 - Sulphur Dioxide
58. SOC - State of Charge
59. SOLR - Solar Radiation Wm^2
60. STS - Ship to Shore
61. TEMP - Temperature °C
62. TEU - Twenty-foot Equivalent Unit
63. UI - User Interface
64. V - Voltage
65. VRLA - Valve Regulated Lead–Acid
66. WTG - Wind Turbine Generator

1 Introduction

The research focuses on the management of the energy and integration of solar, wind, and battery energy storage technology. Historical wind speed variation, solar radiation, humidity, temperature, and rainfall data within the South African port environment are captured. This will be translated to available generation capacity in terms of kW.

South Africa is ranked as one of the world's most intensive energy-intensive nations, owing to its reliance on coal as its primary source of fuel for electricity generation and its wide use of liquid fuel for transport [1]. South Africa’s electricity supply is severely constrained, electricity costs are rising sharply, liquid fuels are subject to exchange rate risk and both sources of energy carry a high environmental risk.

There are different sources of Greenhouse Gases (GHG) [2], but Fossil-Fuel based electricity generation is one of the largest sources of greenhouse gas emissions [3]. This coupled with the increasing electricity demand has motivated the need to integrate a vast amount of renewable energy such as wind, solar, and diesel with the electricity grid. The focus to reduce the emission footprint is gaining support and interest globally

The South African Department of Energy is exploring ways to reduce high costs and eliminate unreliability of supply. The Department has issued two determinations to enable an additional 13 000 MW into the electricity grid. In the short and medium-term that the IRP envisions a “just transition” from a high- to a low-carbon emission environment. At the same time, the Department aims to diversify electricity generation sources, as well as ensure local and regional development. [4]

The research is done in the South African port environment. The focus is on the management of energy and Integration of Renewable Energies. In the past electricity was easily available and as a result, most of the distribution networks were designed to operate in a circular configuration with a single source. With all the environmental requirements and energy security, the traditional energy sources are limited, as a result, an alternative source of energy is required. The world has started to think seriously about some alternative energy sources in the past decades which are renewable energy. The combination of different alternative energy technologies is a solution that would not only address the energy costs but also environmental issues at the port. Not all technologies are suitable for the port environment.

1.1 Research Questions and Methodology

The background to the problem is that a port terminal's volume throughput is heavily dependent on the supply of electricity. Electricity has been identified as a major risk due to the increasing energy costs, increasing industrialization, and aging infrastructure. The port terminals' primary energy sources are electricity (59%) and diesel fuel (33%) with the remainder constituting distillate fuel oil, petrol, and other sources for cooking and welding. An energy management plan is necessary to alleviate the cost of energy (i.e., grid or diesel) as well as the peak demand on the terminal. Optimizing the operations is one method of improving energy usage, however, in the port environment, the volume throughput has a higher priority than the energy management. As such alternate methods to manage the energy usage need to be investigated.

This research proposes several Renewable Energy Sources (RES) Integrated into Distributed Generation (DG) from solutions using a combination of wind and solar technologies, diesel combined with Battery Energy Storage System (BESS). In this regard, a model developed unpacks the design philosophy, challenges, mitigation strategy as well as preferred solution. The Homer and Matlab simulation tools are used for the optimization of the RES.

The port terminal operations are such that operations port's operations performance indicators dictate how your energy performance is, as such it is difficult to manage the energy usage. The performance indicators are hours spent per ship (ship working hours), berth productivity, and tonnage per hour to list the few. The main focus of the research is to provide answers to the following:

- What is the best way to manage a port terminal's energy performance to reduce costs?
- What is the best combination of alternative sources of supply to optimize energy use and reduce GHG emissions in the port terminal?
- What is the best indicator of energy usage management?

The Guidance to Energy Management book [5] as well as the best practice, ISO 50001 will be used as a framework in the analysis of energy management in the port environment. The ISO 50001 provides guidelines on how to identify significant energy uses and manage energy usage to improve efficiency. Combined with this ISO international best practice, the Guidance to Energy Management book is used as a guide for the analysis of the energy bills and understanding of the life cycle costing. It is also used for renewable energy sources management guidelines.

1.2 Hypothesis

The hypothesis is that the hybrid renewable energy system is a viable solution in reducing energy consumption at the port terminal, reducing the reliance on fossil fuels, and ultimately reducing the cost of electricity. A secondary hypothesis is that the hybrid renewable energy system would form part of an energy management plan as it would be adaptable to the energy needs of the port operations, rather than the port operations changing to fulfil the needs of this plan.

1.3 Importance of Study and Contribution

The conventional coal power plants around South Africa have reached the design life span and can no longer be refurbished to a productive, efficient, and reliable level. The environmental issues underscore the importance of introducing renewable technology. The study demonstrates that the distributed generation and storage performed by a variety of small, grid-connected referred to as distributed energy resources s mitigate the energy security issues in the port environment and reduction of CO_2 emissions.

Distributed resources can help reduce the reliability and capacity problems to which an aging or overstressed grid is liable. Distributed generators can be designed to operate properly when islanded, giving local distribution systems and customers the ability to ride out major or widespread outages.

The study contributes to reducing dependence on major power plants. This results in eliminating the need to erect new big power generation and deferral of new capacity. It also demonstrates that PV Solar and Wind Turbine Generation can reduce environmental impacts and gas greenhouse gas emissions. This is because many distributed generators units are renewable or low emission generators based sources.

The price of energy is very expensive in South Africa and statistics to predict unit cost increase due to the old infrastructure and high maintenance cost to name a few. The research also presents financial calculations that demonstrate a reduces price volatility in energy markets and increases energy security by diversifying energy sources and reducing dependence on complex large systems.

What has led to the research problem is that the port desires to improve supply reliability and power management, with independence from utility grid systems, distributed generation systems offer easy maintenance of power, voltage, and frequency. It also offers the possibility of combining energy storage and management systems, with reduced congestion.

Even though there are programmes available for optimization of the solution recent research has shown that improper placement of distributed generators on a power network could jeopardize system performance [6]. Hence analysis of the energy performance using actual site environment, radiation, and climate data, the optimum location of distributed generation units is determined. Based on this research work, a model is designed to ascertain the best scenario based on the given location for the suitability of the wind and solar power combined battery storage, connected onto the Grid.

The key indicator for this research is the improved LCOE, a DG model providing the alternative source(s) of energy based on the South African port environment, reduction of GHG emissions, and reduced electricity peak demand.

This objective will be achieved by reviewing key energy indicators for port operations around the globe. Analyze their energy performance against the set operational key indicators and determine the LCOE. There is a benchmark on the port operation performance and this will be used as drivers to determine the port energy performance KPIs. The port energy management framework development is not resolved and this limitation necessitates a need for the research work.

1.4 Dissertation Structure

The proposed dissertation structure is as follows,

1.4.1 Chapter 2 Literature Review

The chapter presents a literature review. The literature review covers the comprehensive overview of the port terminal's energy management, efficiency measures against the port operations strategy, and optimization of the hybrid renewable electrical energy systems in the port environment. The systems reviewed include PV solar, wind turbine generation, DG, energy storage, sustainability, and environmental issues. It covers an overview of the South African electricity supply status. The later part of the chapter covers the software, algorithms for energy analysis, and optimization review.

1.4.2 Chapter 3 Energy Analysis of the Port Terminals

In this chapter, we provide an over of the port electrical layout, energy analysis of the port, and equipment used in the port. It covers into detail climate challenges and required weather conditions for the port operation to confirm the viability of the renewable sources of supply. Electricity regulations govern all developments in the electrical space, it can sometimes be a showstopper on new distributed generation developments, this chapter also focuses on the South African electricity regulations and licensing requirements for renewable technologies.

1.4.3 Chapter 4 Matlab and Homer Optimization

The chapter covers in detail the integration of renewables in the Port Terminal. It presents the loading of the port terminal and technology integrated i.e., photovoltaic generation, Wind Power Generation, Battery Energy Storage System (BESS) using Matlab and Homer optimization tools.

Both MATLAB and Homer optimizing tools analyze the different technologies and the results are presented in the next chapter, including the total cost of the system.

1.4.4 Chapter 5 Simulation and Results of Hybrid Energy System

The chapter presents the optimization of the hybrid system results from the Matlab and Homer tools used in the previous chapter to optimize the hybrid energy system. The optimization results include detailed analysis of the annual peak electric demand, demand charge reduction calculations, energy daily peak – Grid, carbon dioxide (CO_2) emissions, LCOE, cost analysis, and total cost of the system.

1.4.5 Chapter 6 Conclusion

The chapter presents the conclusion and solution recommendations.

2 Literature Review

The port terminals' operation efficiency is managed from key operational performance indicators such as arrival rate, waiting time, service time, turn-round time, tonnage per ship hour in port, number of gangs employed per ship per shift with less focus on the energy performance, and efficiency management. Energy efficiency has emerged as a key point in the port industry because of different factors such as the increasing electricity costs as most terminals are dependent on electricity as a core source of supply for operations. The adoption of stronger environmental regulations and the increasing pressure of the local governments or municipalities bylaw and community on the surrounding ports impose a new challenge to the port terminal environment with regards the energy management.

Electricity supply systems are under severe pressure because of increasing power demand and aging coal power plants in South Africa. An alternative source of energy is the solution not only to respond to the demand but also for the environmental commitments that are to reduce the heat-trapping gases such as Sulphur Dioxide (SO_2), Nitrogen Oxides (NOx), and Carbon Dioxide (CO_2) that are contributing to the emissions.

CO2, NOx, and SO2 are substantial pollutants in our air and a direct result of coal power plants. It is also one of the causes of some serious health problems such as lung cancer, asthma, emphysema, and bronchitis. As a result, thousands of people are tragically hospitalized or die each year. It is seriously toxic to human health. These gases originate primarily from fossil fuel combustion at power plants, coal power plants, and even cars and mobile equipment. Simulation is done on the ozone air pollution over the eastern United States by using a downscaled climate model linked to a regional air pollution model results for the 2020s, 2050s, and 2080s indicates an increase in Ozone (O3) concentration increase by 2.7, 4.2, and 5.0 ppb respectively [7].

2.1 Energy Efficiency in Port Terminals

The port industry is an energy-intensive sector, generating negative externalities and environmental impacts in several areas. This necessitates the adoption of an innovative green strategy. The energy cost is one of the biggest costs for the port terminal industry. The theoretical models and qualitative methods for investigating energy consumption in the port terminals are still underdeveloped.

The world's total energy consumption was regulated by mandatory energy-efficiency standards around 2014 [8]. The focus was on significant industries. These standards mostly address industries that strongly impact energy consumption. The ISO 50001 known as energy management system standards encourage organizations to establish systems and processes to gradually improve energy efficiency and measure energy consumption.

Not all ports are ready to embrace the implementation of ISO 50001. Only a limited number of ports have been certified with the ISO 50001, these Hamburg Port Authority in Germany, Port of Antwerp in Belgium, Port of Felix Towe in the UK, Port of Arica in Chile, Baltic Container Terminal in Poland, and Noatum Container Terminal Valencia in Spain. These ports have achieved this goal mostly because they have corporate policies and energy management plans to enlist goals and establish frameworks for energy efficiency [9]. A port energy management plan should cover energy consumption analysis, energy mapping, and energy efficiency considerations [10].

2.1.1 KPIs

A study of the energy management of the Port of Rotterdam indicates that there are still gaps in the calculation of energy consumption and selection of the energy management KPIs. A collaborative effort to calculate the effective energy consumption KPIs from the 43 terminals located in the several ports demonstrates the following results below in Table 2-1 [11]. The samples concessionaires were collected from different port operations such as general cargo multipurpose and container, dry bulk, and liquid bulk terminals. The energy efficiency is measured using the tonnage as a driver. The electrical consumption is monitored per commodity per tonnage moved. The port’s standard energy consumption KPI indicates that about 2.53 kWh of electricity is used to move a tonnage in the container terminal. For the dry bulk and liquid bulk, it would be 2.44 kWh/ Ton and 4.21kWh/ Ton respectively. About 1.91 kWh is used to move a tonnage in the Multipurpose Terminals.

Table 2-1 Port Energy Consumption: Standard KPI **(Source 2020-IAME -Energy Consumption in ports-Satta et al)*

Terminal Category	Sample	Relevant KPIs	KPIs Equivalent Electricity Consumption
	No. of sample concessionaires	Electrical Consumption	kWh/Ton-eqv
General Cargo - Multipurpose	5	1,01	1,91
General Cargo Container	4	3,27	2,53
Dry bulk terminal	5	4,07	2,44
Liquid bulk terminal	7	6,73	4,21

Many ports and terminals endeavor to enhance energy efficiency as energy prices have increased drastically through the years. Port operation is heavily dependent on energy. Added to the energy security are the climate change challenges facing the port industry resulting in stricter environmental regulations adoption by authorities to limit pollutants and GHG emissions arising from energy consumption. Increasingly, port operational strategies and energy usage patterns are under scrutiny [9].

2.1.2 Port Operating Strategies

The port operational strategies (e.g. peak shaving, operations optimization), technology usage (e.g. electrification of equipment, cold-ironing, energy storage systems), and energy management systems (e.g. smart grid with renewable energy) for improving the energy efficiency and environmental performance of ports and terminals analysis is not conclusive. Research gaps and future research directions are identified. Analysis shows that there is a great potential for ports to achieve further energy efficiency and researchers have many impactful research opportunities.

The research for the energy demand of international shipping including seaport sanctions that the increasing energy demand results in higher energy costs, pollutants, and GHG emissions. Energy costs are the significant overhead for ports and terminals and reducing these costs might bring valuable cost reductions [12].

It is concluded from the research that emission reduction is a direct consequence of the energy efficiency, electrification of equipment, the use of alternative fuels, and renewable energy sources. It is evident that these aspects, along with operational efficiency, will largely contribute to the next generation port concept. The energy efficiency cannot be separated from the day-to-day port operation, there is a positive correlation between port operational efficiency and port energy efficiency. It is evident that increasing the entire port operational efficiency of resources would reduce the energy consumption, and thus enhance the energy efficiency [13].

Most energy management research for energy efficiency in ports and terminals is still in progress. Even though there are more than a hundred and forty (140) journals studies completed which include technical reports by ports, press releases by companies, the energy management for the port operation is not conclusive. The composition of these studies shows that the port operations and energy efficiency methodology analysis is a work in progress [14].

2.1.3 Port Energy Management

As an energy management system consists of management planning, initial supply planning, and smart energy management the port must establish an energy management strategy. The energy management strategy covers all sources of energy requirements for the port not only the traditional energy demand sauces [5].

Port operators are acknowledging that energy supply cannot only be from fossil fuels, but it can also include clean fuel including renewable sources. It is interesting to also note an increasing number of pots around the world adopting renewable energy sources. Some of these ports are working on KPI for smart and sustainable ports [15] [16] [9].

The German maritime sector emphasizes the importance of renewable energy, especially onshore wind energy, solar energy, and geothermal energy, for German ports [17]. There is more apatite globally to introduce alternative sources of energy. Ports such as Hamburg Port installed more than 20 wind turbines with a capacity of above 25 MW and installation of few more new turbines.

There is also a focus on PV solar technology. Hamburg Port has also covered warehouse rooftops with PVs and expects an electric generation capacity of more than 500 MWh per year [18]. Ports are reassessing their sources of supply and diverting to other renewable sources such as tidal power generation, wave energy, geothermal energy and all these are subject to investigation for ports.

Implementing an energy management system to corroborate the efficacy of energy management strategy is crucial. A comparative analysis is performed to assess the impacts of different system and design parameters on the optimal solution [19].

Energy Management principles first need to be applied to existing infrastructure (operations/or buildings) before the consideration of renewable technologies for energy efficiency gains and/or reductions in operational energy costs such as the PV solar technology. It is also known that Energy Management principles cost less to implement, improve overall energy usage across the organization, lead to a lower carbon footprint, and reduce operational costs through the efficient use of energy. These principles serve to introduce an energy efficiency mindset that is indispensable for any organization wishing to become a leader in energy-efficient processes. The very same principle forms the basis of the preparation work of the port energy management.

2.1.4 Levelized Cost of Energy (LCOE)

The energy cost must be understood and benchmarked to reach a common conclusion. LCOE is used to assess the energy generation costs of energy technologies. This method has been mainly used for electricity generation costs. Energy cost cannot be disconnected from the day-to-day energy management cost hence the need to use the LCOE approach. The purpose of the LCOE method is to compare and benchmark energy technologies across scale, geography, and type to find the lifetime energy supply costs. Cost evaluation for the proposed wind, PV solar, BESS, and a diesel generator is crucial in determining an energy supply solution [20].

The LCOE method has been used for numerous purposes of cost evaluation for the alternative sources of energy such as for photovoltaic solar energy and electrical energy storage [21] [22], wind energy, and for hybrid systems similar to this research that combine PV, batteries, and cogeneration [23] [24] [25]. LCOE costs are useful for purposes such as determining costs of generating energy since developers use this information during electricity sales negotiations to ensure that the price, they receive exceeds the price of generation. The derived model enables a quick comparison of combined PV and storage power plants with other forms of energy generation, for example, diesel generation. This could prove helpful in the current discussion about diesel substitution especially in South Africa since the standby generator supply seems to be the favored alternative source of supply in off-grid applications. In general, the combined Levelized cost of energy lies between the LCOE of PV and LCOE of storage.

As per cost analysis done by the RE institutions and in particular, the International Renewable Energy Agency the renewable energy costs continue to fall and renewable power generation is increasingly becoming the default source of least-cost new power generation this includes developing countries like South Africa. Renewable power generation technologies are not just competing head-to-head with fossil fuel options such as coal without financial support, but increasingly undercutting them, in many cases by a substantial margin [26].

2.2 Hybrid Renewable Electrical Energy System

There are different sources of greenhouse gas but the Fossil-Fuel-based electricity generation is one of the largest sources of greenhouse gas emissions [27]. This coupled with the increasing electricity demand has motivated the need to integrate a vast amount of renewable energy such as wind and solar with the electric grid. The focus to reduce the emission footprint has increased globally. In developed European countries the authority has mandated that by the next decade, which is about 2030, wind energy should contribute to 20% of the electric power consumption. This runs aggressively with renewable energy integration targets that have been set across the world for different forms of renewable energy.

The research is done in the South African port environment. The focus is on the Management of Energy and Integration of Renewable Energies. In the past, electricity was easily available and as a result, most of the distribution networks were designed to operate in a circular configuration with a single source. With all the environmental requirements and energy security issues, traditional energy sources are limited. The thinking around the world supports the distributed generation that incorporates alternative energy sources, which are renewable energy [28]. The combination of different alternative energy technologies is a solution that does not only address the grid complexity but also environmental issues. There is no doubt that not all technologies are suitable for the environment.

Renewable energy has a variety of technology, such as fuel cells, wind turbines, photovoltaic (PV), small hydro and wave energy [29] that requires power quality monitoring. Some technologies like induction generators can be directly connected to the grid. Microgrids can help with the integration and management of Distributed Energy Resources (DERs) [30] [31]. Microgrids offer the advantages of onsite generation, which include reduced distribution loss, improved power quality, and reliability [31].

The requirement for energy storage exists since some of the energy is available at specific times of the day [32]. As much as there is free access to natural energy from the different technologies, there are challenges such as the power quality [33] issues and with the divest port equipment this is something worth a thorough analysis. Some of these technologies require conversions from Alternative Current (AC) and Direct Current (DC) or vice versa due to starting transients and the power converters are required for interfacing with the grid.

2.2.1 PV Solar Technology

South Africa is ranked as one of the world's most energy-intensive nations. Electricity supply is a constraint, energy costs are rising sharply, liquid fuels are subject to exchange rate risks, and both electricity and liquid fuels carry a high environmental cost. The breakdown of energy consumption in South Africa for 2017 is shown below in Figure 2-1.

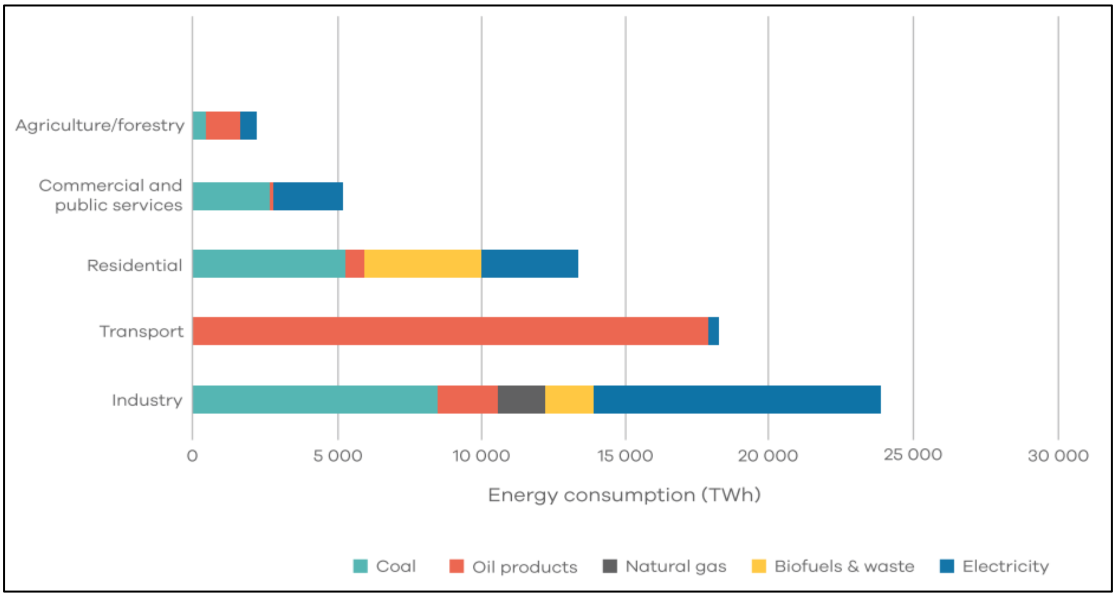


Figure 2-1 - 2017 Energy consumption in South Africa (TWh) [34]

The effects of climate change are being felt across the globe. The levels of carbon dioxide in the air are at their highest peak in all of Earth's known history. Since 1880 global temperature has risen by 1.7˚C with nine of the ten warmest years in the past century being recorded after the year 2000. The burning of fossil fuels for energy is one of the leading factors of humankind's impact on climate change.

Renewable energy sources, on the other hand, make use of available energy from nature and space around us. The sun, for example, is a rotating thermonuclear furnace, 1.4 million kilometres wide in diameter that fuses hydrogen atoms into helium. The result of that fusion is approximately 3.8×1020 MW of energy that radiates outward into space from its surface. The average irradiation that reaches the outer edge of the Earth's atmosphere, 149.6 million kilometres away from the sun, is 1367±2 W/m2.

Due to the tilted elliptic shape of the Earth and the rotation about its axis, the amount of irradiation as indicated in figure 2-2 below and the angles at which it arrives on the Earth's surface varies at different locations globally. South Africa's location on the planet provides ample opportunity for solar energy harvesting with most areas averaging more than 2,500 hours of sunshine annually and on average solar radiation levels ranging between 4.2 and 6.5 kWh/m2 within a single day.

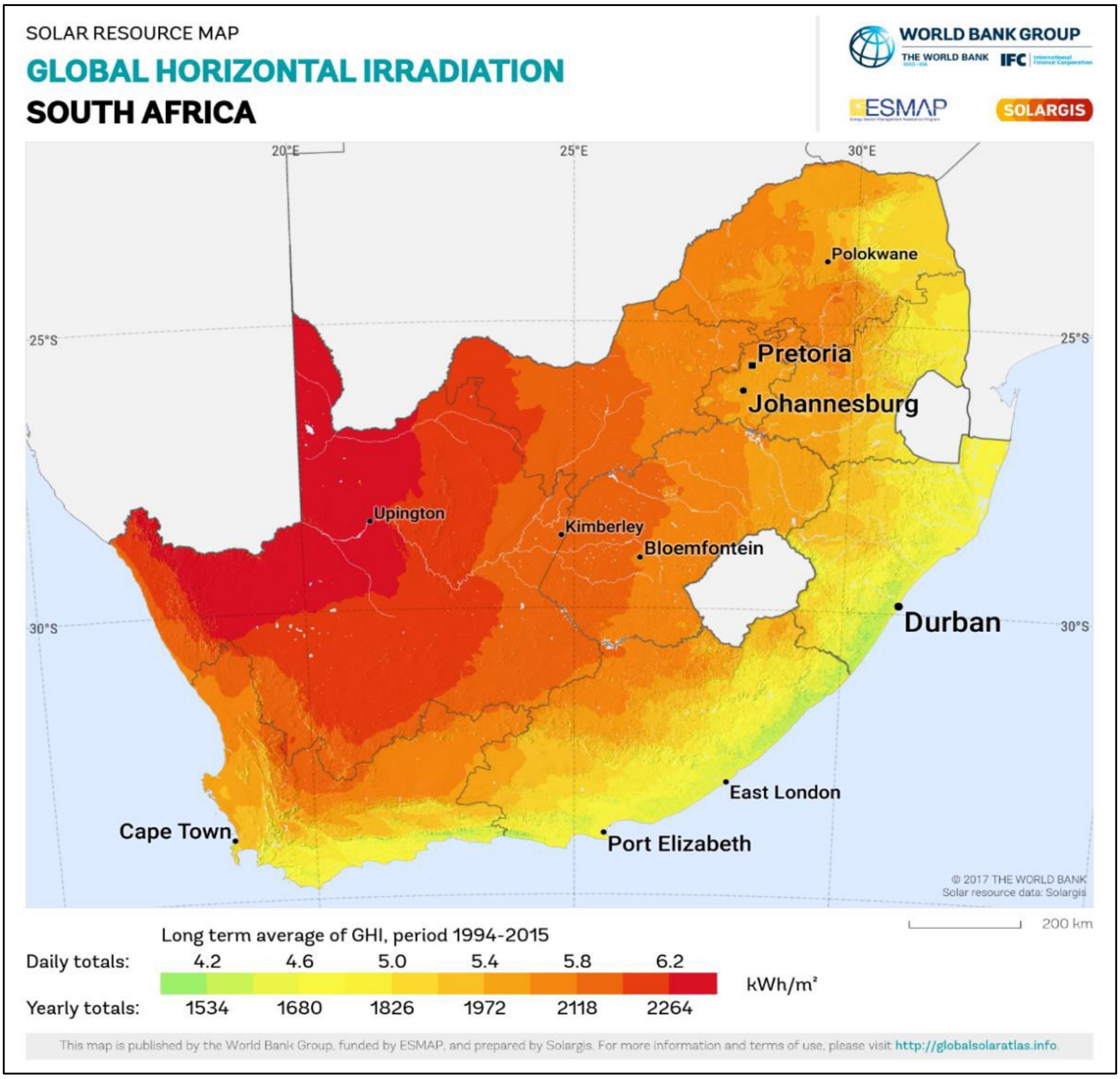


Figure 2-2 - Solar Irradiation Resource Map of South Africa. [35] **

**Source: Global Solar Atlas 2.0, Solar resource data: Solargis, The World Bank

Global Horizontal Irradiation/Irradiance (GHI) is the sum of direct and diffuse radiation received on a horizontal plane. GHI is reference radiation for the comparison of climatic zones. It is an essential parameter for the calculation of radiation on a tilted plane. This GHI is the methodology used in the research to determine the viability of the PV Solar in the Durban area. The sun's path across the sky varies with the seasons. In summer, the sun rises in the south-east and sets in the south-west whilst traveling higher and further across the sky. As illustrated in Figures 2-3, during winter, the sun's path is lower and shorter with the sun rising in the northeast and setting in the northwest direction. In autumn and spring equinox occurs where the sun rises due east and sets due west. In the Southern Hemisphere, it is, therefore, optimal to face solar harvesting panels north.

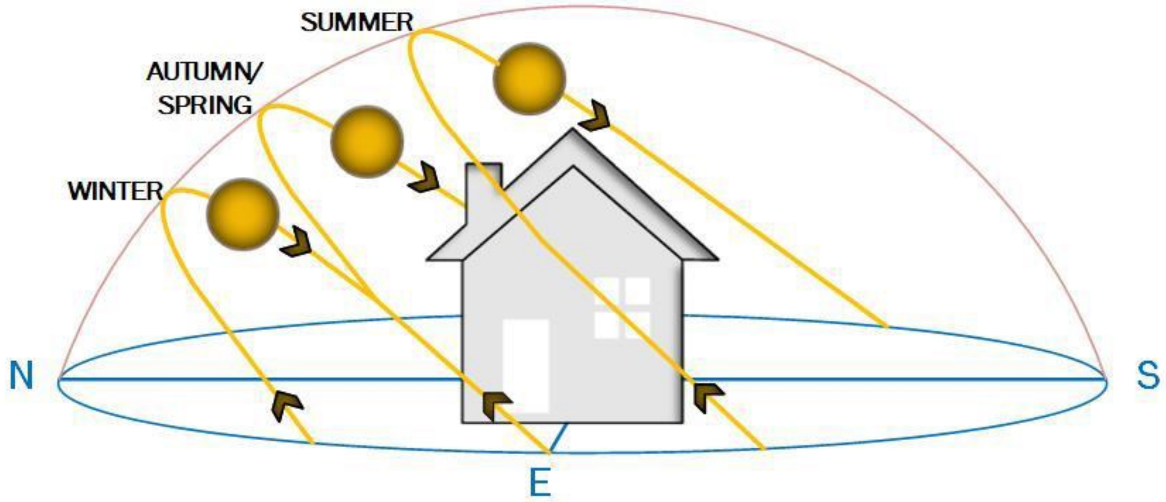


Figure 2-3 - Seasonal sun paths in the Southern Hemisphere.

A basic understanding of solar geometry is important to have to be able to plan and execute a PV solar project. The research proposes consideration of the alternative source of energy that includes the PV solar and we can appreciate the information from the illustrative diagrams both figure 2-3 and 2-4 that the sun path and PV solar panels and surface tilt position against the position of the sun are important in harvesting the maximum solar radiation levels.

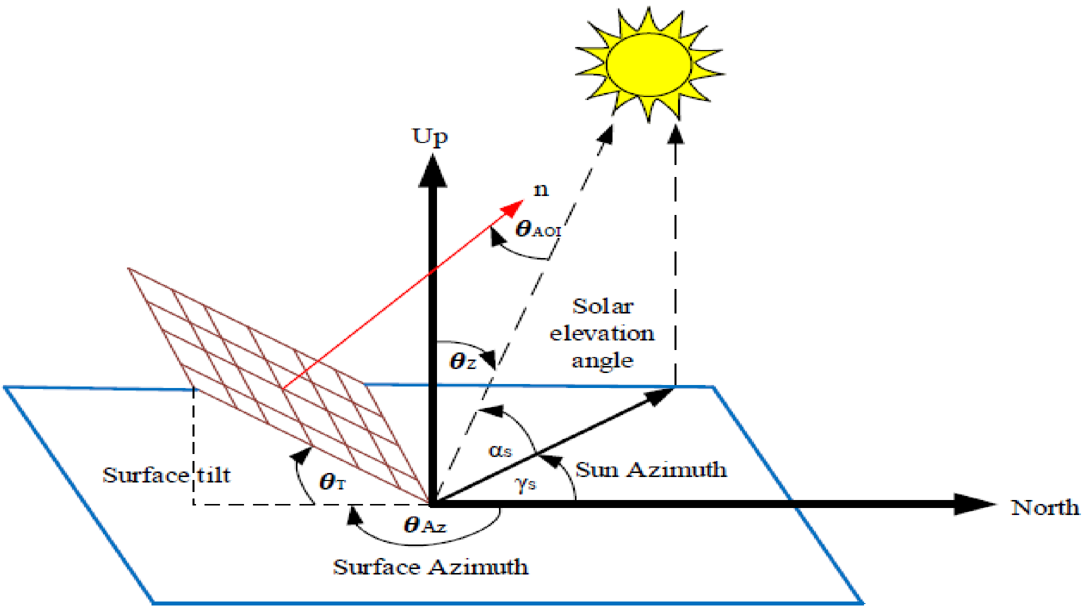


Figure 2-4 - Solar geometry and positioning. [36]

Instead of only considering official regulatory standards for PV installations in South Africa, this research incorporates local and international best practices, where applicable, to provide an overview approach of the Solar PV implementation. As outlined by the Grid Connection Code for Renewable Power Plants (RPPs) in table 3-2 connected to the electricity transmission system in South Africa [13], the following categories shall be used to determine the PV plant category and various sizes, as defined by the installed capacity at the point of connection.

Table 2-2 - Categories of Renewable Power Plants as defined by the Grid Code

Plant Size	Category
0 - 1 MVA	A
0 < 13.8 kVA	A1
13.8 kVA < 100 kVA	A2
100kVA < 1MVA	A3
1 MVA ≤ 20 MVA	B
≥ 20 MVA	C

Compliance with this and other codes requirements depends on the interaction between the RPP and the grid to which it is connected. The Grid Connection Code [13], as approved by the National Energy Regulator of South Africa (NERESA), is an accompaniment that is required to be adhered to where required.

As above-mentioned the grid-tied system where the solar panels of the PV plant are connected in parallel to the Grid through a grid-tied inverter (GTI) is recommended for this research. The inverter must be NRS - 097 certified to be selected as a suitable choice for this type of installation.

2.2.2 Wind Turbine Generation

The economics of wind turbine generation in this research crucially depend on the wind resource at the site. Detailed and reliable information about the speed, strength, direction, and frequency of the wind resource has been captured and is shared in the next chapters. This information is vital when considering the installation of a wind turbine energy generation and is a critical factor to the success of the installation.

We must understand the purpose of a wind turbine in connection with the other power sources. The purpose of the wind turbine is directly connected to how much energy it is supposed to generate. The options that exist in wind turbine generators are between the electricity generated for commercial usage and electricity generated for private usage. Turbines for private and commercial usage can be off-grid or on-grid. When a hybrid system is taken under consideration, it can be used with a connection to a grid and other power resources [37].

Most wind turbine manufacturers state in their sales catalogue how much a specific wind turbine can generate. According to the size classes of the turbines, there are five different sizes, with five different rated power ranges.

- Micro: 0 – 10 kW
- Small: 11 – 100 kW
- Medium: 101 kW – 1 MW
- Large: 1 MW – 10 MW
- Ultra-large: 10 MW and more

2.2.2.1 *Wind Turbine Power Connection*

The size of the turbine can be used to determine its usage. Small to medium size can both be used in applications where a power grid is needed and where it is not, because they can be for private and commercial usage. When considering the usage for the private use, the electricity varies from 100kW up to commercializing electricity up to 1MW

Hybrid systems are intended to assist harvest more energy can also be used with medium-sized wind turbines. In most applications where large-sized turbines have been used the applications are usually where a power grid is needed because the electricity is being sold, so it needs to be connected to the power grid. The common challenge with all renewables is the storage of your harvested energy. The capital cost of the technology sometimes is unaffordable when the intended purpose is not clearly defined. It is crucial the understanding of the requirements and including the kW demand is concluded with the understanding of the pros and cons of the energy storage system. One of the main advantages of a turbine connected to a grid is that there is no storage problem [38].

2.2.2.2 *Turbine Sizes*

The sizes available as abovementioned can be classified in line with the outputs. Wind turbines can be classified into five categories according to their capacities [38] :

An ultra-large wind turbine is a turbine that has a capacity of more than 10 MW, and these are feasible when consider being commercial usage [38].

Large wind turbine: these types of turbines are commonly known as megawatt wind turbines because of the power ratings from 1 MW up to 10 MW. This turbine size has become the popular and main preferred wind turbine in the market, especially off-shore wind farms [38].

Medium-sized wind turbine: because of the output kW this has been the most common type. The power ratings of the medium size turbine are from 100 kW to 1 MW. This type can be used on both on-grid and off-grid systems for urban, rural, hybrid systems, distributed power, wind power plants, and obviously, energy storage is always an option depending on the solution recommended. This can be used for private and commercial setups.

Small wind turbine: have rated power of less than 100 kW. They can be best for private usage [39]. These type turbines can be perfect for the following setup,

Micro wind turbines; are small in size but their contributions are required. Their rated power is less than 10 kilowatts.

Based on the size the low cut-in speed turbine can operate at moderate wind speed and can therefore be installed in most areas around the world [38]

It is crucial to understand whether the wind turbine is for private use or commercial use before deciding on size. [40]

2.2.3 Distributed Generations (DGs)

The integration of DGs would minimize the loading effect of the transmission line, and therefore reducing of power losses. However, on the other hand, the integration of DGs raises other concerns such as system stability and maintenance. It is essential that the effect of distributed generation on energy losses for different penetration levels are established [41] [42] [43]. With the growing penetration of renewable distributed generations in distribution systems, the effective integration of DGs has become a major concern [44].

There are challenges linked to power conversion from DC converted to AC power of desired voltage and frequency. There are voltage and frequency fluctuation problems of micro-grid in the standalone and grid-connected operations [45]. Due to the volumes of wind, there may be grid congestion or a weak grid. Some of the technical issues are to look at the very high level of power stability as the systems are from time to time subjected to disturbances [46] and [47]. Large-scale energy storage system in the power system has been widely used. Different types of energy storage are considered for the RES, superconducting magnetic energy storage, supercapacitors energy storage, energy storage, and other energy storage technology to ascertain the status, maturity, and application [46].

As the energy security improves with the introduction of the RES, this introduces a need for optimum utilization of the variable speed wind turbines and improvement of grid-connected wind sources power fluctuation [48]. These are power quality issues associated with distributed generation technologies. Grid connection brings other additions such as the voltage fluctuations and harmonic distortion [48] and [49]

2.2.4 Battery Energy Storage System

The operation in the port involves energy management of different equipment. The number of Renewable Energy Sources (RES) Integrated into DG from solutions using a combination of wind and solar technologies will require a Battery Energy Storage System (BESS). Rising electricity prices and risks associated with the port energy demand driven by the port throughput there is a need to develop alternative means of the energy storage system. BESS is one of the most attractive systems because of its high reliability, efficiency, and low pollution [50].

BESS can play a key role in increasing capacity at the port and improving the reliability of electricity distribution. In this context, BESS can be a reliable storage source to manage and share efficiently the DER. Among the different BESS technologies, lithium-ion (Li-ion) is considered one of the reliable and affordable technology to its favourable characteristics in terms of energy conversion efficiency, energy and power density, and lifetime. It is important to understand the economic feasibility of the application of Li-ion batteries in support of DG. In the next chapter, this perspective is confirmed by evaluating the total cost of ownership (TCO) under different Cases. Furthermore, the application of BESS in support of DG from RES and load shift maximizes the intended benefits and return on investment.

The BESS does have limitations that encompass relevant aspects of the systems such as charge and discharge efficiency of batteries or efficiency of the power conversion system, the self-discharge of the storage system, the influence of depth of discharge on the lifetime of the batteries. The next chapter presents a holistic total cost of ownership of BESS.

There are several kinds of batteries to be considered for the port operation. The following are currently being used in the industry,

- lead-acid battery,
- Ni-MH battery,
- Ni-Cd battery, and
- Li-ion battery

There are several advantages associated with the BESS such as high power density, greenhouse gas reduction, high working cell voltage, peak demand shift, high power density, and reliable grid supply [51]. Even though there are benefits with regards, the BESS there are also limitations. The capacity of the battery is a fundamental challenge for battery useful life. The state of charge (SOC) of a battery, which is used to describe its remaining capacity, is a very important parameter for a control strategy [52]. The battery performance was calculated taking into consideration the SOC. The SOC is an important parameter and if accurately estimated it can not only protect the battery, but can also prevent over-discharge, and improve the battery lifespan [53].

The limitation is that the chemical cannot be directly accessed and as a result, the SOC estimation remains a complex exercise [54]. As seen from the list above, there are limited battery models to select from; the parametric uncertainties, poor accuracy, and reliability of SOC can contribute to a poor battery [55]. Accurate estimation of the SOC is not only an important parameter of a battery on the performance but can also protect and prevent the battery overcharge or discharge and improve the battery life span resulting in positive environmental contributions.

2.2.5 Environmental Issues

Not all challenges are technical and require complicated engineering solutions some are not technical but have severe sustainability and environmental consequences if ignored and can reduce the performance of the technology and the return on investment may not be realized. Some of the non-technical issues include the following;

(a) Wind speed resulting to weak or congested Grid [56], [57] and [58]
(b) Climate change issues [59]
(c) Challenges resulting from the 4^{th} industrial revolution developments.
(d) Reduction of Green House Gases (GHG).

(e) The global energy balance highlights the energy flows into the atmosphere. This demonstrates how the climate system as a whole maintains its energy balance. Similarly, individual components of the climate system such as the ocean, atmosphere or land maintain an energy balance otherwise these systems would either heat or cool over the cycle of one year. [59]

2.3 Software and Algorithms for Energy Analysis and Optimization

The research presents distributed generation solutions that require simulation and algorithms tools to analyze and optimize the energy solution. Some of the software tools available and used to analyze energy and energy systems are listed below.

2.3.1 Matlab/Simulink

The Matlab/Simulink is a known software available in the market used for modeling energy and other solutions. Simulink is a block diagram environment for multi-domain simulation and Model-Based Design. It supports system-level design, simulation, automatic code generation, and continuous test and verification of embedded systems. Simulink provides a graphical editor, customizable block libraries, and solvers for modeling and simulating dynamic systems. Integrated with MATLAB it enables the incorporation of MATLAB algorithms into models and export simulation results to MATLAB for further analysis [60]

2.3.2 Hybrid Energy Systems Toolkit

Hybrid Energy System Models presents a few techniques to model a large variety of hybrid energy systems in all aspects of sizing, design, operation, economic dispatch, optimization, and control [61]. To do this, the user introduces a search space of possible components, including diesel generators, wind turbines, solar photovoltaic installations, and battery storage along with technical and economic inputs for each element.

The tool is Microsoft Excel-based. This Microsoft Excel-based workbook simulates operation for each possible configuration of the system that results from the search space of components introduced by the user. Some of the parameters and information that can be presented by this system are hourly time series generated for electric demand, solar radiation, and wind speed based on data introduced by the user. [62]

2.3.3 HOMER Pro / HOMER Grid

The software is used as a platform to analyze real-time dynamic data. Critical decision variables like the size of the PV array, number of wind turbines, size of the battery storage system, size of converters, dispatch strategy and size of generators are given due weight in the optimization process using data from NASA's meteorological department and local data manually loaded. The uncertainties of weather conditions, renewable energy resources like hourly wind speeds, a lifetime of PV array, hourly data sets of load or renewable resources, cost analysis have been given due care in obtaining the sensitivity analysis, which is an added advantage of using HOMER. The aim of analyzing the energy performance and providing the distributed generation as a clean energy source at the port demonstrates our environmental commitment to reduce greenhouse gasses.

HOMER Grid is a tool that can help outline different options for reducing a site's electricity bill. It compares the costs and savings for installing different combinations of batteries, solar panels, and generators. HOMER Grid uses a powerful optimization to find the system that maximizes your savings. It allows the input of hourly power consumption profile and matches renewable energy generation to the required load. It is used to analyze the distributed generation grid potential, peak renewables penetration, ratio of renewable sources to total energy, and grid stability. A decision to invest in technology is based on several factors but mainly based on the cost and benefits of the solution as a result a large number of technology options and the variation in technology costs and availability of energy resources make project design decisions difficult. The HOMER simulation tool optimization and sensitivity analysis algorithms make it easier to evaluate the many possible system configurations [63] and options available. HOMER has a comprehensive optimizing function that is useful in determining the cost of various energy project Cases. This functionality allows for the minimization of cost and optimization of case-based on the technology selected and other various factors [64]. These inputs provided, which describe technology options, component costs, and resource availability is used to simulate different system configurations or combinations of components and generate results that can be viewed as a list of feasible configurations sorted by net present cost, the total available energy, and depending on the configurations maintenance costs.

HOMER Grid also displays simulation results in a wide variety of detailed tables and graphs that combine the different technologies to provide a Case that can be used to compare configurations and evaluate them on their economic and technical merits. The use of the different load Cases as proved in the next section below can also be used to determine the Levelized cost of electricity (LCOE) [65] considering the integration of the proposed technology, that is the wind, solar energy, battery storage, and standby diesel-fuelled generator set.

A Homer model system consisting of a wind turbine, PV system, diesel ac generator, battery, and converter system was investigated using different load profiles. The cash flow summary results demonstrate that an increased load profile leads to more capital, operating, replacement, increase fuel, and a salvage value of the project for the wind turbine, PV, diesel and rate battery systems. However, the converter system was found to be independent of the load profiles. HOMER software is flexible, user-friendly, and more generic in terms of control strategies compared to other simulation tools. [66].

2.3.4 DER Cam

The Distributed Energy Resources Customer Adoption Model (DER-CAM) Software Solution is known to be a set of three associated software modules. Like other simulation tools, these entail a server-based optimization engine, which contains an optimization algorithm and the supporting mathematical solvers, known to be a user interface (UI), and a server application that permits users to remotely access the optimization engine. DER-CAM is an efficient optimization engine with additional elements for enabling generalized access.

The DER Cam is a decision support tool designed to analyze investment solutions of distributed energy resources (DER) for use by individual buildings and microgrids. It supports a wide variety of DER technologies. It can be used to study both grid-connected and remote, off-grid microgrids, based on either AC or DC infrastructure [67].

The DER Cam tool was used for a case study in the Austrian Campus building. About 35 employees and about 600 students are based at that Campus building [68].

2.3.5 iHOGA

The iHOGA (improved Hybrid Optimization by Genetic Algorithms) is one of the software reviewed. iHOGA is a software developed by one of the universities in Spain for the simulation and optimization of Hybrid Stand-alone Systems of Electric Power Generation based on Renewable Energies. iHOGA can simulate and optimize systems of any size. It can also simulate and optimize distributed generated systems connected to the AC grid. It has the capability to define different cases of Net Metering.

Despite iHOGA having the above advantages, the main disadvantage of iHOGA software other than it not being as user-friendly as HOMER is that it takes a longer time to simulate. This is most cases is when the genetic algorithm is considered either as primary algorithm or secondary algorithm or both. Despite iHOGA having the above advantages, the main disadvantage of iHOGA software other than it not being as user-friendly as HOMER is that it takes a longer time to simulate when Genetic Algorithm is considered either as Primary Algorithm or Secondary Algorithm or both. The iHOGA packages have been used to size HRES for the Aralvaimozhi community. The analysis of the results provides an opportunity to compare and comment on the facilities provided by these two software packages. The iHOGA software has not been much explored like HOMER software. [66]

2.3.6 OpenDSS-G

OpenDSS (Open Distribution System Simulator) is a power distribution system simulator. This software has been released by EPRI (Electrical Power Research Institute). It is one of the frequently used simulation engines with many characteristics found in other commercial simulation tools, as well as many additional features aimed at supporting ongoing research efforts on distribution system simulation. Some of the built-in solution abilities include harmonics and time-mode power flow, snapshot, fault current study, probabilistic, parametric, and dynamics studies [69].

This tool can be used for planning and analysis of multi-phase distribution systems, analysis of distributed generation interconnection, annual simulations, storage modeling, and analysis. OpenDSS was designed to receive instructions via scripts, allowing greater flexibility to the user. With regards, the communication protocol the program can be accessed through a stand-alone executable version and the COM interface. It provides a text scripting interface, which allows complete interaction with the program [70]. OpenDSS can be linked to other software platforms (e.g. MATLAB) using the COM interface [71]. This tool has been developed to advance the capabilities of EPRI's Open Source Distribution System Simulator OpenDSS to guide the industry on the distribution power system analysis tools and techniques [72].

2.3.7 DigSilent

DigSilent has 25 years of history, set standards and trends in power system modeling, analysis, and simulation. Like most simulation tools there are proven advantages of the software tool these are the overall functional integration, its applicability to the modeling of generation, transmission, distribution, and industrial grids including the analysis of the grids' interactions [73]. The tool is equipped with various electric component models, convenience for the research and study of power systems with a distributed generation [74].

2.3.8 OPEN

The OPEN (Open Platform for Energy Networks) tool is an open-source software platform for integrated modeling, control, and simulation of smart local energy systems. OPEN offers an extensible platform for developing and testing energy system management applications. The intent is to bridge the gap between academic research and industry. OPEN is used to combine multi-phase distribution network power flow, energy market modeling, nonlinear energy storage modeling, and receding horizon Optimization for providing a solution [75]. The tool is designed to easily integrate with third-party packages. The development of OPEN has also been motivated by gaps identified with existing energy management tools and the importance of DERs. The latest version of OPEN is available to anyone for download [76] since it is open-source.

2.3.9 Optimization Algorithms

In the optimization algorithms of the research, the objective is simply to minimize the cost of production, maximize the efficiency of the production of energy. An optimization algorithm is a procedure, which is executed iteratively by comparing to provide various solutions until an optimum, or satisfactory solution is found. There are several different algorithms from the commonly known genetic algorithms and particle swarm optimization algorithms available for optimization [77].

There Homer optimization algorithms are proposed in some of the research work to refine the hybrid electrical power network to supply a single residence's electrical load located in Coimbatore, Tamilnadu. The load shape of the household is considered by the pattern of energy usage used and supplied for different electrical uses by the PV, Wind, and Diesel Generator (DG) set similar to our research work. The simulation and optimization of the scheme are carried out by the Hybrid Optimization System for Electric Renewable (HOMER) model from the National Renewable Energy Laboratory (NREL). The various analyses were discussed like Net Present Value (NPV), Energy Expense, Energy Output, Usage, Excess Energy generated by individual components of the system, and the pollution produced [78].

3 Energy Analysis of the Port Terminal

This chapter covers detailed information on various loads in the port, identifies the energy requirements, looks at the loading on the system. It also covers the available environment measurements at the port and analyses the wind speeds. An overview of the port electrical layout, energy analysis, and equipment used in the port is discussed in detail. It covers into detail climate challenges and required weather conditions for the port operation to confirm the viability of the renewable sources of supply. In South Africa, Electricity regulations administer all developments in this space and can sometimes be viewed as a hindrance to new distributed generation developments and other new technologies. detailed discussion on the South African electricity regulations and licensing requirements for renewable technologies is included.

3.1 Energy Requirement for the Port

Due to the increasing aggregate demands of electrical power for new developments and upgrades to existing facilities around the port and industrial area, the existing security of supply is under threat, with system strengthening and enhancements required for the same. The present bulk supply voltage of 33 kV down to 11kV by the Local Municipality is not sustainable. The load flow indicates that the future load required in the port of Durban exceeds the current available capacity. The load is modelled using inputs from existing loads and the future capital infrastructure development projects. The current and future loads were summated and superimposed on the existing Port profile using all large additional electrical loads as listed for current and future projects in the Port of Durban.

The primary sources of energy in the port are electricity and diesel fuel with the remainder constituting distillate fuel oil, petrol, and other sources for cooking and welding. The electricity is mainly used for operations equipment such as ship to shore cranes, rail gantry cranes, area lighting, buildings, and other auxiliary services. Figure 3-1 below depicts the port primary energy sources layout. The diesel fuel energy is mainly for mobile operations equipment such as the straddle carrier, reefer supply via a standby generator set, rubber tyre gantry (RTG), front-end loader, forklift, and other operations equipment.

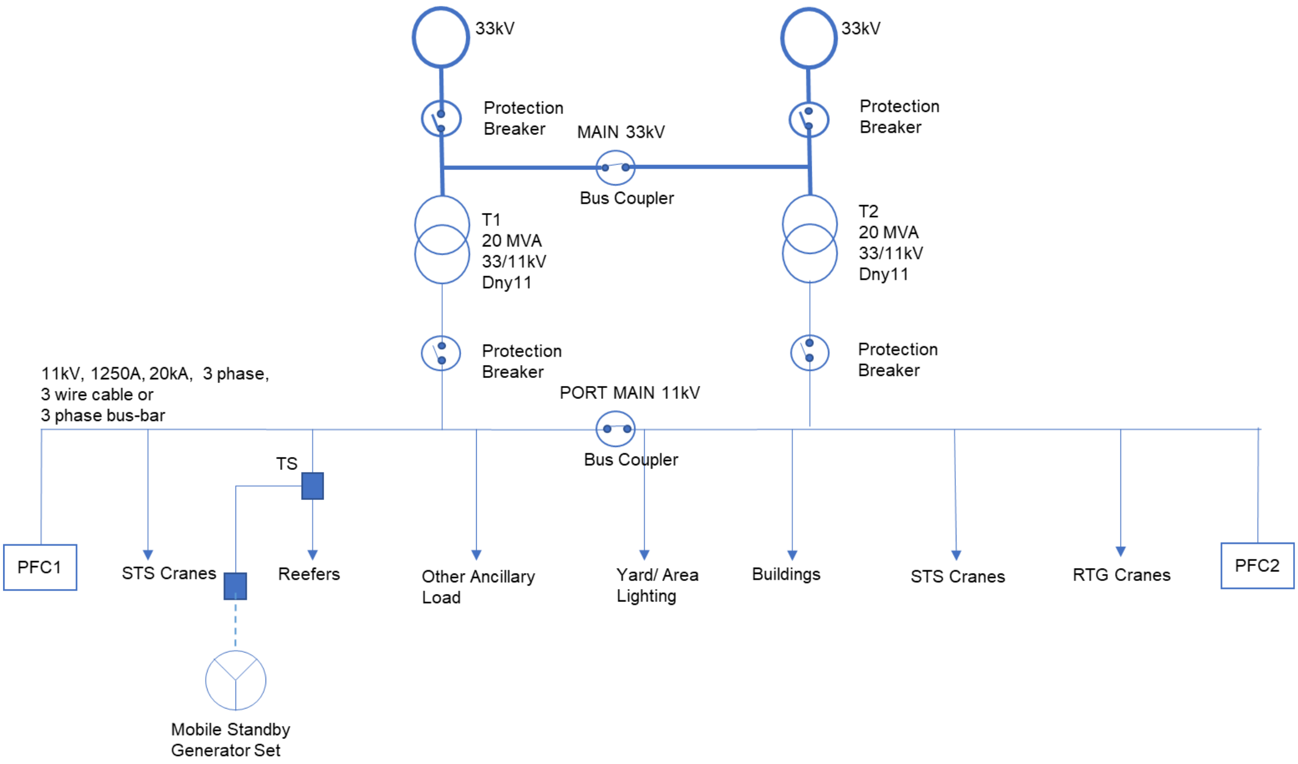


Figure 3-1 Existing Electrical Schematic

As shown in figure 3-1 above the port is fed from a 33 kV main via a firm 20 MVA 33/11 kV connection. The port operations bulk supply feed from 33/11kV stepdown transformer. The load for each type of equipment is as follows,

PFC: The system has a power factor correction unit that requires some upgrades. The system reading is averaging at about 0.76 PF. This is a concern since the result indicates that this is not close to the unit. The DG can improve power factor but this is out of the scope of this study.

STS Canes: The Ship to Shore (STS) cranes are fed directly from the 11kV feed. The demand is exceeding the available capacity and the cranes are the significant energy user. The cranes contribute close to 55% of the total energy load. These cranes have the capability to regenerate. The crane's average consumption is between 175 000 kWh to 250 000 kWh and the electrical supply is the only source of energy. Alternative sources of energy are considered to address the issue.

RTG / RMU

Crane: Rail Tyre Gantry (RTG) cranes is the dual-supplied crane. It is designed to feed on either electricity or diesel source. Similar to the STS Crane, regenerative energy is available from the Rail Mounted Gantry (RMG) and Rubber Tyre Gantry (TRG), Cranes, and other mobile equipment. The energy is recovered using a regenerative brake energy recovery mechanism when breaking and hosting. This technology converts the kinetic energy into a form that can be either used immediately or stored until needed. From the estimate of practically reusable regen energy, it is evident that one could practically save about 30% engine output energy when implementing a regen energy recovery unit (Regen ERU) for the RTG, further details on the estimated regenerative capabilities are part of the information included in this chapter. The regenerative calculations are included below but the simulation does not include the regenerative of the RTG. The potential for embedded generation and regeneration depends on the usage of the crane. Through the regenerative converters, the energy from the generative braking system injects back to the plant grid the power generated during the braking phase of all crane movements. This is during every downward or decelerated motion, instead of being dissipated by resistors.

As long as the crane is in use, regenerative energy is available. The only limitation is that of the weather, it is dependent on the wind speed. When the wind speed reaches 90km/h operations stop. The results from the captured weather data below confirm the wind issue to be a low risk as the highest average wind speed is captured to be about 57 km/h. These crane regenerative capability results are significant to the conclusion of this research and are included in the solution recommendation chapter.

Reefers: The reefer contributes about 23% to the total terminal demand during the reefer season. The calculated undiversified rated power is about 9.2 MVA for the reefer demand. About 2 MVA of the total reefer demand is catered for by the introduction of a mobile standby generator set. The modeling and simulation results provide a solution on how the reefers should be powered without a need to hire additional standby capacity.

Yard and Area Lighting: Yard lighting is used at night-time for operations. The energy would be drawn from the grid or BESS. There is no way to change the operation of this to reduce energy costs. Although the total demand from the area lighting might look insignificant, it contributes to the port energy demand. Lighting takes about 8% of the total energy cost in the port. A possibility of feeding area lighting from renewable resources via the battery energy storage system.

Buildings: The port has a mixture of buildings used for administrative or operations purposes. The load profiles of the admin buildings seem to present a similar demand partner in line with the different seasons of the year. Part of the mixture includes sheds, mess and ablution facilities, and canteens or dining areas. The building's consumptions average between 46000 kWh to 76000kWh over 24 hours depending on the time of the year and operations demand.

As shown in figure 3-1 above, in terms of standard equipment ratings of large power transformers as well to allow for a reserve margin for future growth has resulted in a need for the ports power supply to be increased.

In summary, the diversified power requirements for the port comprises the following,

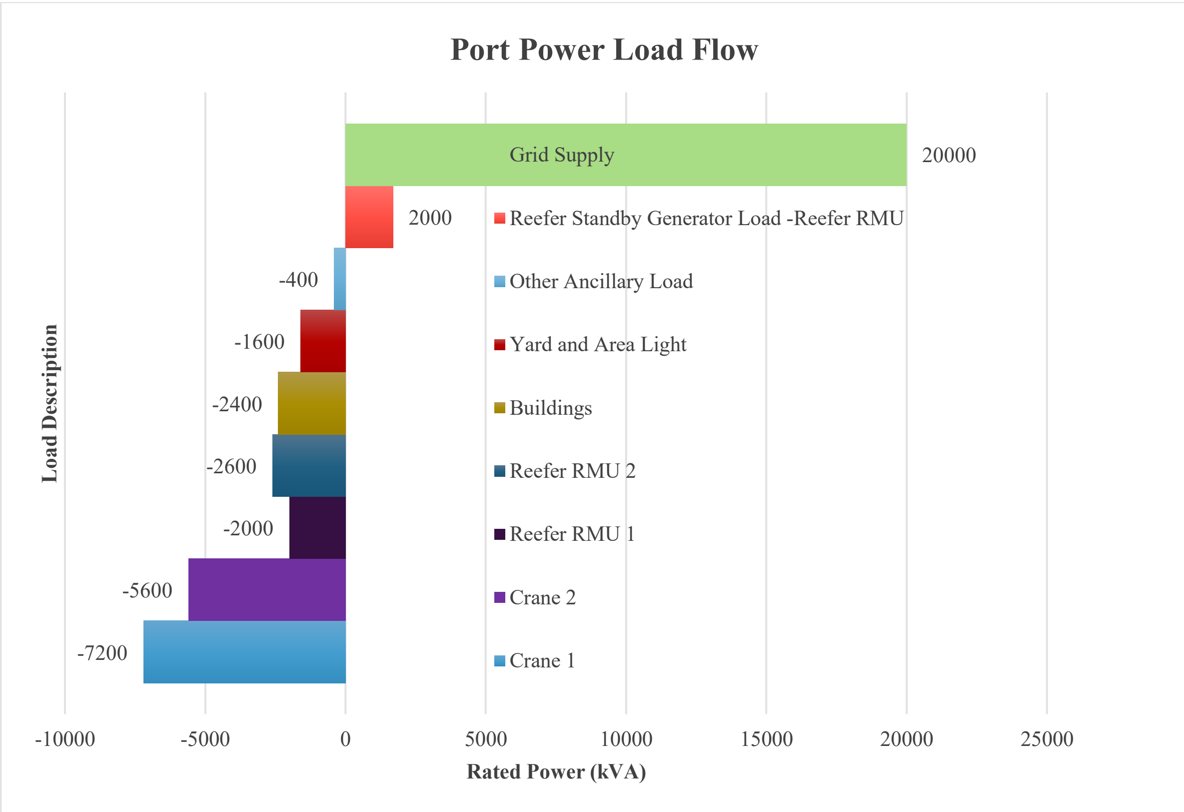


Figure 3-2 - Port Diversified Power

The above figure 3-2 demonstrates the increasing energy demand because of operations requirements. Operations requirements are the key driver of the energy demand and as indicated above the power demand is very close to exceeding the available supply. The following is a need,

- Added source of energy is required to substitute the 2 MVA standby generator dependency during the reefer session
- Alternative sources of energy are required for the cranes operations to deliver on the port KPIs throughput.
- When the port is operating at full capacity, energy efficiency is not considered rather the port operations KPIs such as the ship working hours, the turnaround time to service a vessel seem to be the key drivers of operations. This necessitates a need to look at alternative sources of energy to compensate for the electrical supply high demand and improve port energy management performance.

3.1.1 Crane Load and Performance

The research does not focus on the cranes' energy performance in-depth but the crane operations load is relevant and crucial information for the determination of the renewable's integration methodology. The purpose of the crane load study is to show that the cranes are in constant use, the demand varies based on the operations requirements, time, and the shift per day. The emphasis on this crane study is also to highlight the loading, the possible regenerative capability, and energy available for integration, and this can be considered in further research work. Cranes contribute about 55% of the total energy costs. The graphs below demonstrate the crane's performance for the different operational needs. The study done on the RTG is also applicable to the STS cranes. The technology is more or less the same where energy is regenerated during the hoist and traction times.

The information portrayed in the next Figures 3-3 to 3-6 were collected from the South African port for 12 months. Six cranes were identified, typical performance of each crane was monitored on an hourly basis. The moves are done by each crane, that is the TEU (Twenty-foot Equivalent Unit) container moved are used to analyze and understand the port operation efficiency. This is also a driver of energy usage. These data were collected per shift from each crane and it was measured per hour. This is accurate data as it is used to confirm several TEU containers each crane moved for operational performance and billing purposes.

The following Figures 3-3 to Figure 3-6 show the following,

- The crane's usage per hour for the entire daily operations.
- It can be seen that when considering all the cranes per month, it appears that there is a constant load drawn by the cranes.
- Typical month setup of freight movement and the cranes hourly percentage usage.
- Possibility of introducing the regenerative technology

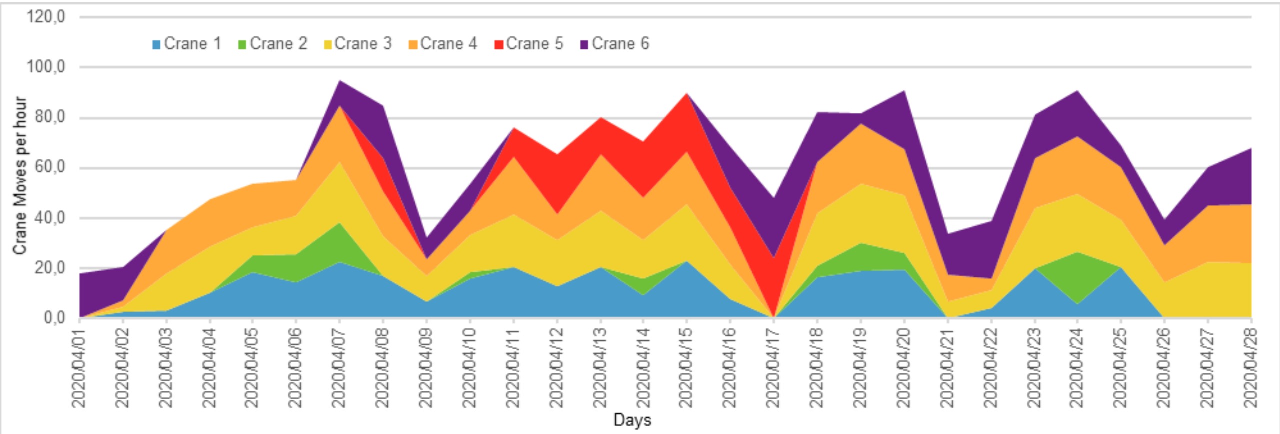


Figure 3-3 Crane 1 to 6 - Monthly Operation Usage

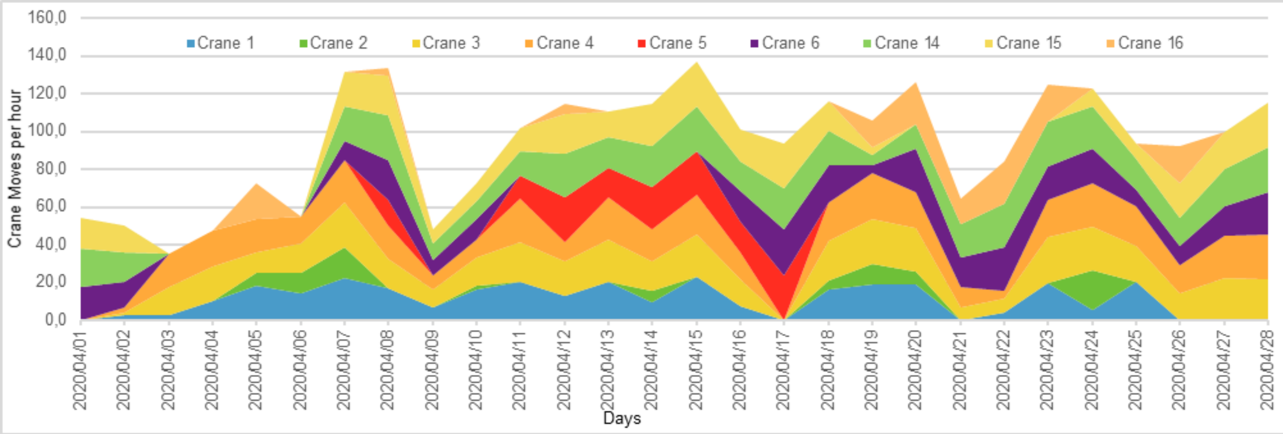


Figure 3-4 Crane 1 to 6, 14 to16 - Monthly Operation Usage

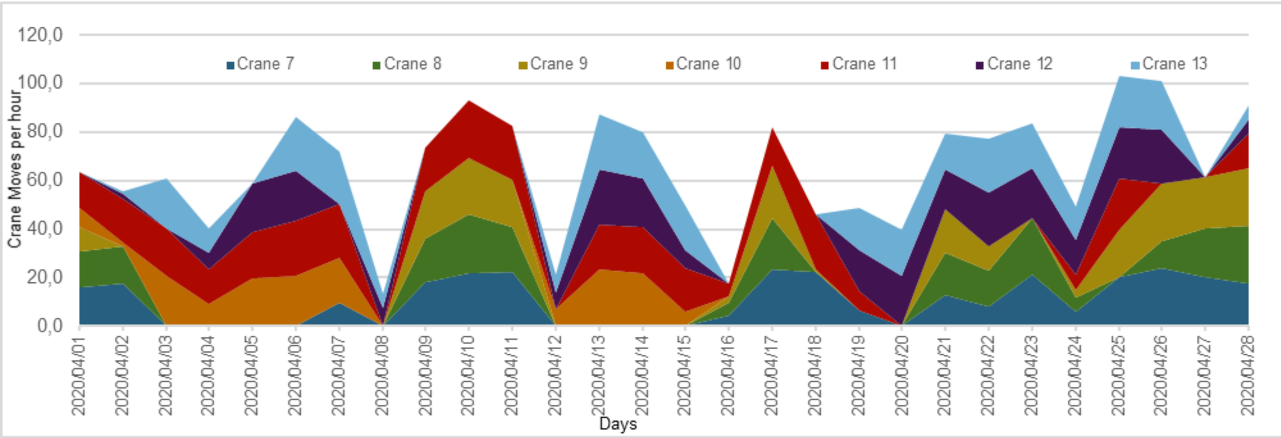


Figure 3-5 Crane 7 to 13 - Monthly Operation Usage

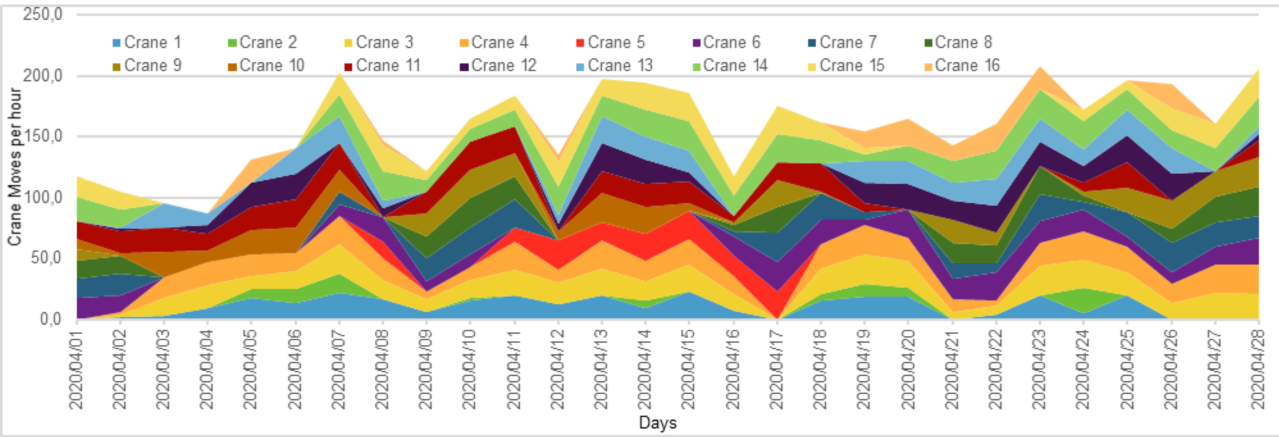


Figure 3-6 Crane 1 to16 - Monthly Operation Usage

3.1.2 Cranes, RUG and RTG – Regenerative Energy

The regenerative capability assessment is done as a standalone calculation exercise to showcase the possibilities of energy savings that exist in the port. Power Data Loggers that satisfy the international best practice monitoring requirements such as NEC Code 220.87 were used to collate information from the different pieces of equipment for a duration between three and twelve months. Power measurements included the KVA, kW, and kVAr. Since the Power Data Loggers were installed on live operational equipment energy usage was also captured, kWh, etc. The calculations below focus on the regenerative energy available from the Rail Mounted Gantry (RMG), Rubber Tyre Gantry (TRG), Cranes, and other mobile equipment. The energy is recovered using a regenerative brake energy recovery mechanism when breaking and hosting. This technology converts the kinetic energy into a form that can be either used immediately or stored until needed. Consideration of regenerative technology in future studies will not only address the energy capacity concern in the port but will also contribute to the improved energy performance efficiency.

The calculations below demonstrate some of the available regenerative capabilities from the different cranes. This can be conducted as a separate study to further improve the energy security issues, unlock available energy capacity for future development. The calculated results are included in the concluding chapter to demonstrate all available solutions for the port.

For this type of application, the following points/comments are noteworthy in line with Table 3-1 and Figure 3-8 (a)-(d):

(a) Understanding the loads on the RTG auxiliaries better and looking into affordable COTS (Commercial-Off-the-Shelf) ways of lowering the baseload (e.g. LED lighting for night shift) is recommended. From the energy analysis and in particular the RTG cranes in this instance, it appears that there is a noticeable 4 kW change in auxiliary load from night operation to daily operation, indicating some very power-hungry lighting that is utilized. This is for safety, but perhaps one could investigate more efficient lighting to reduce the baseload. It currently accounts for >12% of the engine output energy consumption, and a lot of this is at a low engine load.

(b) From the estimate of basically reusable regen energy, it is evident that one could practically save about 33% engine output energy when implementing a regen energy recovery unit (Regen ERU) for the RTG.

- Total energy recovery potential is 80% * 130.87kWh * 24h / 17.615h duty = 142.65 kWh/day (or 42.1 L/day that can be saved). Assuming 350 workdays per year, the fuel saved in a year would be 14,735 L or R 176,820 saved per RTG per year.

(c) Implementing a control scheme after implementation of ERU to maximize the effect of regen on fuel consumption may be feasible. This control algorithm takes energy from the higher efficiency part of the engine operation and places that energy at the lower efficiency loads of the engines. Most engines have about half the conversion efficiency when loading the engine under 10% of the rated load.

An auto stop/start of the engine (Auto Engine Stop/Start) is one way to further unlock energy capacity. AESS systems monitor the main engine parameters (oil temperature, coolant temperature, etc.) and shut down the engine when not loaded and all engine parameters are within specified limits. This can save a huge amount of energy. From the auxiliary energy pie chart, one can see that 40% of the energy during duty was used when no major movements were performed on the RTG. This means that the engine was running at a fixed rpm (which is another inefficiency) of 1800 rpm to produce 60Hz output.

- This means that about 80% *40.6% or 32.5% of the idling auxiliary energy can also be saved by simply being in control of the RTG engine. Comparing this to total engine output energy, this is a >11 % reduction in engine output energy. This is not even considering the low fuel efficiency of the engine at low loads, which would lead to higher g/kWh values on the engine.

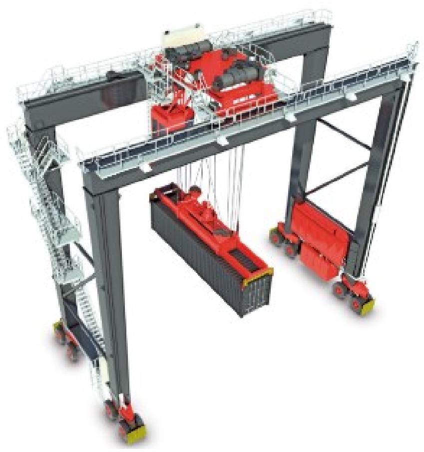
Table 3-2 RTG Crane Consumption Breakdown Table

Consumed Energy Breakdown (Source: Generator Set)			
Total Generator Set Energy provided (Alt output)	320.67	kWh	100.00%
Hoist/Traction drive (drive output)	182.35	kWh	56.87%
Auxiliaries (inverter output)	115.35	kWh	35.97%
Trolley/Traction Drive (drive output)	23.466	kWh	7.32%
Brake Energy Breakdown (Source: Regen)			
Energy burnt in resistor grids (calculated)	132.94	kWh	100.00%
Hoist/Traction Drive (drive, motor side)	118.22	kWh	88.93%
Trolley/Traction Drive (drive, motor side)	14.721	kWh	11.07%
Regen Potential - Generator Set base (Comparison to Generator Set energy)			
Maximum regen recovery (all available energy)	132.94	kWh	41.46%
Practical regen storage and reuse (utility factor 80%)	106.36	kWh	33.17%
Auxiliary Energy - Generator Set base (Implementation of auto stop/start)			
Auxiliaries during idling	46.815	kWh	14.60%
Auxiliaries during working time	68.533	kWh	21.37%
Potential savings (util. factor 80%)	37.452	kWh	11.68%
Auxiliary energy after savings	77.896	kWh	24.29%
Estimated Lighting and Heating energy	41.111	kWh	12.82%
Efficient lighting (40% reduction)	24.667	kWh	7.69%
Lighting + Heating energy savings	16.444	kWh	5.13%
Total Possible Savings (of Generator Set energy)	160.25	kWh	49.97%

Table 3-1 above and Figure 3-8 below show that the potential of the RTGs to reduce fuel (or electricity since the crane has both supply options) consumption by reusing braking energy (regen) is limited to a 32.7% efficiency gain. Looking at the contributing factors towards energy consumption from the Generator Set, it is worthy to note that the auxiliaries have a significant contribution toward total energy consumption. Literally, 36% of the Generator Set output energy is used to power control, air-conditioning, drivers cab, cab heaters, and night working lights. This is due to auxiliary loading being a baseload and continuous over the 17.5-hour duty cycle while other crane activities (hoist, gantry drive) last merely 15-45 seconds with long idle periods in between.

Figure 3-8 Consumable Energy Breakdown (a) Auxiliary Energy (b) Brake Energy Breakdown (c) Regen Potential (d)

3.1.2.1 RTG Regen Schematic



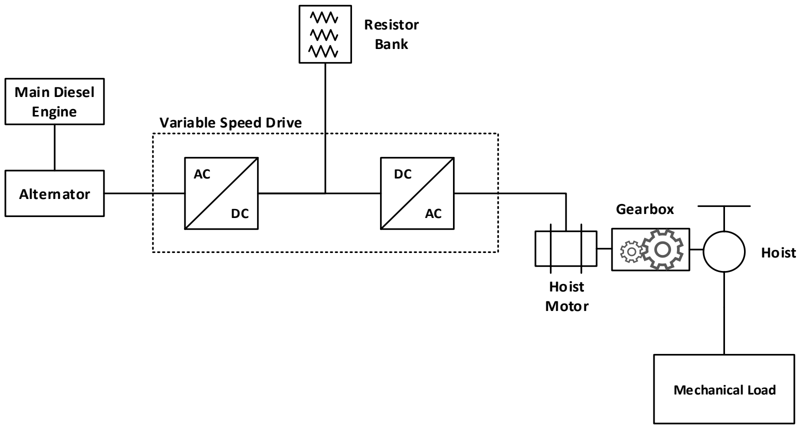


Figure 3-10 Port Environment RTG

Figure 3-9 RTG Schematic

Figures 3-10 demonstrate the port RTG equipment and Figure 3-9 schematic shows the regenerative capabilities available. Detail simulation analysis of this equipment is not included in this research the available capacity is included for the following reasons,

- The port throughput is fixed, as shown in Figure 3-9 the RTG can harvest energy during the hosting
- Figure 3-9 indicates a resister bank since this regenerative is not active, future studies can consider an introduction of BESS for all RTG and cranes feed to harvest the hosting energy
- Introduction of the regenerative technology will improve the port energy efficiency as the key driver for the regenerative energy is operations, the high the operational demand the better is the energy efficiency for the port.

The possible total energy of about 50% can be saved on the RTG engine output energy from a conceptual system point of view. This should be developed much further before this could be used for business case purposes, but it gives a good indication. This energy can be stored through the storage systems proposed.

3.2 Electricity Regulation and Licensing Requirements for the Port Renewable Energy

The introduction of renewable in the Port necessitates a need to obtain a license from the Regulator. The port does not have a license to distribute electricity. Before a preferred option is recommended, we must understand the South African National Energy Regulations in terms of the electricity license requirements.

Section 7(1) of the Electricity Regulation Act No. 4 of 2006 (the Act) states that no person may, without a license issued by the National Energy Regulator of South Africa (the Regulator), a) operate any generation, transmission, or distribution facility, b) import or export any electricity, or c) be involved in trading. There are, however, exceptions to this licensing rule. As per section 7(2) of the Act, certain persons, depending on the scope of their activities, need not apply to the Regulator for a license. [79] Our intention, for now, is to recommend a solution that does not trigger the need to apply for the distributing license.

If the port intends to apply to the Regulator for a license referred to in section 7(1) as indicated above must ensure that the applications contain the certain prescribed information. This information is found in section 10 of the Act. Notably, section 10(g) of the Act requires such an application to contain evidence of compliance with any integrated resource plan (IRP) applicable at that point in time or provide reasons for any deviation from the IRP for the approval of the Minister of Energy (the Minister).

The South African Department of Energy promulgated its first IRP in 2011 [80]. The IRP essentially sets out information on the energy demand level in South Africa, how this demand is to be met and what costs are associated with the means of meeting the demand. The IRP is described as “a South African living plan that is expected to be continuously revised and updated as necessitated by changing circumstances”. At present, the second revision published in March 2011 is the current copy. There has not been an official update to the IRP, but a draft update was published for comment in 2018 by the DoE. Since its promulgation, the IRP has been implemented primarily using Ministerial Determinations that allow for the procurement of energy from new independent power producers (IPP).

As we are recommending producing energy through renewables such as wind, solar, and a combination of battery storage. The Electricity Regulations on New Generation Capacity (the Regulations) define Independent Power Producer (IPP) as any person in which the government or any organ of state does not hold controlling ownership interest (whether direct or indirect), which undertakes or intends to undertake the development of new generation capacity under a determination made by the Minister in terms of section 34(1) of the Act. Section 34(1) of the Act permits the Minister, in consultation with the Regulator, to determine that new generation capacity is needed to ensure the continued uninterrupted supply of electricity. Once this determination is made, IPPs decide whether to participate in the national procurement process. The Regulations give the Minister the power to determine whether the new generation capacity will be established by Eskom, another organ of state, or an IPP. If an IPP is chosen to establish the new generation capacity, the Regulations empower the Minister to determine the identities of the buyers and the procurers of the energy generated.

In this research, our result focuses on the energy generators that do not need a license. The regulation makes provision for the exemption of energy generators. Generators of energy are exempt from the licensing requirements in the following circumstances; however, generators would still be required to register with the Regulator:

(d) those whose generation facilities have an installed capacity of no more than 1 megawatt (MW) who (i) are connected to the national grid, (ii) supply to a single customer, (iii) do not wheel electricity through the national grid, (iv) have entered into a connection and use-of-system agreement with the holder of the relevant distribution license (such as your local municipality) and (v) at the date of entering into such agreement, the Minister has not published a notice stating that the amount of megawatts allocated in the integrated resource plan has been reached;

(e) those whose generation facilities have an installed capacity of no more than 1MW who (i) are connected to the national grid, (ii) operate solely to supply a single customer or related customers, (iii) wheel electricity through the national grid, (iv) have entered into a connection and use-of-system agreement with the holder of the relevant distribution or transmission license and (v) at the date of entering into such agreement, the Minister has not published a notice stating that the amount of megawatts allocated in the integrated resource plan has been reached;

(f) those generation facilities that have an installed capacity of no more than 1MW but, unlike those in points a) and b) above, are not connected to the national grid or have an interconnection agreement if engaged in any of the following activities: (i) operating solely to supply electricity to the owner of the generation facility, (ii) operating solely to supply electricity for consumption by a customer who is related to the generator or owner of the generation facility or (iii) supplying to a customer for consumption on the same property on which the generation facility is located;

(g) those whose generation facilities operate for demonstration purposes only where (i) the electricity produced is not sold, (ii) if connected to the national grid, the generator has entered into a connection and use-of-system agreement with the holder of the relevant distribution or transmission license and (iii) the facility will be in operation for not more than six months;

(h) those whose generation facilities produce electricity from a co-product, by-product, waste product, or residual product of an underlying industrial process where (i) the generation facility is operated solely to supply electricity to the owner of the generation facility in question, (ii) the generation facility is operated solely to supply electricity for consumption by a customer who is related to the generator or owner of the generation facility within the meaning contemplated in section 2 of the Companies Act, 2008 or (iii) the electricity is supplied to a customer for consumption on the same property on which the generation facility is located;

(i) the operation of a generation facility for the sole purpose of providing standby or backup electricity in the event of, and for a duration no longer than, an electricity supply interruption;

(j) the continued operation of an existing generation facility which, immediately prior to the date of commencement of the Schedule, was exempt from the requirement to apply for and hold a license under the Act; and

(k) the continued operation of an existing generation facility which prior to the date of commencement of the Schedule was in operation, and within three months of the commencement of the Schedule had declared non-compliance with the Schedule to the Regulator and signed an agreement to comply within a time frame as specified by the Regulator.

The solution proposed for the port is best to be realized if the option indicate in item c) above is considered. The recommendation is for the energy generated to solely be used for the port operation. However, how the draft IRP update of 2018 might affect the port in terms of the licensing of generators. One notable difference between the IRP currently in force and the draft IRP update of 2018 (Draft IRP Update) is that the latter makes provisions for embedded generation for own use, where facilities have an installed capacity higher than 1MW and not more than 10MW. The Draft IRP Update allocates 200MW per annum for embedded generation for own use of between 1MW and 10MW. The activities that constitute embedded generation for own use are set out in Appendix E of the Draft IRP Update.

Engagement in activities set out in Appendix E of the Draft IRP Update requires an IPP to apply for and hold a license administered by the Regulator. However, until the Draft IRP Update is in force, a would-be generator of this kind would first have to obtain an exemption from the Minister of Energy from the obligation to comply with the IRP currently in force. This is due to, unlike in the Draft IRP Update, there not being any megawatt allocation for generation capacity of embedded generators for own use, hence embedded generation for own use of between 1MW and 10MW still constitutes a deviation from the IRP. Therefore, the acceptance of the Draft IRP Update into law would benefit those engaged in embedded generation for their use of between 1MW and 10MW.

3.3 Durban Port Environmental and Climate Issues

The weather data captured for the Durban area where the ports are is linked with the viability of the integration of renewable sources of energy such as wind and solar technology solutions.

The data collected for this research demonstrates the wind speed averages, wind speed distribution classes, wind turbulence, wind direction distribution, temperature averages, rainfall, rain scale, and wind speed scale. The monitoring of the weather pattern in Durban and Richards Bay coastline area data has been captured as demonstrated in Figures 3-3 to determine the average weather performance. The table below reveals the results of the recorded measurements between 2018 and 2019.

Table 3-3 – Durban Port Weather Conditions

Item	Description	Measurements Results
1	Highest Wind Gust:	117.8 km/h
2	Highest Recorded Average Wind Speed:	56.75 km/h
3	Average Annual Wind Speed:	11.255 km/h
4	Highest Recorded Temperature:	37.8 °C
5	Average Annual Temperature:	14.81°C
6	Lowest Recorded Temperature:	6.1°C
7	Total Annual Rain Fall Days:	120.4 days
8	Total Annual Rain Fall:	828 mm

Wind speed is a fundamental atmospheric quantity caused by air moving from high to low pressure, usually due to temperature changes. It is also defined as the rate at which air flows past a point above the earth's surface. The average annual wind speed in the figures below demonstrates the potential of wind generation technology in the ports along the coastline.

The highest recorded average wind speed in Figures 3-11 is about 57 km/h while the average annual wind speed is recorded to be 12 km/h. The annually average speed seems okay as the typical annual speed in South Africa ranges from 10km/h to 25km/h. Wind turbines can start generating at wind speeds of between 10 km/h to 15 km/h, with nominal wind speeds required for full power operation varying between about

45 km/h and 60 km/h. As suggested by the figures below, the wind speed around the KZN Coastline, Durban Port to be precise is sufficient to generate energy.

The wind speed data captured at the Durban Ports below in Figures 3-11 and figure 3-12 (a) and (b) demonstrates the available energy capacity that can be harvested from the wind turbine. Based on the wind turbine generation curve from the average wind speed of about 12km/h close to 100MWh of energy can be produced annually.

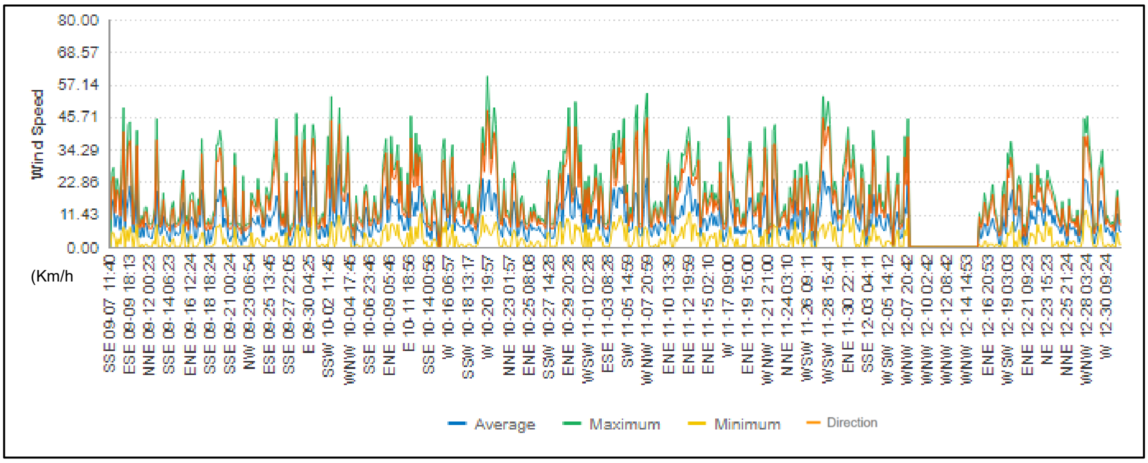


Figure 3-11 - Durban Port Wind Speed (a)

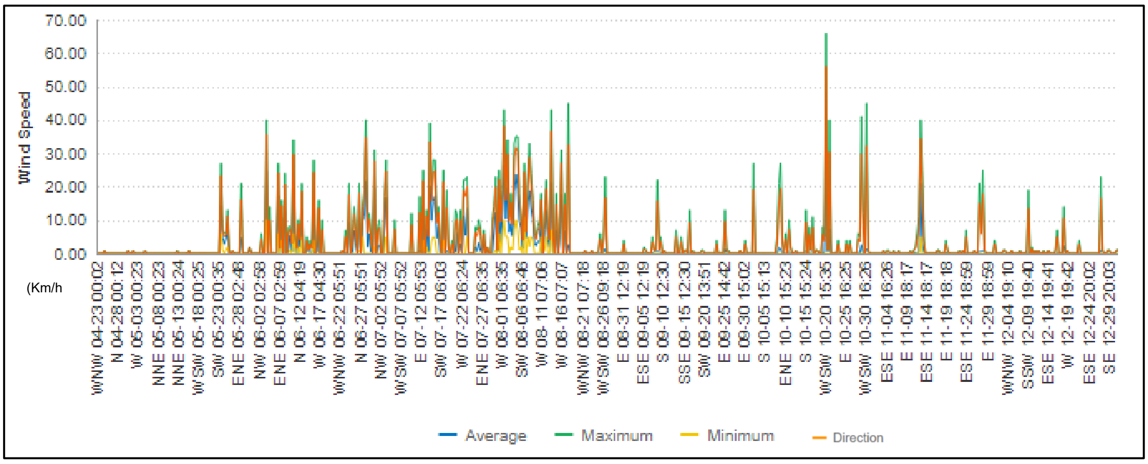


Figure 3-12 - Durban Port Wind Speed (b)

As abovementioned figure 3-12 in most cases, PV solar panels are tested at 25 °C, and thus solar panel temperature is generally viable if it ranges between 15 °C and 35 °C during which solar cells produce at maximum efficiency. The weather captured in the different ports depicts that the temperature is within the recommended ranges for PV solar technology. Figures 3-13 and Figure 3-14 (a) and (b) below display an average temperature through the year of about 15 and a maximum of 39 in the Durban metropolitan and slightly more in the Richards Bay Coastal line area

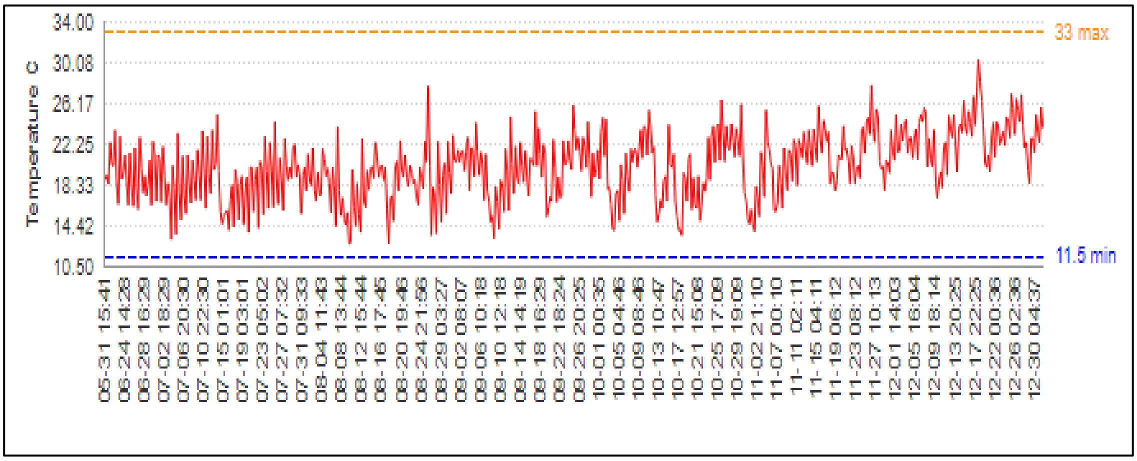


Figure 3-13 - Durban Port Annual Temperature (a)

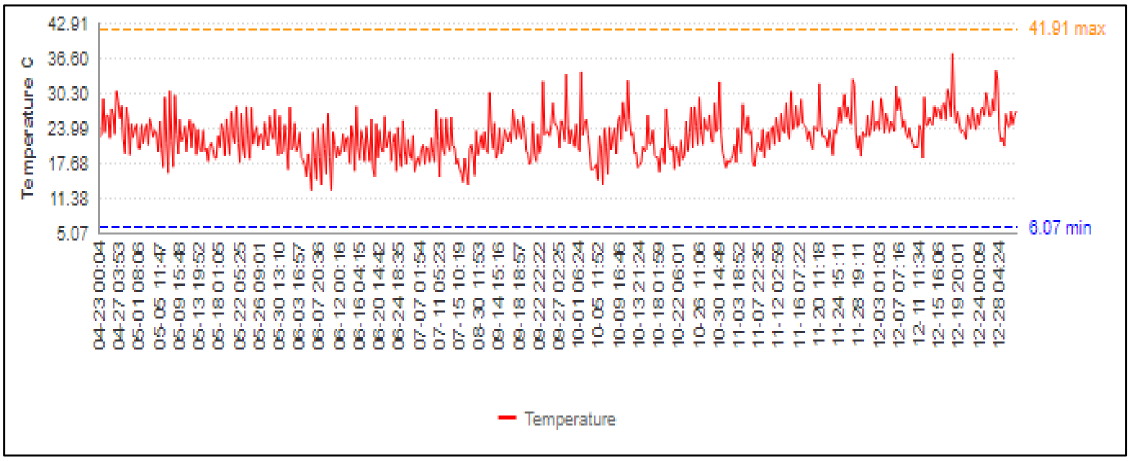


Figure 3-14 - Richards Bay Annual Temperature (b)

Air temperature (also known as dry-bulb temperature) as shown in Figure 3-15 below is the temperature of the ambient air when the measurement device is shielded from radiation and moisture. Air temperature plays a large role in PV system performance as PV modules and inverters are cooled convectively by the surrounding air. While wind speed and air pressure may seem to be unrelated properties of air, they are the same property for all fluids, including air and water. The wind is air pressure converted into the movement of air. When air slows down, its pressure increases. The kinetic energy or momentum of a moving air mass is converted into static atmospheric pressure as the air mass slows down. This means that higher wind speeds will show lower air pressure readings.

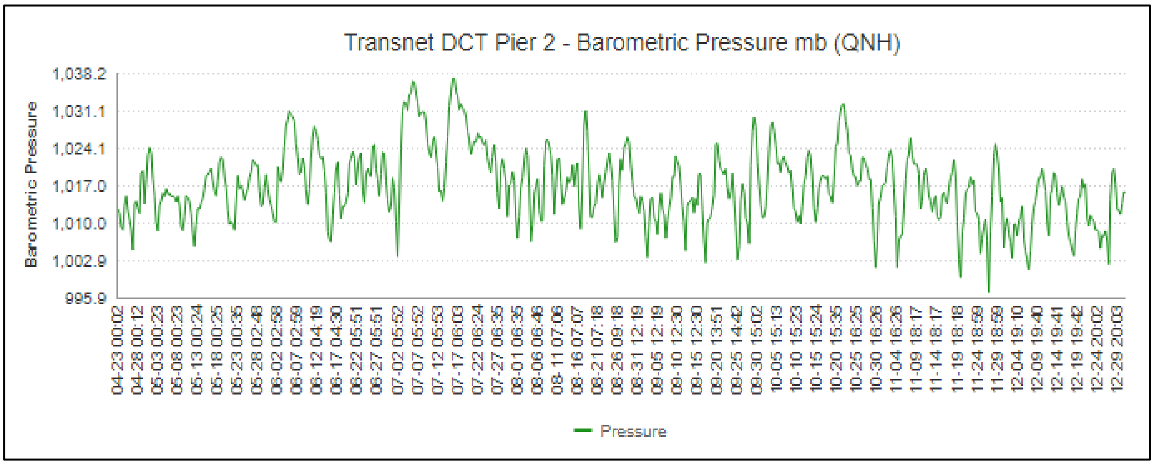


Figure 3-15 - Durban Port Barometric Pressure

Humidity can slow PV Solar efficiency in many ways. Where in average as shown in Figure 3-16 and Figure 3-17 humidity ranges in (40-78 %), resulting in a minimal layer of water vapor at the front solar cell directly facing Sun. The Solar energy which strikes the solar cell is subjected to loss in absorption/reflection of energy. There have been approximate losses of about 15-30% of the energy in addition to 30%

- Tiny water droplets, or water vapor, can collect on solar panels (like beads of sweat) and reflect or refract sunlight away from solar cells.
- This reduces the amount of sunlight hitting them and producing electricity.
- Consistent hot, humid weather can degrade the solar panels themselves over their lifetime.

Solar panel manufacturers are well aware of the effect humidity has on solar panels in humid areas. There are precautions to prevent humidity from deteriorating solar panels faster, such as edge sealants and using low ionic conductive materials.

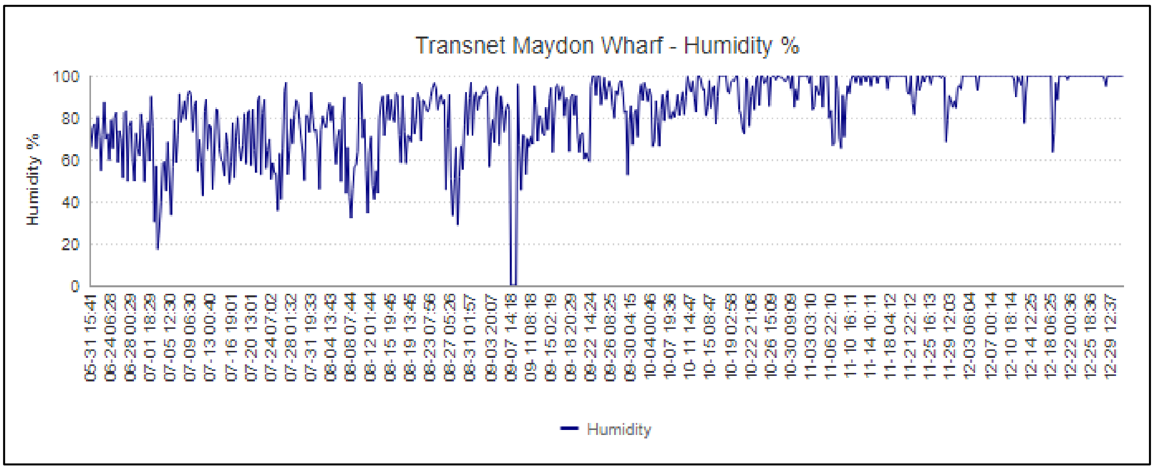


Figure 3-16 - Durban Port Annual Humidity %

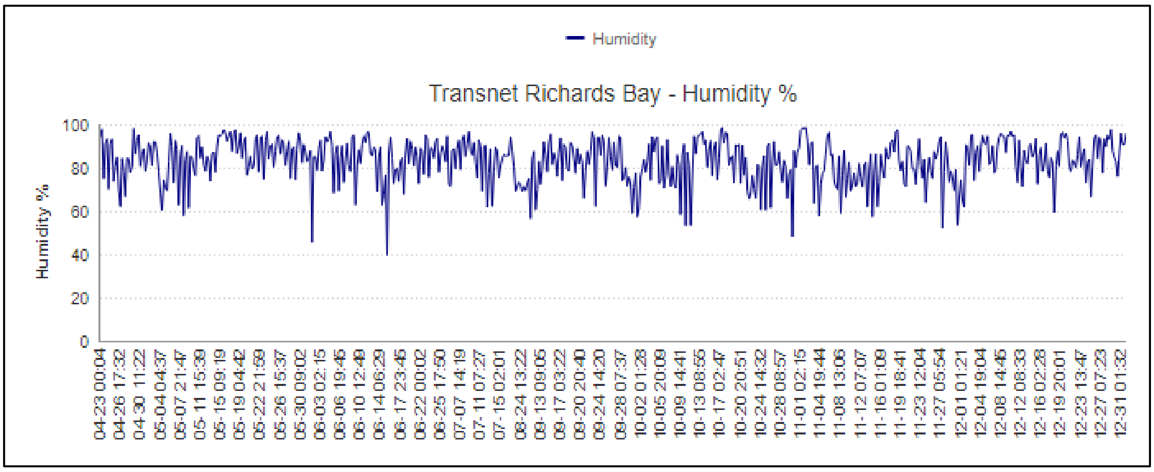


Figure 3-17 - Richard's bay Terminal Humidity %

3.4 WTG Technology

The highest recorded average wind speed in the Durban port is about 57 km/h while the average annual wind speed is recorded to be 12 km/h. Wind turbines can start generating at wind speeds of between 10 km/h to 15 km/h, with nominal wind speeds required for full power operation varying between 45 km/h and 60 km/h. As suggested by the Figures below, the wind speed around the Durban Port is adequate to generate energy.

Figure 3-20 Wind Turbine Generation Curve below demonstrated the meaning of the wind speed against available wind turbine energy capacity. The information is a critical siting criterion since this determines the cost of generating electricity. The change in the wind speed determines the power in the wind. Any increase change in the wind speed, even small can produce large variations in the economic performance of a wind turbine generation.

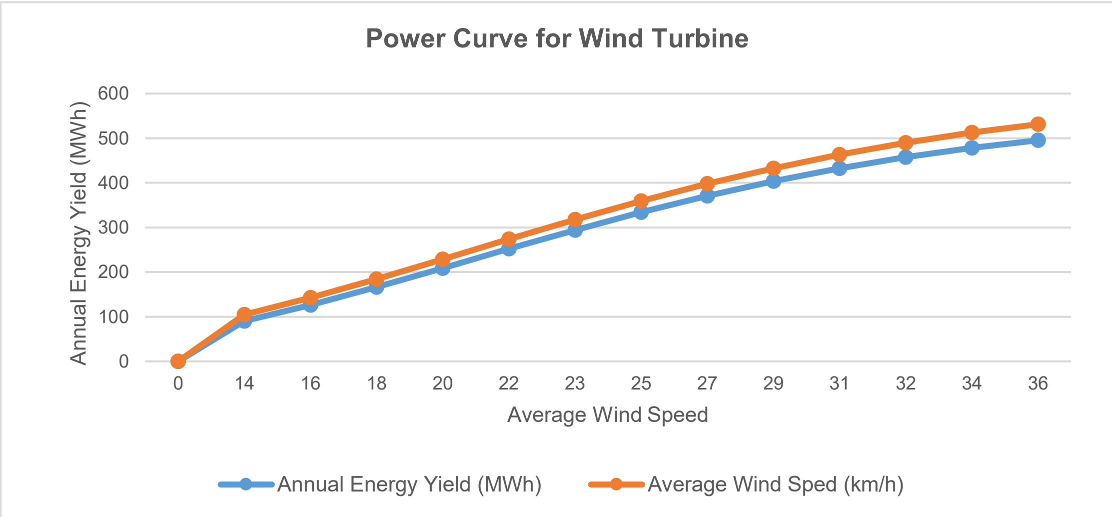


Figure 3-18 Wind Turbine Generation Curve

The results confirm the viability of wind turbine generation. However, there are several factors considered in the Homer simulation to quantify the return on investment such as the surface roughness of the terrain. The power curve graph for the recommended wind turbine demonstrates the available annual energy yielded from the wind starting from as low as 10km/h of the wind speed.

The XANTM-21 100 kW wind turbine rated at 100kW electrical power with a power factor of about 0, 9 (inductive and capacitive) is the suitable and recommended solution. It has a cut-in wind speed is about 11km/h, a cut-out speed of 72km/h, and the survival wind speed is rated at 250 km/h. The severe tornado wind speed is rated between 155 and 205 km/h. The highest wind speed recorded in South Africa is below 190 km/h and for the Durban area, in particular, the proposed wind turbine survives, as the maximum wind speed of about 118 km/h recorded is below the proposed wind turbine survival threshold.

For the port operation, a rotor diameter of about 21 m with 3 blades is recommended. To make sure that safety and control of the system are not compromised, in line with the power regulations the wind turbine is installed complete with a variable speed stall with aeroelastically-tailored blades. The product is a freestanding tower with a total mass of about 7.5 tons complete with a 38 m hub. The anticipate total energy to be harvested from the wind technology is capped at 1MW. Each turbine is slightly different and for the envisaged combined power output of 1MVA, each turbine should be sized accordingly. To harvest the required 1MVA, 13 units are proposed and more simulation results are developed to demonstrate the combined power output in the next chapter.

3.4.1 Energy Analysis

Part of the energy analysis includes understanding the port energy needs in relation to the renewable technology proposed. The correct sizing of the power plant needs to be determined. As detailed in the previous chapters' detailed analysis of the seasonal and daily energy requirements, weather patterns are crucial for the identification of site and PV panels. The needed kW PV solar is 1000kWp.

The analysis confirms that the implementation of renewable energy is behind due to the long return on investment (ROI) horizons that are typical of these types of systems, which is attributed to the larger initial CAPEX outlay and additional lifecycles costs.

As part of the energy analysis exercise, the following parameters were considered, as a minimum, when considering the implementation of a Solar PV plant in the port:

- Annual Energy Consumption
- Energy Time of Use
- Energy Cost
- Solar PV Type

3.4.2 Solar PV Type Selection

The schematic layout in Figures 3-21 below designates the electrical tie-in point for the PV solar plant to be at the Grid. The Solar PV plant must be situated as close as possible to the electrical tie-in point to reduce electrical losses for the overall system, cable, and installation cost. According to the research, a grid-tied PV solar system is the most preferred for the port energy solution.

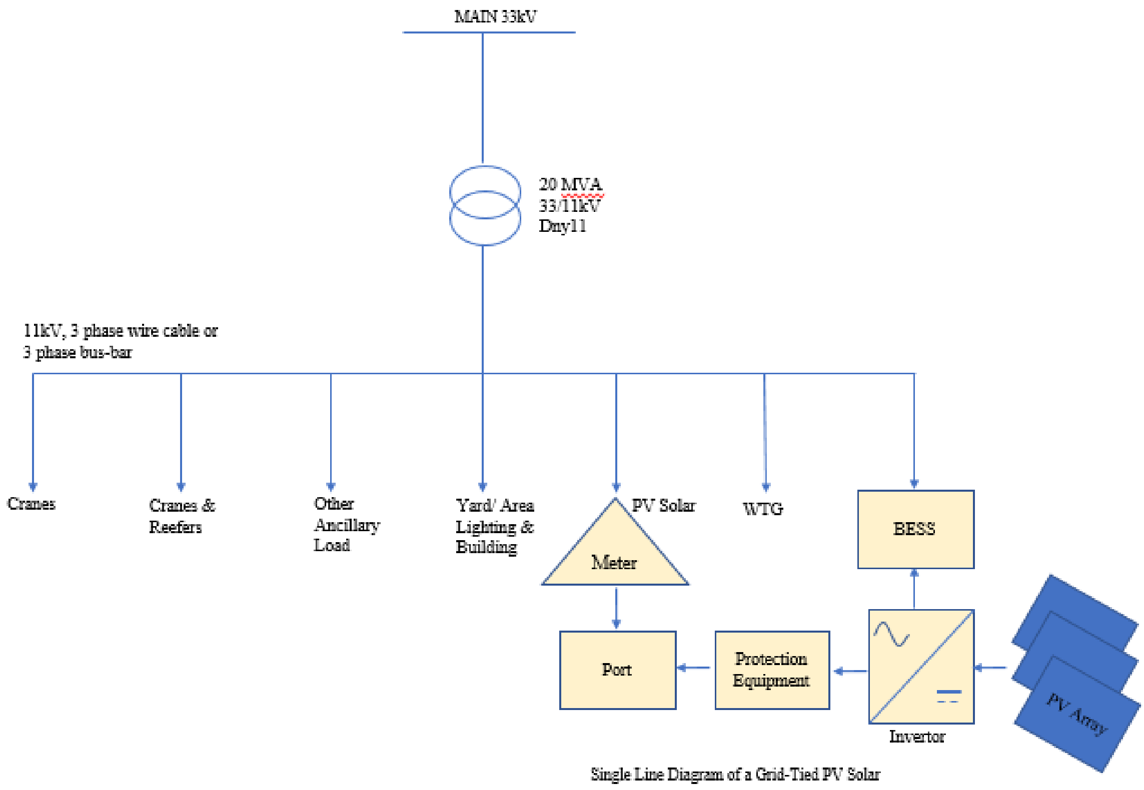


Figure 3-19 Grid-tied PV Solar system

3.5 Hybrid Distributed Generation Solution for the Port

The schematic indicates what the envisaged hybrid distributed generation for the port would look like. In the next chapter, we will see how the distributed generation is integrated and the simulation results of the performance.

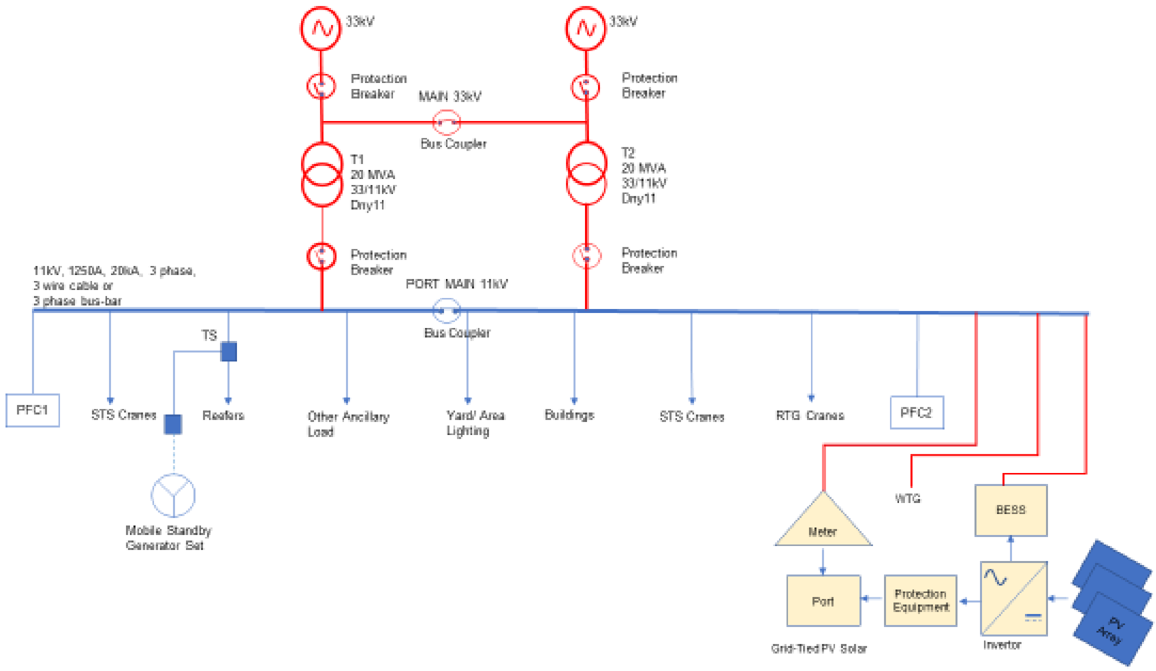


Figure 3-20 Proposed Schematic Layout of the Proposed Solution

The next chapter covers in detail the integration of renewables in the Port Terminal. It presents the loading of the port terminal using data collected from a live South African port presented in this chapter. The technology integrated i.e., photovoltaic generation, Wind Power Generation, Battery Energy Storage System (BESS) is done using Matlab and Homer optimization tools. Both MATLAB and Homer optimizing tools analyze the different technologies and the results are presented in the next chapter, including the total cost of the system.

4 Matlab and Homer Optimization

The energy analysis looks at the average annual amount of energy used in the system, how renewables integrate, contribute to the energy usage and how a Battery Energy Storage System (BESS) could be used to enhance the integration. The analysis further looked at the costs associated with the Grid power, renewables, and standby generator set.

4.1 Loading of the Port Terminal

The maximum demand for the port is very close to the NMD. The local municipality monitors and applies penalties if the maximum demand is exceeded. During the peak months August to December, the energy demand is > 8.5 MW and this excludes the added 2 MW provision for the reefer mobile via the standby generator set. Depending on the reefer demand, the requirement for the standby generator is not limited to 2MA. The demand can double during peak season.

The simulation demonstrates the following;

- how the peak load can be reduced
- how available energy can be harvested from the renewable energy
- From January to March the energy is averaging about 4.5 MWh
- October to December energy peak is greater than 8.5 MWh
- The high demand time is between 06h00 and 17h00

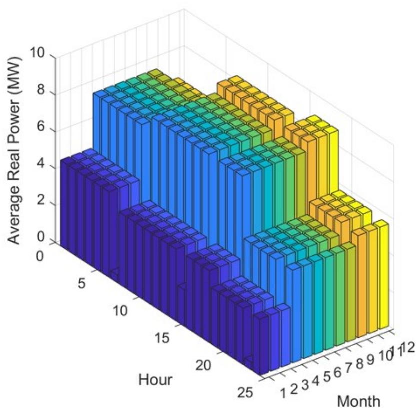
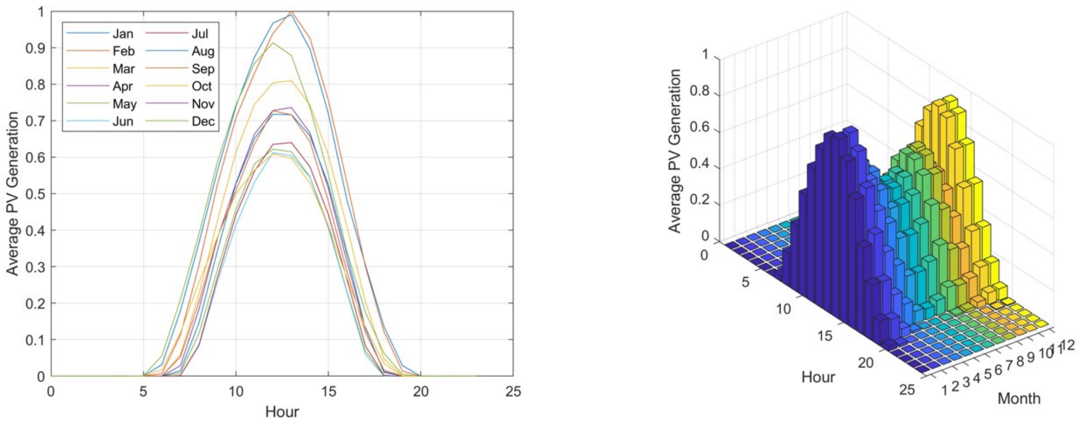


Figure 4-1: Profiles for Average Loading at the Port

4.1.1 Photovoltaic generation

The information for the PV was taken from the SAURAN information for Durban [81], where the Global Horizontal Irradiance GHI) was used. As indicated in the previous chapters the GHI is used in the simulation for the comparison of climatic zones and calculation of radiation on a tilted plane. It must be noted that this would be an underestimation of the PV generated; however, as this is an energy study it is deemed suitable. It is assumed that the system is sized such that 1 PU of generation produces 1 MWp of power.

The PV generation in the port consists of outputs demonstrated in the figure below:



(a) **(b)**

Figure 4-2: Normalised PV Generation for Durban

The pattern on graphs (a) and (b) demonstrate that the following

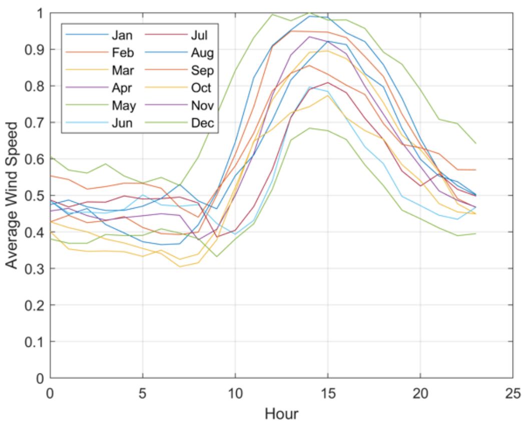
- there is more energy to be harvested as the season changes
- Available energy to be harvested between 06h00 and 17h00 varies from > 0.5 MWp to 1 MWp
- During the summer months up to 0.9 MWp is available to be harvested.
- The average PV generated during the winter months is low compared to the summer season

4.1.2 Wind Power Generation

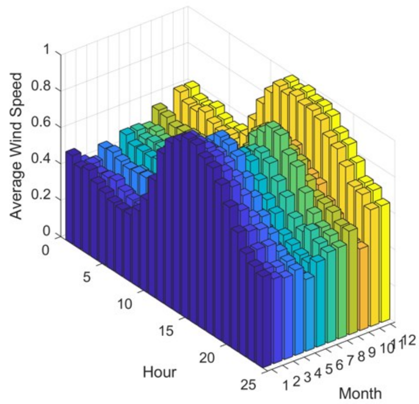
The information for the wind speeds was measured at the port terminal from dedicated weather stations meters. The information used for the calculation is the average wind speed for all directions. The power generated is determined from the following equation where power was based on the 100 kW XANT M21 power curve with a speed cut, v_c, of 3 m/s and a rated speed, v_r, of 11 m/s.

$$P(\mathrm{v}) = \begin{cases} 0 & v < v_c \\ P_r \times \dfrac{v - v_c}{v_r - v_c} & v_c \leq v < v_r \\ P_r & v_r \leq v \end{cases} \tag{1}$$

The velocity of the wind was determined from the measurements at the port terminal following which the power generated was calculated and then averaged per hour per month. The Figure 4-3 graphs below demonstrate the average speed per day for the different months. It is expected that the actual power generated from a wind turbine would be different due to the power generation curve of the wind turbine generation as well as the specifics about wind direction. However, this would be covered more accurately in the following chapter.



(a)



(b)

Figure 4-3: Normalised Wind Speeds for Durban

4.1.3 Battery Energy Storage System (BESS)

The methods and BESS models adopted for the computation of the energy balance of a DG and BESS combined system are briefly described. The model considers the case where a generic DG system and the user's loads are both connected to the grid at the same point of delivery. In this case, storage systems are typically used to increase the share of self-consumption of the DG system, by storing the energy produced and, afterward, release for load shifting when the power demand of the load increases. For the energy analysis, the focus is on the shifting of energy away from peak time.

For discharging

$$SOC(t) = SOC(t-1) + \frac{P(t)}{\eta_{dis} \times C_t} \qquad (1)$$

For charging

$$SOC(t) = SOC(t-1) + \frac{P(t) \times \eta_{ch}}{C_t} \qquad (1)$$

Where

SOC(t)	is battery state-of-charge at time t (%)
SOC(t-1)	is battery previous state-of-charge (%)
P	is the power discharged or charged from the grid
t	is time in hours
n	is the efficiency of the battery and converter system
Ct	is the total storage capacity (in kWh).

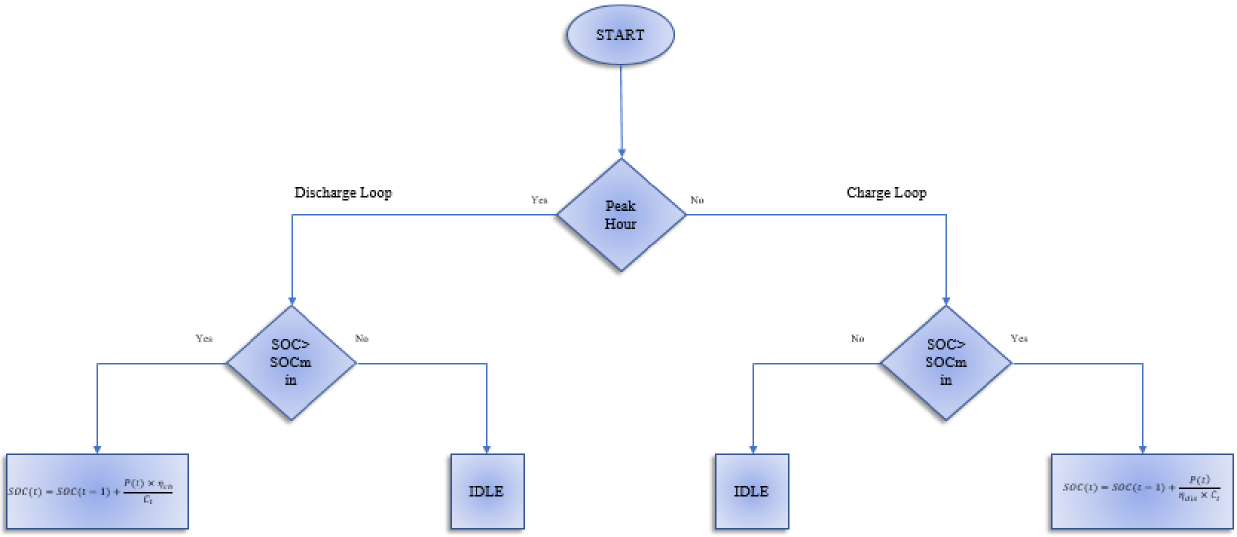


Figure 4-4: Flowchart of the Charging and Discharging Algorithm of the BESS

4.1.3.1 The different battery chemistries considered:

Lithium-ion (LA): Lead-acid batteries is designed for optimal capacity with the drawback of limited loading, slow charging, and reduced durability. The most significant differences between the two battery types listed in table 4-1 below are the system-level design considerations and lifespan.

"Deep-cycle" and "shallow cycle" lead-acid batteries can be found in lead batteries and are commonly used for automotive start.

The deep cycle is recommended for the distributed generation setup since the batteries will often discharge at a low rate over the course of multiple hours. As indicated below the depth of discharge for this battery is about 50%

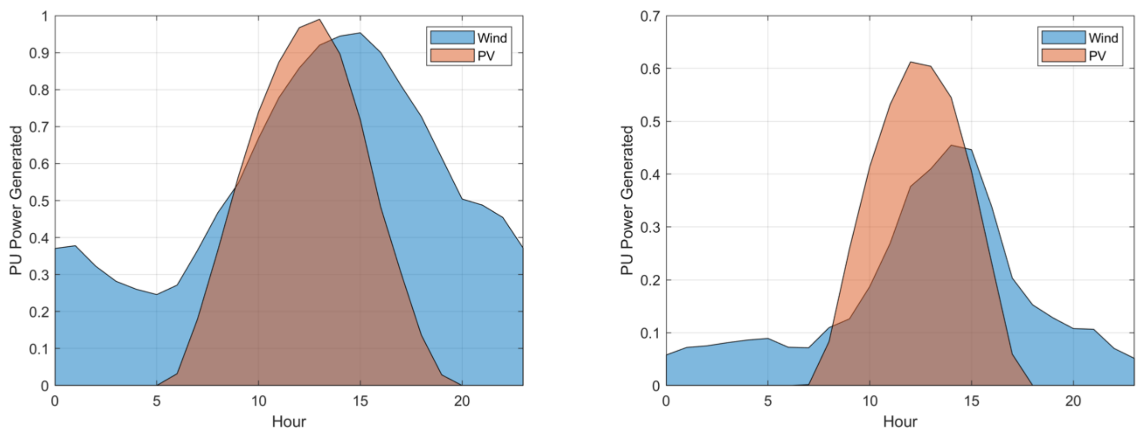
Lithium-Ion (LI): Lithium-ion battery or Li-ion battery is a type of rechargeable battery. All lithium-ion cells are "deep cycle" meaning that they have the ability to be fully charged and discharged. The life of the battery will significantly increase if the depth of each discharge is limited to 80% of the rated capacity. This battery as indicated in table 4-1 has a longer life span compared to the lead-acid type.

Table 4-1 Battery Comparison

Battery Chemistry	Capacity	Cycles Life	Depth of Discharge (DoD)	Life (years)
Lead Acid (LA)	1000 kWh	1,200 @ 50%	50%	5
Lithium-Ion (LI)	1000 kWh	1,900 @ 80% DoD	100%	10

4.1.4 Hybrid Systems

Figure 4.5 shows a per unit power generation comparison of the wind power and PV power for January and June. In January the peak power generated occurs at a similar time. This would make it challenging to optimize the size of each of the different generators. Similarly, in June the peak power generation also occurs at similar times. In this case, however, the PV has a higher peak

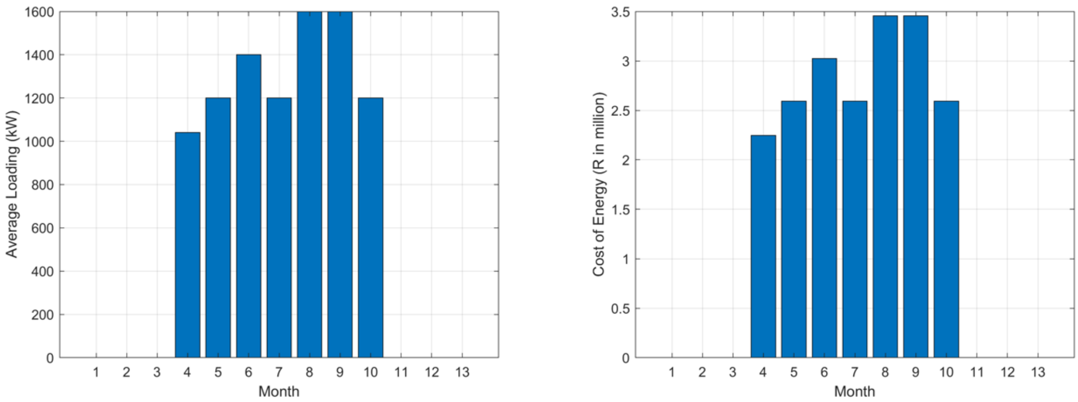


(a) (b)

Figure 4-5: Normalised Wind and PV Generation for Durban (a) January and (b) June

4.1.5 Diesel Standby Generator Set

The diesel generator is required to supply the refrigerated containers. The need for the supply to the reefer containers is usually between March and Oct every year and it usually peaks around August. The need for the 2 MVA standby generator set is necessitated by the seasonal reefer energy demand that increases the NMD and results in the hiring of the standby generator set. The generator set is not a fixed installation. The table below indicates an estimated cost of about R20 million that is paid every year for the running cost supplying a total energy amount of 6.65 MWh. The diesel generators are not embedded, they run off-grid so it was not included in the modeling but the manual calculation of the standby generator cost and energy is included in the conclusion for further study.



(a) **(b)**

Figure 4-6: Diesel generator loading (a) and cost (b)

Figures 4-6 (a) and (b) demonstrate the following,

- The energy load of the synchronized standby generator set
- In April the kW load is about 1MW
- It peaks during September and October and drops in October
- The cost of energy in (b) is directly linked to the energy load demand

4.2 Energy and System Costs

The LCOE is often taken as a measure for defining the cost of electrical energy. It is the net present value of the unit cost of electricity. The LCOE is calculated based on the energy provided to the system, and the NPV would include the cost of energy bought from the system. In the case of hybrid systems, the energy generated by a PV system for example can be used to charge the batteries and not provide energy back to the grid.

The net present value (NPV) of the system is given by:

$$NPV = \sum_{k=0}^{n} \frac{I_k + M_k}{(1+r)^k} \tag{1}$$

Where:

I_k is the annual investment cost (this would consist of the initial investment cost and the replacement cost)

M_k is the annual operating and maintenance cost

r is the discount rate

n is the life of the system

and Levelized Cost of Energy (LCOE) is considered using the following formula:

$$LCOE = \frac{NPV}{\sum_{k=0}^{n} E_k} \tag{1}$$

Where:

E_k is Electricity generated in the year k

n is a lifetime of the system

Note that table 4-2 below does not include the tax incentives. The summary cost in the table below depicted the PV, wind systems combined with BESS initial cost, maintenance cost, and replacement cost cycle.

Table 4-2 Summary of costs used in the model based on the IRENA reports and an exchange rate of 15 ZAR to USD [82] [83]

System	Initial Investment Cost	Maintenance Cost	Discount Rate	Annual Degradation Rate	Replacement Cost	Replacement Cost Cycle
PV	R 15 000 / kW	R 300 / kW / year	7%	1%	Decreases 29% per annum	25 years
Wind	R 30 000 / kW	R 300 / kW / year	7%	1.6%	Decreases 9% per annum	25 years
BESS – LA	R 900 / kW + R 1290 / kWh	1.5 % Initial cost / year	7%	5%	Decreases 10% per annum	5 years
BESS – LI	R 900 / kW + R 2280 / kWh	1.5 % Initial cost / year	7%	5%	Decreases 10% per annum	10 years

4.3 Optimising the Total Cost of System

The total cost formula is used to combine the variable and fixed costs of providing goods to determine a total.

The NPV in the formula below represents the monetary value of a series of future cash flows by today. All future cash flows are therefore discounted with a predefined interest rate or discount rate.

The net present value is often used in the context of cost-benefit analysis where it is a common indicator for the profitability of project or investment alternatives:

- A positive NPV suggests that the investment is profitable, i.e. the return exceeds the predefined discount rate).
- The NPV is negative if expenses are higher or occur earlier than the returns. Thus, the investment does not yield the
- A net present value of 0 indicates that the investment earns a return that equals the discount rate.

The total cost of N years of the installation is given by:

$$\mathrm{TC} = \sum_{n=0}^{N} (\mathrm{Electricity} + NPV_{wind} + NPV_{pv} + NPV_{bess}) \tag{1}$$

The objective function was given by:

$$\min \mathrm{TC(x)} \tag{1}$$

Where the variables are given by:

$$\mathrm{x} = [P_{wind}, P_{pv}, P_{bess}, C_{bess}] \tag{1}$$

Where:

Pwind	is the rated power of the wind generator
Ppv	is the rated power of the PV system
Pness	is rated power of the BESS
Cbess	is the rated capacity of the BESS

The function was implemented as shown below. The generator and storage rated powers are passed into the function. The power generated is determined for that hour of that month. The load is determined for that hour and that month. These values are then included in MatPower and a load flow is done [84]. The outputs are recorded and the algorithm repeats for every hour of every month. Once the load flows are complete the total cost is calculated. The genetic algorithm iterates through different values of the generator and storage ratings to find the lowest total cost.

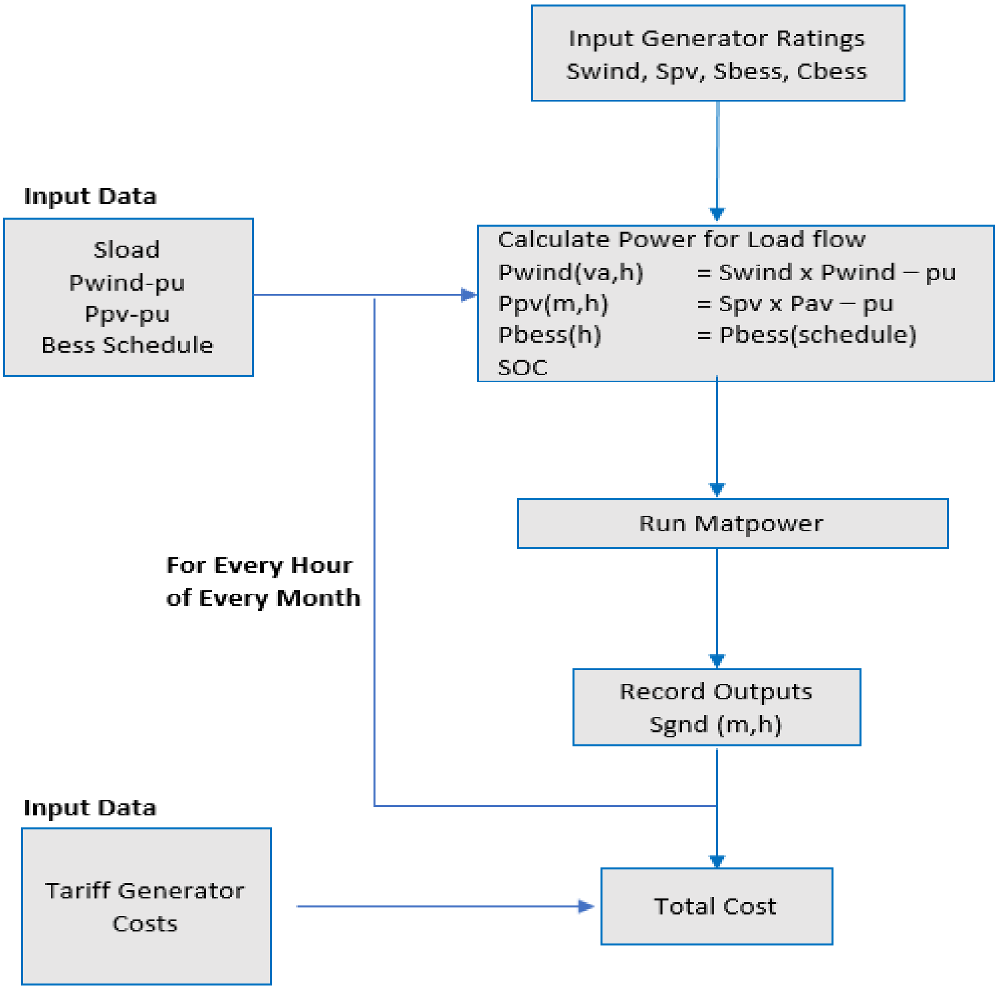


Figure 4-7: Optimization Algorithm

4.4 Study Cases

The following were the bases of the case study,

- The eThekwini Local Municipality Industrial Time of Use tariffs were used
- Discount rate is 7%
- Inflation rate of electricity is 7%

The following cases studied in the energy analysis shown below, where the constraints and limits for each study.

Table 4-3 Study Cases for the Energy Analysis including the Integration of Renewables into the Port Terminal

Case Number	Case	Inequality Constraints	Limits	Curtailment*
1	Base Case	None	None	
2	Base Case Wind Gen	None	$0 < P_{pv} \leq 1MW$	1 MW
3	Base Case PV Gen	None	$0 < P_{wind} \leq 1MW$	1 MW
4	Base Case Wind Gen BESS	$P_{wind} - P_{bess} \leq 1MW$	$0 < P_{wind} \leq 2MW$ $0 < P_{bess} \leq 1MW$ $0 < C_{bess} \leq 20MWh$	None
5	Base Case PV Gen BESS	$P_{pv} - P_{bess} \leq 1MW$	$0 < P_{pv} \leq 2MW$ $0 < P_{bess} \leq 1MW$ $0 < C_{bess} \leq 20MWh$	None
6	Base Case Wind Gen PV Gen BESS (LI)	$P_{wind} + P_{pv} - P_{bess} \leq 1MW$	$0 < P_{pv} \leq 1MW$ $0 < P_{wind} \leq 2MW$ $0 < P_{bess} \leq 1MW$ $0 < C_{bess} \leq 20MWh$	None
7	Base Case Wind Gen PV Gen BESS (LA)	$P_{wind} + P_{pv} - P_{bess} \leq 1MW$	$0 < P_{pv} \leq 1MW$ $0 < P_{wind} \leq 2MW$ $0 < P_{bess} \leq 1MW$ $0 < C_{bess} \leq 20MWh$	None
8	Base Case Wind Gen PV Gen BESS (LI)	None	None	None

What are the limitations of the above model?

4.5 Simulation Power System Model

Homer Grid simulation tool is used to integrate the distributed generation hybrid solution i.e. photovoltaic generation, Wind Power Generation, and Battery Energy Storage System into the existing municipal Grid. The Homer Grid tool is used to optimize the hybrid energy system. The optimization results include detailed analysis of the annual peak electric demand, demand charge reduction calculations, energy daily peak – Grid, carbon dioxide (CO_2) emissions, and cost analysis

HOMER Grid was selected as the simulation tool to check the feasibility analysis and performance of the system provide the best strategy of the distributed energy sources along with its ability to achieve the best combination of energy mixes for a system.

The core requirement of the research is to analyze hourly load data for the whole year and strategize to minimize the cost of electricity. It also provides the flexibility to design the system capable of analyzing the energy based on any changes in the input parameters such as the different electricity tariff structures, fuel costs and percentage of renewable energy penetration. Data from NASA's meteorological department and local data were manually loaded from part of the Homer Grid simulator. The uncertainties of weather conditions, renewable energy resources like hourly wind speeds, a lifetime of PV array, hourly data sets of load or renewable resources, cost analysis have been given due care in obtaining the sensitivity analysis, which is an added advantage of using HOMER Grid.

The research simulation power system model is a development with the Homer Grid software. The model schematic as indicated below entails a municipal permanent connection to the port. According to the local municipality, the main supply tariff classification used for the port is the Industrial Time of Use (IToU). The main supply is coupled with the 2 MVA standby generator set that is usually hired to boost the load for the reefer season usually happening between April and September each year

The combined system is analyzed to provide the minimum emission levels. The Homer simulation was used to demonstrate the integration of renewable energy using distributed generations. The maximum demand analysis looked at the power drawn from the grid. A significant component of the cost of electricity is the maximum demand. The maximum demand is dependent on the power quality (in terms of reactive power) and the loading of the power system. As much as the maximum demand can be reduced passively by power factor correction equipment, in this case we look at actively achieving this through the integration of renewable energy systems as the power drawn from the grid can be improved and the reactive power can be compensated for power factor improved.

Notified Maximum Demand (NMD) – this is the maximum capacity considered in kVA, as measured over 30 minutes integrating period, per supply point of delivery (POD) that the port is contracted to the supply authority to make available during all periods. As per the eThekwini Local Municipality NMD rules, the NMD is the capacity reserved by the customer to provide for the maximum demand requirements in all periods. The NMD should not be exceeded unless otherwise agreed to via a formal approval process.

The NMD for the study is confirmed to be 16 MVA and the local electricity supply authority monitors and applies penalties if the maximum demand is exceeded. The NMD is agreed upon by both parties in writing. According to eThekwini when the agreed demand is exceeded the relevant tariff charges are applied. A tariff component, per kVA, registered, based on the highest demand registered over a rolling 12-month period, during peak and standard hours.

Over and above the NMD, the Network Access Charge (NAC) rule is applied. The NAC is based on the higher of the NMD, the current demand, or historical demand as described by the NMD.

In addition, the chargeable kVA is utilized for the calculation of the Network Access Charge (NAC). This result in an increase in the Excess Network Percentage (ENP). The ENP is calculated as the percentage difference between the maximum demand and the NMD [85]

4.5.1 Power System Model Components

The power system model components include:

- **Distributed energy resources (DERs**) — the distributed energy resources considered in this research range from diesel generators, renewable energy sources include PV solar and wind turbine generators. The DERs are combined with the battery storage and diesel generator for better results and renewable energy penetration. The renewable energy
- **Converter —** as abovementioned the DERs are made up of PV Solar and Wind Turbine Generator. The is a need for a converter to link the system with the main AC Grid. A converter is an integral part of the system as it converts DC to AC and vice-versa.
- **Electric load —** the electric load is made up of the port equipment and building services system. The electric load can be further divided into critical loads and non-critical loads. The average electricity demand to be met for port operation plays an important role in the consideration of the entire distributed generator system.

- **Battery energy storage system —** the recommended systems do have limitations in terms of when the energy can be harvested. Therefore, the storage device is an integral part of the distributed generation network. Complete reliance on renewable energy sources is not possible due to their unpredictable nature. Since the operation is day and night, there is a need to store the excess energy produced during intervals of high energy penetration and can then be used to meet high energy demand or during times when there is very low energy penetration.

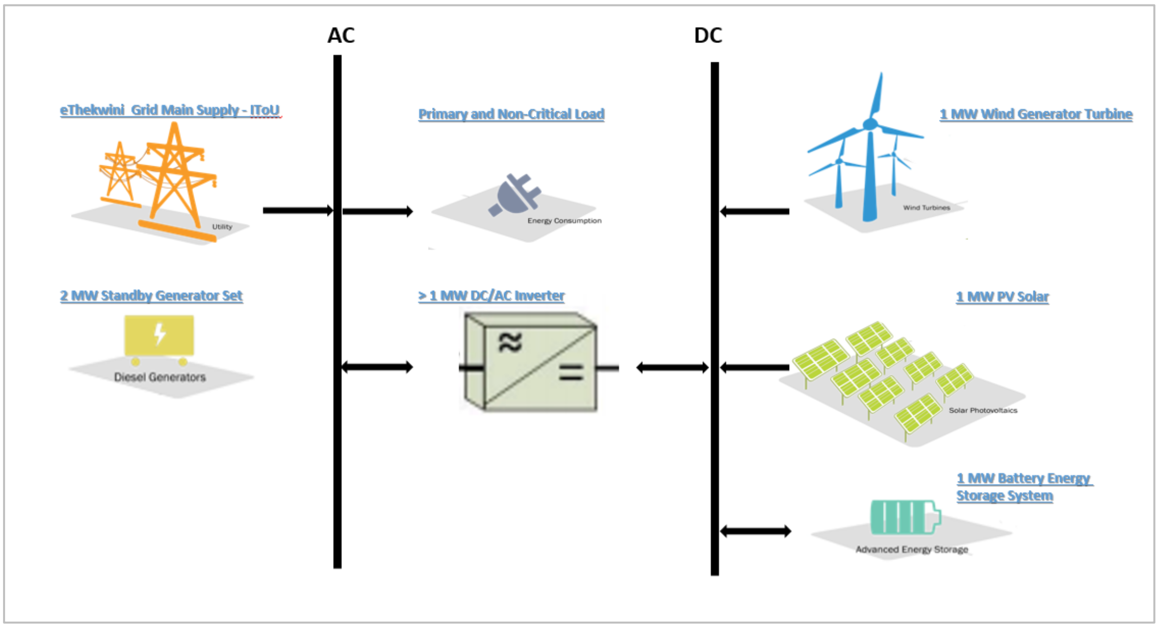


Figure 4-8 Simulation - Power System Architecture

The distributed generation schematic components include after the primary loads the BESS, Converter, PV Solar, and WTG.

4.5.2 Simulation Loads

The following is the monthly primary load profile used for the simulation.

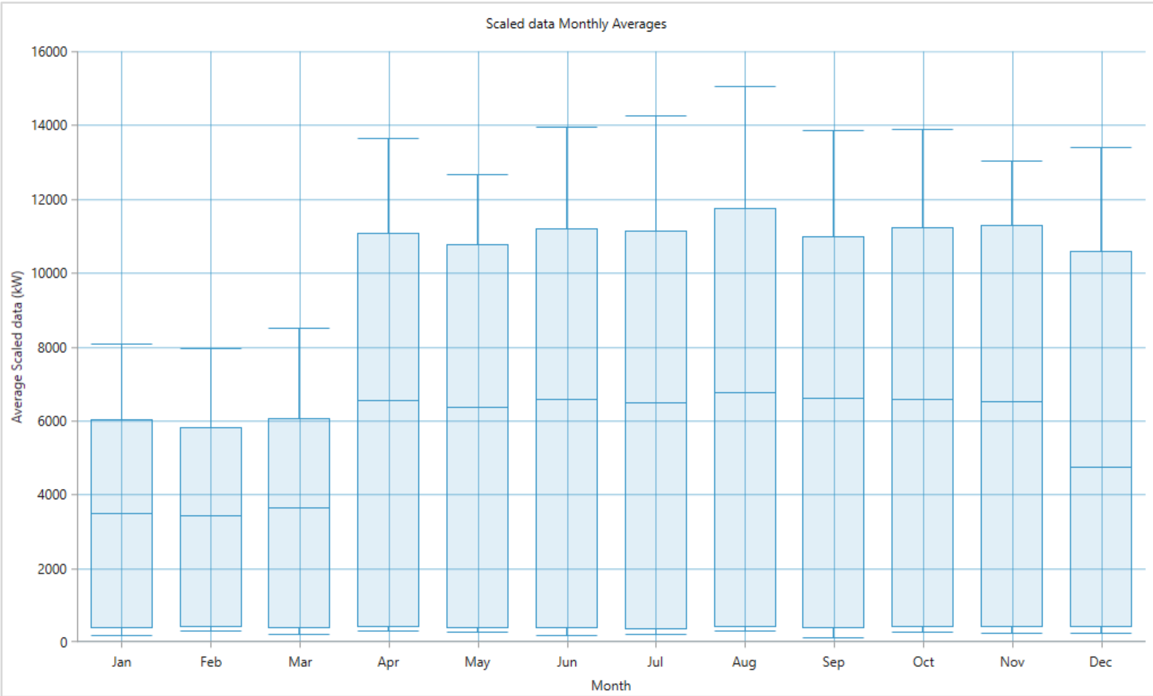


Figure 4-9 Monthly Base Line - Primary Load

The maximum energy demand during March is about 8,514.13kW. The average daily maximum energy demand is about 6,067.80kW. The simulation confirms the month of August to be the peak month in terms of energy demand. The maximum peak demand is 15, 057.00 kW. There is a peak also noted on the daily maximum demand. It is about 11,740.87 kW, which demonstrates an increase of about 27% compared to the March results.

The load metrics considered for the simulation are as follows,

Description	Baseline
Average (kWh/day)	135 866,74
Average (kW)	5 661,11
Peak (kW)	15 057
Load Factor	0,38

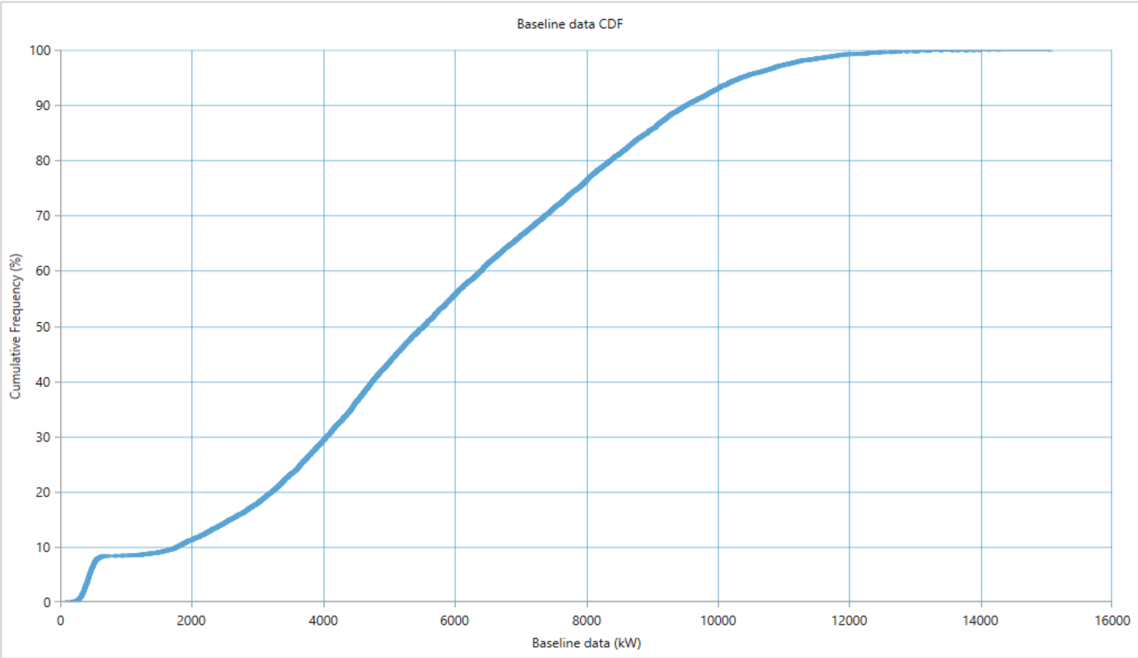


Figure 4-10 Baseline Data - Cumulative Distribution Function (CDF)

It can be seen from the CDF graph above in Figure 5-3 that based on the port energy data at the 10th percentile, that is the cumulative frequency, baseload is about 2MW and at 95th percentile, that is the upper threshold, the load is about >16 MW. This confirms the baseline data cumulative frequency distribution over a month. The graph below in Figures 5-5 highlights the daily energy profile measure per hour.

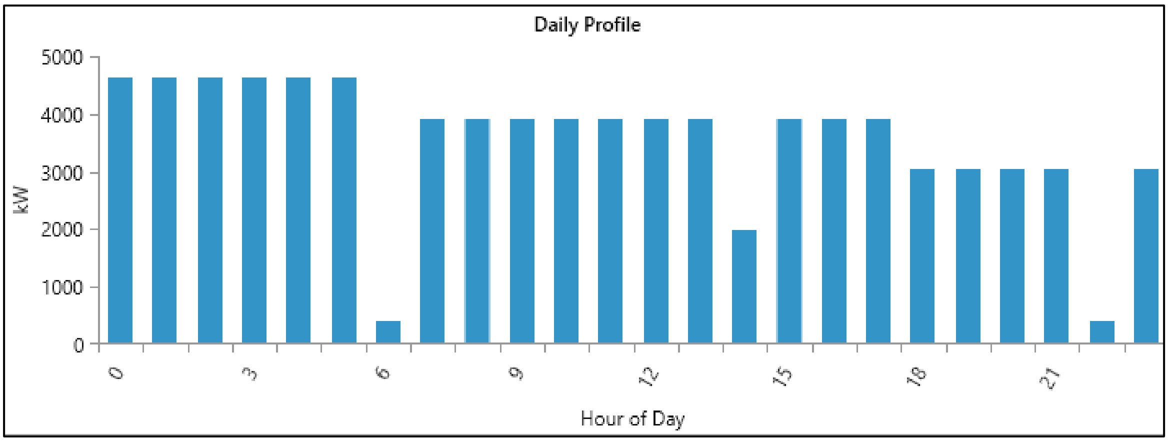


Figure 4-11 Daily Load Profile

The daily profile above in Figures 5-4 zooms in on the detail displayed on the CDF graph but with the emphasis on hourly performance. A load of less than two MW is noted during operation shift change and these tiers up with the 10th percentile cumulative frequency on the previous graph. Three times daily, the reduction is demonstrated. More than 55% of the cumulative frequency % demonstrates that is 5th percentile cumulative frequency the load is above 5MW

The average electric energy consumption as per the table below confirms an annual peak in the energy consumption during August.

Table 4-4 Average Electric Energy Consumption

Daily	Monthly	Annual
135 770,0 kWh/day	4 129,7 MWh/month	49 556,1 MWh

Annual Peak Electric Demand: 2018 August / 15 037,33 kW

The following results from the yearly electric primary load displayed in Figure 5-5 below are noted as follows;

- The first two months of the year demonstrate a low energy demand;
- Load demand is reduced during the three shifts changes at 06h00, 14h00, and 22h00;
- Highest energy demand is noted to be around the month of August;
- The yearly energy profile on the Figure above indicates that the energy load profile is made up of 24 hours, 365 days of year operation;
- Load demand is low during Jan –March, and December, from the heatmap it is averaged about 4,5MW.
- There is a higher load demand increase from March to September and is displayed in the heatmap load profile below where the monthly averages for the months are between 4MW and 8,1 MW.

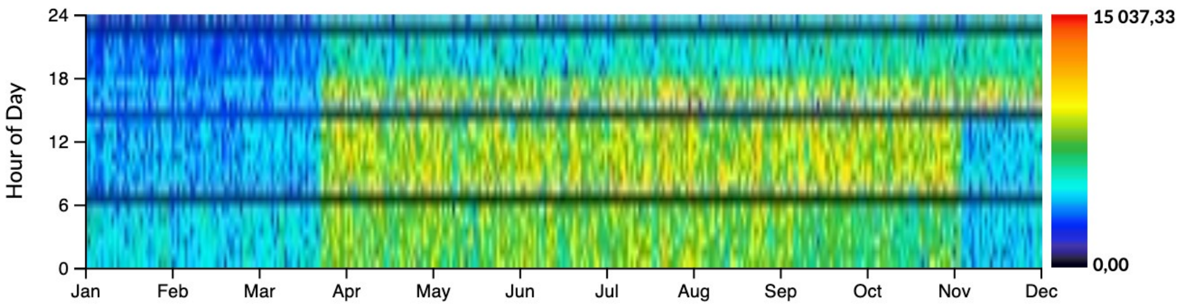


Figure 4-12 Grid Energy – Yearly Loading Profile

The annual peak electric demand graph below in Figure 5-6 demonstrates the following;

- The annual peak electric demand is around the month of August and is recorded at about > 15 MW
- The peak annual MMD for the port is 16 MVA. The peak electric demand of about 15MW noted at about 15h00 during the month of August is an indication that distributed generation is required
- The average demand from the August month is registered at 6.7 MW
- The August power demand daily average is about 380 kW, this is demonstrated in the graph below at about 06h00 and again at 22h00.

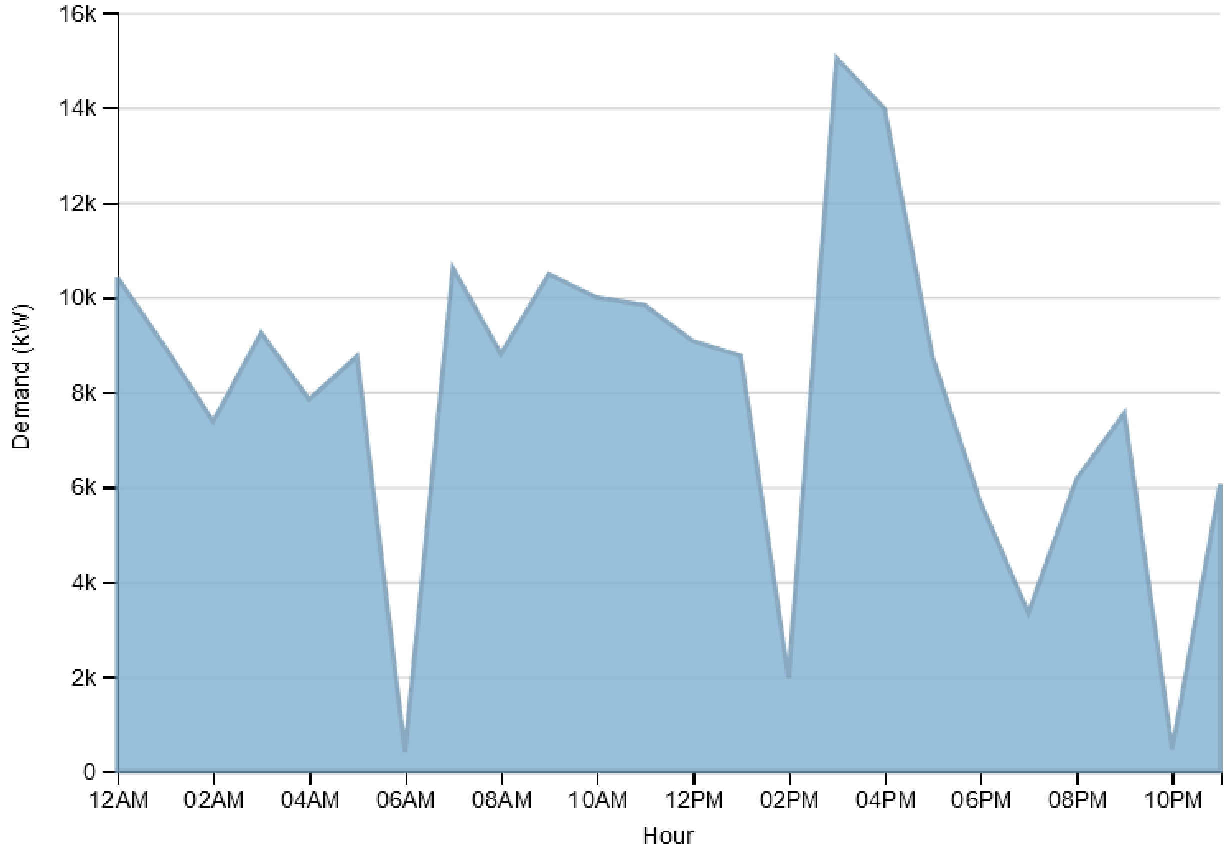


Figure 4-13 Load Profile for the Day on Which the Largest Demand Occurs (19 August)

4.5.1 Solar Radiation Profile

In Figure 5-14, the solar radiation data for a period of one year for Durban is shown which is obtained from the NASA surface Meteorology website. The location is approximately 29 degrees, 52 minutes South to latitude, and longitude 31 degrees 1, 31 minutes East. The average clearness index is estimated at 0.62 while the average daily radiation is approximately 4,51kWh/m2/Day

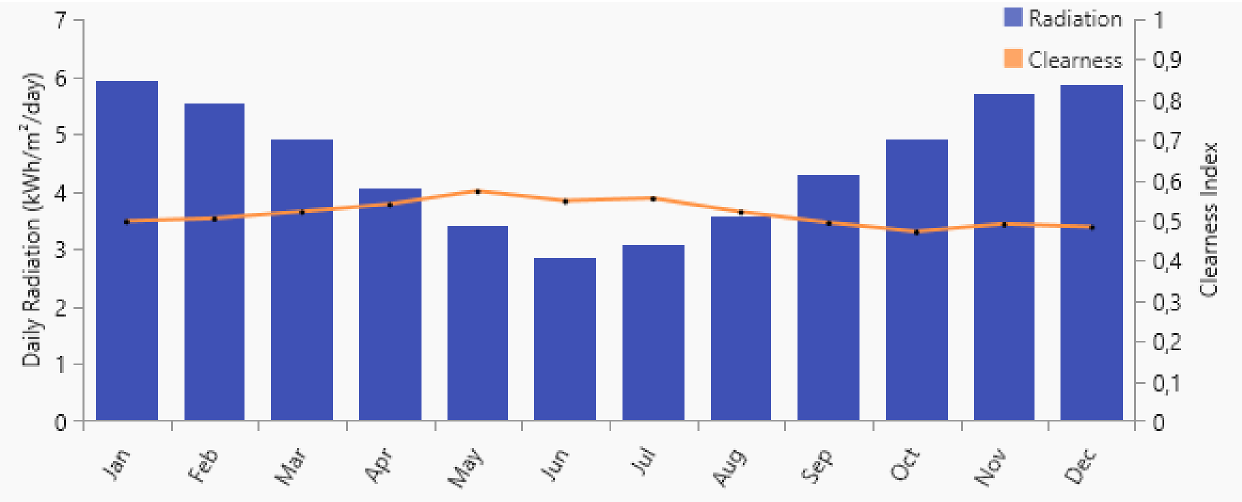


Figure 4-14 Monthly Average Solar Global Horizontal Irradiance (GHI) Data

In line with the weather meters installed around the port, the Homer temperate data from the NASA Prediction of Worldwide Energy Resource (POWER) data shows in Figure 5-15 below also confirms the annual average temperature to be about 21.83°C.

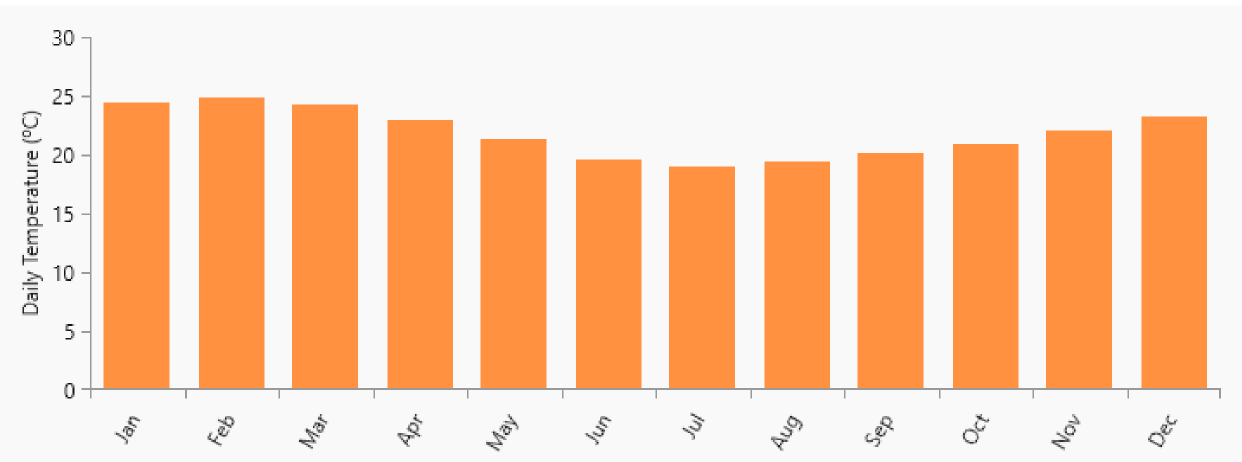


Figure 4-15 Monthly Average Temperature Data

4.6 Homer Optimization Tool

The Homer optimization tool analyses the average daily electric energy consumed at the port is about per day, month, and annualized. The existing demand from the existing load profile results depicts a monthly electric energy consumption and annual of 4 129.7 MWh and 49 556.1 MWh respective with an annual peak electric demand of about 15 MW in August.

4.6.1 Homer Cases

Homer looked at the following Cases:

- Case #1: Solar + Wind + Storage: BESS + Municipal Grid
- Case #2: Wind + Storage: BESS + Municipal Grid
- Case #3: Solar + Wind + Municipal Grid
- Case #4: Wind + Municipal Grid
- Case #5: Solar + Storage: BESS + Municipal Grid

The HOMER system analyzed demonstrates the integration of renewable energy using distributed generations. The few cases shown above demonstrate the extent capacity available, provide the minimum emission levels, costs analysis, and savings overview. These results are included in the conclusion and recommendation chapter with the standby generator set results to propose a solution to reduce the diesel cost, provide alternative supply for the reefer and reduce the CO2 emissions.

4.6.2 Base System Electric Bill Considered

The total energy cost considered is as detailed in table 4-5 below. The port energy charged for a full year is demonstrated. Consumption per month, including demand and fixed charges, are for the port of Durban is presented in table 4-5 below.

Table 4-5 Detailed Base System Electric Bill

	January	February	March	April	May	June
Energy Charges	R1 978 032	R1 732 504	R2 018 956	R3 543 021	R3 637 501	R5 660 570
Consumption (kWh)	2 605 714	2 297 848	2 707 901	4 708 248	4 750 538	4 754 375
Demand Charges and Peak Demand	R0 8 084 kW	R0 7 957 kW	R0 8 503 kW	R429 311 13 633 kW	R0 12 675 kW	R1 501 631 13 964 kW
Fixed charges (R)	R580 500	R580 500	R580 500	R580 500	R580 500	R580 500
Monthly Total	R3 678 726	R3 415 635	R3 777 730	R6 012 635	R5 974 423	R8 176 140
Annual Total	**R70 876 667**					

	July	August	September	October	November	December
Energy Charges	R5 730 158	R6 091 879	R3 393 173	R3 606 731	R3 459 976	R2 512 716
Consumption (kWh)	4 823 464	5 031 338	4 766 584	4 889 888	4 681 569	3 509 138
Demand Charges and	R2 522 751	R5 136 407	R1 162 843	R1 310 983	R0	R0
Peak Demand	14 255 kW	15 037 kW	13 860 kW	13 892 kW	13 020 kW	13 385 kW
Fixed charges (R)	R580 500	R580 500	R580 500	R580 500	R580 500	R580 500
Monthly Total	R8 286 003	R8 756 124	R5 894 224	R6 112 318	R5 844 682	R4 948 028
Annual Total	**R70 876 667**					

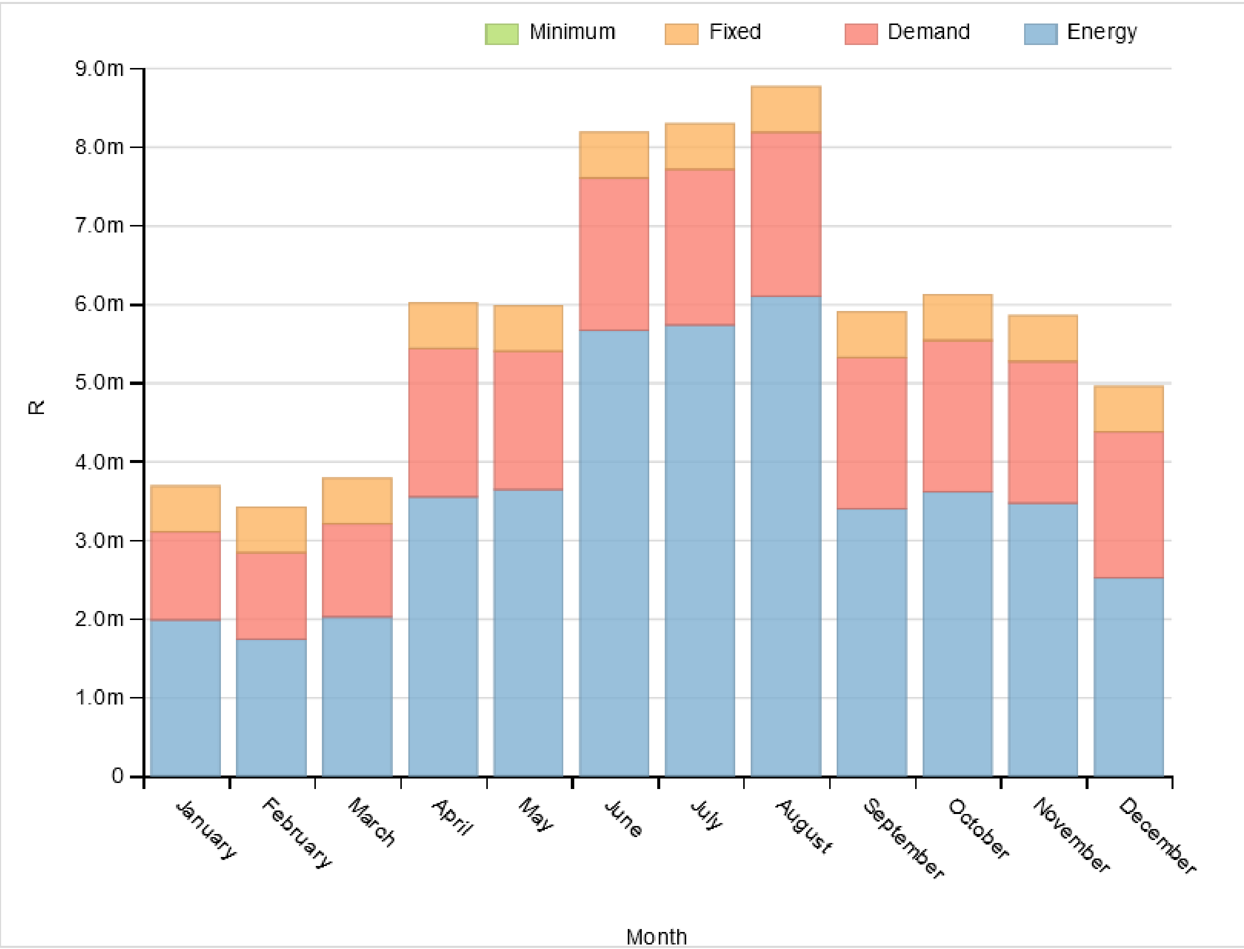


Figure 4-16 Base System - Monthly Electricity Bill

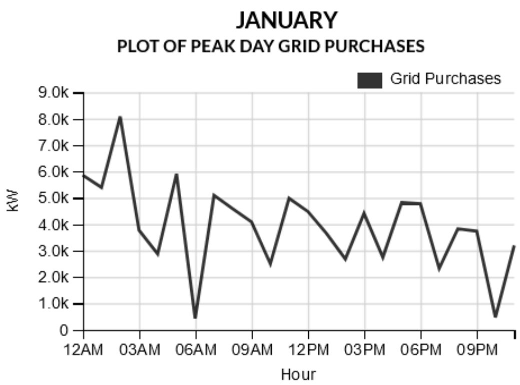
The graph above shows the following information considered in the homer simulation,

- Energy costs for the first three months is about R 2 mil
- There is a spike during the months June to August in energy demand from about R2 mil to R5.8 mil average
- Demand charges are about R1, 2 mil but with the increase in the energy demand, the demand charge is directly affected.

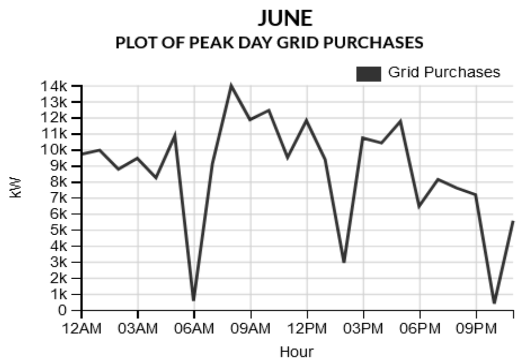
- An increase of about 50% on-demand charges is noted in the month of August
- Other fixed charges average to about R0, 6 mil per month.
- As per the table above, the total annual energy cost is about R70, 9 mil.

The Figures below represent the grid purchased energy for the different seasons during the year. The energy and costs are determined using the genetic algorithm in Matlab and Homer. Results are noted as follows:

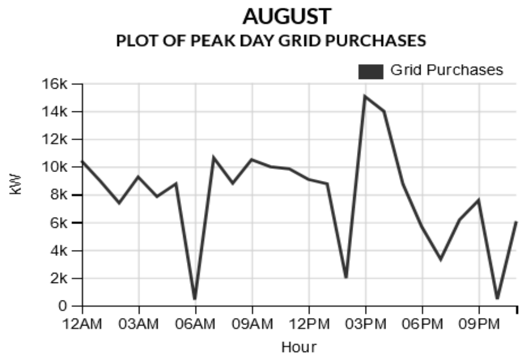
- The grid demand limit for the month of January as indicated in Figure 5-8 (a) is noted at about 7.1 MW. The Matlab results demonstrated in the previous chapter are aligned with Figure (a) below where the daily average maximum is noted at about 6MW and average at about 3,5 MW.
- Figure 5-8 (b) below demonstrate results from the Homer simulation similar to the Matlab results from the previous chapter. The daily average maximum for the month of June is about 11 MW while the average load is noted at about 6,6MW
- Results from both Homer and Matlab software confirm the peak load to be in the month of August at about 15MW as demonstrated below in Figure 5-8 (c). The daily average is about 6,7MW
- Figure 5-8 (d) the peak day grid purchased is averaged to about 4,7 MW for December
- The grid purchased power demonstrated in Figure 5-8 (a)-(d) is noted to be R3,6 mil for the month of January, R8,1 mil for June, R8,7 mil for August, and R4,9 mil for December. The Matlab results demonstrate the rate results except that the fixed charges are not included.



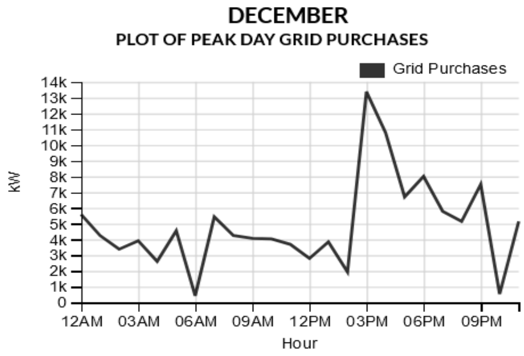
(a)



(b)



(c)



(d)

Figure 4-17 (a), (b), (c), and (d) Peak Day Grid Purchased

4.7 Conclusion

The chapter covered in detail the integration of renewables in the Port Terminal. The loading of the port terminal and photovoltaic generation, wind power generation, Battery Energy Storage System (BESS), and diesel generation technologies integrated using the Homer and MATLAB as an optimizing tool demonstrates that there are opportunities within the port to integrate hybrid and address the energy security issue. The MATLAB analysis of the different technologies and cost results is compared with the Homer tool result to confirm the viability of the solutions and demonstrate in the next chapter.

5 Simulation and Results of Hybrid Energy System

5.1 Introduction

This chapter focuses on the maximum demand feasibility analysis, using the HOMER Grid and Matlab simulation program. The study comprises an energy mix of a PV system, a Wind Energy system, a Battery Energy Storage System, and a Diesel Generator. The results of the energy maximum demand analysis include a cost analysis with details of the Net Present Cost and the Levelized Cost of Electricity. The lowest LCOE and NPC are determined through the analysis of the system with the PV, wind turbines, battery, and a diesel generator.

5.2 Homer Simulation Results

This section presents a summary and comparison of the potential and preferred system. The following sections give details on Case #1 to Case #5 and high-level details on each system.

5.2.1 Case # 1: Solar + Wind + Storage: BESS + Municipal Grid

This case consists of a combination of the wind, solar, battery storage, and municipal grip systems.

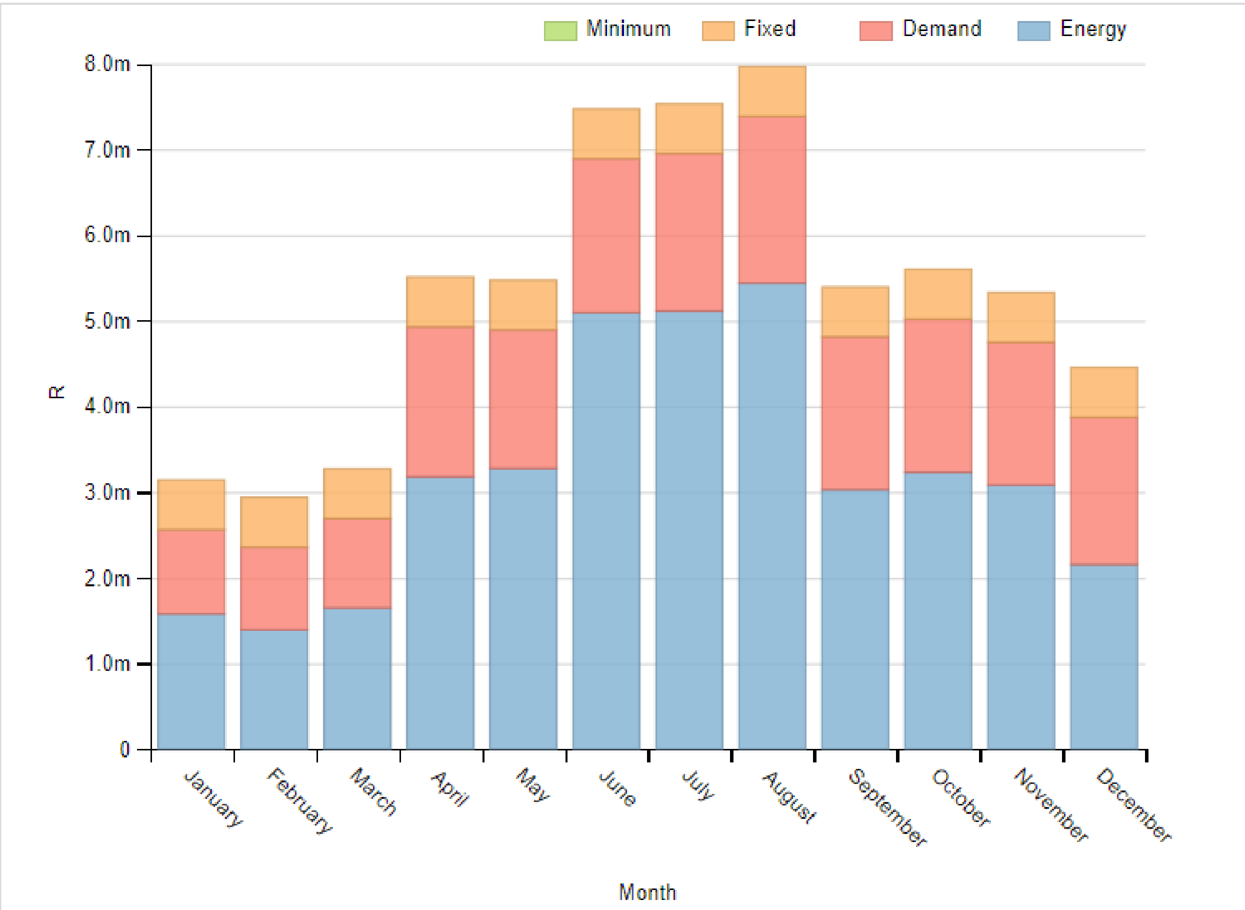


Figure 5-1 Case 1 - Monthly Electrical Bill Breakdown

In comparison to the Matlab algorithm case, the Figure 5-9 graph above distinguish the following:

- Excluding the fixed cost that is not included in the MATLAB, the electricity bill for the months of Jan is about R2,8 mil and >R7 mil for August the peak month
- The energy consumption cost is noted to be greater than R 5 mil for August and reduces to about R 2 mil in December

The following table presents an overview of the costs and savings for the integration of the solar, wind, BESS into the existing municipal electrical grid.

Table 5-1 – Case #1: Savings Overview

Description	Wind + BESS + Municipal Grid
Average annual energy bill savings:	R6 832 600,00
CAPEX	R38 419 420,00
Payback time (simple/discounted):	6,0/6,0 years
Internal Rate of Return (IRR)	15,17%
Project lifetime savings over 20 years:	R136 652 000

The installation components recommended for the Case #1 system are as per the table below. Note that the table includes the estimated unit price and installation cost.

Table 5-2 Components List and Costs - Case 2

Component	Price	Installation Size	Total Installed Cost	Annual Expenses
PV	R15,00/watt	822 kW	R12 324 550	R246 491/yr
WTG 100 kW	R3 000 000,00/ea.	12 ea.	R36 000 000	R360 000/yr
BESS1WMh	R3 180 000,00/ea.	2 ea.	R6 360 000	R95 400/yr

5.2.1.1 Case # 1 System – Electrical Bill

The energy charge below is for the quantity of energy in kilowatt-hours (kWh) used at the port in total for the month. The demand charge is for the highest peak power draw in kilowatts (kW) for the month. Finally, the fixed charge is a charge that is the same every month and is not affected by your consumption or peak demand. The Figure below helps provide the calculated based system electrical bill. The simulation results for each month demonstrates the different electric charge on monthly basis. Homer ensures the accuracy of the results by checking that the baseline electricity costs listed below (energy and demand charges) match the actual electricity bills.

The electricity bill is crafted from the live monthly bills paid to the local municipality. The bill tariff used is Industrial Time of Use made up of energy charge, demand, peak, and fixed charge. The simulation electricity bill predicted for case 1 is as per Table 5-3 below,

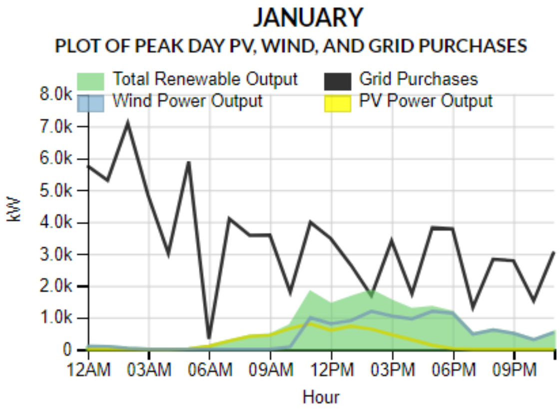
Table 5-3 Base System Electric Bill – Case 1

	January	February	March	April	May	June
Energy Charges	R1 575 829	R1 389 204	R1 645 221	R3 175 504	R3 272 413	R5 092 296
Consumption (kWh)	2 119 793	1 881 058	2 262 228	4 265 675	4 334 689	4 348 640
Demand Charges	1 990 kWh	2 456 kWh	2 732 kWh	1 270 kWh	1 450 kWh	3 015 kWh
Peak Demand	R981 920	R966 524	R1 042 956	R1 750 628	R1 617 851	R1 796 498
Sales	7 086 kW	6 975 kW	7 526 kW	12 633 kW	11 675 kW	12 964 kW
Fixed charges (R)	R580 500	R580 500	R580 500	R580 500	R580 500	R580 500
Monthly Total	R3 138 249	R2 936 229	R3 268 677	R5 506 632	R5 470 764	R7 469 294

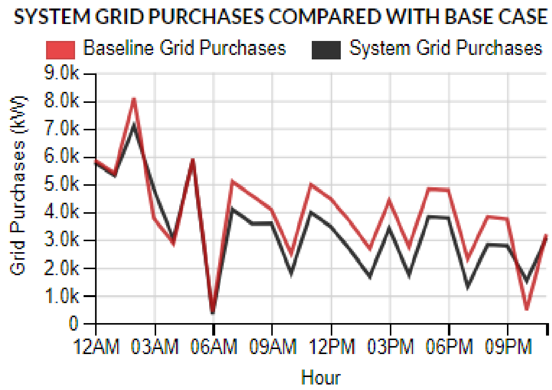
	July	August	September	October	November	December
Energy Charges	R5 111 682	R5 437 143	R3 026 931	R3 228 501	R3 079 715	R2 151 597
Consumption (kWh)	4 379 374	4 560 312	4 277 302	4 394 098	4 188 318	3 031 772
Demand Charges	R1 836 773	R1 945 174	R1 782 511	R1 786 721	R1 665 634	R1 718 841
Peak Demand	13 255 kW	14 037 kW	12 863 kW	12 894 kW	12 020 kW	12 404 kW
Sales	1 762 kWh	3 654 kWh	3 776 kWh	3 866 kWh	2 503 kWh	983 kWh
Fixed charges (R)	R580 500	R580 500	R580 500	R580 500	R580 500	R580 500
Monthly Total	R7 528 955	R7 962 816	R5 389 942	R5 595 722	R5 325 850	R4 450 937
Annual Total	R64 044 068					

The simulation results on the table above validate few things, i) energy charge is higher during the reefer season ii) the results prove that the annual peak energy demand is in August, and iii) the annual total electric bill is about R 64 million.

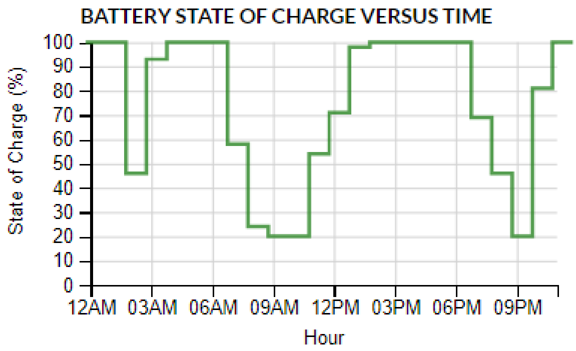
5.2.1.2 Case 1 Performance Summary



(a)



(b)

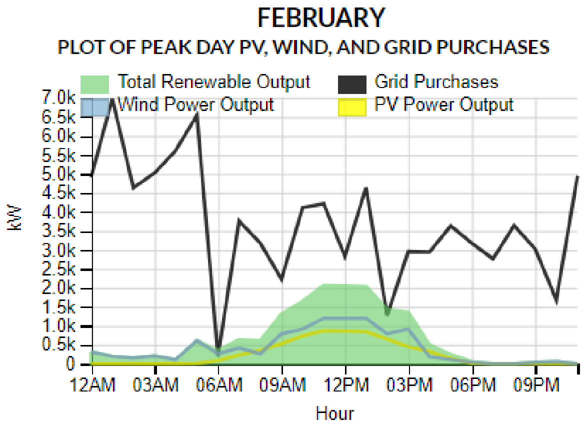


(c)

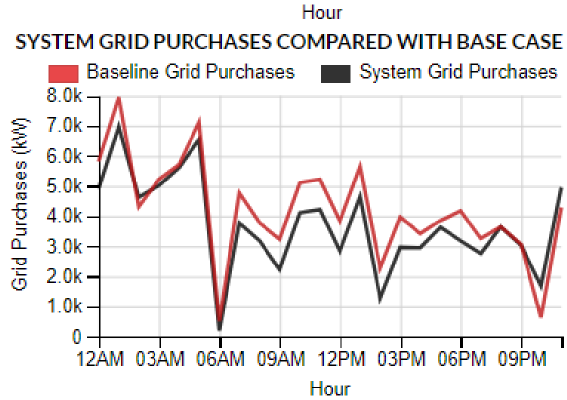
Figure 5-2 Case 1 Homer Graphs: (a) Combination of Renewable & Grid (b) Baseline and System Grid (c) BESS

The following similarities are noted between the Matlab and Homer simulation results on the above-displayed Figure 5-10,

- About 0.1MVA power is harvested through the wind technology at about 00h00
- Power > 0.1 MVA harvested from the PV solar technology contributes to the Grid from as early as 06h00 in the morning as shown in Figure 5-10 (a).
- The PV solar reaches its harvest peak at about 12h00
- The penetration of the renewable is seen in Figure 5-10 (b) between 11h00 and 17h00 the purchased grid is reduced
- The total renewable is above harvested is above 1 MW 10h00 to 16h00.
- The Depth of Discharge (DoD) is at 0% between 12h00 and 18h00, this is due to the renewable energy harvested
- Similar results were noted in the previous chapter from the Matlab simulation. A power greater than 1 MW is harvested from the renewables and penetrates to the Grid between 11h00 and 18h00 as shown on Figure 5-10 (a) – (c)



(a)



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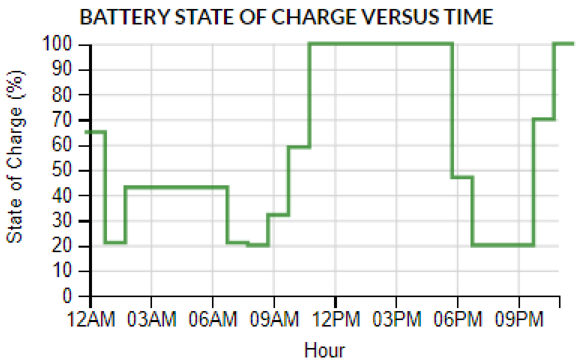
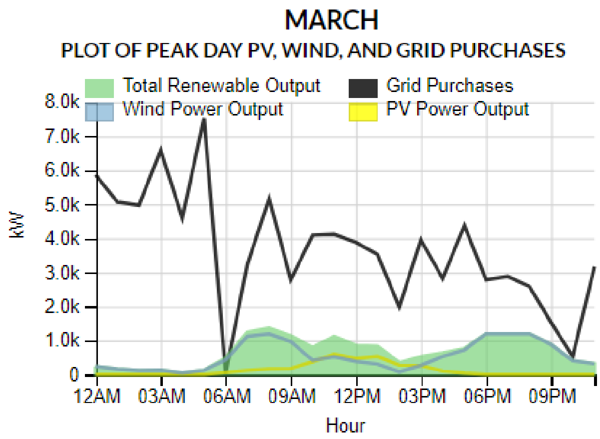


(c)

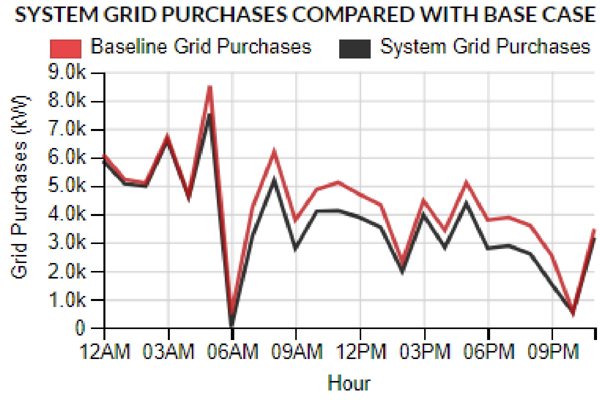
Figure 5-3 Case 1 February Homer Graphs: (a) Combination of Renewable & Grid (b) Baseline and System Grid (c) BESS

The following similarities are noted between the Matlab and Homer simulation results on the above-displayed Figure 5-11,

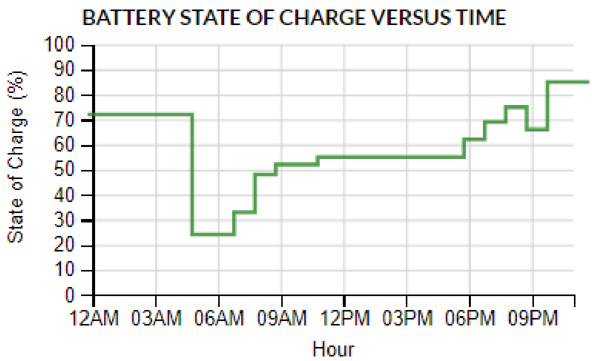
- Renewable power harvested during the night is recorded to be averaging at about 0.4 MVA through wind technology from 18h00 to 06h00 as shown in Figure 5-11 (a).
- The penetration of the renewable is seen in Figure 5-11 (a) – (c) between 06h00 and 18h00. About 0.9 MW of power from PV solar and 1.2 MW power from wind is available to the grid.
- The purchased grid electricity can be reduced by more than 2,1 MW of power from the renewables
- The Depth of Discharge (DoD) is at 0% for most of the time during the day, due to the renewable energy harvested
- Similar results are noted in the previous chapter from the Matlab simulation. There seems to be higher demand during the night for the month of February. The power demand is averaging at > 4 MV between 00h00 and 06h00



(a)



(b)



(c)

Figure 5-4 Case 1 March Homer Graphs: (a) Combination of Renewable & Grid (b) Baseline and System Grid (c) BESS

The following similarities are noted between the Matlab and Homer simulation results on the above-displayed Figure 5-12,

- It is interesting to note that during the month of March there is more to harvest from the wind renewable during the night from 18hoo to 23h00 compared to the previous month.
- Renewable reached a peak of about 1.2 MW between 18h00 and 21h00 and mainly from the wind technology
- The battery State of Charge is averaging above 60% as shown on Figure 5-12 (c) this is aligned due to the renewable energy harvested during the abovementioned period
- The grid power demand is averaging at > 4.5 MV between 18h00 and 06h00 as shown in Figure 5-12 (a) – (c) and similar results are noted from the Matlab results

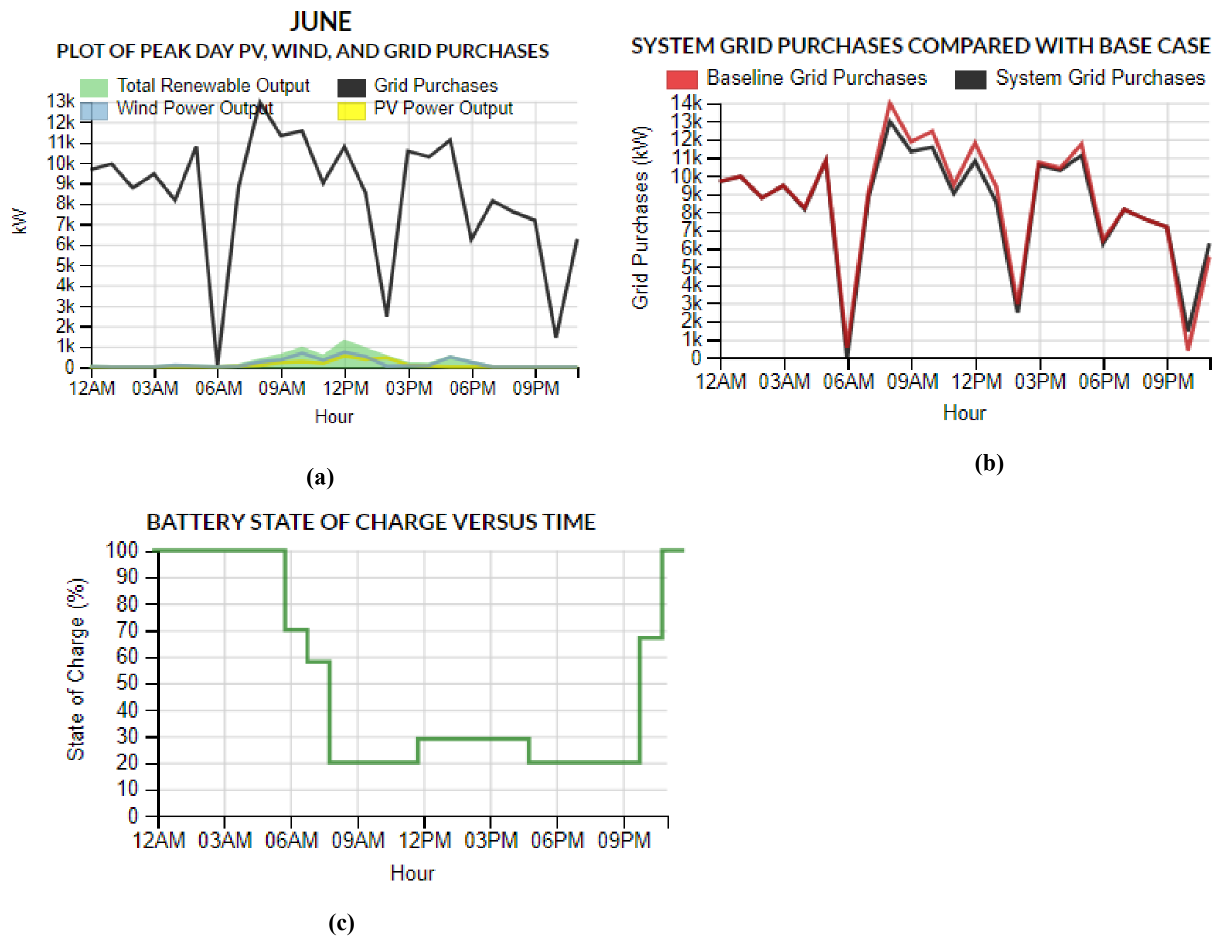
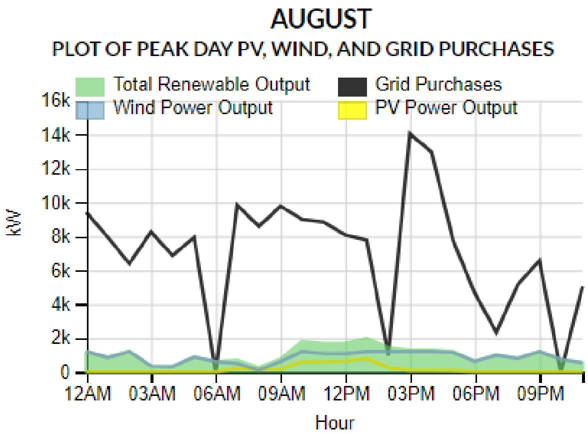


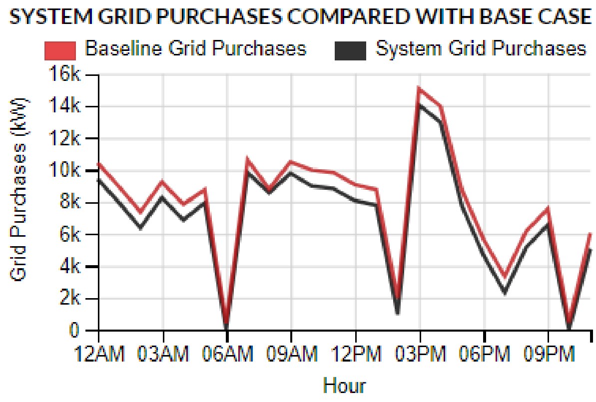
Figure 5-5 Case 1 June Homer Graphs: (a) Combination of Renewable & Grid (b) Baseline and System Grid (c) BESS

The following similarities are noted between the Matlab and Homer simulation results on the above-displayed Figure 5-13,

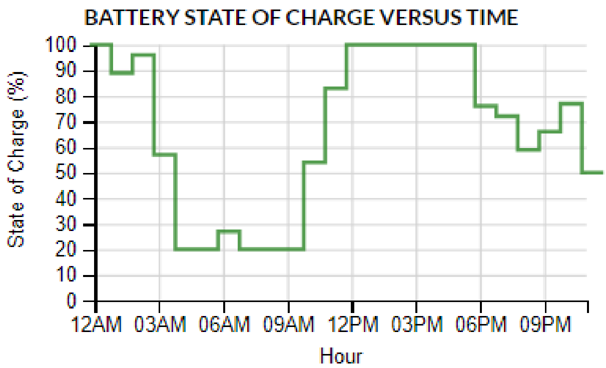
- Renewable power harvested during the night low compared to the previous months. This is linked to seasonal change.
- There is remarkable penetration though of the renewable as shown in Figure 5-13 (a) – (c) between 06h00 and 18h00.
- A peak of power harvested is noted at about 12h00 to be at > 1, 2 MV. The same peak is noted from the Matlab simulation.
- About 0.9 MW of power from PV solar and 1.2 MW of power from wind is available to the grid.
- From both the Matlab and Homer simulation, a peak in the harvested power is noted at about 12h00 for the PV at about 0.5MW and wind at 0.8 MW.
- The depth of discharge is fluctuating from 20% to 70% due to the low renewable energy available for harvesting as shown in Figure 5-13 (c)



(a)



(b)



(c)

Figure 5-6 Case 1 April Homer Graphs: (a) Combination of Renewable & Grid (b) Baseline and System Grid (c) BESS

The following similarities are noted between the Matlab and Homer simulation results,

- The Homer and Matlab results confirm the month of August to be the peak month as shown on the graphs above Figure 5 14 (a) and (b)
- During August there is renewable power available for harvest throughout the day, the wind technology is leading
- From 06h00 to 18h00 in the evening, power > 1 MW can be harvested
- The BESS is required from 18h00 in the evening. The SoC drops from 100% at 18h00 to 20 % at 02h00. It peaks up at 10h00 as shown in Figure 4-14 (c) when the renewables start to penetrate again in the system.

5.2.2 Case # 2 Wind + Storage: BESS + Grid

The following table presents an overview of the costs and savings for the integration of the solar, wind, BESS into the existing municipal electrical grid.

Table 5-4 – Case #2: Savings Overview

Description	Wind + Storage: BESS + Grid
Average annual energy bill savings:	R6 495 710,00
CAPEX	R35 092 200,00
Payback time (simple/discounted):	5,8/5,8 years
Internal Rate of Return (IRR)	15,91%
Project lifetime savings over 20 years:	R129 914 200

5.2.2.1 Case 2: Electricity Bill

This case consists of a combination of the wind, solar, battery storage, and municipal grip systems.

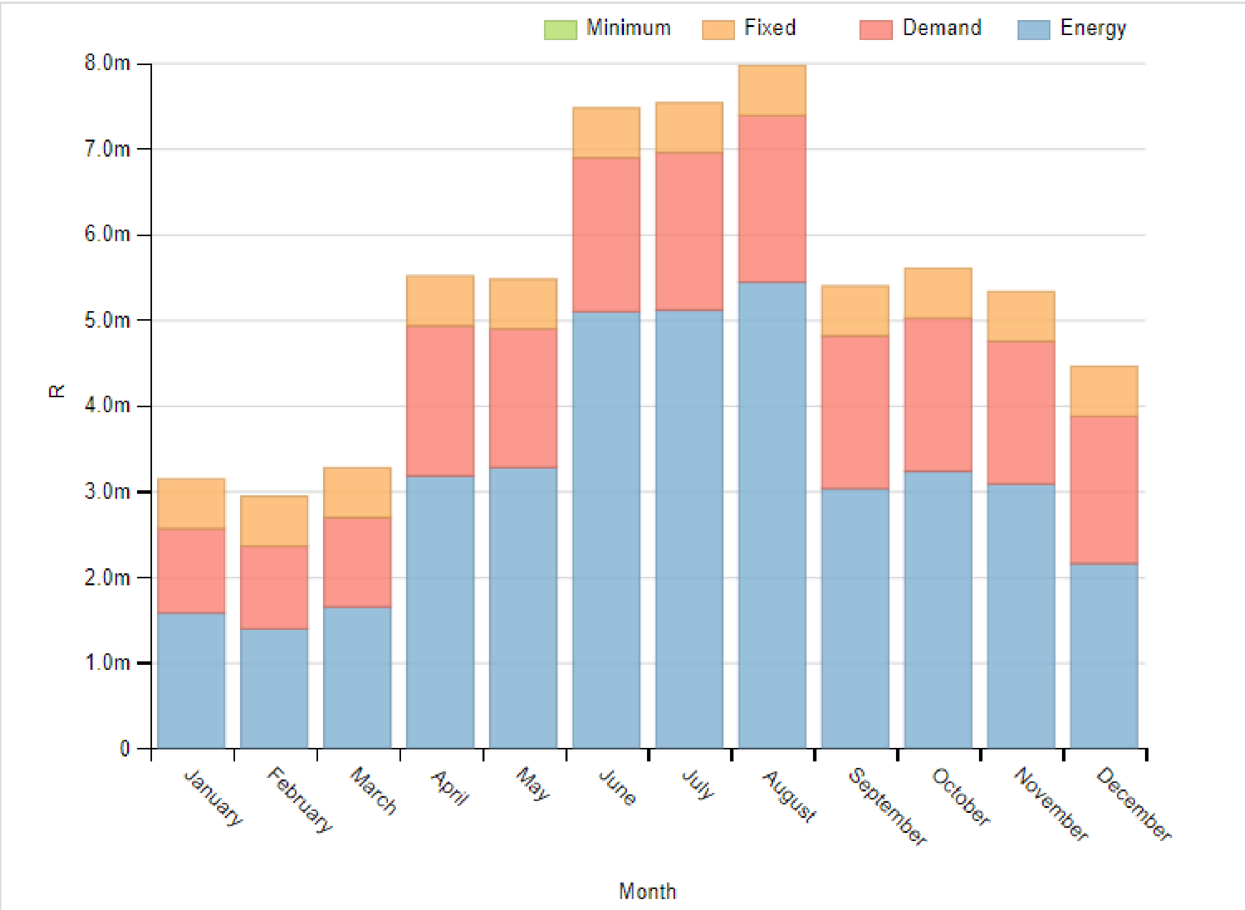


Figure 5-7 Case 2 - Monthly Electrical Bill Breakdown

5.2.2.2 Case 2 Performance Summary

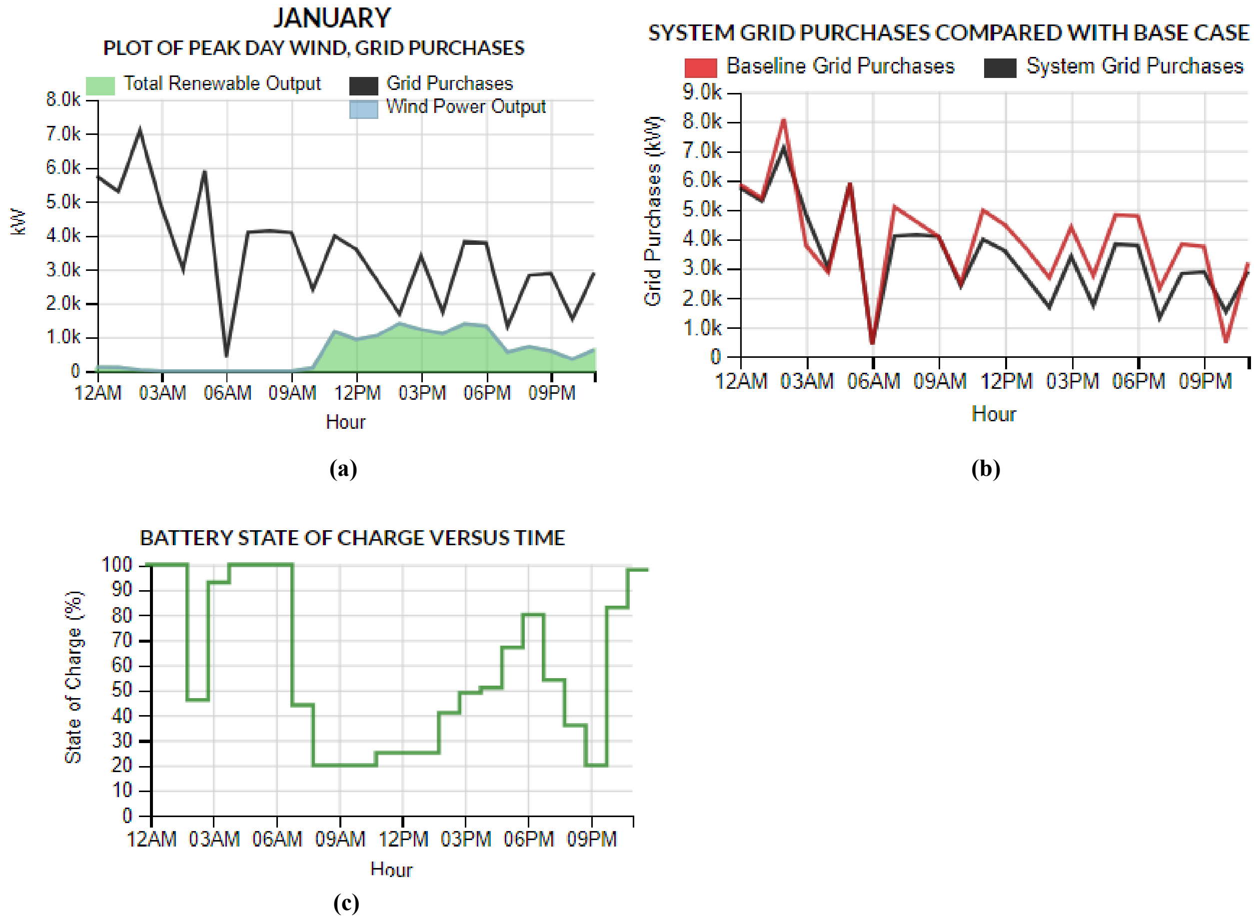


Figure 5-8 Case 2 January Homer Graphs: (a) Combination of Renewable & Grid (b) Baseline and System Grid (c) BESS

The Figures above in 5-16 (a) - (c) demonstrate the following regarding the system performance during the month of January,

- The highest municipal peak Grid purchased for the month noted on the Homer and Matlab simulation is about 7 MW
- The highest renewable output recorded is > 1.4 MW
- The peak baseline Grid purchased is about 8.1 MW as shown in Figure 5-16 (b)
- The state of charge percentage graph in Figure 5-16 (c) correlates with the periods when the renewable power is harvested

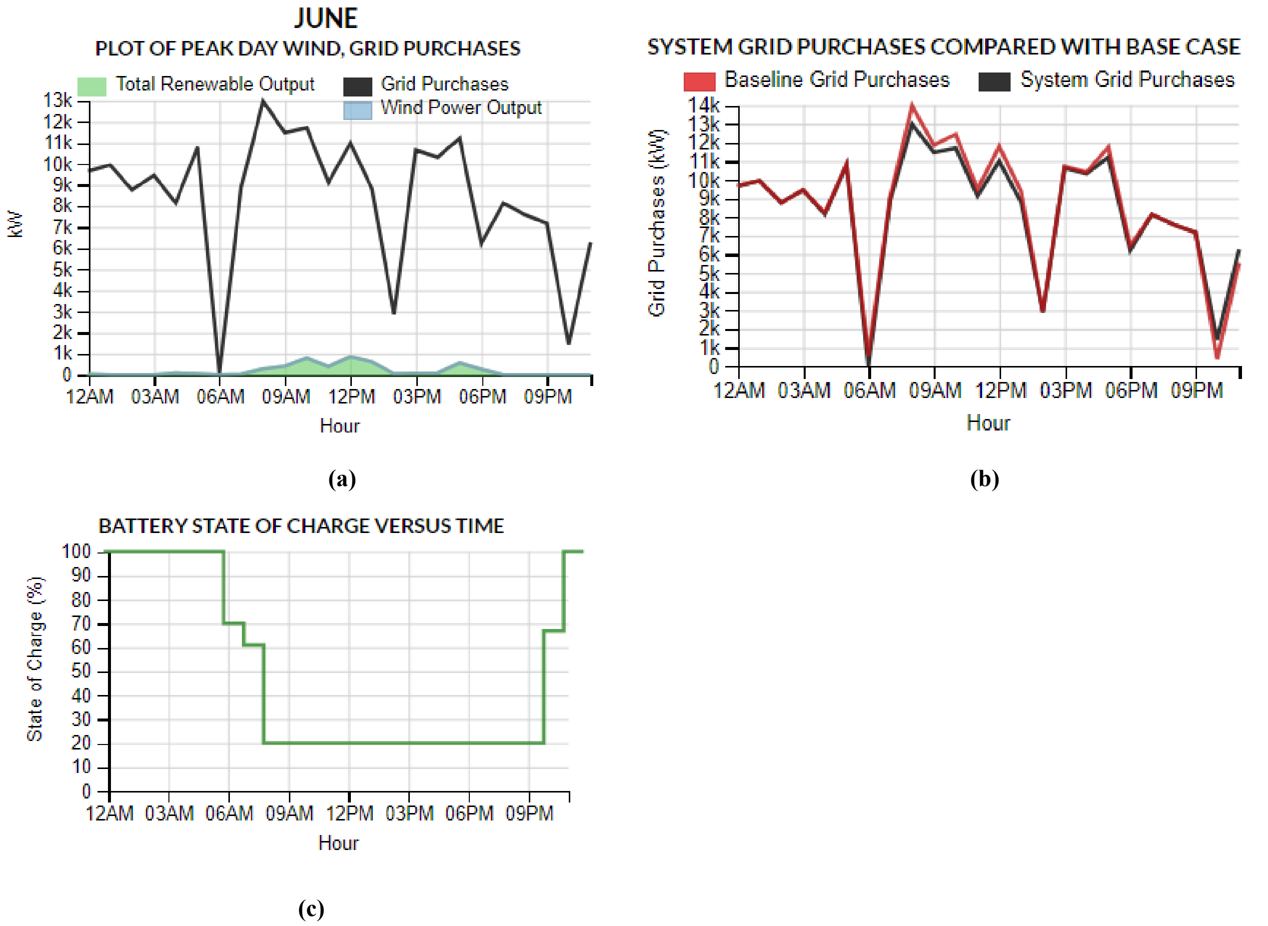


Figure 5-9 Case 2 June Homer Graphs: (a) Combination of Renewable & Grid (b) Baseline and System Grid (c) BESS

Figures 5-17 (a) – (c) above demonstrate the system performance during the month of June as follows,

- The highest municipal peak Grid purchased for the month is about 13 MW
- During the June winter month, there is not much to harvest from the wind renewable according to the results on graph 5-17 (a)
- The wind power peaks up at about 07h00 and reaches its peak at 10h00. At 10h00 and 12h00 the wind system can harvest power > 1 MW
- The state of charge percentage graph correlates with the period when the renewable energy is harvested. The DoD is 0% between 22h00 and 18h00 and drops to 80% between 08h00 and 21h00 as shown in Figure 5-17 (c).

5.2.3 Case # 3 Solar + Wind + Grid

The following table presents an overview of the costs and savings for the integration of the solar, wind, BESS into the existing municipal electrical grid.

Table 5-5 – Case #3: Savings Overview

Description	Solar + Wind + Grid
Average annual energy bill savings:	R5 489 070,00
CAPEX	R33 975 220,00
Payback time (simple/discounted):	6,8/6,8 years
Internal Rate of Return (IRR)	13,50%
Project lifetime savings over 20 years:	R109 781 400

5.2.3.1 Electricity Bill

This case consists of a combination of the wind, solar, battery storage, and municipal grip systems.

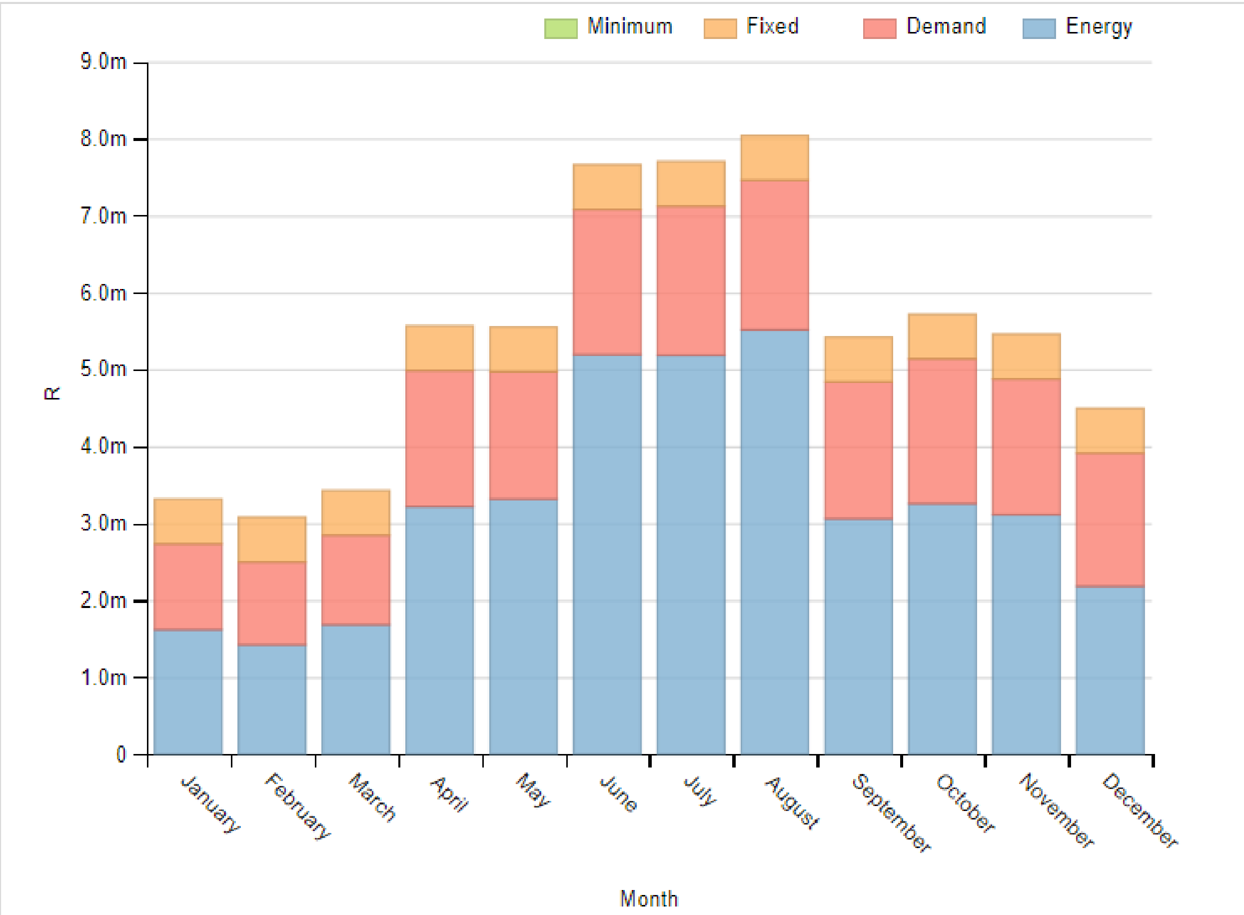


Figure 5-10 Case 3 - Monthly Electrical Bill Breakdown

5.2.3.2 Case 3 Performance Summary

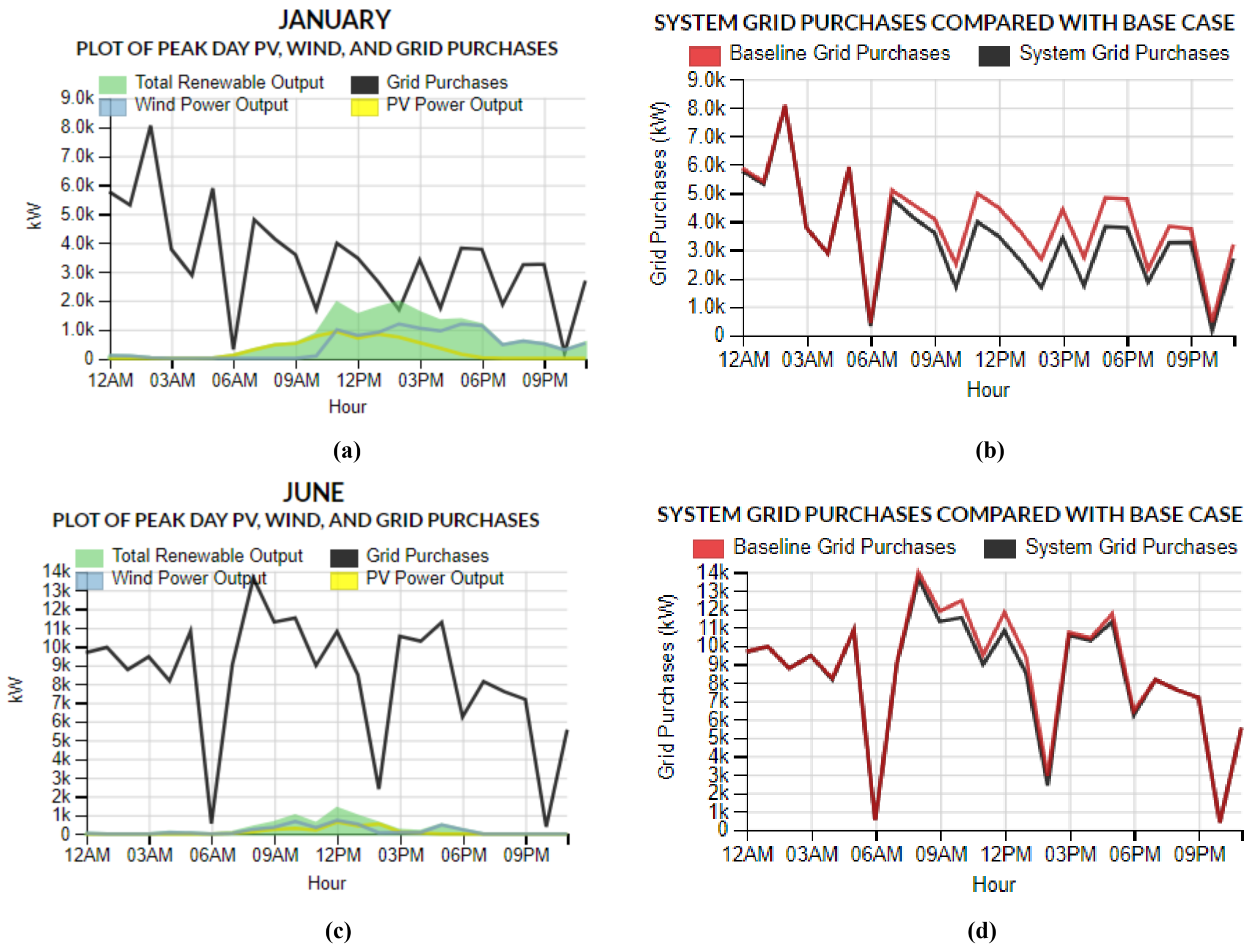


Figure 5-11 Case 3 January & June Homer Graphs: (a), (c) Combination of Renewable & Grid (b), (d) Baseline and System Grid

Figures 5-19 (a) – (d) above demonstrate the system performance during the months of January and June as follows,

- Between 09h00 and 21h00 in the evening, the wind power output confirms the availability of renewable greater than 1 MW
- The peak Grid purchased for January is about 8 MW Figure 5-19(b) and about 8.4 MW for June shown in Figure 5-19(d)
- During the June winter month, there is not much to harvest from the wind renewable according to the results on graph 5-19 (d)
- The wind power peaks up at about 07h00 and reaches its peak at 10h00. At 10h00 and 12h00, the wind system can harvest power > 1 MW
- The Matlab simulation confirms the results demonstrated in Figure 5-19 (a) that the peak power output is > 1.5 MW at about 14h00

5.2.4 Case # 4 Wind + Grid

The following table presents an overview of the costs and savings for the integration of the solar, wind, BESS into the existing municipal electrical grid.

Table 5-6 – Case #4: Savings Overview

Description	Wind + Grid and Base
Average annual energy bill savings:	R4 986 580,00
CAPEX	R31 500 000,00
Payback time (simple/discounted):	6,9/6,9 years
Internal Rate of Return (IRR)	13,19%
Project lifetime savings over 20 years:	R99 731 600

5.2.4.1 Electricity Bill

This case consists of a combination of the wind and municipal grip systems.

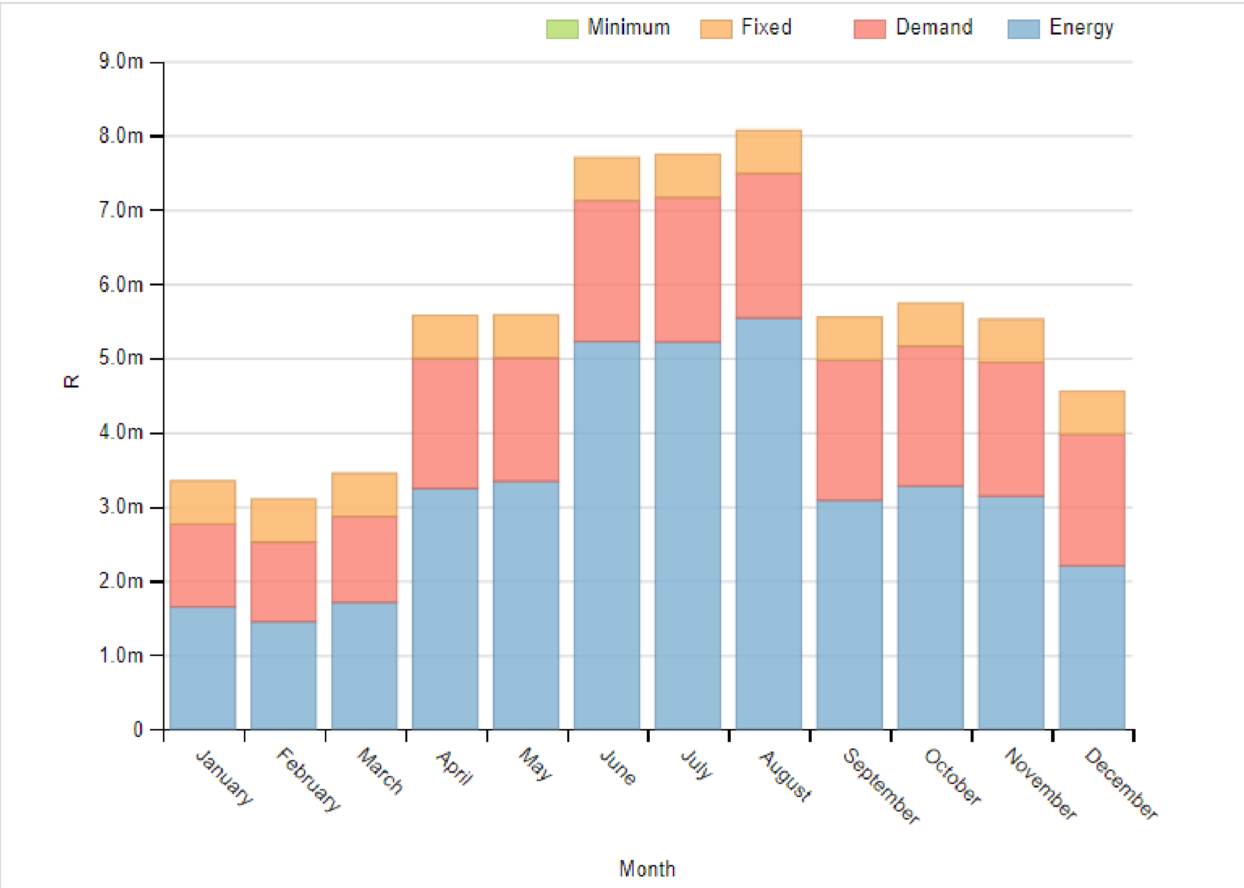


Figure 5-12 Case 4 - Monthly Electrical Bill Breakdown

5.2.4.2 Case 4 Performance Summary

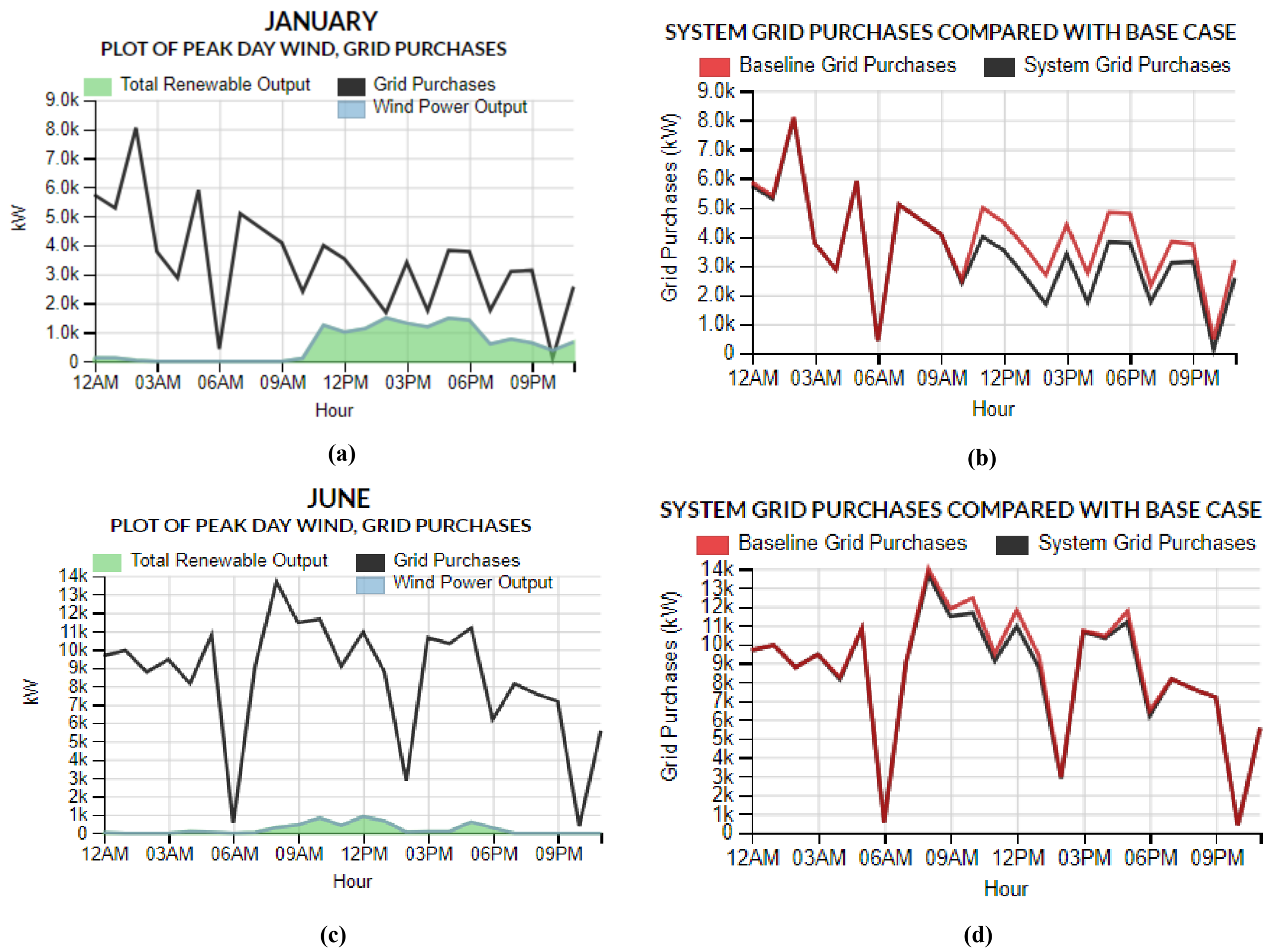


Figure 5-13 Case 4 January & June Homer Graphs: (a), (c) Combination of Renewable & Grid (b), (d) Baseline and System Grid

The homer simulation results demonstrated in Figure 5-21 (a) – (d) demonstrate the following,

- Depicts the peak power output to be > 1.5 MW at about 14h00
- Between 09h00 and 21h00 in the evening, the wind power output confirms the availability of renewable greater than 1 MW
- The peak Grid purchased for January is about 8.1 MW Figure 5-19(b) and about 14 MW for June shown on Figure 5-19(d)
- During the June winter month, there is not much to harvest from the wind renewable according to the results on graph 5-19 (d)
- The wind power peaks up at about 07h00 and reaches its peak at 10h00. At 10h00 and 12h00, the wind system can harvest power > 1 MW

5.2.5 Case # 5 Solar + Storage: BESS + Grid

The following table presents an overview of the costs and savings for the integration of the solar, wind, BESS into the existing municipal electrical grid.

Table 5-7 – Case #5: Savings Overview

Description	Solar + Storage: BESS + Grid
Average annual energy bill savings:	R4 262 710,00
CAPEX	R19 434 080,00
Payback time (simple/discounted):	4,6/4,6 years
Internal Rate of Return (IRR)	19,85%
Project lifetime savings over 20 years:	R85 254 200

5.2.5.1 Electricity Bill

This case consists of a combination of the solar, storage, and municipal grip systems.

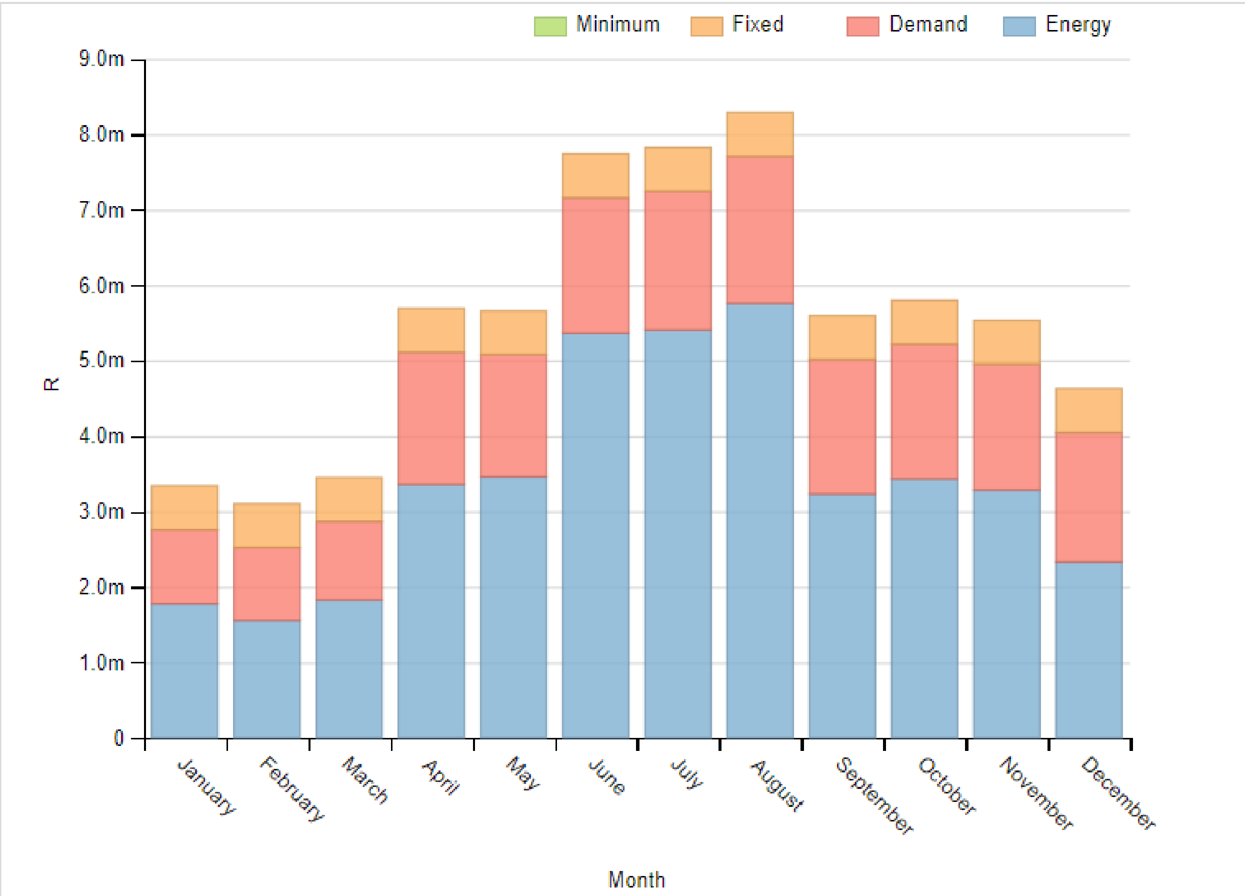
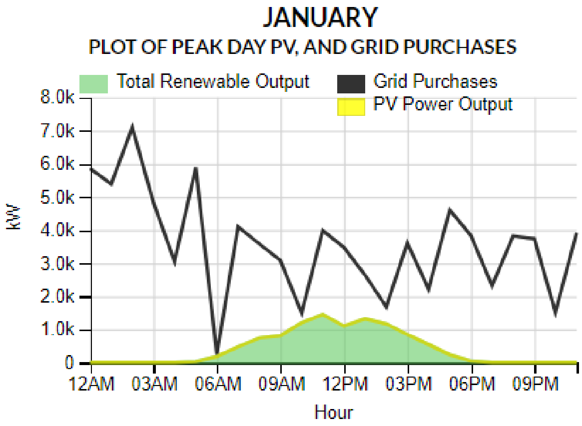
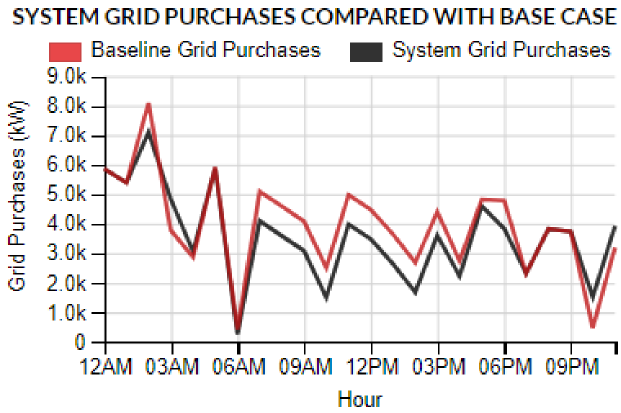


Figure 5-14 Case 5 - Monthly Electrical Bill Breakdown

5.2.5.2 Case 5 Performance Summary



(a)



(b)

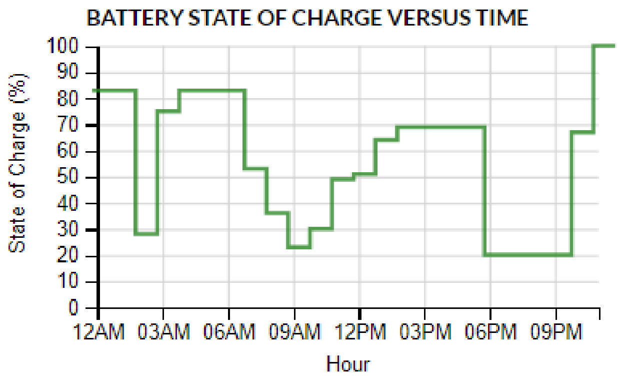


Figure 5-15 Case 5 January Homer Graphs: (a) Combination of Renewable & Grid (b) Baseline and System Grid (c) BESS

The following is noted from the Homer simulation results in Figure 5-23 (a) – (c) above in comparison with the Matlab simulation;

- The demonstrated in Figure 5-23 (a) flags the peak power output to be > 1.5 MW at about 11h00
- Between 06h00 and 18h00 in the evening, the PV Solar power output confirms availability of renewable
- The peak Grid purchased for the month is about 8.1 MW Figure 5-23(b)
- It is notable that when the demand increases at about 01h00 and 02h00, the BESS kicks in. The SoC is dropped from above 80% to 30% in Figure 5-23 (c).
- The penetration of renewable has an impact from 09h00 and the coloration is seen on how the battery recharges up from this time.

5.2.6 Carbon Dioxide (CO_2) Emissions

Green House Gases (GHG) - as stated in the introductory chapters, the main intention is not to only address the energy demand issue but to also respond to the environmental challenges, that is to reduce the CO_2 Emissions. The introduction of the distributed generation has contributed positively to the reduction of GHG. The simulation results as presented in the table below demonstrate a total of about 28 137, 2 metric ton/yr of CO_2 emissions reduction if the wind and solar technology are introduced with the combination of the battery storage in the port environment.

Table 5-8 Environmental Impacts

	Base Case	Solar + Wind + Storage: BESS + Grid	Wind + Storage: BESS + Grid	Solar + Wind + Grid	Wind + Grid	Solar + Storage: BESS + Grid
Environmental Impact						
CO_2 Emissions* (metric ton/yr)	31 300,8 t/yr	27 835,3 t/yr	28 072,5 t/yr	28 075,9 t/yr	28 309,9 t/yr	29 859,8 t/yr
Months	**January**	**February**	**March**	**April**	**May**	**June**
Monthly Total (metric tons)	1 647 t	1 452 t	1 711 t	2 976 t	3 002 t	3 005 t
	July	**August**	**September**	**October**	**November**	**December**
	3 048 t	3 180 t	3 012 t	3 090 t	2 959 t	2 218 t
Annual Total (metric tons)	**31 301 t/yr**					

Based on the monthly energy consumption combined with the renewable technologies above-mentioned, the CO2 reduction average to about 2608 metric tons per month with a total annual reduction of about 31 301 metrics tons/year.

There is a total of about 2, 79% of energy produced from the PV solar distributed to the grid about 1 410 647 kWh/year. The wind turbine generation produced about 10% of the total energy produced resulting in 5 045 537 kWh/year of energy distributed to the grid. Close to 44 043 259 kWh is from the Grid purchased energy, as indicated below it contributes close to 87% of the total kWh/year

5.3 Matlab Simulation Results

5.3.1 Case 1 – Base Case

Case 1 presents the base case where there is no integration of renewables and all power is drawn from the grid. The following is noted:

- The load is simulated with a power factor of 0.7. The loading is higher in the peak period (April to October) due to the higher loads drawn from the Reefers. This can be seen from the peak demand during the month of January at 4.5 MW and 8.5 MW in June
- The total cost peaks from June to August cost about R8 million with a large component of this being the energy costs. This is also peak season for the grid.

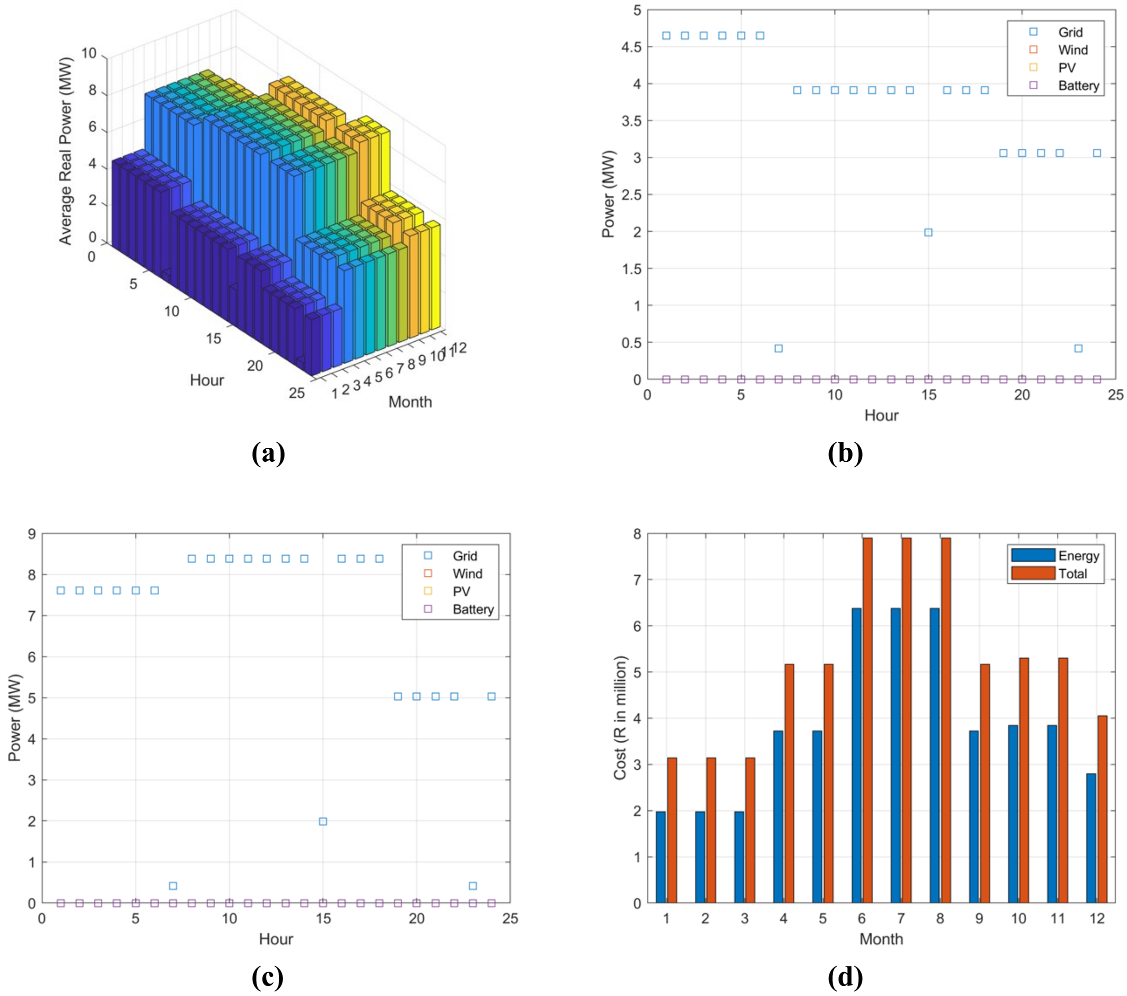
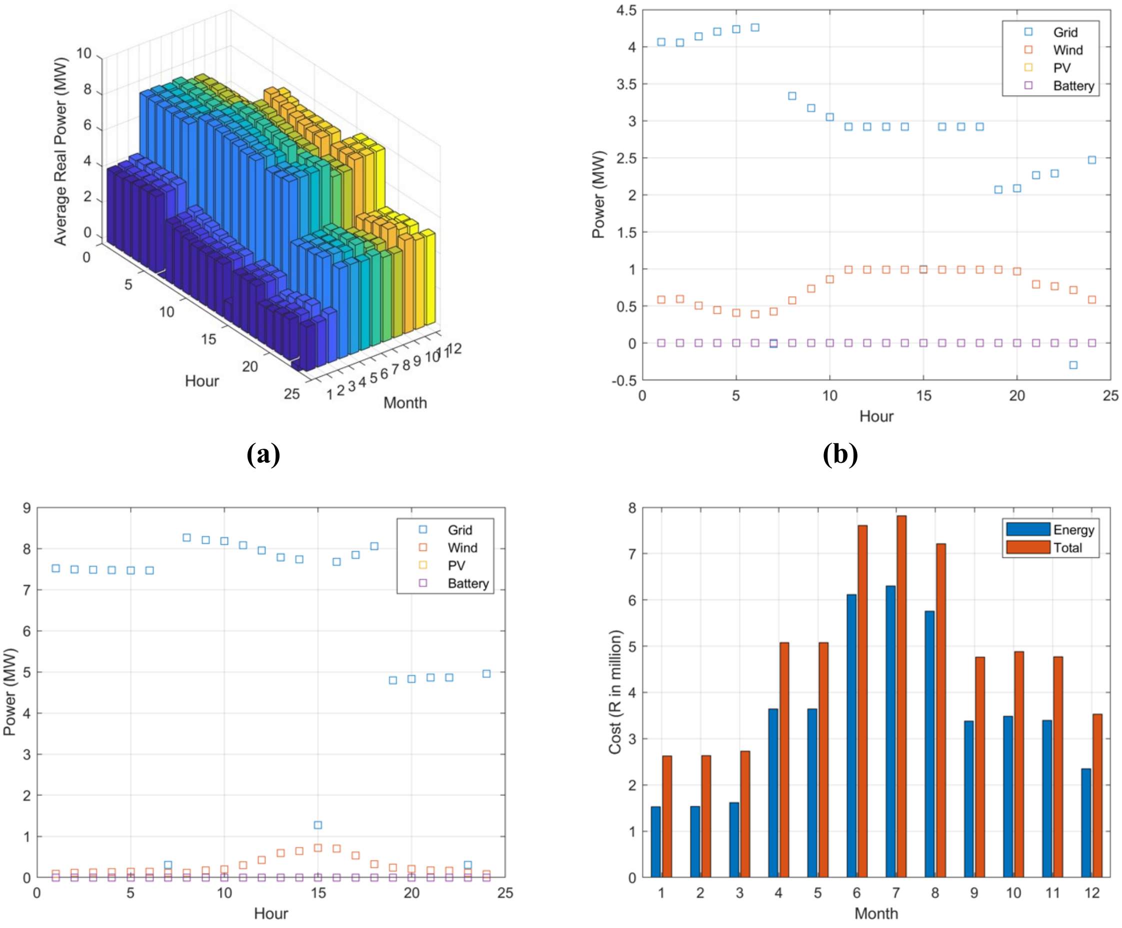


Figure 5-16 Results for Case 1 (a) Power Supplied from the Grid per Hour per Month, (b) Power Supplied and Generated for January, and (c) June, (d) Monthly Cost of Electricity

5.3.2 Case 2 – Wind Generation Integration

The integration of wind generation to the Grid provides the following improvement:

- Added power is injected into the grid averaging about 0.5 MW and reaching the peak of > 1MW at about 15h00 on an average daily performance
- During June the daily Grid peak demand was about 8.5MW during peak demand at 15h00 but with the introduction of the wind turbine it has plummeted from >8MW to about 2.5MW.
- There are energy saving costs noted during the peak months that are as a result of the wind harvested. This is evident when comparing the cost of electricity with the base case.



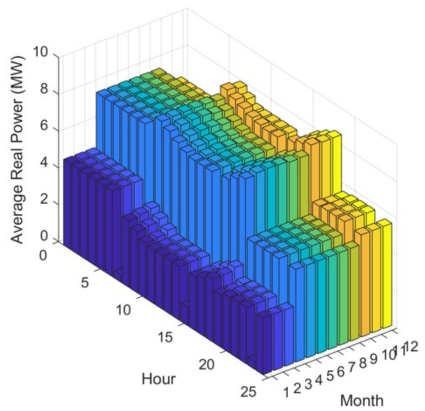
(a) (b) (c) (d)

Figure 5-17 Results for Case 2 (a) Power Supplied from the Grid per Hour per Month, (b) Power Supplied and Generated for January, and (c) June, (d) Monthly Cost of Electricity

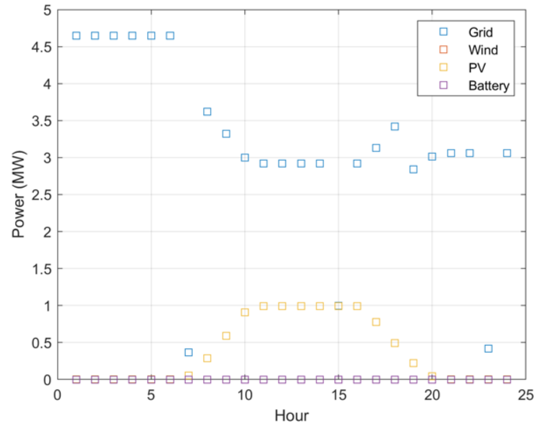
5.3.3 Case 3 – PV Generation Integration

The results present the following,

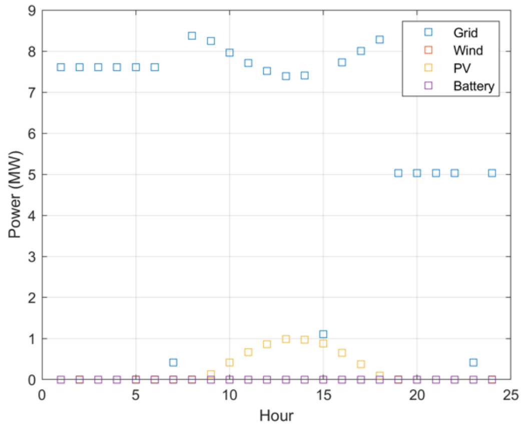
- The PV generation injected power assist to reduce the peak demand between 8h00 and 16h00
- A similar pattern is seen in January but the PV solar is capped at not > 1MW.
- Reduction in energy cost during June, July, and August



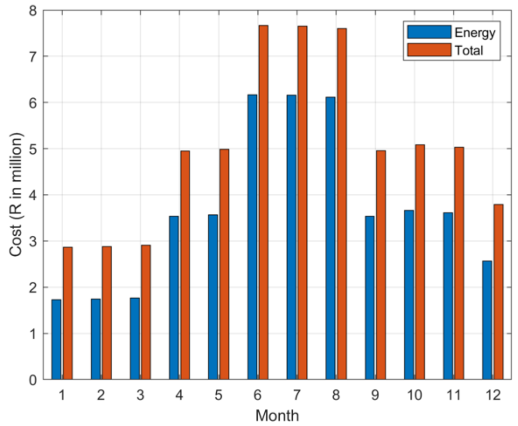
(a)



(b)



(c)



(d)

Figure 5-18 Results for Case 3 (a) Power Supplied from the Grid per Hour per Month, (b) Power Supplied and Generated for January, and (c) June, (d) Monthly Cost of Electricity

5.3.4 Case 4 – Wind Generation with BESS Integration

The introduction of the BESS in wind generation provides the following positive results,

- It can improve the PF.
- The harvested wind power that averages greater than0.6 MVA the day is made available when needed via the BESS
- Grid peak is reduced from greater than 4 MW to about 2.5 MW in January
- Average daily hourly energy reduction of about 0.5 MW in June
- There is not much energy cost reduction

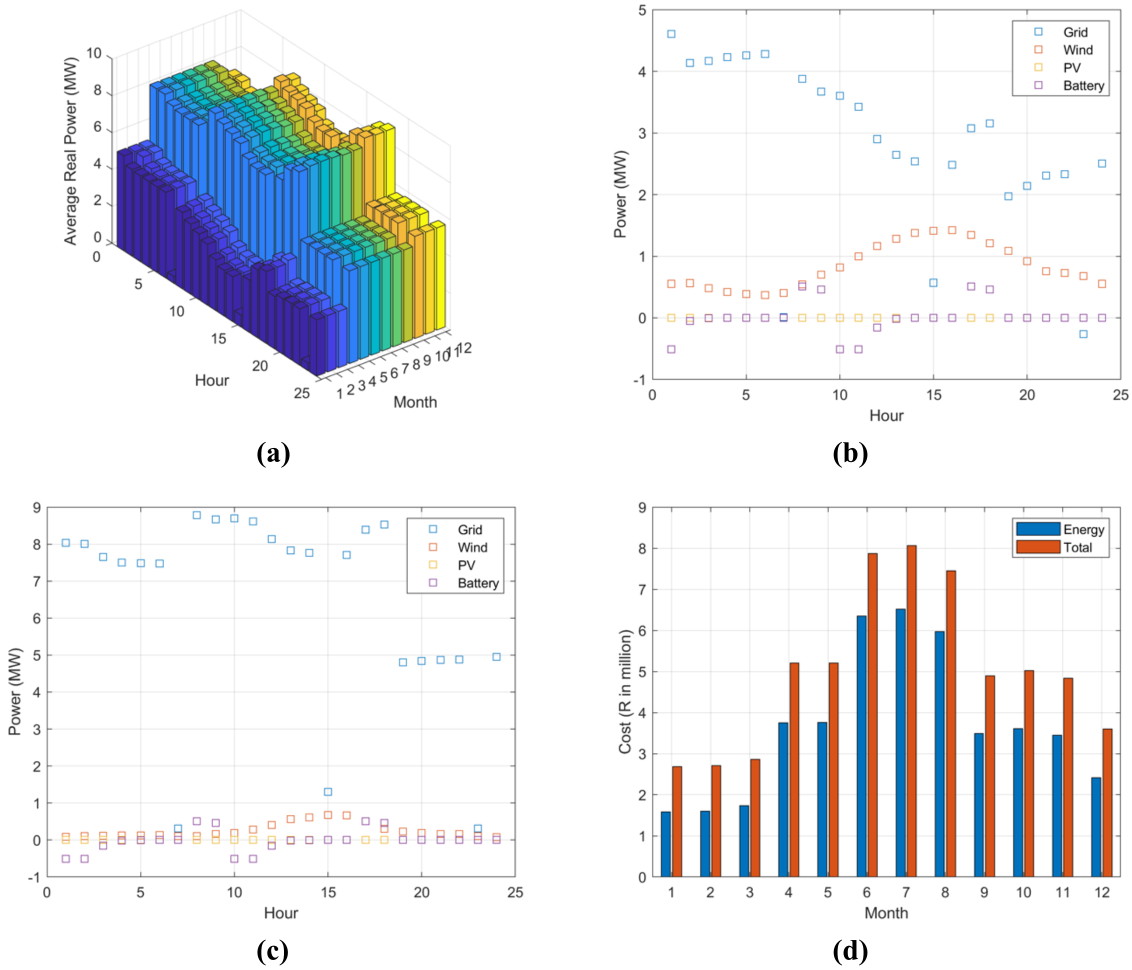


Figure 5-19 Results for Case 4 (a) Power Supplied from the Grid per Hour per Month, (b) Power Supplied and Generated for January, and (c) June, (d) Monthly Cost of Electricity

5.3.5 Case 5 – PV Generation with BESS Integration

The BESS integration in the PV and Grid yields the following positive results,

- It improves the power curve and reduces the demand
- Power supply-demand is reduced from about 4 MW to 2.5 MW with the PV and BESS integration, during January
- The injection of the PV generation with the BESS resulted in about a 1 MW reduction of Grid demand in June during the peak harvesting time the PV technology.

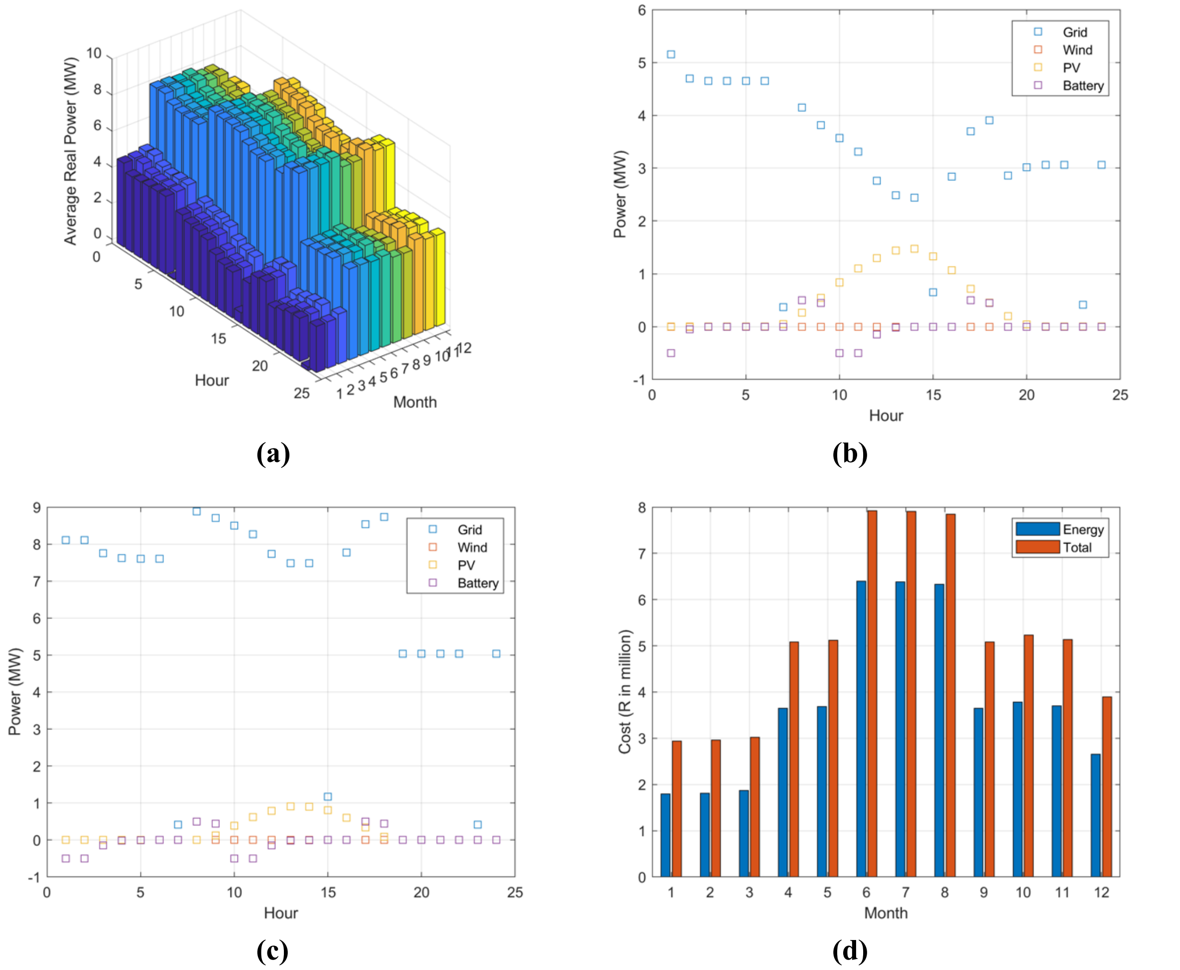


Figure 5-20 Results for Case 5 (a) Power Supplied from the Grid per Hour per Month, (b) Power Supplied and Generated for January, and (c) June, (d) Monthly Cost of Electricity

5.3.6 Case 6 – Wind Generation, PV Generation and BESS Integration (LI)

The results of the wind, PV, and BESS are as follows,

- The peak months are July to November, demand time is between 06h00 and 18h00
- Peak demand is reduced from 4 MW to about 2.5 MW in January during the peak time
- The BESS is capped at 1MW
- During the January and June month battery has shown a Depth h of Discharge (DOD) of 50%

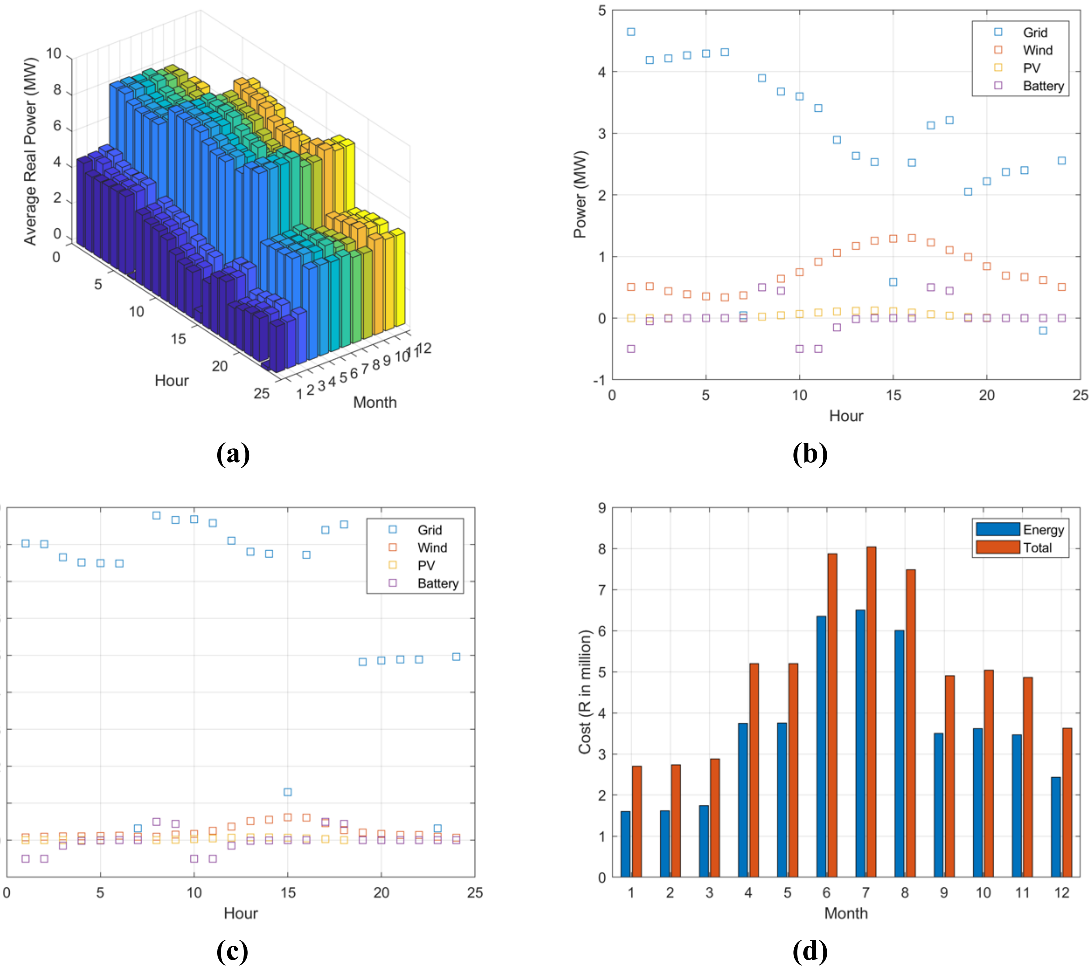


Figure 5-21 Results for Case 6 (a) Power Supplied from the Grid per Hour per Month, (b) Power Supplied and Generated for January, and (c) June, (d) Monthly Cost of Electricity

5.3.7 Case 7 - Wind Generation, PV Generation and BESS Integration (LA)

The results of the wind, PV, and BESS (Lead Acid) are as follows,

- The peak months are July to November, demand time is between 06h00 and 18h00
- Peak demand is reduced from 4 MW to about 2.5 MW in January during the peak time
- The BESS (LA) is capped at 1MW
- During the January and June month battery has shown a Depth h of Discharge (DOD) of 50%
- The efficiency between the two batteries (LA & LI) plays a huge wrong in the total performance of the BESS. Generally, the different types of batteries have a different % of DoD. The LA is 50% and LI is 80%

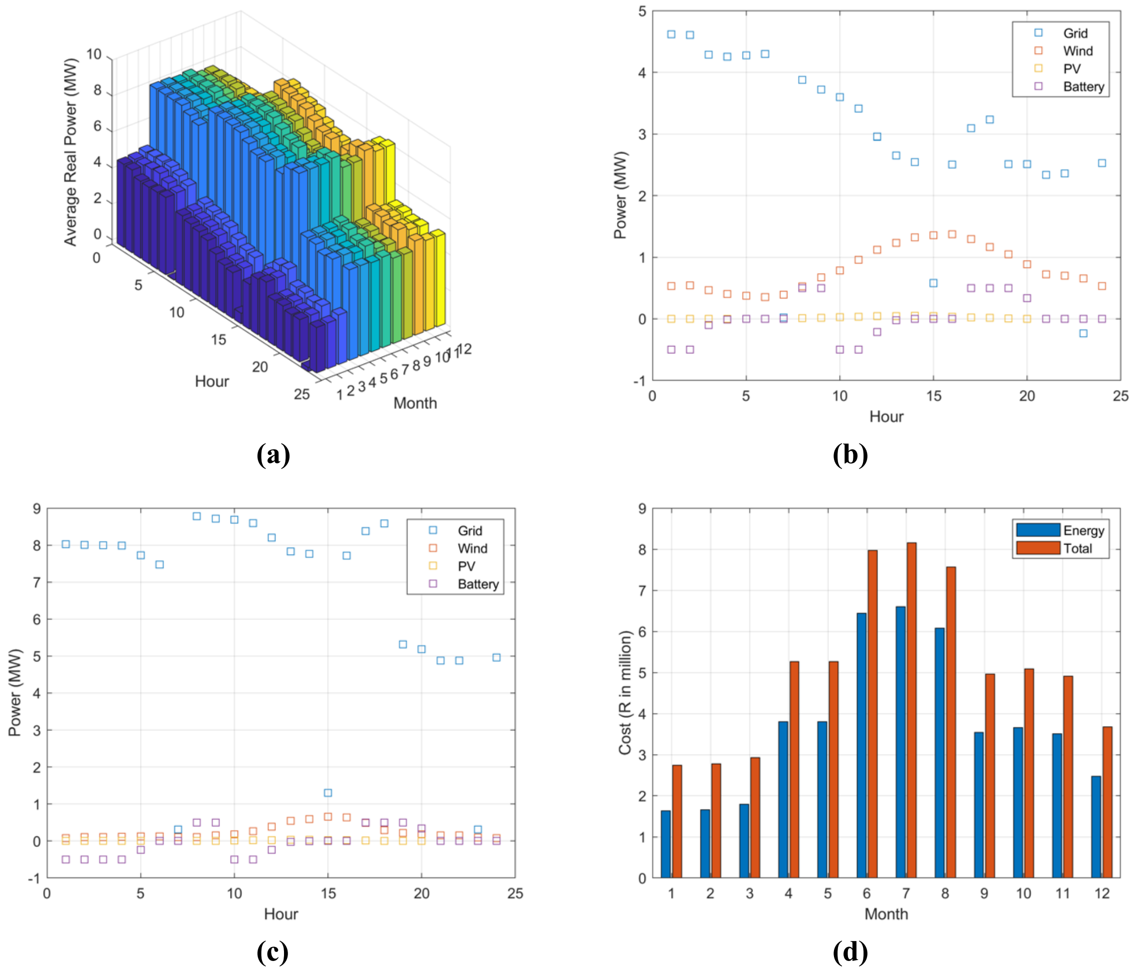


Figure 5-22 Results for Case 7 (a) Power Supplied from the Grid per Hour per Month, (b) Power Supplied and Generated for January, and (c) June, (d) Monthly Cost of Electricity

5.4 Discussion

5.4.1 Cost Analysis

The homer simulation cost analyses results demonstrate that Case 1 is the lowest-cost system. The NPC is about R1.3 billion against the base case NPC of R1.42 billion. The initial capital required for the project is about R38. 4 mil. The operational and maintenance cost for the proposed case is R64 million per year against the R70.9 million per year for the base case. The levelized cost of energy has improved from R1.43/kWh base case to R1.35/kWh for the recommended case 1 solution. Regarding the savings, the annual utility bill savings is R6.83M/yr. The net present utility bill savings are estimated at R137million with the annual demand charge savings noted at R1.65 million. About R5.18 million is captured to be the annualized energy charge savings.

Table 5-9 Homer Optimization Costs and Savings Analysis

	Base Case	Case 1: Wind + Storage: 1MLI + Grid	Case 2: Solar + Wind + Storage: 1MLI + Grid	Case 3: Storage: 1MLI + Grid	Case 4: Solar + Storage: 1MLI + Grid	Case 5: Solar + Wind + Grid
Costs and Savings						
CAPEX	R0	R38 419 420	R35 092 200	R33 975 220	R31 500 000	R19 434 080
OPEX	R70 876 660	R64 802 890	R65 054 760	R65 942 100	R66 340 090	R67 129 710
Annual Total Savings (R)	R0	R6 073 776	R5 821 908	R4 934 560	R4 536 572	R3 746 952
Annual Utility Bill Savings (R)	R0	R6 832 600	R6 495 710	R5 489 070	R4 986 580	R4 262 710
Annual Demand Charges (R/yr)	R20 545 450/yr	R18 892 030/yr	R18 895 440/yr	R19 706 220/yr	R19 881 790/yr	R18 893 380/yr
Annual Energy Charges (R/yr)	R50 331 220/yr	R45 152 040/yr	R45 485 520/yr	R45 681 380/yr	R46 008 300/yr	R47 720 580/yr
Economic Metrics						
Discounted payback time (yrs.)		6,0	5,8	6,8	6,9	4,6
Simple payback time (yrs.)		6,0	5,8	6,8	6,9	4,6
LCOE (R/kWh)	R1,431/kWh	R1,346/kWh	R1,348/kWh	R1,362/kWh	R1,367/kWh	R1,375/kWh
IRR %		15,17%	15,91%	13,50%	13,19%	19,85%
Net Present Cost (R)	R1 417 533 000	R1 334 477 000	R1 336 187 000	R1 352 817 000	R1 358 302 000	R1 362 028 000

The results in the above table 5-11 can further demonstrate cost savings with the introduction of the standby generator set in the system. About R20 million is spent per year on the standby generator set to secure 2 MVA refer feeds. The LCOE for the standby generator only is about R2/ kWh but an improved LCOE can be realized when the 2 MVA standby generator annual cost is injected into the project and renewable power output requirement is increased by the same size MW generator set.

5.4.2 Cash Flow

On the economic metrics, the IRR is about 15% with the simple payback of about 6 years as demonstrated below. The ROI output variable is about 11%. This is the average yearly difference in nominal cash flows over the project lifetime divided by the difference in capital cost.

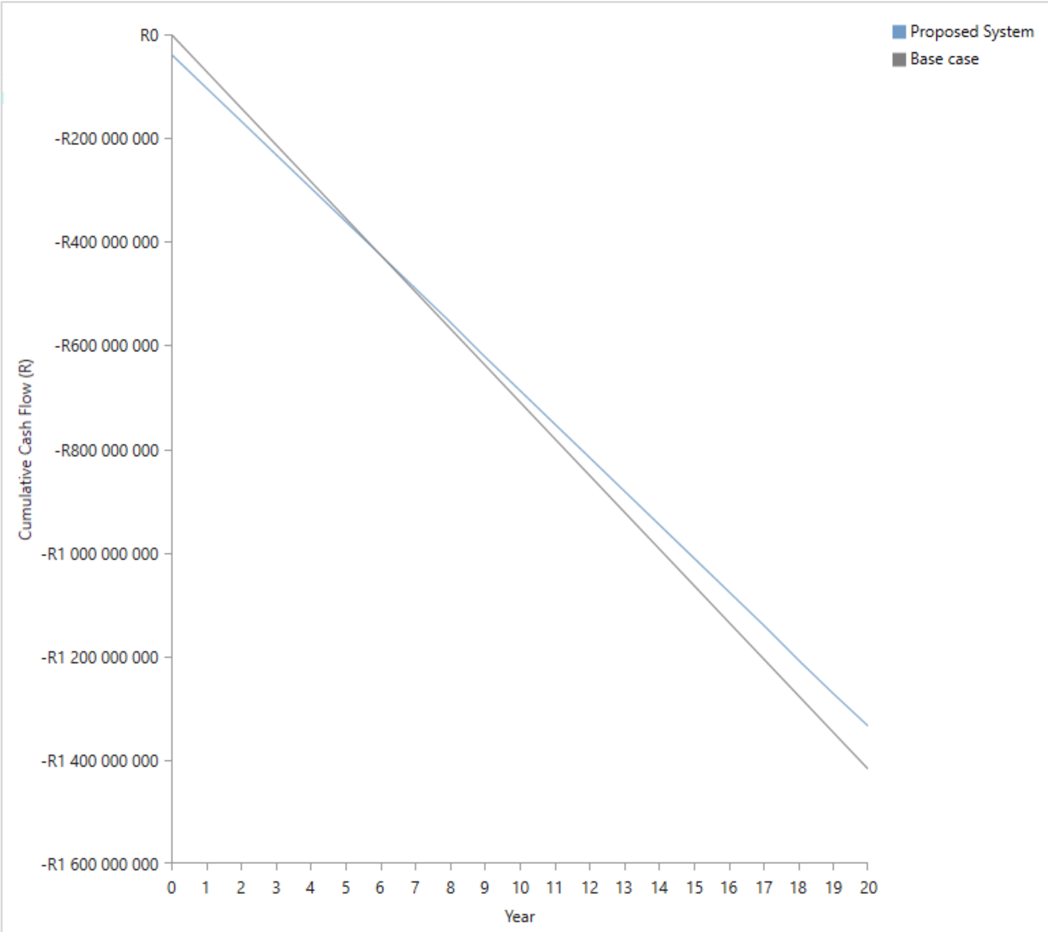


Figure 5-23 Case 1 Cash Flow

5.5 Summary and Discussion

Table 5-10 Summary of results

Case	Details of Generation		Total Energy from the Grid per Annum (MWh)	Total Cost per Annum	Total Energy Cost per Annum	NPV of Integrated Components	LCOE of Integrated Components***
1	Base		49741	R 63.29m	R 46.71m	-	-
2	Pwind	1591 kW	46623	R 58.28m	R 42.39m	R57.28m	R 1.27 / kWh
3	Ppv	1629 kW	46707	R 60.07m	R 43.91m	R34.21m	R 1.20 / kWh
4	Pwind	1510 kW	46704	R60.40m	R44.23m	R81.76m	R 1.71 / kWh
	Pbess	511 kW					
	Cbess	1026 kWh					
5	Ppv	1502 kW	48396	R62.15m	R45.72m	R58.4m	R 1.77 / kWh
	Pbess	503 kW					
	Cbess	1006 kWh					
6	Pwind	1376 kW	46836	R60.54m	R44.34m	R78.92m	R 1.71 / kWh
	Ppv	125 kW					
	Pbess	501 kW					

	Cbess	1002 kWh				
7	Pwind	1452 kW	47507	R61.30m	R45.00m	R91.09m	R 1.84 / kWh
	Ppv	49 kW					
	Pbess	501 kW					
	Cbess	2006 kWh					
8	Pgen	7038 kWh	49741	R20,7m	R19,6m	-	R 2/kWh

*** Does not include the tariff's monthly fixed charge costs

The following is noted from the different cases considered in the Matlab from the summary Table 4-4 above;

Case 2:

- Case 2 demonstrates a reduction in the total energy from the Grid per annum
- There wind turbine injects about 1591 kW power to the grid over 12 months
- The LCOE is about R1,27/kWh
- A reduction of about 3118MWh is observed from the results

Case 3:

- The PV solar compared to the case 2 wind turbine has an LCOE of about R1,20/kWh.
- A total of about 1692 kW of power is injected into the grid
- The introduction of PV solar reduces stress from the Grid per annum to a total of about 3034 MWh

Case 4 and Case 5:

- Case 4 and 5 demonstrate an increase in the LCOE, this is as a result of the introduction of the battery storage.
- Case 5 demonstrates a higher LCOE of R1.77/kWh
- The benefit of the introduction of the Bess is the ability to flatten the demand curve but shift the stored harvested power to peak demand hours.
- About 2005 kW for each case is generated from the PV solar and wind generation technologies

Case 6:

- The total energy from the grid is reduced by 2905 MWh per annum
- The combination of PV solar with the wind turbine introduces a penetration of the renewable to the grid to a total of about 1501 kW
- About R2,37 million of energy cost is reduced per annum

Case 7:

- This case combines the PV Solar, Wind Generation, and BESS
- The LCOE is noted to be the highest, R1,84/kWh

Case 8:

The LCOE for the introduction of the generator is about R2,00/kWh

The issues with the model include:

- The time of use tariffs did not currently take into account the differences on the weekends.
- The battery charge and discharge were not optimized; they were set for peak times.
- The constraint set for the sizing of the generator and BESS inverter did not take account of the hourly operation.
- The wind data and wind generator power curve modeling could have been more accurate.
- The PV data and PV generator could be more accurately modelled.
- The diesel generation could be included.

The hybrid generation constraint could be optimized. i.e. It is currently set for the rated generation, not the generation per hour. For example, the PV generation dominates in winter and the method may not currently take this into account

5.6 Conclusion

It was noted from the comparison of Matlab and Homer that both tools have capabilities to compare the costs and savings for installing different combinations of batteries, solar panels, and generators. This is clearly stated in Cases 1 to 5 and demonstration graphs abovementioned.

We have seen from this chapter that both the Matlab and HOMER software use a powerful optimization tool to find the system that maximizes savings. Using the input of hourly power consumption profile from the port energy it matches ed renewable energy generation to the required load.

The solution presented from Case 1 using HOMER and Matlab demonstrates that there is renewable power available for harvesting during the night through wind technology from 18h00 to 06h00 and it is about 0.4 MVA and > 1MVA. The penetration of the renewable is demonstrated on the PV solar cases Figures and is recorded to usually harvest between 06h00 and 18h00. Simulation power captured from PV solar using the Homer tool was between 0.2 MW to > 1 MW. This is harvested power available to the grid and to be stored via the BESS.

The limitation of the Matlab compared to the Homer is that with regards to the purchased grid electricity and cost analysis it cannot match the electricity tariff and analyze the network to provide the best solution taking into consideration all seasonal tariffs and other monthly charges. The fixed charges and other monthly charges could not be included in the Matlab simulation whereas in the Homer the simulation had taken into consideration the entire tariff structures including seasonal tariff changes.

Homer allows for the minimization of cost and optimization of cases based on the technology selected and other various factors. The cost comparison between cases 1 to 5 in this chapter demonstrates an annual total savings of between R6 million and 3,7 million depending on the solution and case considered. The case 2 scenario which incorporates the PV Solar + Wind + Storage + Grid has a potential of energy saving of about R5,5 million per annum taking into consideration all energy costs.

The optimization method used is novel since it was developed from a typical port operation environment using the energy management best practice as a benchmark.

The recommended solution will not only address the South African port operations but will also unlock other uncertainties regarding the port energy management performance benchmark and DG solution recommended to address the energy requirements for the port operation.

Further improvements to the modeling could be to investigate the direction of the PV panels and the regenerative power to further reduce the grid demand and GHG but these optimized hybrid model predictions are accurate since the data set is developed from a live port operation and can form bases for further research work.

6 Conclusion and Recommendation

6.1 Conclusion

This research presents a feasibility study of a grid hybrid renewable energy system for the improvement of energy security and improved energy management in the South African port. Therefore, a hybrid system of PV, wind, battery, and a diesel generator are selected and the optimum sizing of each component in the hybrid system is done using the HOMER and MATLAB software. Even though there is a capital investment requirement of about R39, 8 m required for this solution, there are benefits such as the CO_2 emission reduction to a value of about 28147,1 metric ton/yr. The total NPC of the recommended solution is R1 234 248 00 to implement the project. The effect of the changes on the LCOE of this system is analyzed by combining different sources of energy and the cases are presented. Simulation results showed the LCOE for the recommended option: Solar + Wind + Battery Storage + Generator to be R1, 245/kWh. The calculated discounted payback time and simple payback time is about 2,8 years. Annual utility bill savings of about R15,2m and annual total savings of about R15,3. The project lifetime savings over 20 years is about R306m. The diesel standby generator set as a standalone has an approximate LCOE of R 2/kWh. The standby generator set LCOE of R2/kWh is almost double if compared with the hybrid supply LCOE of R1.35 kWh.

In conclusion, the integration to the municipal grid of the PV solar, wind with battery storage is the solution recommended for further study.

6.2 Recommendations

There is further research required for the recommended distributed generation hybrid network model for the port integrates renewable sources of energy such as wind and solar technology combined with the battery storage system. As indicated in Chapter 3, the regenerative technology for the crane is another solution to be further investigated.

The energy management, KPIs for the port requires further research work and benchmarking to determine the best solution for the port.

The Regulation given by the minister of Energy to further increase the generation capacity to > 1 MW for the IPP without the need for a license was announced when the research was almost completed. Increasing the renewable capacity to > 1 MW will not only improve the LCOE but will also further reduce GHG by double the 28147,1 metric ton declared. The BESS can be increased by 3 MW and the renewable by a further 2 MW to eliminate the standby generator set.

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A Appendix A – Matlab Implementation

A.1 Matlab Code

A.1.1 Initiation File

```
%clear;

%[wind_h,solar_h] = enviro_dat();
%load('env_data.mat')

% Gen and Load profiles
load('load_data.mat')

%[wind_h] = env_wind()

%wind_h(isnan(wind_h))=0;

% Load
S_load = load';
pf_load = 0.7;
S_load = S_load/pf_load/1e3;        % MVA

% Wind power generator daily profile
S_wind = 1e-3*1*wind_h';            % MVA
pf_wind = 0.99;

% Solar power daily profile
S_pv = 1e-3*1*solar_h';             % MVA
pf_pv = 0.99;


% Battery power daily profile
% Replacing the Wind generator with Battery

C_bat = 1e-3;                      % Total Capacity Wh (10 MWh)
h_peak = zeros(1,24);
h_peak(8:9)=1;
h_peak(17:22)=1;
h_off = zeros(1,24);
h_off(10:16)=1;
h_off(1:5)=1;
%h_off(10:16)=1;
%h_off(21:24)=1;
n_ac = 0.85;                     % Inverter efficiency
n_ch = 0.90;                     % Charge efficiency
n_dis = 0.90;                    % Discharge efficiency
SOCmin = 0;                    % State of charge min - for LA set to 0.5
SOCmax = 1.00;                   % State of charge max
V = 12;                          % Nominal battery voltage
E_bat = 0.2*C_bat;               % Total Stored Energy Wh
P_inv = 1e-3;                    % Inverter size (VA) (max discharge power)
P_con = P_inv;                   % Charge power (VA)
P_bat = 0;
Q_bat = 0;

% Initialise the model with the following data.
P_wind = S_wind*pf_wind;
Q_wind = S_wind*sin(acos(pf_wind));

P_pv = S_pv*pf_pv;
Q_pv = S_pv*sin(acos(pf_pv));

P_load = S_load*pf_load;
Q_load = S_load*sin(acos(pf_load));
```

A.1.2 Main File

```
clear;

tic
%
% x = [0 0 0 0];                          % Scenario 1 - Base case.
% TOC = f_TOC(x)

%
%  x = [1591 0 0 0];                          % Scenario2 - Upper limit set to 2MW and the power
curtailed to 1MW.
%  TOC = f_TOC(x)

x = [0 1629 0 0];                    % Scenario3 - Upper limit set to 2MW and the power curtailed
to 1MW.
TOC = f_TOC(x)

x = [1510 0 511 1026];                 % Upper limit set to 2MW and the power curtailed to 2MW.
Constrained that Pwind-Pinv = 1MW
TOC = f_TOC(x)

x = [0 1502 503 1006];                 % Upper limit set to 2MW and the power curtailed to 2MW.
Constrained that Ppv-Pinv = 1MW
TOC = f_TOC(x)

x = [1376 125 501 1002];                %LI - Upper limit set to 2MW and the power curtailed to
2MW. Constrained that Ppv+Pwind-Pinv = 1MW
TOC = f_TOC(x)

x = [1452 49 501 2006];                % LA - Upper limit set to 2MW and the power curtailed to
2MW. Constrained that Pwind-Pinv = 1MW
TOC = f_TOC(x)

toc

fTOC = @(x)f_TOC(x)


 A = [1,1,-1,0;
     0 0 4 -1];
 b =[1e3;
     0];
% A = [];
% b = [];

Aeq = [];%[0,0,1,0];
beq = [];
lb = [0,0,500,0];
ub = [2e3,2e3,1e3,20e3];
nonlcon = [];
Intcon = [1:4];

options = optimoptions('ga','PlotFcn',{@gaplotbestf});
options = optimoptions(options,'MaxGenerations',100);
[P,TOCf] = ga(fTOC,4,A,b,Aeq,beq,lb,ub,nonlcon,Intcon,options)

toc

 function TOC = f_TOC(x)

x_wind = x(1)
x_pv = x(2)
x_bat = x(3)
y_bat = x(4)

dct_int1

SOC_bat = 0.5;              % Start with fully charged battery

S_wind = S_wind*x_wind;
S_wind(S_wind>1)=1;
S_pv = S_pv*x_pv;
S_pv(S_pv>1)=1;
```

```
P_inv = P_inv*x_bat;
P_con = P_con*x_bat;
C_bat = C_bat*y_bat;


M = 12;
H = 24;
b = 1;


 for m = 1:M
%
 for h = 1:H
%m
%h

% Loading
P_load_H = S_load(m,h)*pf_load;
Q_load_H = S_load(m,h)*sin(acos(pf_load));


% Generation

P_wind_H = S_wind(m,h)*pf_wind;
Q_wind_H = S_wind(m,h)*sin(acos(pf_wind));

P_pv_H = S_pv(m,h)*pf_pv;
Q_pv_H = S_pv(m,h)*sin(acos(pf_pv));


define_constants;

mpc = loadcase('dct')

mpc.gen(2, PG) = P_wind_H;
mpc.gen(3, PG) = P_pv_H;


% Battery loop
if b == 1
% Discharge loop
if h_peak(h) == 1
    if SOC_bat >= SOCmin
       P_bat = min(P_inv,(SOC_bat-SOCmin)*C_bat);
        SOC_bat = SOC_bat - P_bat/n_dis/C_bat;
        mpc.gen(4, PG) = -P_bat;
    else
        mpc.gen(4, PG) = 0;
    end
        mpc.bus(4, PD) = 0;
elseif h_off(h) == 1
% Charge loop
    if SOC_bat < SOCmax
        P_bat = -min(P_con,(SOCmax-SOC_bat)*C_bat);
        SOC_bat = SOC_bat - n_ch*P_bat/C_bat;
        mpc.bus(4, PD) = -P_bat;
    else
        mpc.bus(4,PD) = 0;
    end
        mpc.gen(4, PG) = 0;
elseif h_off(h) == 0 && h_off(h) == 0
          mpc.gen(4,PG) = 0;
          mpc.bus(4,PD) = 0;
end

SOC(1,h) = SOC_bat;

end

mpc.bus(4, QD) = 0;
mpc.gen(4, QG) = 0;

mpc.bus(5, PD) = P_load_H;
mpc.bus(5, QD) = Q_load_H;


mpopt = mpoption('verbose',0,'out.all',0);
```

```
results = runpf(mpc,mpopt);

PG1(m,h) = results.gen(1,PG);
SG1(m,h) = PG1(m,h)+j*results.gen(1,QG);
PG2(m,h) = results.gen(2,PG);
SG2(m,h) = PG2(m,h)+j*results.gen(2,QG);
PG3(m,h) = results.gen(3,PG);
SG3(m,h) = PG3(m,h)+j*results.gen(3,QG);
PG4(m,h) = results.gen(4,PG);
SG4(m,h) = PG4(m,h)+j*results.gen(4,QG);

P1(m,h) = results.bus(5,PD);
Q1(m,h) = results.bus(5,QD);
P4(m,h) = results.bus(4,PD);
Q4(m,h) = results.bus(4,QD);

% Check if iteration successful
if results.success == 0
break;
display('Failed run')
end

end

end


dct_optim1

dct_plot

 end
```

A.1.3 Post processing file

```
% Energy Rate (R/kWh)
rate_low =
[0.54,0.54,0.54,0.54,0.54,0.54,0.78,1.12,1.12,1.12,0.78,0.78,0.78,0.78,0.78,0.78,0.78,0.78,1.12,1.12,0.78,0.78,0.54,0.54];
rate_high =
[0.61,0.61,0.61,0.61,0.61,0.61,3.24,3.24,3.24,1.05,1.05,1.05,1.05,1.05,1.05,1.05,1.05,3.24,3.24,1.05,1.05,1.05,0.61,0.61];

rate(1:5,:) = rate_low.*ones(5,24);
rate(6:8,:) = rate_high.*ones(3,24);
rate(9:12,:) = rate_low.*ones(4,24);

% Network Demand Charge (R/kVA)
NDC =   97;

% Network Access Charge (R/kVA)
NAC = 32;

% Notified Maximum Demand - kVA you need - charged at 18 MVA
NMD = 18e3*NAC;

% Monthly service charge (R)
SC = 4500;

% 33 kV Voltage Surcharge (%)
VS = 0.03;


EnergyAnnual = 30.4*sum(sum(PG1))          % MWh

ECave = 1e3*PG1.*rate;
TECave = 30.4*sum(ECave');

NDCave = 1e3*mean(abs(SG1'))*NDC;
NACave = 1e3*max(abs(SG1'))*NAC;
TSave = NDCave+NMD;


% Total Energy Cost per Month
TEm(1,:) = TECave;

% Total Cost per Month
TCm(1,:) = (1+VS)*(TECave+NDCave+NMD)+SC;


TCm = TCm/1e6;
TEm = TEm/1e6;

TCy = sum(TCm')
TEy = sum(TEm')

nload = 20;
r = 0.07;
TOC = TCy;

for t = 2:nload
 %   TOC = TOC + TCy*((1+r)^t-1)/r/(1+r)^t;
    TOC = TOC + TCy*(1+r)^t;
end

TOC = nload*TCy                 % This is in R millions
%
% Tm = [TEm',TCm'];
%     figure(12),bar(Tm),     grid     on,     ylabel('Cost     (R     in     million)'),
xlabel('Month'),legend('Energy','Total')
% print('cost5b.png','-dpng','-r300')


dep = 1;

% Investment and LCOE for the Wind Generator
SCwind = x_wind;                % Power in kW - What about capacity?
r = 0.07;                       % Discount rate
```

```
PCwind = 30000*SCwind;          % Project system cost - R30000/kW
LCCwind = 300*SCwind;           % Lifecycle cost (Maintenance) - R300/kW/year
nwind = 20;                     % Lifetime
TEwind = 0;                     % Total energy
TCwind = 0;                     % Total cost
de_wind = 0.016;                % Annual degradation of energy produced

for t = 1:nwind
    TEwind = TEwind + 30.4*sum(sum(1e3*real(SG2)))*(1-de_wind)^t/(1+r)^t;
    TCwind = TCwind + LCCwind;
end

TEwind;
TCwind = dep*PCwind+TCwind;

LCOEwind = TCwind/TEwind        % Target LCOE = 1.34 R/kWh
TCwind = TCwind/1e6

% Investment and LCOE for the PV Generator
SCpv = x_pv;                    % Power in kWp - What about capacity?
r = 0.07;                       % Discount rate
PCpv = 15000*SCpv;              % Project system cost - R15000/kW
LCCpv = 300*SCpv;               % Lifecycle cost (Maintenance) - R300/kW/year
npv = 20;                       % Lifetime
TEpv = 0;                       % Total energy
TCpv = 0;                       % Total cost
de_pv = 0.01;                   % Annual degradation of energy produced

for t = 1:npv
    TEpv = TEpv + 30.4*sum(sum(1e3*PG3))*(1-de_pv)^t/(1+r)^t;
    TCpv = TCpv + LCCpv;
end

TEpv;
TCpv = dep*PCpv+TCpv;
LCOEpv = TCpv/TEpv              % Target LCOE = 2.04 R/kWh
TCpv = TCpv/1e6

% Investment and Levelized Cost of Storage for the Battery system
SCbat = x_bat;                  % Power in kW
SSbat = y_bat;                  % Storage in kWh
DODbat = 20;                    % Depth of discharge
r = 0.07;                       % Discount rate
PCbat = 0;
if x_bat < 500
   PCbat =  1800*SCbat;          % For less than 500 kVA - Small Inverters
else
   PCbat =  900*SCbat;           % For more than 500 kVA - Large Inverters
end
PCbat = PCbat + 2280*SSbat;      % Project system cost: R900/kW - Inverter + R1290/kWh for LA
Batteries pr R2280/kWh for LFP Batteries
LCCbat = 0.015*PCbat;           % Lifecycle cost (Maintenance) - 1.5% of installed cost
nbat = 20;                      % Lifetime
rbat = 10;                       % Replacement cycle in years: 5 years for LA and 10 years for
LFP
rdrop = 0.1;                    % Drop in cost per annum
RCbat = 0;                      % Replacement cost
TEbat = 0;                      % Total energy delivered to the system
TPbat = 0;                      % Total energy purchased from the system
TCbat = 0;                      % Total cost
de_bat = 0.05;                  % Annual degradation of battery produced


EDbat = -PG4;
%EDbat = EDbat(EDbat>0)
EPbat = P4;
%EPbat = -EPbat(EPbat<0)
for t = 1:nbat
    TEbat = TEbat + 30.4*sum(sum(1e3*EDbat))*(1-de_bat)^t/(1+r)^t;
    TPbat = TPbat + 0.54*30.4*sum(sum(1e3*EPbat))*(1+r)^t;
    TCbat = TCbat + LCCbat;
end

for t = 1:nbat/rbat
   RCbat = RCbat + 2280*SSbat/(1+rdrop)^(t*nbat/rbat);
end
```

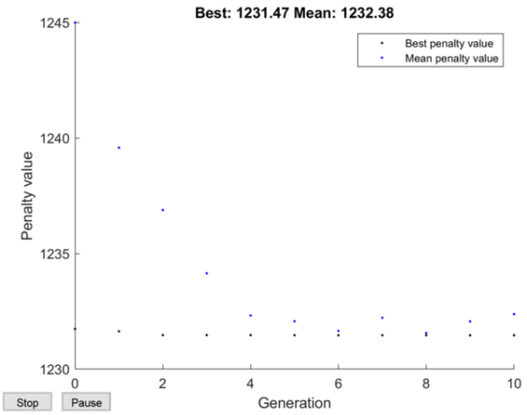
```
TPbat;
PCbat;
RCbat;
TCbat = dep*PCbat+TCbat+TPbat+RCbat;

LCOSbat = TCbat/TEbat       % Target LCOS = 5 R/kWh
TCbat = TCbat/1e6
% Diesel Costs

% LCOE Total

TCall = (TCwind+ TCbat + TCpv)*1e6;
TEall = TEbat + TEpv + TEwind;

LCOE = TCall/TEall


% Inverter Cost

% R3000/kW - Inverter

TOC = TOC+TCwind+TCpv+TCbat;
```

A.1.4 Matpower file

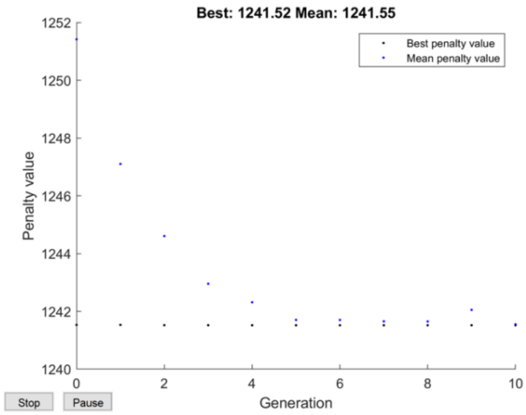
```
function mpc = dct
%    Power flow data for dct terminal 10 bus, 4 generator case.

%   MATPOWER

%% MATPOWER Case Format : Version 2
mpc.version = '2';

%%-----  Power Flow Data  -----%%
%% system MVA base
mpc.baseMVA = 100;

%% bus data
%   bus_i   type    Pd  Qd  Gs  Bs  area    Vm  Va  baseKV  zone    Vmax    Vmin
mpc.bus = [
    1   3   0   0   0   0   1   1   0   11  1   1.1     0.95;
    2   2   0   0   0   0   1   1   0   11  1   1.05    0.95;
    3   1   0   0   0   0   1   1   0   11  1   1.05    0.95;
    4   1   0   0   0   0   1   1   0   11  1   1.05    0.95;
    5   1   10  10  0   0   1   1   0   11  1   1.05    0.95;
];

%% generator data
%    bus Pg   Qg   Qmax    Qmin    Vg   mBase    status  Pmax     Pmin     Pc1  Pc2  Qc1min   Qc1max
Qc2min   Qc2max  ramp_agc    ramp_10 ramp_30 ramp_q  apf
mpc.gen = [
    1   23.54   0   150 -20 1   100 1   80  0   0   0   0   0   0   0   0   0   0   0   0;
    2   23.54   0   150 -20 1   100 1   80  0   0   0   0   0   0   0   0   0   0   0   0;
    3   23.54   0   150 -20 1   100 1   80  0   0   0   0   0   0   0   0   0   0   0   0;
    4   23.54   0   150 -20 1   100 1   80  0   0   0   0   0   0   0   0   0   0   0   0;
];

%% branch data
%   fbus    tbus    r   x   b   rateA   rateB   rateC   ratio   angle   status  angmin  angmax
mpc.branch = [
    1   2   0.02    0.1 0.02    0   0   0   0   0   1   -360    360;
    1   3   0.02    0.1 0.02    0   0   0   0   0   1   -360    360;
    1   4   0.02    0.1 0.02    0   0   0   0   0   1   -360    360;
    1   5   0.02    0.1 0.02    0   0   0   0   0   1   -360    360;
];
```

A.2 Matlab GA Results

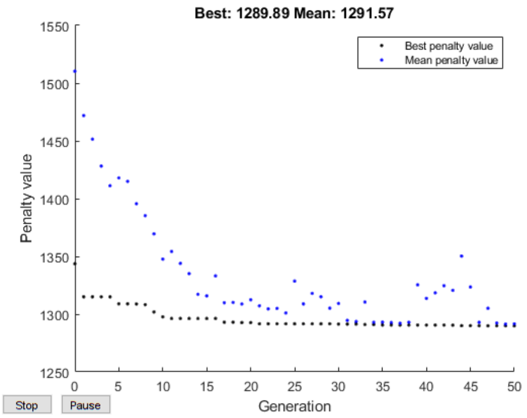
The plots below show the penalty value against the generation for the various cases studies for the Matlab genetic algorithm. The penalty value represents the total ownership cost of the system. In the plots, the best penalty value and the mean penalty value. It can be seen in the plots how the mean value converges towards the best value over the number of generations.



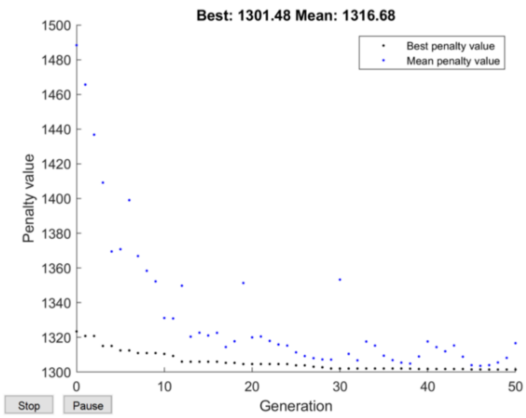
(a)



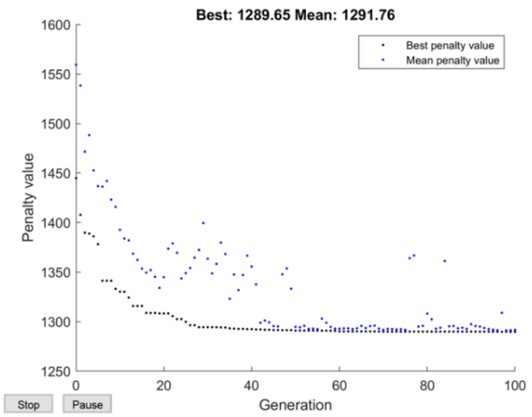
(b)



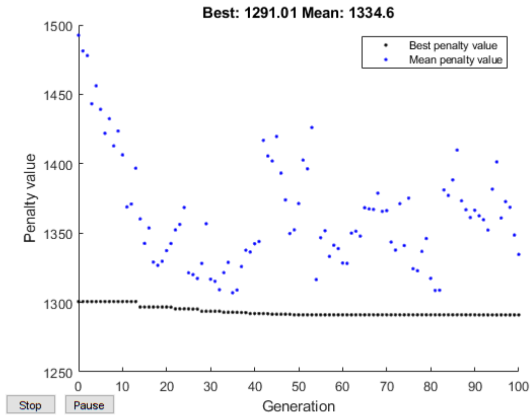
(c)



(d)



(e)



(f)

Figure A- 1 – GA Solutions for (a) Case 2, (b) Case 3, (c) Case 4, (d) Case 5, (e) Case 6, (f) Case 7