

Department of Electrical and Computer Engineering

**Optimization of Energy Storages in Microgrid for Power Generation
Uncertainties**

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Liaqat Ali

August 2016

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Abstract

Microgrid is a cluster of distributed generation units, electrical energy storage units, reactive power sources, and distributed loads which can operate in grid-connected and islanded modes. This research mainly focuses on selecting an economically-suitable standalone power supply system for some small and remote off-grid towns in Western Australia, Australia. Existing power systems of such remote towns in Australia have adverse environmental impacts and contribute to global warming due to the utilization of fossil fuels, especially diesel and gas. The possible electricity supply systems for such towns can vary from a diesel/gas-based generator towards a hybrid system composed of a generator, wind turbine, photovoltaic system, and battery energy storage. In recent environmental pollution and energy crisis, photovoltaic and wind power generation are playing a vital role in energy production. However, the output power of wind power generation and photovoltaic is generally unsteady and unpredictable. This type of output power fluctuations can seriously degrade the network security. In order to limit the cost of the system and to propose the most economically feasible solution, various combinations of supply systems are considered. These systems are analyzed in this research by the help of HOMER software to determine the optimal architecture and the control strategy of the supply system. This study has used real demand data of the towns, as well as the prices of different electrical components in the Australian market. The scenario which yields the minimum cost of energy is defined and

suggested. Another aim of this analysis is to investigate and illustrate the impact of a small annual load growth on the size of the selected components for the selected power system as well as the total net present cost and the cost of electricity. A sensitivity analysis is also performed to analyze the impact of uncertainties of some of the parameters in the outcome of the study to obtain the optimized cost of the selected system.

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List of Abbreviations

BSS	Battery storage system
COE	Cost of energy
DG	Diesel generator
HPS	Hybrid power system
HOMER	Hybrid optimization of multiple energy resources
ICC	Initial capital cost
MG	Microgrid
NPC	Net present cost
NEM	National electricity market
OMC	Operational and maintenance cost
PV	Photovoltaic
RE	Renewable energy
SWIS	Southwest interconnected system
WA	Western Australia
WT	Wind turbine

Chapter 1 Introduction

1.1 Introduction

In the majority of the countries around the world including Australia, electricity utilities have experienced a sustained increase in the electrical demand in the last decade, which is predicted to continue in the future years [1-3]. For this reason, the utilities are adding new power plants into their existing electric systems or modernizing the electricity generation and distribution technologies to cope up with this increasing demand. As a result, in the last decade, the end-users of electricity systems have experienced a sustained increase in their electricity tariffs and bills [4]. On the other hand, renewable energy (RE) based resources are being utilized more and more in the electric systems, mainly due to concerns about environmental pollution, energy crisis, and technical developments that yield cheaper and more reliable electricity from these resources [5]. In the electric networks of some countries such as Australia, Germany, and Spain, and especially in their distribution networks, RE resources such as solar and wind have found a large penetration [6-7]. Even though the wind and solar power are experiencing rapid development as promising clean energy resources, their generated power is intermittent. Therefore, energy storage systems such as batteries are accompanying wind turbines (WT) and photovoltaic (PV) units to overcome the rapid and frequent intermittency of their output powers [8]. The application of battery storage systems

(BSS) facilitates a consistent power generation by renewable energies and a steady supply of electricity to the users [9-11].

In Australia, existing power system can be considered as a prime cause for current greenhouse or global warming effects as more than 75 % of the energy is produced from fossil fuels. In 2007-08, Australia's energy production (including its exports of energy) was dominated by coal, which accounted for 54 % of total Australian energy production in energy content terms, followed by uranium with a share of 27 %, natural gas with a share of 11 % and crude oil of 6 % [13]. Australia's abundance of coal has helped to keep energy prices low, and more than three-quarters of the country's electricity is generated by coal-burning plants. However, Australia's dependency on coal-fired power gives it one of the world's highest per capital greenhouse gas emission rates [14-15]. In contrast, RE can be used as the panacea for solving the climate change or global warming problems as they are free from greenhouse gas emissions. There is unprecedented interest in RE, particularly the solar and wind energy, which provide electricity without increasing the CO₂ emissions. Therefore, there is a critical need for a robust and sustainable power transmission and distribution system which is intelligent, reliable, and environment friendly, to overcome various problems associated with the existing power system. Currently, 15-20 % of the world's total energy demand is covered by RE. From start of 21st century, RE has experienced one of the largest growths in percentage terms. The world's RE production share has been calculated as 19 % in 2007. However, 16 % was due to hydroelectric energy production; hence, wind and PV (the most promising RE) contributed a very modest energy production [16]. Around 7 % of the Australian electricity generation is contributed by RE, with 4.5 % sourced from hydro-electricity, while wind energy contributes 1.5% of the total electricity

generation. Thereby, it is necessary to modernize the Australian environmental policy to build a climate-friendly environment for the future and to bring a higher percentage of RE into the energy mix [17].

The state of Western Australia (WA) is generously endowed with RE resources, mainly the solar and wind. Except Perth, which is the state's capital, the remaining population of the state inhabit in numerous small and remote towns. The electrical demand of each of these towns is usually supplied by a stand-alone off-grid power supply system (resembling an islanded microgrid (MG)) [18-20]. For each of these towns, the main sources of the energy are diesel/gas-based generators. However, solar energy is generously available in the majority of those towns, especially the ones distributed in the outback of the state while wind energy is plentiful in the towns in its coastal areas. Consequently, these towns have a chance of supplying a significant portion of the electrical demand from the available REs [21]. Currently, REs are supporting WA to meet the community's long-term energy requirements, while supporting the growing economy. However, they consist of only a small percentage of the total electricity generation of the State. In 2012-13, only 4.4 % of the total electricity generation came from renewable sources; while the state has recorded rapid growth in electricity consumption with an annualized growth rate of 5 %, over the 10 years before that [22]. WA has a goal to reduce its gas emissions by 60 % by 2050. To achieve this target, the Government of WA supports investments in RE sector to bring a clean energy future for Australia. Many RE projects are currently being investigated, or under commissioning, in order to help WA to contribute 20 % RE based electricity generation by 2020 (the national RE target) [23].

1.2 Background

Microgrids can provide an avenue for increasing the amount of distribution generation and delivery of electricity. Many studies have been done to date on microgrid technology and operations, but fewer studies exist on demonstration programs and commercial microgrid development [21]. Nowadays demand, consumption and price of electricity are rapidly increasing. To meet these requirements, more high powered electrical plants have to be introduced or the structure of energy production needs to be changed with different approaches such distributed generation sources. Among DG sources, renewable energy sources have found more applications mainly due to increasing concern about environmental issues [61]. Various renewable energy resources, wind power generation and photovoltaic system has found more applications in distribution and residential networks [7]. Moreover, with global environmental pollution and energy crisis, distributed power generation system based on renewable energy such PV and wind power generation, is playing a more and more important role in energy production [5]. Combining the suitable energy resources along with defining their ratings and operation strategies have been the focus of recent researches and different new techniques have been proposed in literature which aim to enhance the performance of such systems by proper placement and planning, while minimizing the cost of distribution system and satisfying system technical constraints [12].

1.3 Electricity Supply in Australian Remote Areas

Remote areas of Australia are defined by Australian Standard Geographical Classification, with respect to the physical road distance to the nearest town or service center, and is shown in Figure 1.1a [24], which constitutes 86 % of the

country. Figure 1.1b shows the map of WA (2006) showing areas of varying geographic remoteness [25]. Figure 1.1c illustrates the resident population density (2001 – 2011) in different parts of WA which indicates that in capital city ‘Perth’ population is growing at rate of 26.2 % and at rate of 15.8 % in rest of WA [27]. As per Australian Bureau of Statistics, 63% of Aboriginal and Torres Strait Islander people in Australia live in remote and very remote areas. It is noticeable that 25 % of all Aboriginal and Torres Strait Islander people in Australia live in remote or very remote areas compared to 2 % for non-Aboriginal and Torres Strait Islander people. Figure 1.1d shows the increase in the number of the inhabitants of WA between 2001 and 2011 [26].

Due to long distances between the remote towns and the existing power lines, which are close to urban towns and cities with high electricity consumption, as well as the low population and small level of electricity demand in remote towns, the construction and expansion of electricity networks to remote areas is not cost effective for the utilities. As a result, the electricity grid of Australia is only available in some limited areas; i.e. the eastern and southern parts of Australia, referred to as national electricity market (NEM), and the southwest of WA, referred to as southwest interconnected system (SWIS). The NEM grid gives an entirely interconnected transmission network, allowing determined market power flows across the Australian Capital Territory, New South Wales, Queensland, South Australia, Victoria, and Tasmania. It accounts for around 90 % of total electricity supply in Australia and supplies 19 million residents and around 199,000 GWh annually [27]. The SWIS grid in WA supplies approximately 17,900 GWh annually to 910,000 inhabitants. For the other parts of Australia, the utilities generate

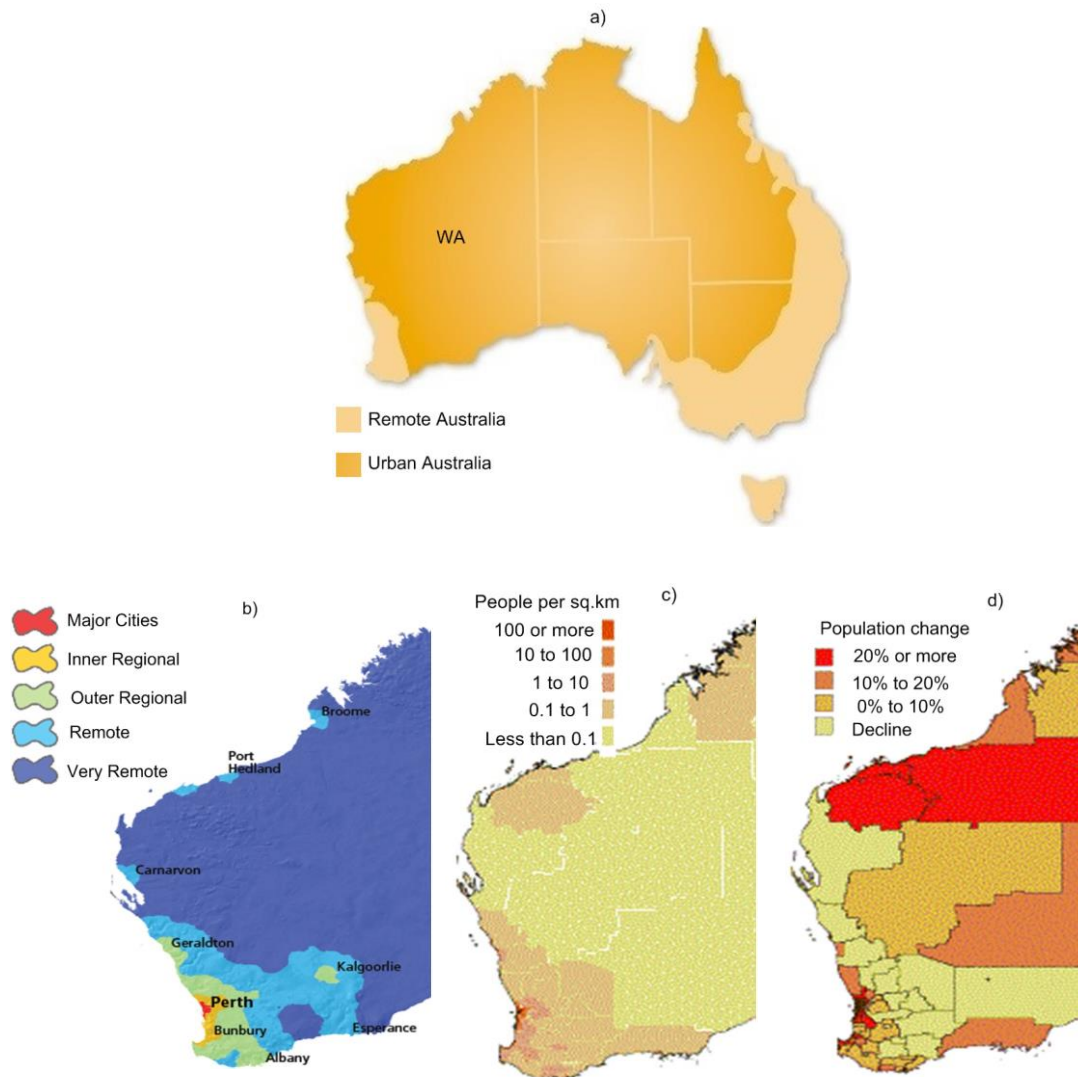


Figure 1.1 (a) Remote and urban areas of WA, (b) WA’s areas of varying geographic remoteness, (c) WA’s population density, and (d) Change in WA’s population.

electricity locally, referred to as off-grid electric systems, as depicted in Figure 1.2a [28] while Figure 1.2b illustrates the different types of off-grid generation in Australia [29]. In such situations, gas and diesel-based generations are the most common methods. The major problems of such electricity generation systems are the fuel price, fuel transportation by extra-long fuel trucks (known as road trains), difficulty of fuel transport through seasonally impassable routes, the necessity and cost involved in building and expanding the gas pipelines, and CO₂ emissions. Patrol

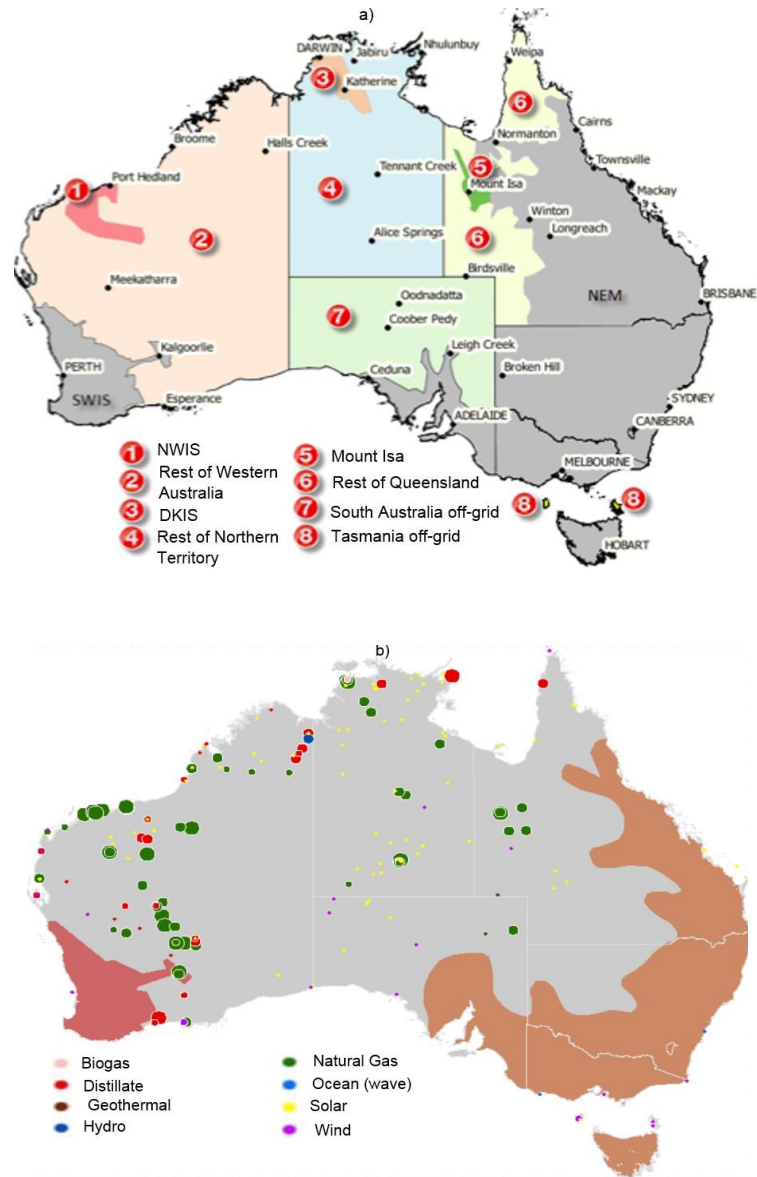


Figure 1.2. (a) Australian off-grid map and (b) Australia off-grid electricity generation systems.

sniffing is one of the other issues that is observed in the indigenous communities of Australia and has forced Australian government to subsidize the production of opal petrol, a non-sniffable fuel [30].

Considering the fact that Australia has high potential for electricity generation from RE resources such as solar and wind, and considering the modern technical knowledge for generating electricity from such resources, expansion of highly efficient energy harvesting techniques as well as the reduced

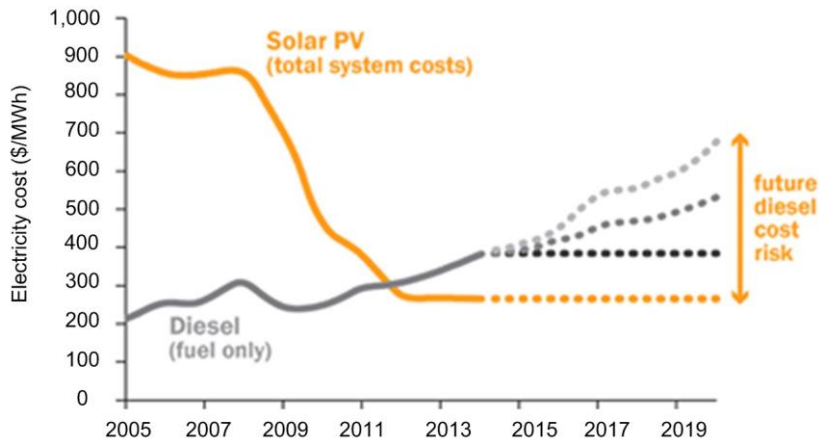


Figure 1.3. Comparison of the cost of electricity generation between DG and PV systems.

costs of such facilities, it is anticipated that the RE based resources take a larger portion of electricity production in Australian remote areas. Figure 1.3 provides a comparison between the cost of generated electricity by a solar system and a diesel generator (DG) in the last 10 years till 2020 [38]. The figure illustrates, at this time, it's cheaper to produce electricity from RE sources like PVs than with existing DGs only in many off-grid regions. As an example, Horizon Power, the electric utility supplying remote areas of WA, has calculated the cost of electricity generation by their diesel and gas generators in remote locations respectively about 50 and 35 cents per kilo Watt per hour (¢/kWh) while they have calculated the cost of electricity production from a hybrid power system (HPS) of DG and PV system as low to mid 20 ¢/kWh .

1.4 Considered Remote Towns

This paper focuses on the off-grid and remote towns of Laverton ($28^{\circ}37.5'S$, $122^{\circ}24.4'E$) located 957 kilometers north-northeast of WA capital (Perth) and Mount Magnet is located 560 km northeast of Perth (see Figure 1.4). These towns are

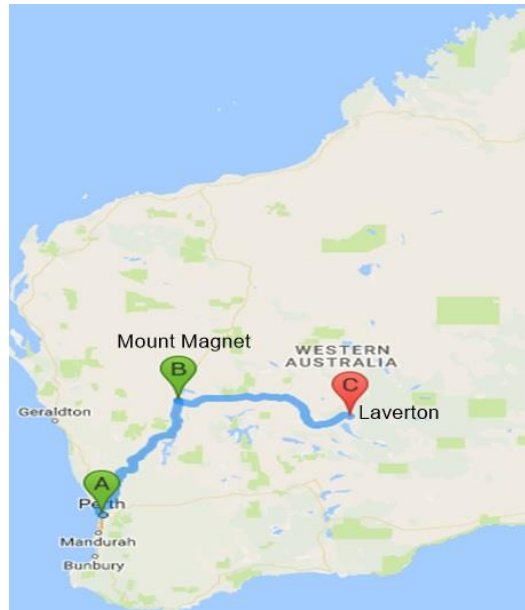


Figure 1.4. Considered Remote Towns Laverton and Mount Magnet on WA Map

currently supplied by a DG. The fuel cost and its transportation are the main issues that the local electrical utility ‘Horizon Power’ is challenging with. The small and medium/large business customers of the town are charged at 29.4 and 33.9 ¢/kWh, respectively, while the residential customers are currently charged at 25.7 ¢/kWh [31]. Thereby, the supply of electricity to the customers of the town is not beneficial for the local utility, as the total cost of energy (COE) generation is higher than the electricity tariff based on which the customers pay back to the utility.

1.5 Aims and objectives of the thesis

The main focus of this paper is to design a suitable standalone HPS for an off-grid and remote town in WA and to evaluate the impact of such systems on the cost of electricity generation for the local utilities. After selecting the most feasible system, another focus is to study the impact of the load growth on the outcomes of the selected system. As the load grows gradually, the components of the selected system need to be chosen accordingly to cope up the growing load demand of the

town. Currently, the supply of electricity to the customers is not a profitable trade for the local utility company ‘Horizon Power’ due to higher value of the total cost of energy compared to the existing electricity tariff. Therefore, the government has to pay a significant subsidy annually. In this study, different scenarios are taken into consideration for the selected town to improve the power supply system from a DG based system into a sustainable hybrid one. For this purpose, one or more types of REs are considered. To propose the most economically feasible solution and to limit the cost of the selected system, different supply systems are analyzed by Hybrid Optimization of Multiple Energy Resources (HOMER) software [32-33]. In this research parameters like size and number of sources are optimized and HOMER software is used for optimization. Because of its simplicity and effectiveness, HOMER is one of the common software tools that is used in the design of RE systems [34-35]. The software contains a simulation tool that simulates the operation of a hybrid MG, an optimization tool that examines the possible combinations of system types, and sorts the systems according to the optimal variety of choices, and a sensitivity tool that considers uncertainties [36]. The cash flow summary of each studied supply system is obtained which is used for the optimal cost allocation of each component in the system [37]. To suggest the most suitable systems, the main consideration of this analysis is the minimum COE, net present cost (NPC), and emissions [38-40]. The real demand data of the town, as well as the prices of different electrical components in the Australian market, are utilized in this study.

1.6 Research Gap and Contributions

Despite many theoretical studies, there is a research gap on optimal design and operation of practical hybrid systems in microgrid formations. Microgrids are

anticipated to be the future of modern distribution networks which have reduced costs, minimized energy losses, high energy savings, increased reliability, high energy generation ratio from renewable energy resources and self-healing properties. This research work analyzes different hybrid power systems that can be used in remote town of Western Australia. The main contribution includes:

- a. Find the economically most suitable option for selected remote towns.
- b. Evaluate the impact of load growth on selected systems.

1.7 Significance of research

MG is the future of distribution networks which has reduced costs, minimized energy losses, high energy savings, increased reliability, high energy generation ratio from renewable energy resources and self-healing. This research focuses on minimizing the effect of uncertainty in solar and wind energy generation by using a battery storage system. The main contribution of this research is to develop hybrid power systems for remote towns of Western Australia that give minimum values economically and also reduce the emission to make sure the safe and friendly environment. Limited publications are available on this topic; therefore, this work addresses a significance research gap.

1.8 Structure of the Thesis

This thesis is organized in five chapters: **Chapter 1** outlines the research aims and objectives along with the need and the justification through a literature review for the research topic. **Chapter 2** considers eight different combination of hybrid power system for remote town Laverton and propose a most suitable standalone power system. HOMER software is used to perform the simulation and analysis.

Chapter 3 focus on the impact of the load growth on the outcomes of the selected system for Laverton, in the analysis load growth from 1-3 % has been considered.

Chapter 4 develop a suitable standalone hybrid power system for Mount Magnet and conduct a feasibility analysis to achieve the most economic model. The simulations have been performed through HOMER software. Finally, in **Chapter 5** the conclusions drawn from this research and the recommendations for future research are highlighted.

Chapter 2 Selection of a Suitable Standalone Power System

This chapter focuses on selecting a suitable standalone power supply system for a small and remote off-grid town in WA, Australia. To limit the cost of power supply system and to propose the most economically feasible solution for this town, different systems are considered. The considered systems, varied from a DG based option towards a HPS composed of a DG, WT, a PV system and BSS are analyzed by the help of HOMER software and using the real demand data of the town as well as the prices of different electrical components in the Australian market. The scenario which yields the minimum COE and the minimum NPC is defined and suggested. A sensitivity analysis is also performed to evaluate the impact of uncertainties of some of the parameters in the outcome of the study.

2.1 Selected Remote Town

This research focuses on the off-grid and remote town of Laverton in the Goldfields-Esperance region of WA, located at the western edge of the Great Victoria Desert, 957 kilometers north-northeast of the State's capital, Perth (see Figure 2.1). This town is currently supplied by a DG. The fuel cost and its transportation are the main issues that the local electrical utility, Horizon Power, is facing. Supply of electricity to the customers in the town is not currently a beneficial



Figure 2.1. Laverton, an off-grid town in Western Australia, Australia.

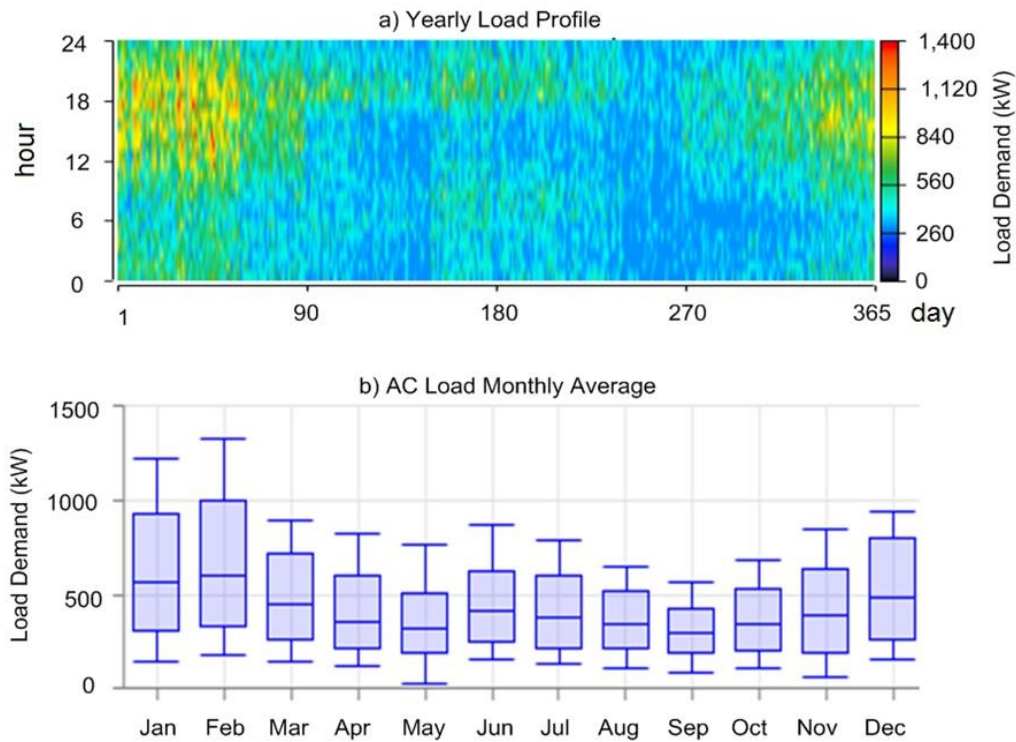


Figure 2.2 Load demand profile of Laverton in 2015.

trade for the local utility as the total COE generation is higher than the electrical tariff, based on which the customers pay back to the utility.

The peak demand of Laverton is 1,321 kW, but it has an annual average energy consumption of 9,977 kWh per day [41]. Figure 2.2a shows the average daily load profile of this town while Figure 2.2b illustrates the minimum, maximum and average of the demand in each month of 2015. These figures illustrate that Laverton

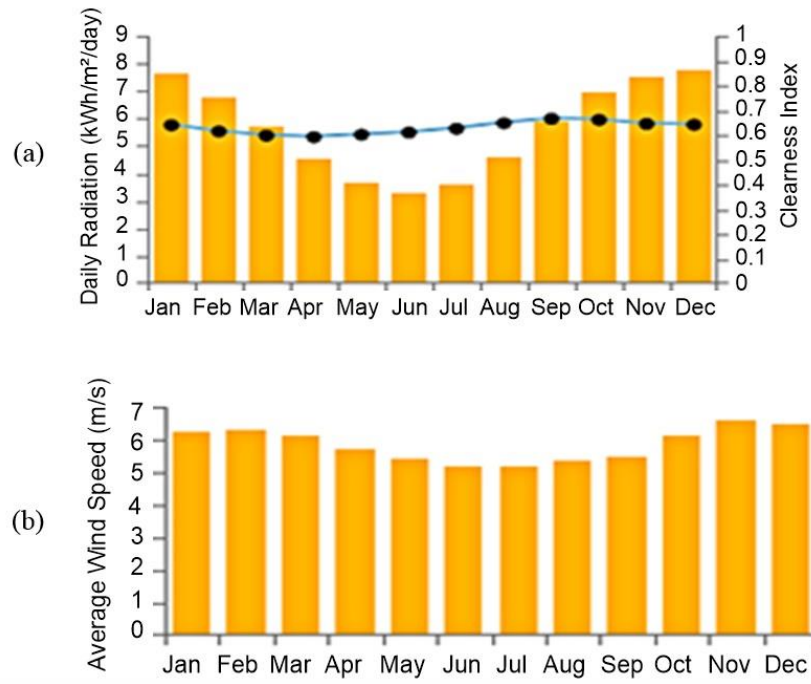


Figure 2.3. (a) Historical average daily solar radiation and clearance index for Laverton, (b) Historical average wind speed in Laverton.

has an average demand of approximately 400-600 kW throughout the year while it can observe a maximum demand of above 1,000 kW from December to February.

The climate of Laverton is semi-arid with mild to cool winters and hot summers, and the maximum mean daily temperature varies between 17 °C in July to 36 °C in January [42]. For wind speed and solar radiations, Laverton has a good profile. From NASA database over a 22-year period (1983 - 2005), the monthly average solar radiation for Laverton, is as depicted in Figure 2.3a. This figure illustrates that in different months of the year, the average solar radiation varies between 4 to 8 kWh/m² per day. In addition, it is seen that the average solar energy radiation is at the highest level from September until March. The monthly average wind speed data for Laverton, also taken from NASA database over a 10-years period (1983-1993), is about 5-7 m/s [43] shown in Figure 2.3b.

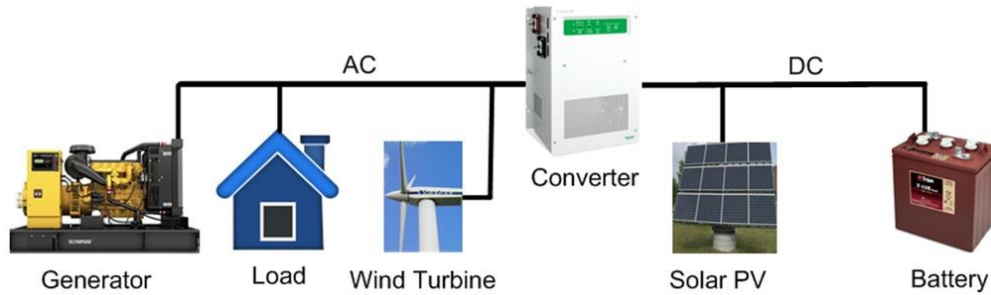


Figure 2.4. Schematic diagram of hybrid MG system.

2.2 Considered Hybrid Standalone Power System

The considered standalone power supply for Laverton consists of a PV system, WTs, and a BSS. As the production of electricity using renewable resources is random in nature, there is a chance of complete outage of resources. To overcome this situation, a DG is also connected to the system to generate the required extra power during energy deficiency periods. The PV and BSS are attached to a dc bus whereas the loads, the WTs and the DG are assumed to be linked to the ac bus. Thereby, a bi-directional power electronics-based converter is needed to convert the dc voltage generated by the PV and BSS to the ac voltage, and also to charge the BSS from the ac bus [44-45]. Figure 2.4 shows the schematic diagram of the considered hybrid MG system. The BES is assumed to be initially charged with the help of the PV and the WT, and the load is fed with this power being converted through the converter. The DG runs at its full capacity whenever required while its surplus power will be fed to the BSS until it reaches its maximum capacity.

The total NPC represents the life cycle cost of the system. It includes the initial capital cost (ICC) of the system components, the cost of any component replacements that occur within the project lifetime, the cost of maintenance and fuel. It is the combination of all costs and revenues that occur within the project life, with

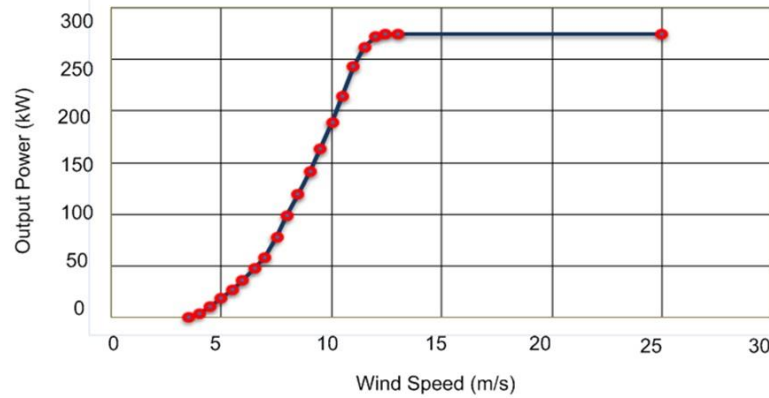


Figure 2.5 Wind Speed Profile.

future cash flows discounted to the present. The NPC is calculated by

$$NPC = \frac{C_{ann}}{CRF} \quad (2.1)$$

where C_{ann} is total annualized cost (i.e., the sum of the annualized costs of each system component), and CRF is capital recovery factor, calculated from

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (2.2)$$

where i is annual interest rate or real discount rate (%), which is used to convert between one-time costs and annualized costs in percentage [29], and N is Project lifetime (year). Annual interest rate is calculated by

$$i = \frac{i' - f}{1 + f} \quad (2.3)$$

where i' is the nominal discount rate (%), which represents the rate at which one can borrow money [37], and f is the expected inflation rate (%) over the project life.

The COE is the average cost per kWh of useful electrical energy produced by the system. To calculate the COE, the annualized cost of producing electricity is divided by the total served electrical demand.

In this study, the real interest rate is considered to be 7 % [46], the project

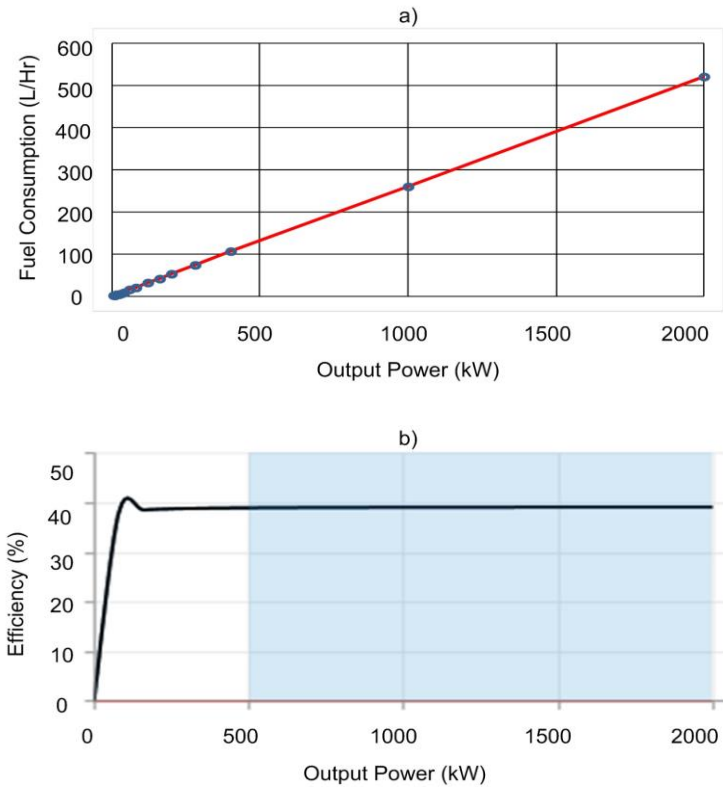


Figure 2.6. (a) DG fuel flow curve and (b) DG efficiency curve.

lifetime is taken to be 25 years, and the inflation rate is assumed to be 2 % on average during the project life [47].

The considered PV modules in this study are the range of 100 to 3,000 kW. A WT of 275 kW (model GEV MP-C) has been considered [48]. The starting wind speed of the considered WT is 4 m/s and its cut off wind speed is 12.5 m/s as seen in the WT power-wind speed profile of Figure 2.5 [43]. The DG is considered to be in the range of 100 to 2000 kW. The minimum loading of the DG is assumed to be 25 % of its nominal capacity while the fuel consumption and efficiency of the DG with respect to its output power [49-50] are shown in Figure 2.6. It illustrates that the DG fuel consumption (L/hr) increases linearly with respect to the output power while the efficiency of the DG increases above 40 % when its output power is above 100 kW. A Trojan IND17-6V BSS has been considered [51], and the quantity of BSSs have been assumed in the range of 100 to 3,000. Also, a Leonics converters GTP503S [52]

in the range of 100 to 1,500 kW is taken into account. In this research, it is assumed that each power equipment is replaced at the end of its life length and for each equipment replacement cost is equal to the initial equipment cost. More technical parameters and the costs for PV, WT, BSS, DG and converter are listed in Table A1 in the Appendix.

2.3 Studies and Analysis Results

To design the most economically feasible standalone HPS for Laverton, eight different cases have been considered. Laverton is currently supplied by a DG. Also, the study of the solar irradiation and wind speed in the town illustrates a good potential for each of these resources to be considered as a source of electricity generation. On the other hand, due to the intermittency of solar and wind energies, a combination of either energy storage such as BSS or DG with them is essential. Considering these facts, eight technically feasible cases can be considered to generate the required electricity for Laverton; i.e.,

- Case-1: DG-based system only,
- Case-2: WT-PV-BSS: a combination of WT and PV with BSS,
- Case-3: DG-PV: a combination of PV with DG,
- Case-4: DG-WT-PV: a combination of PV and WT with DG,
- Case-5: DG-PV-BSS: a combination of DG and BSS with PV,
- Case-6: DG-WT: a combination of WT with DG,
- Case-7: DG-WT-BSS: a combination of DG and BSS with WT,
- Case-8: DG-WT-PV-BSS: a combination of DG and BSS with both PV and WT.

HOMER software has been used for this analysis and also to select the optimal sizing of the components of the standalone HPS [57-59]. HOMER utilizes the real data of the electrical demand of the town, its historical wind speed, and solar radiation, as well as the costs of each electrical component. It simulates thousands of

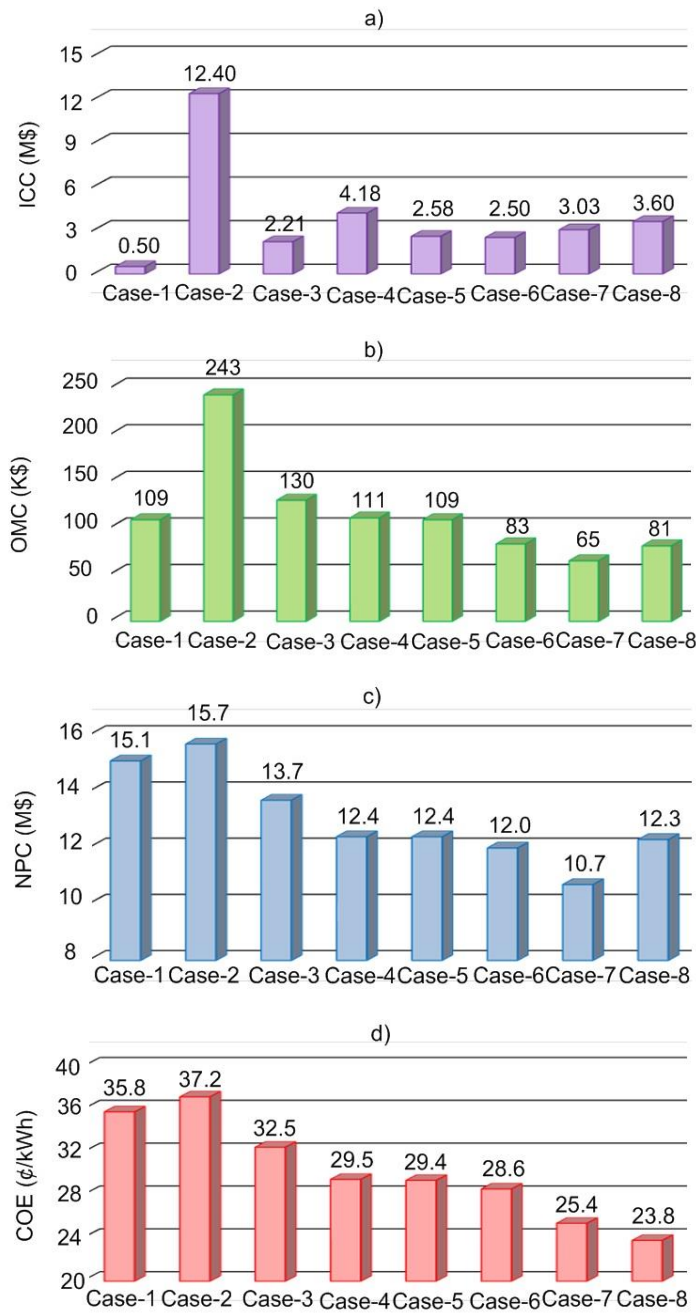


Figure 2.7. Comparison of the capital and O&M costs, NPC and the COE for the most optimal condition of each considered power system supply for Laverton.

system configurations, optimizes for lifecycle cost and generates results of sensitivity analyses on most of the inputs. For each value of the input, it repeats the optimization process, so it is possible to examine the effects of changes in the value on the results.

Case-1 assumes that the standalone HPS consists of a DG only. Case-2 considers a system composed of PV, WT and BES systems. Case-3 to 8 consider that

Table-2.1 Outcome of the Optimization Analysis for the Standalone Power Supply System of Laverton.

Case No.	System Type	DG (kW)	PV (kW)	No. of 275 kW WTs	No. of 1,231 Ah BSS	Converter (kW)	COE (¢/kWh)	NPC (M\$)	ICC (M\$)	OMC (K\$)
1	DG	1,250	0	0	0	0	35.8	15.1	0.50	109
2	WT-PV-BSS	0	2,750	9	3,000	1,200	37.2	15.7	12.40	243
3	DG-PV	1,025	1,000	0	0	500	32.5	13.7	2.21	130
4	DG-WT-PV	1,000	750	7	0	350	29.5	12.4	4.18	111
5	DG-PV-BSS	750	1,000	0	250	600	29.4	12.4	2.58	109
6	DG-WT	1,000	0	6	0	0	28.6	12.0	2.50	83
7	DG-WT-BSS	750	0	6	250	250	25.4	10.7	3.03	65
8	DG-WT-PV-BSS	700	545	5	275	450	23.8	12.3	3.60	81

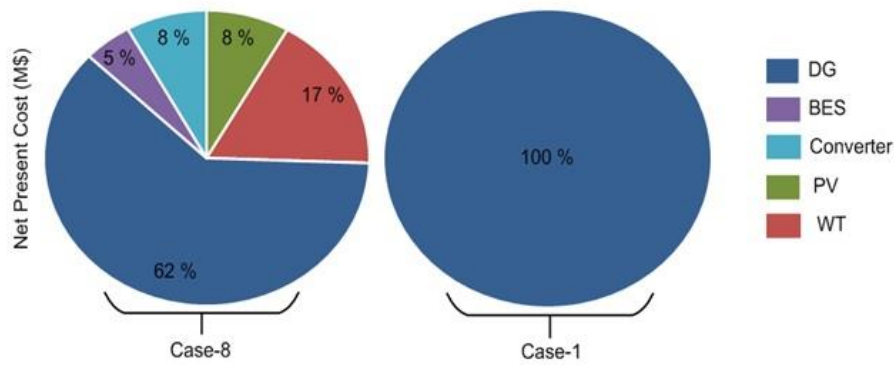


Figure 2.8. Components NPC summary for case-1 (current situation) and case-8 (suggested solution).

the DG is used in combination with a PV system and/or WTs and/or a BSS. For each case, a combination which gives the minimum COE is selected. The most optimum results for each case (i.e., the optimal number and rating of each component) are summarized in Table 2.1. Figure 2.7 also presents a comparison between the values of COE, NPC, and the ICC and operation & maintenance cost (OMC) of each case. From this figure, it can be seen that the COE is 35.8 ¢/kWh and the NPC is approximately 15.1 million dollars (M\$) over a 25-year when Laverton’s demand is supplied by a DG only (case-1). The COE decreases to 32.5 and 28.6 ¢/kWh respectively when Laverton’s demand is fulfilled by a combination of DG-PV and DG-WT. It is further reduced to 29.4 and 25.4 ¢/kWh respectively when a suitable BSS is also taken into consideration. It can be seen from Table 2.1 that case-8 (consisting of a 700 kW DG, a 545 kW PV system, five 275 kW WTs, 275 BSS of 1,231 Ah, and a 450 kW converter) yields the minimum COE of 23.8 ¢/kWh and the minimum NPC of 12.3 M\$. Although the current scenario of supplying Laverton by a DG only (case-1) has the highest COE and NPC, it has the minimum ICC of 0.5 M\$ but a large OMC of 0.109 M\$. Comparing these data with case-8, it can be seen that the combination of DG, WT, PV and BSS gives has a larger ICC (3.60 M\$) but a

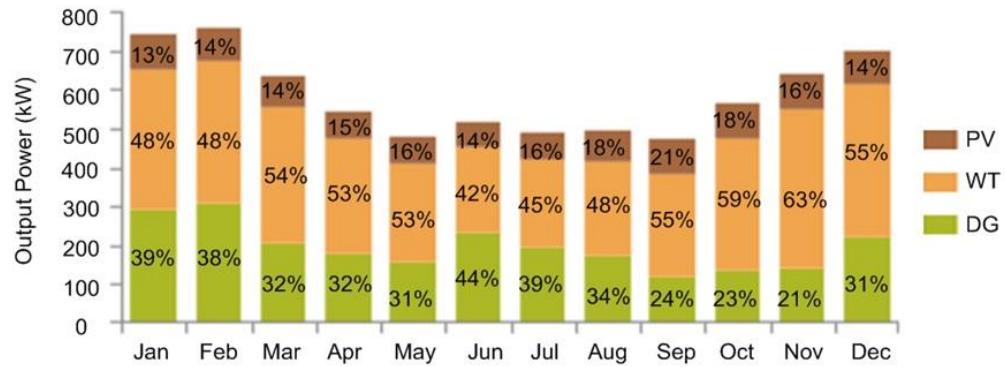


Figure 2.9. Monthly average electricity generation in the selected system.

smaller annual OMC (81 k\$). However, ICC of proposed model is higher than the current scenario. Therefore, the system of case-8 is the most economically feasible model and provides the cheapest solution throughout the project life.

Figure 2.8 shows the distribution of the NPC for each component of the power system in case-1 (the current standalone system) with case-8 (the suggested standalone HPS). As seen from this figure, although the NPC of case-8 is about 20 % less than the one of case-1, the majority of the NPC of the suggested system is due to the presence and operation of a DG. This is because a standalone HPS without a DG needs a PV system, WTs, and a BSS with large quantities and/or ratings which further increases the NPC to 15.7 M\$ (case-2).

Figure 2.9 demonstrates the monthly average electricity generation by case-8. This figure shows that wind energy has a significant contribution (51.02%) in the total generated energy of the selected hybrid standalone system while the DG and PV system provide respectively 30.64 and 18.35% of the total energy of Laverton. Figure 2.10a shows the amount of the generated power from the DG in the current system (case-1) while Figure 2.10b shows this level in the selected system (case-8). It can be seen that the DG in case-1 continuously operates throughout the year and has an output power that varies 300 and 1,400 kW. On the other hand, the DG in

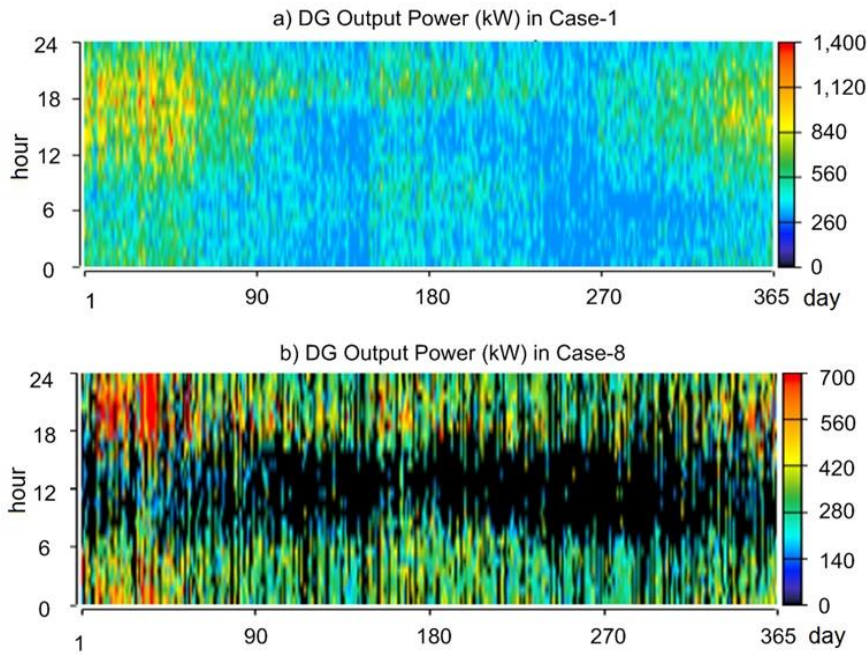


Figure 2.10. Annual DG output power for (a) the current system, and (b) the selected system.

case-8 has a maximum power production of 700 kW, and it turns off at middays in which the PV system generates power and has the highest electricity generation in the evening and night periods (between 6 pm to 6 am), due to the unavailability of the power from the PV system.

The use of renewable energy sources in the generation reduces the emission of CO₂, SO₂, and NO_x in the atmosphere. Figure 2.11 shows that the selected system

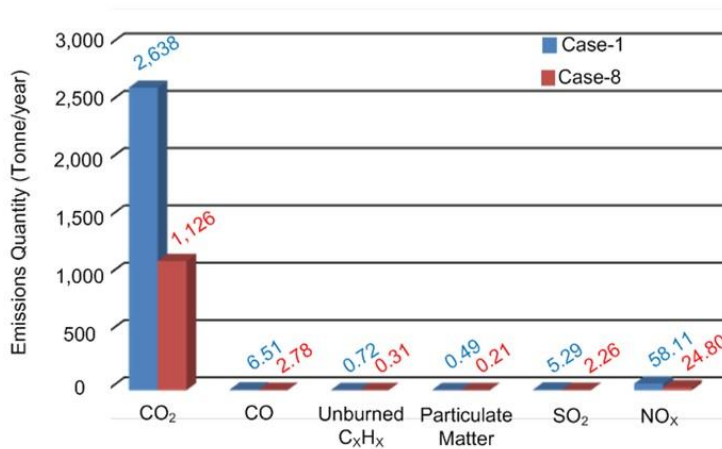


Figure 2.11. Comparison of emissions between the existing and the selected systems.

(case-8) reduces the emissions approximately by 43% compared to the current system (case-1). In the proposed system, the DG operates for 4,732 hours annually which is about 50 % less as the number of hours of operation of the DG in the current system. Accordingly, its fuel consumption is reduced by about 55 % annually. Therefore, the proposed sustainable hybrid system not only reduces the COE but also reduces the emissions.

To analyze the effect of uncertainties in each of the considered parameters for the analysis, a sensitivity analysis is performed. First, it is assumed that the diesel price for the DG may vary in the range of 1.1-1.5 \$/liter, and the project life length

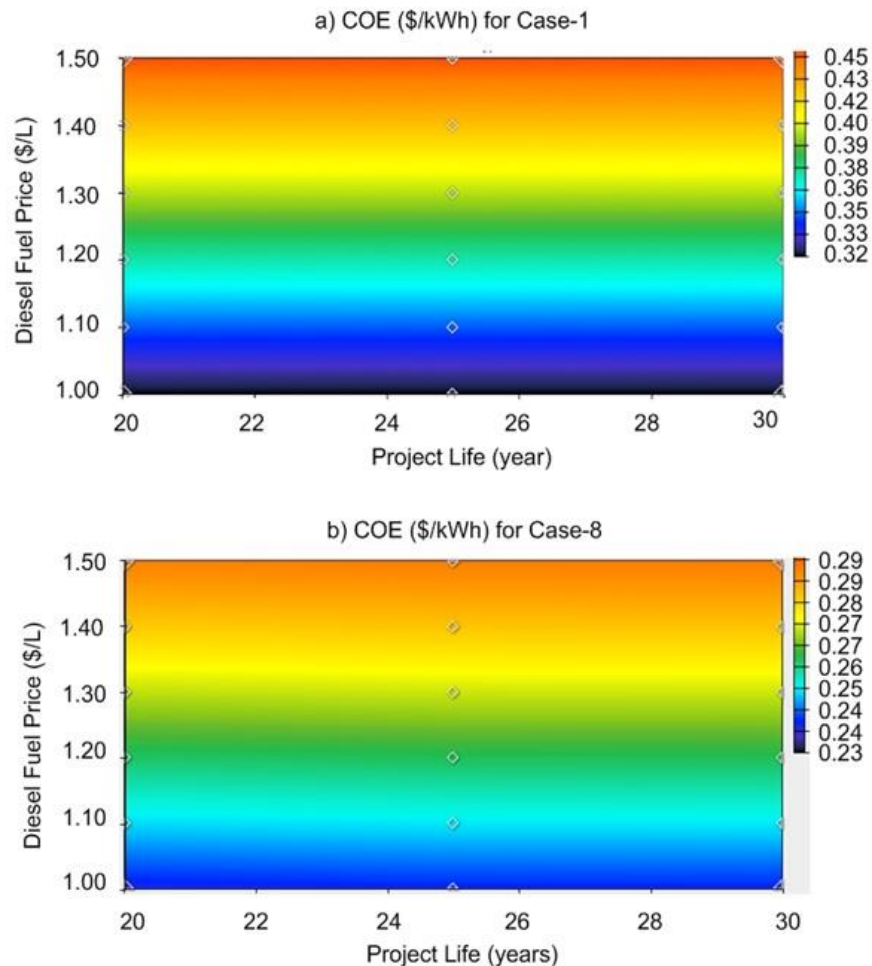


Figure 2.12. Sensitivity analysis result of COE for (a) the current system, and (b) the selected system.

Table-2.2 Results of Sensitivity Analysis for Case-1

Project Lifetime (Years)	Diesel Fuel Price (\$/L)	DG (kW)	COE (¢/kWh)
20	1.1	1250	35.8
25	1.1	1250	35.8
30	1.1	1250	35.8
20	1.2	1250	38.4
25	1.2	1250	38.4
30	1.2	1250	38.4
20	1.3	1250	41.2
25	1.3	1250	41.2
30	1.3	1250	41.2
20	1.4	1250	43.9
25	1.4	1250	43.9
30	1.4	1250	43.9
20	1.5	1250	46.7
25	1.5	1250	46.7
30	1.5	1250	46.7

Table-2.3 Results of Sensitivity Analysis for Case-8

Project Lifetime (Years)	Diesel Fuel Price (\$/L)	DG (kW)	PV (kW)	No. of 275 kW WTs	No. of 1,231 Ah BSS	Converter (kW)	COE (¢/kWh)
20	1.1	700	545	5	275	450	23.8
25	1.1	700	545	5	275	450	23.8
30	1.1	700	545	5	275	450	23.8
20	1.2	700	545	5	275	450	24.9
25	1.2	700	545	5	275	450	25.0
30	1.2	700	545	5	275	450	25.0
20	1.3	700	545	5	275	450	26.1
25	1.3	700	545	5	275	450	26.1
30	1.3	700	545	5	275	450	26.2
20	1.4	700	545	5	275	450	27.3
25	1.4	700	545	5	275	450	27.3
30	1.4	700	545	5	275	450	27.3
20	1.5	700	545	5	275	450	28.4
25	1.5	700	545	5	275	450	28.5
30	1.5	700	545	5	275	450	28.5

may range from 20 to 30 years. Figure 2.12, Table 2.2 and Table 2.3 shows that the COE for the current and selected systems in these conditions. It can be seen from this figure that an increase in the diesel price has a significant effect on the system's COE as it increases almost linearly as a function of the diesel price. However, the project life does not affect the COE tangibly.

The sensitivity analysis can be repeated for the size of the power components.

Figure 2.13 illustrates the COE for the selected option if the capacities of the power

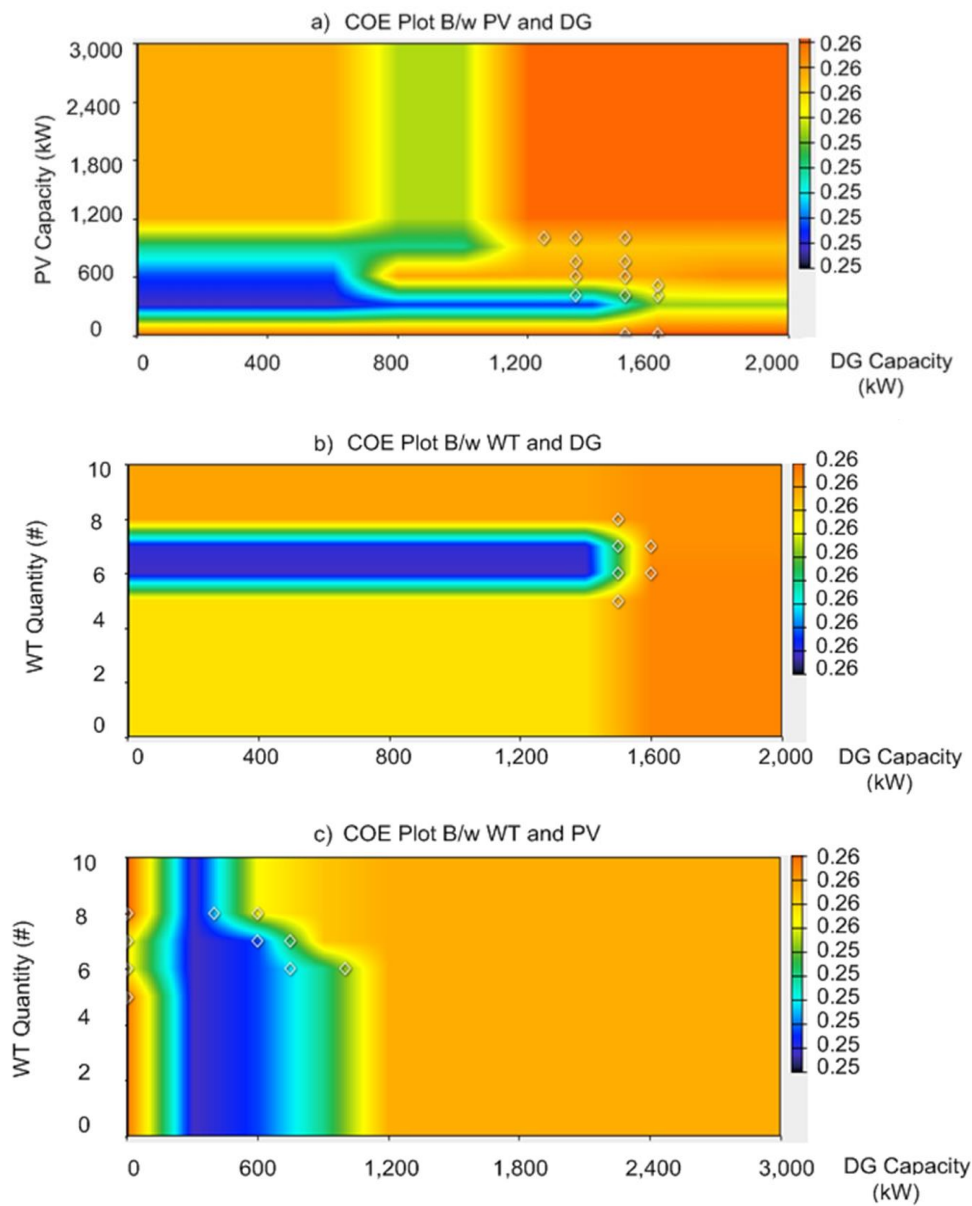


Figure 2.13. Optimization surface plots of COE for case-8 (Suggested Solution).

components are varied, can be expressed as a function of DG rating, PV rating and WT quantity as seen in Fig. 16 optimization surface plots. Fig. 16a illustrates that cost of energy is minimum if the total capacity of PV system is less than 700 kW and the DG capacity is below 1400 kW. However, the COE increases for other capacities of PV systems. It can be seen from Fig. 16b that the COE is minimum if 6-9 WTs are installed and DG capacity is less than 1,400 kW. It can also be seen that the COE increases when DG capacity is more than 1,400 kW for any number of WTs. From Fig. 16c it can be seen that the COE is minimum when the total capacity of PV system is between 200-600 kW while less than 8 WTs existing. It can also be seen that the COE is maximum when the total capacity of PV system is above 600 kW irrespective of the number of WTs.

2.4 Conclusions

Nowadays, the Australian government, utilities, and research communities are trying all together to increase the use of RE. The most promising sources of energy among RE sources are solar and wind. This study uses HOMER simulation software to investigate the prospects of RE, and particularly the wind and solar energies, for one of WA's remote towns, Laverton, for which the local utility is not gaining benefit for supplying electricity by an existing DG. The COE, NPC, ICC, OMC, and emission analysis were assessed to compare the performances of different type of hybrid models. This study utilized the real data like electrical load demand of the town, its historical wind speed, and solar radiation as well as the price of each electrical component from the Australian market. To select the most suitable standalone power system, eight different cases were considered. The studies reveal that in the current situation (i.e., supplying the demand of the town by a DG only),

the COE is very high (35.8 ¢/kWh) while the customers of the town are currently charged below that (25.7 ¢/kWh). This study demonstrates that the local utility company does not gain financial benefit when supplying the demand through the existing system. On the basis of economic analysis, it is shown that if an appropriate combination of a DG, PV system, WTs and a BSS along with a converter is considered, the COE can be decreased by approximately 30 % (to 23.8 ¢/kWh), and it will closely match the current price of electrical tariff. Also, the fuel consumption will be reduced by about 55 %, and the emissions will be more controllable. In overall, the recommended HPS is the most likely one in meeting the load demand of the town, and the COE is comparable to existing electricity tariff.

Chapter 3 Impact of Annual Load Growth on Standalone System

This chapter presents a suitable sustainable standalone power system for an off-grid town in Western Australia. To reduce the percentage of the electricity generated by a diesel generator in this remote town, a sustainable system is considered that consist of wind turbines, a photovoltaic system and a battery storage system, along with a diesel generator. The analysis aims to investigate and illustrate the impact of a small annual load growth on the size of the selected components for the sustainable power system as well as the total NPC and the COE of electricity for the chosen system. The analyses are carried out by the help of HOMER software.

Most of the changes in the world's established energy supply system are due to the growing energy demand, energy security concerns, environmental problems, an increase in oil prices, and competition to achieve clean energy technologies. The last few years has observed a continuous increase in the price of electricity along with an increase in the level of power consumption for the utilities around the world. To overcome the increase in the load growth, larger and newer electrical plants should be installed which consequently can increase the electricity generation prices even further. Alternatively, the design of power production systems needs to be modernized by considering different novel techniques. From this perspective, applications of RE sources for electricity generation are very appealing for the

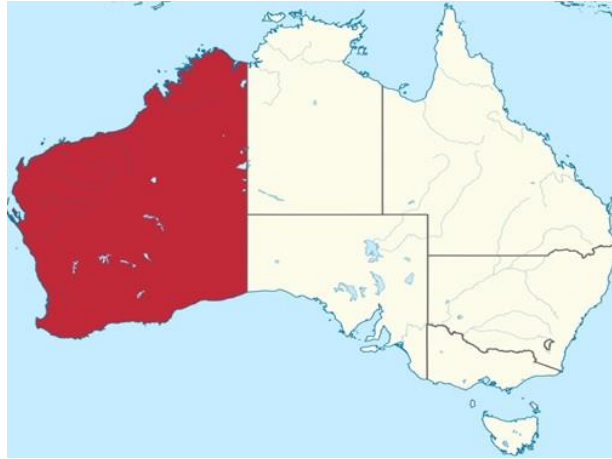


Figure 3.1. Map of WA.

utilities among other techniques, due to environmental pollution and energy crisis concerns [61, 5]. These are also valid for Australian government and utilities. Based on [62], it is anticipated that the electricity demand of Australia will grow at 0.9 to 1.5 % annually although it has been reduced due to energy efficiency and demand-side measures. The Australian government supports the investments on RE to meet the clean energy future for the state. Such projects can lead to energy security and lower emissions [63]. Strong government policies are made to reduce pollution and produce clean energy cheaper which will make changes in Australia's energy mix over the coming years.

WA (see Figure 3.1 [42]) has the second highest per capita emissions overall amongst all the Australian states. However, it has some of the best solar and wind resources in the world, and these resources can support the state to achieve the long-term energy requirements of its community, while supporting a growing economy. Unfortunately, renewable sources of energy constitute only a small percentage of total electricity generation of the state. WA has Australia's second largest wind farm with a capacity of 206 MW [64]. By 2030, near to 37 % of WA's electricity is expected to be generated from RE resources [65]. One of the primary interesting

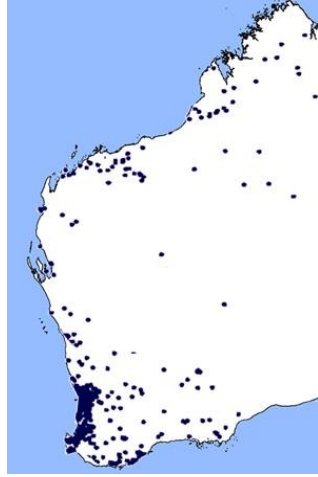


Figure 3.2. Population distribution in WA.



Figure 3.3. Considered off-grid town in this study.

applications of REs in WA is its remote areas and towns. Figure 3.2 illustrates the population distribution in the WA. As seen from this figure, about 77% of the State’s population live in the southwest of the State and the remaining live in its regional, remote and very remote areas. Also, according to [66], only 34% of the indigenous population of WA lives in its major cities while approximately 41% of them live in the remote and very remote areas. Horizon Power, the local utility that is responsible for supplying electricity to the regional, remote and very remote towns, and communities of the state mostly provides electricity to these areas by diesel or gas-based generators. However, the fuel price and its transportation difficulty, especially due to seasonal conditions, are their main technical challenges. As these areas have abundant solar and wind type resources, using a sustainable standalone system, instead of a fossil-fuel based generator is a more economical option. In this chapter, load growth is forecasted on the bases of data provided by Horizon Power.

After selecting a suitable sustainable standalone HPS for an off-grid town in WA, the impact of the load growth has been focused on the outcome of the selected system. As the load demand increases, the components of the sustainable

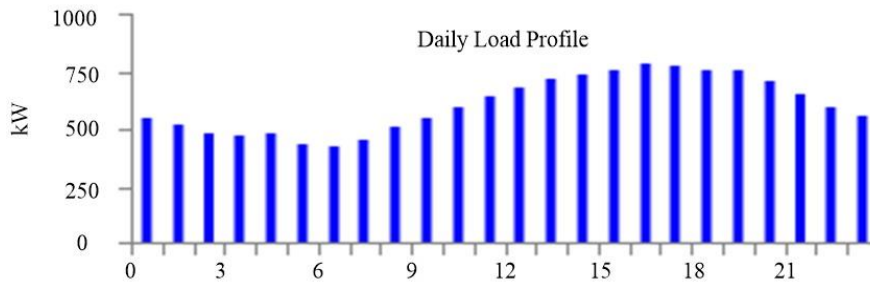


Figure 3.4. Electrical Daily Load profile of Laverton in 2015.

system need to be appropriately selected to meet the growing energy demand of the remote communities. Over the last four years, a 1.1% demand increase is observed in the remote areas of WA [1-2]. This chapter aims to investigate the impact of this annual load growth for the selected sustainable standalone HPS, over a 25-year life length of the system. The analyses, carried out by the help of the HOMER software, are compared mainly with respect to the COE and NPC of the system.

3.1 Renewable Energy Resources

Laverton is an off-grid remote town located at 28°37.5' S, 122°24.4' E (see Figure 3.3). In chapter 2.1 already discussed in detail about the weather and energy consumption of Laverton. In this research, Laverton's solar radiation and wind speed data are taken from NASA atmospheric science data center [67]. The average daily load profile of the town is illustrated in Figure 3.4. It can be seen from load profile figures that December-February of each year and especially in afternoon (around 1800 Hours) maximum power consumption is observed.

3.2 Sustainable Power System Model

In this study, the thought standalone sustainable HPS is a combination of WT, PV system, and BSS on top of a converter and a DG, as illustrated

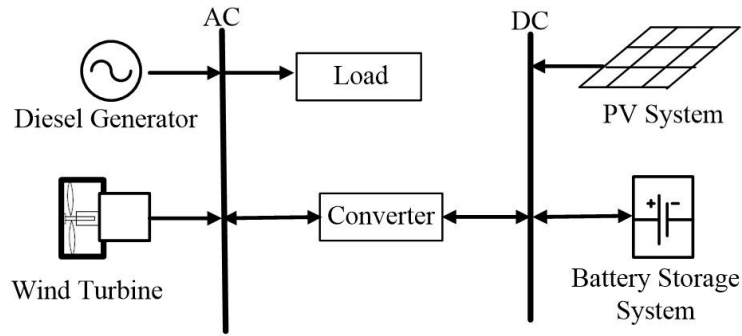


Figure 3.5. Schematic diagram of selected sustainable power system.

schematically in Figure 3.5. As the power generation from renewable resources is intermittent in nature, there is a possibility of system outage; thus, to generate extra power during energy deficiency periods, the DG is included. The considered bi-directional converter is required to convert the dc voltage produced by the PV and BSS to the ac voltage and charge the battery, while WT are assumed to be generating ac voltage at their output. HOMER software is used for selection and sizing of sustainable HPS components that facilitates the design of considered sustainable HPS in stand-alone mode. HOMER can be used for simulating and optimizing the appropriate size of the components of the power system. It can model both technical and economic factors and provides a valuable overview to compare the cost and feasibility of different configurations [37].

The project lifetime is thought to be 25 years, Australia inflation rate is 2% on average for life of the project [47], and the real interest rate is about 7% [46]. Some of the technical parameters and considered ICC, OMC of a flat plate PV module, a 275 kW GEV MP-C WT [48], a Trojan IND17-6V 1,231 Ah BSS [51], a Leonics GTP503S 125 kW converter [52] and a DG of 675 kW, are provided in Table-A1 in the Appendix. WT power curve is shown in Figure 3.6, which illustrates the variation in its output power with respect to the wind speed. To get most optimized values of components for selected sustainable system, different sizes are

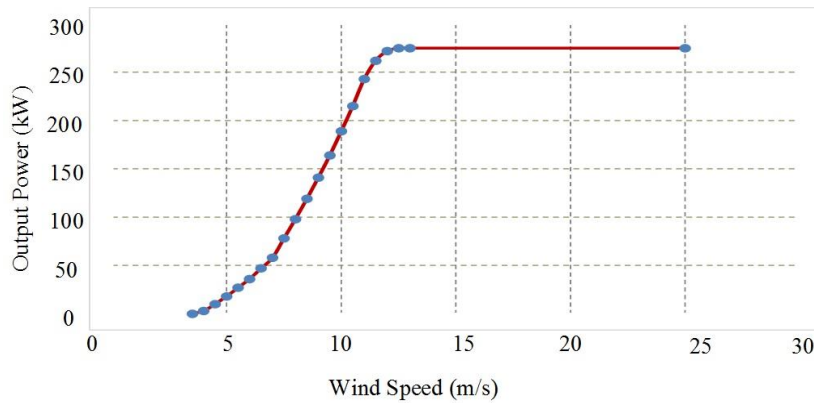


Figure 3.6. The output power of the considered wind turbine on wind speed.

considered; i.e., a 100-900kW DG, a 100-700 kW PV system, a 100-800kW converter, 1-10 WTs and 100-500 number of BSS.

In the previous chapter already concluded that the combination of a DG, a PV system, WTs and a BSS provided the minimum COE and the minimum NPC, which was selected as the most suitable solution. However, this analysis assumes a fixed load demand and did not project the annual load growth during the lifetime of the project.

3.3 Numerical Analysis Results

One of the major effects of the rapid population growth is an increase in the load demand that requires an upgrade of the current power generation system. WA is one of the fastest growing states in Australia, and its population has increased by 3.3% in the period of 2012-2013, while in 2015 a growth of 1.3% is noted [68-69]. In this study, a load growth of 1-3% is considered in 25 years for Laverton, based on which the analysis will be performed to find its impact on the outcomes of the defined standalone HPS. For this analysis, the proposed most suitable standalone HPS is considered that consists of a DG, WTs, a PV system, a BES system and a converter.

Table 3.1 Optimization Results for the Standalone Power Supply System of Laverton.

Load Growth (%)	DG (kW)	PV (kW)	No. of 275 kW WTs	No. of 1,231 Ah BSS	Converter (kW)	COE (¢/kWh)	NPC (M\$)	ICC (M\$)	OMC (k\$)
0	700	545	5	275	450	23.8	12.300	3.600	81
1	700	565	5	280	450	23.8	12.500	3.630	82
1.5	700	555	5	275	450	23.8	12.500	3.610	82
2	700	550	5	280	450	23.8	12.600	3.620	82
2.5	700	560	5	290	450	23.8	12.600	3.640	83
3	700	565	5	290	450	23.8	12.700	3.650	83

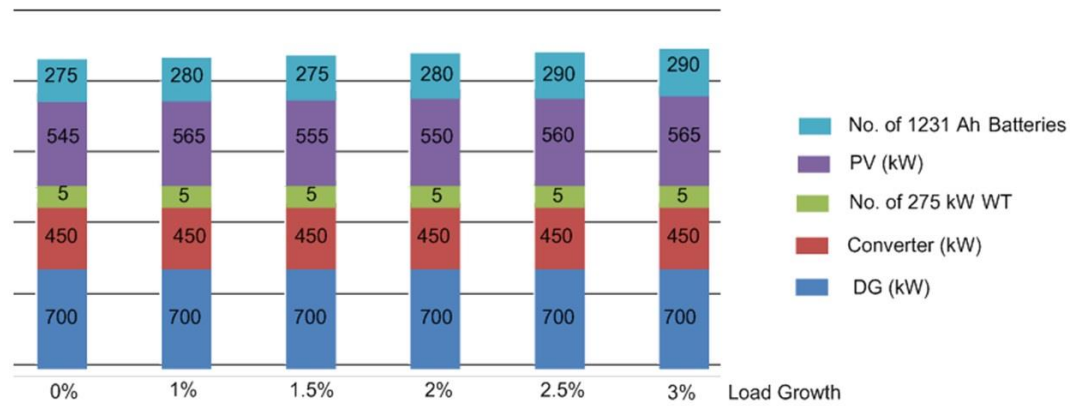


Figure 3.7. Suitable combinations for each component under load growth.

Table 3.1 illustrates the results for current demand with 0% load growth, consist of a 700 kW DG, a 450 kW converter, a 545 kW PV system, 5 WTs of 275 kW and 275 number of BSS of 1,231Ah, which result in a COE of 23.8 ¢/kWh, NPC of 12.3 M\$, ICC of 3.60 M\$ and OMC of 81 K\$. The most optimized options of standalone HPS for each case of load growth can be seen in Table 3.1.

The study illustrates that due to the slight load growth if 0 to 3% considered over the life length of the project, there is not any change in the size of the DG and the converter and the number of WTs. However, with the load growth of 3%, the size of the PV system has increased by 4%, and the number of the batteries is enlarged by 5%. On the other side, these small modifications have only resulted in a 3% increase in the NPC, 1.4% growth in the ICC and a 2.4% rise in the OMC costs over the project's life length. This study shows that the most economical solution considering a load growth of 3% does not affect the COE for the selected sustainable standalone HPS. Figure 3.7 illustrates a comparison between the size of the selected electrical components or their numbers for each case of load growth. Moreover, the slight changes in the NPC and OMC due to load growth of 1–3% can also be compared in Figure 3.8a and Figure 3.8b, respectively.

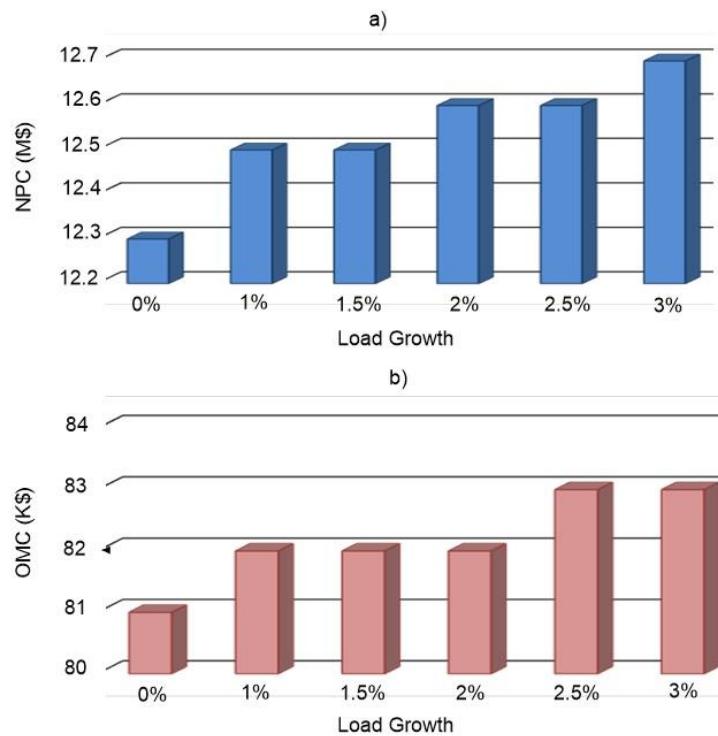


Figure 3.8. Comparison of considered sustainable system (a) Net present cost and (b) O&M Cost

3.4 Conclusions

This chapter presents a suitable sustainable standalone HPS for Laverton, an off-grid town in WA, with an average electricity demand of 400-600 kW and a maximum demand of 1.2 MW. To reduce the percentage of the electricity generated by a DG in this remote town, a sustainable system, consisting of WTs, a PV system and a BSS on top of a DG and a converter, has been selected as the most economical solution.

The analysis illustrates that due to the small growth of below 3%, the size of the diesel generator and the converter, and the number of wind turbines is not affected over the life of the project. However, the number of the considered batteries is increased by 10% and the size of the PV system has grown by 7%. The study illustrates that the NPC and the COE of the selected system are barely affected considering even a 3% demand increase over a 25-year period for this

remote town. This study yields that by selecting this economical solution, the COE will be 23.7-23.8 ¢/kWh considering 1-3% load growth which will closely match the current electricity tariffs defined by the local electricity utility.

Chapter 4 Feasibility Analysis of a Sustainable System

This chapter compares various stand-alone HPS for the remote town of Mount Magnet in Western Australia and proposes the most feasible solution. In this area, most of the towns are supplied with stand-alone generators, while a hybrid RE power system is an alternative technique to the existing system for which a feasibility analysis is conducted in this chapter. This research considers both environmental and economic aspects to design the most feasible hybrid power system. HOMER software is used to conduct the cost analysis considering different combinations of DG, WTs, PV systems, converters, and BSS.

The electricity demand has increased rapidly all around the world in the last decade. Therefore, in addition to finding newer and cheaper techniques of electricity generation, as the required element of economic development, the environmental effects of electricity production have become very important when selecting a sustainable and environmentally-friendly system [70]. Among the distributed generation resources, REs have found more applications. Wind and solar systems are experiencing fast developments as promising clean energy resources; however, due to the intermittent generation, their output power is strongly fluctuant. The effect of their unsteady generation is usually controlled by the application energy storage systems [9].



Figure 4.1. Mount Magnet, an off-grid town in Western Australia.

Most of Australian remote areas and islands are supplied by diesel or gas-based generators, which not only are expensive but also face many challenges related to the maintenance and reliability aspects. These existing power systems are also a cause of global warming as majority of electricity is generated through the burning of fossil fuels, resulting in a large amount of CO₂ production. Therefore, it is more important to use RE for power generation system, not only because they are environmental friendly but also because they are very convenient, cost effective, and reliable [71]. In the last few years, renewable energy has experienced one of the largest growths in percentage wise and to bring a higher percentage of renewable energy resources into the energy mix, it is required to modernize the Australia's policies [18]. Australia is also an active member of the International Renewable Energy Agency (IRENA), which is dedicated to support all kinds of initiatives to increase the RE [72]. To cover the large load demands of WA through RE, various small and large units are being installed currently [23, 73].

In this study, the remote town of Mount Magnet is considered (see Figure 4.1), that is located 560 km northeast of WA's capital, Perth. Currently, generators

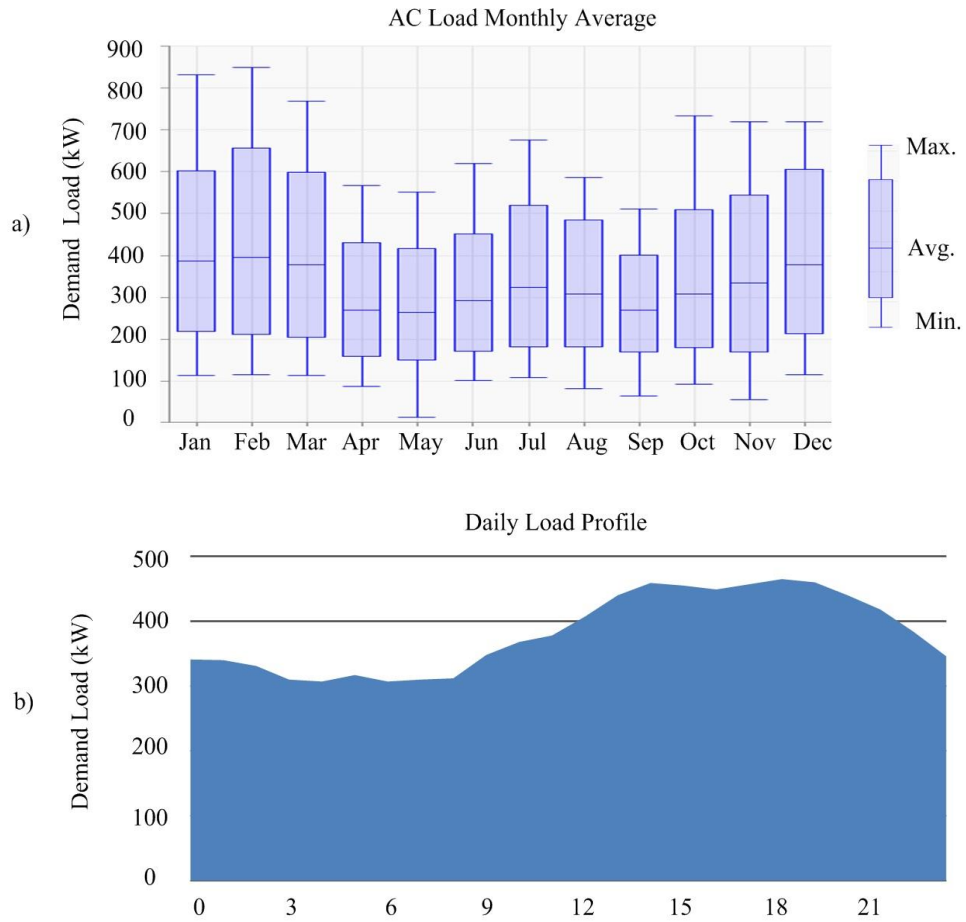


Figure 4.2. Load demand profile of Mount Magnet in 2015-16.

are used to meet the electrical load of the town; however, the local utility company, Horizon Power, is interested to install a PV system coupled with an energy storage system to meet the current energy requirement [74]. The aim of this study is to develop a suitable standalone HPS and conduct a feasibility analysis to achieve the most economic model. In this regard, different combinations are considered which consist of DGs, PV systems, WTs, BSS, and power electronics-based converters [75-76]. To find the most optimal results, numerous simulations have been performed using the HOMER software which repeats the optimization process thousands of times for each considered case and input [37]. To perform the feasibility study considered input factors are electrical load, solar radiations and wind speed, while output factors are COE, NPC, OMC, DG's fuel and emissions. At the end, the hybrid

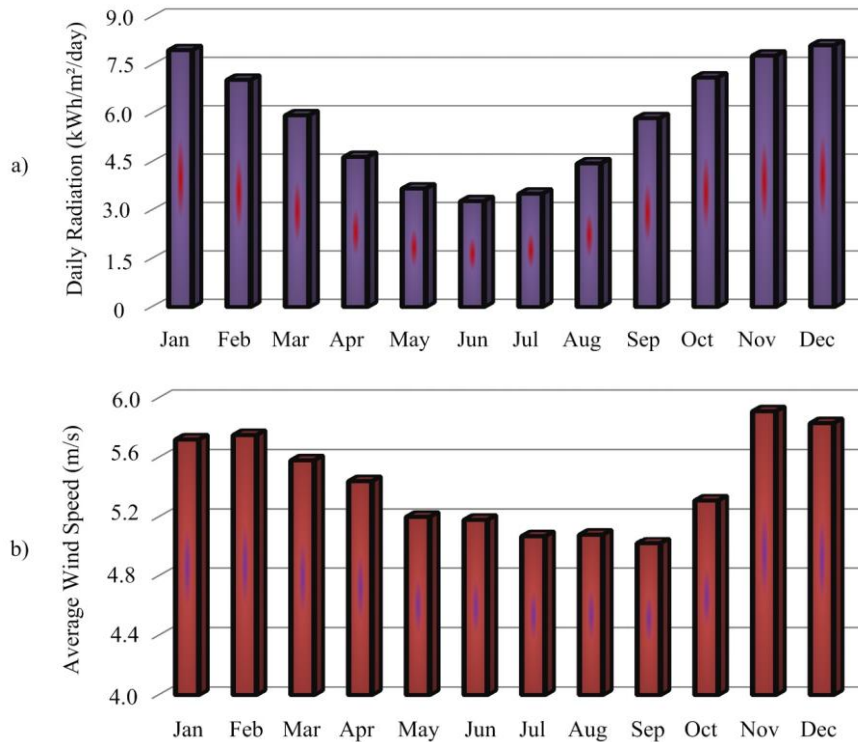


Figure 4.3. (a) Historical average daily solar radiation for Mount Magnet, (b) Historical average wind speed in Mount Magnet.

power system with the minimum COE, which is based on the NPC, OMC, DG’s fuel and emissions, over the life of the project, is selected and proposed for this remote town.

4.1 Energy Resources

The design of HPS is based on some input variables to optimize the cost and size correctly. Therefore, before designing the model, parameters like the load profile, wind speed, and the solar radiation are defined for the town of Mount Magnet. This town has an arid climate with hot summers and cool winters, with an average daily temperature ranging from 18.8 °C in July to 37.9 °C in January [77]. The peak electricity demand of Mount Magnet is 849 kW, but it has an annual average energy consumption of 7,816 kWh per day. Figure 4.2a illustrates the minimum, maximum and average of the demand in each month of 2015-16, while

Figure 4.2b shows its average load profile per day. These figures illustrate that the considered town has an average demand of approximately 300-450 kW throughout the year while it can observe a maximum demand of above 700 kW from December to March.

Mount Magnet has also a good profile for solar radiations and wind speed. Its monthly average solar radiation, captured from NASA database over a 22-year period (1983-2005), is shown in Figure 4.3a. From this figure, it can be seen that the solar radiation varies between 3 and 8 kWh/m² daily in different months of the year. It can also be seen that the solar energy generation is at the highest level during September till March. The monthly average wind speed data for Mount Magnet, captured from NASA database over a 10-year period (1983-1993), is shown in Figure 4.3b. This figure shows that the average wind speed is about 5-6 m/s [78].

4.2 Design of the Probable Hybrid System

The considered HPS, shown schematically in Figure 4.4, is modeled based on the availability of RE resources in the considered remote town. Since the selected town is rich in solar radiations and has an acceptable wind speed, it is quite feasible to install a PV system and WTs. As the irradiance and wind speed is intermittent in nature, therefore, BSS is also considered to be connected with system through a converter. DG is also considered to improve the system continuity. To obtain the most suitable stand-alone HPS, different combinations of system components are taken into account.

For this study, the overall project life is considered as 25 years; the inflation rate is taken as 2 %, and the real interest rate is assumed to be 7 %. The diesel price is thought to be 1.1 \$/liter for the lifetime of the project [46-47, 79]. The main

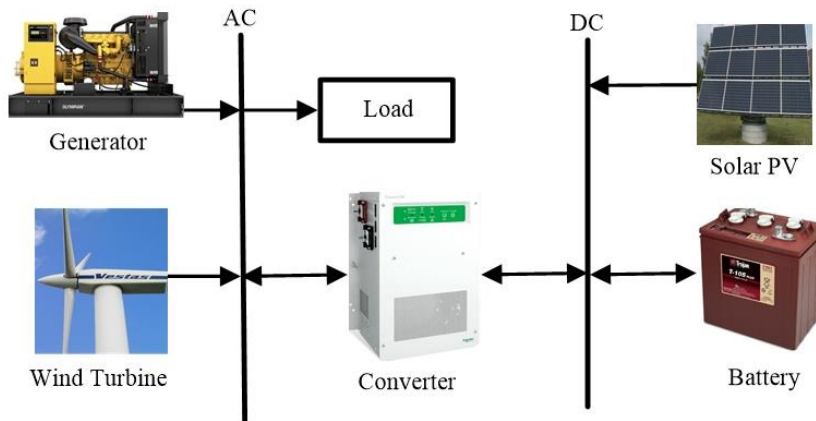


Figure 4.4. Schematic diagram of a probable hybrid power system.

components of the HPS are a PV module, a 275 kW WT [48], a DG, Trojan IND17-16 BSS [51], and a 125 kW Leonics convertor [52]. Different ratings and/or number of these components along with their ICC and OMC are listed in Table A1 in Appendix.

4.3 Cost Analysis Results

The system has been analyzed using the real load profile, historical weather data, and the price of each system components from Australian market by the help of HOMER. The aim of the optimization process is to consider different combinations of HPSs and to determine the most optimized solution for the considered remote town. The optimized results are defined considering the minimum COE and NPC, however, ICC, OMC and emission are also discussed.

In this study, Case-1 represents the existing technique to supply the electricity to the town through a DG only. In Case-2, the standalone power system consists of WTs, a PV system, and a BSS. However, from case-3 to 5, the BSS is connected with a DG and/or WT and/or solar PV to achieve most optimized result. Table 4.1 shows the most optimized results for all type of system configurations from Case-1 to 5.

Table 4.1 Optimization Results for Considered Standalone Power Supply System of Mount Magnet.

Case No.	System Type	DG (kW)	PV (kW)	WT (number of 275 kW)	1,231 Ah BSS (Number)	Converter (kW)	COE (¢/kWh)	NPC (M\$)	ICC (k\$)	OMC (k\$)
1	DG	750	0	0	0	0	38.0	15.4	300	65
2	WT+PV+BSS	0	1,750	5	2,300	750	30.4	12.3	8,230	165
3	DG+PV+BSS	450	800	0	210	450	31.3	11.5	1,990	78
4	DG+WT+BSS	450	0	6	230	250	28.9	10.7	2,880	47
5	DG+WT+PV+BSS	400	500	4	230	350	26.3	10.7	2,900	62

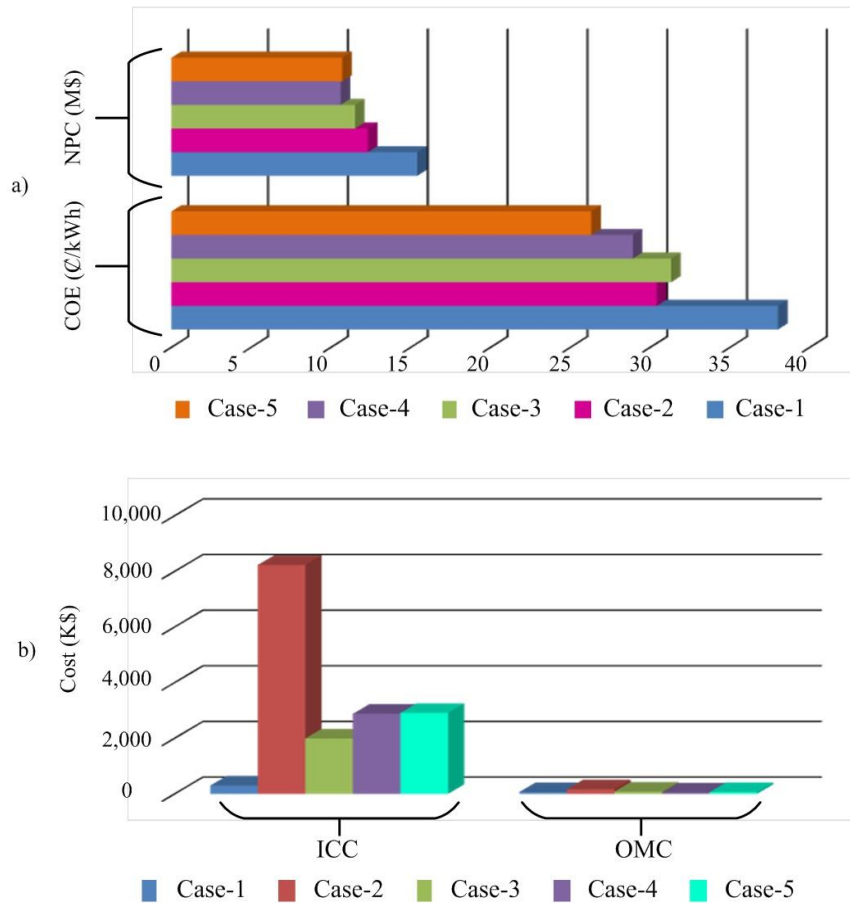


Figure 4.5. Comparison of different configuration for Mount Magnet: (a) Cost of energy and Net present cost and (b) Initial capital cost and Operation & maintenance cost

The most optimal situation for case-1 is when the town's demand is supplied by a 750 kW DG, which has a COE of 38 ¢/kWh, an NPC of 15.4 M\$, an ICC of 300 k\$ and an OMC of 65 k\$ for 25 years. However, for the system of case-2 which is composed of a 1,750 kW PV system, five 275 kW WT_s, 2,300 number of BSS of 1,231 Ah, and a 750 kW convertor, the COE and the NPC reduced to 30.4 ¢/kWh and 12.3 M\$, respectively, although the ICC and the OMC are higher than case-1.

In case-4, when a 450 kW DG is connected with six 275 kW WT_s, 230 BSS of 1,231 Ah, and a 250 kW convertor, the COE, the NPC and the OMC further reduced 24, 31 and 28 %, respectively. However, the ICC is 2.88 M\$ higher than that of case-1.

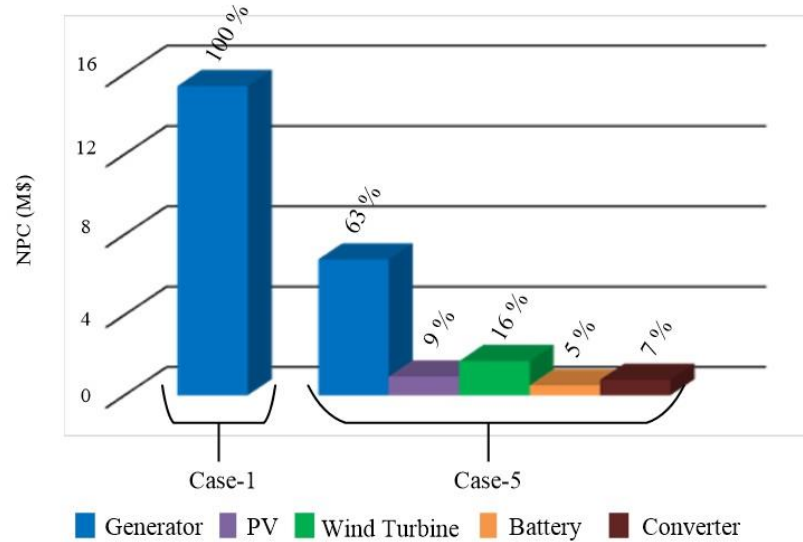


Figure 4.6. Components NPC summary between Case-1 and Case-5.

It can be seen that case-5 (combination of a 400 kW DG, a 500 kW PV system, four 275 kW WTs, 300 number of BSS of 1,231 Ah, and a 350 kW convertor) gives the minimum COE of 26.3 ¢/kWh, along with the NPC of 10.7 M\$, and the OMC of 62 k\$ per annum. However, the ICC is more than that of case-1 but 65 % lower than the one of case-2. Through the comparison, it is evident that case-5 is economically the most suitable standalone HPS for the considered town. The simulation results for each of configuration can also be compared visually in Figure 4.5 that shows the optimal values of COE, NPC, ICC and OMC for each case individually.

A comparison between the distribution of NPC for each component in case-1 (the existing system) and case-5 (the proposed system) is illustrated in Figure 4.6. From the figure, it can be seen that even though the NPC of the proposed case is reduced to 31% compared to the existing system but still majority of the NPC is due to the presence and operation of the diesel generator. Figure 4.7 shows the flow chart to calculate the most feasible solution for proposed hybrid power system.

Table 4.2 provides a comparison of the emissions for case-1, 4, and 5. The

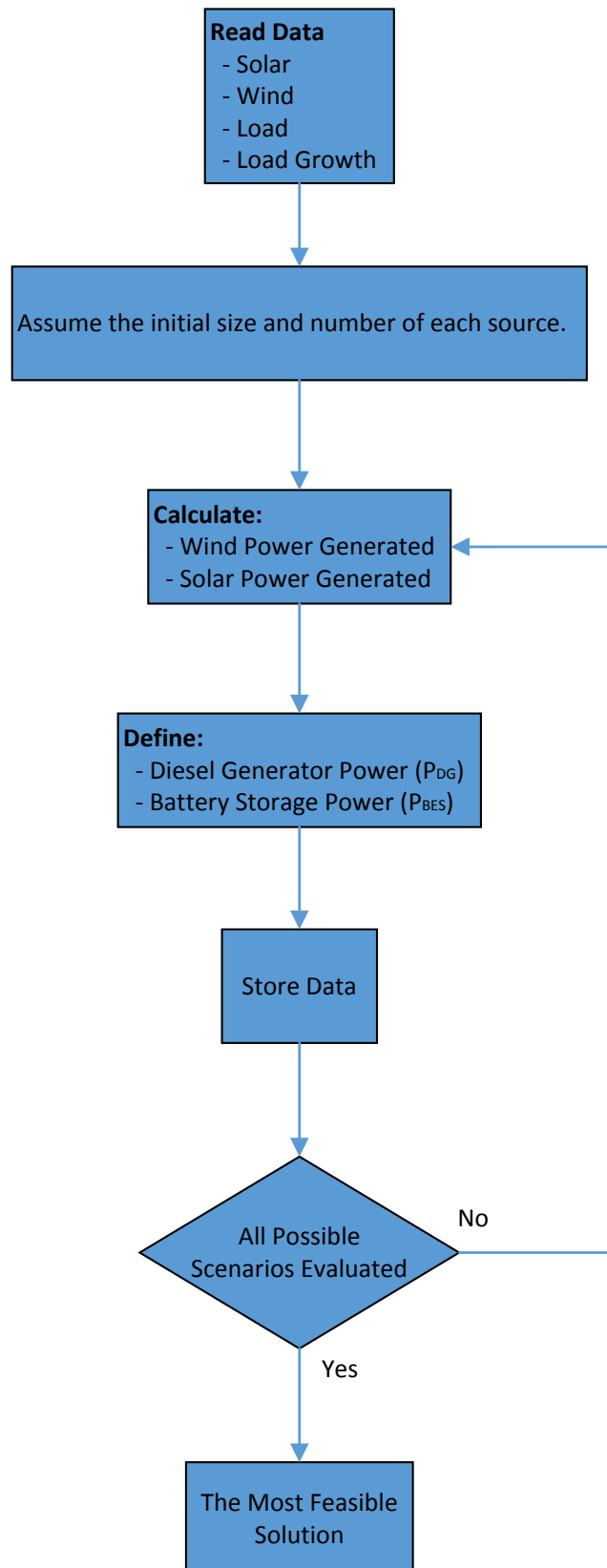


Figure 4.7. Flow chart to calculate most feasible solution for hybrid power system

Table 4.2 System Emission [Tones/Year].

Emission Components	Case-1	Case-4	Case-5	Unit
Carbon Dioxide	2,309.69	1,204.52	1,042.59	Tones/Year
Carbon Monoxide	5.70	2.97	2.57	
Unburned Hydrocarbons	0.63	0.33	0.28	
Particulate Matter	0.43	0.22	0.19	
Sulfur Dioxide	4.64	2.42	2.09	
Nitrogen Oxides	50.87	26.53	22.96	

main cause of emission is due to the operation of DG; therefore, the preferred HPS needs to have the minimum operating hours of the DG. In case-4 and case-5, each of the emission components are reduced to 48 % and 55% respectively in comparison to those of case-1. On the other hand, the fuel consumption of case-5 is minimum with 55 % reduction in case-1 while the DG operating hours is also reduced to 40 % in case-1.

From the above analysis, case-5 is not only suitable due to the minimum values of COE, the NPC and the OMC, but also has the least emissions to the environment which play a vital role in designing a climate-friendly hybrid power system. It is also observed that wind energy has more prospect compared to solar energy, and play an important contribution in hybrid power system as it is possible to generate electricity from WTs more often than the PV systems. Therefore, a hybrid power system utilizes both wind and solar resources can be more useful than other HPSs.

4.4 Conclusions

The main objective of this chapter is to conduct a feasibility analysis to select the most economically suitable sustainable standalone HPS for Mount Magnet, a

remote and off-grid town in Western Australia. HOMER software has been used for simulations and uses the real load demand of the town, the historical solar and wind speed data, as well as price of each system component in Australian Market. The analysis illustrates that when the town is supplied by only one DG of 750 kW the COE is 38 ¢/kWh; however, when supplied by a 400 kW DG, a 500 kW PV system, four 275 kW WTs, 300 number of BSS of 1,231 Ah, and a 350 kW convertor, the COE reduced 26.3 ¢/kWh over the project life of 25 years. Moreover, in comparison to the current system, the emissions and the diesel generator operating hours of proposed system reduced to 55 % and 40 % respectively.

Chapter 5 Conclusions and Recommendations

This chapter summarizes the general findings of the thesis. Some recommendations for future researches in the areas of the thesis are also introduced here.

5.1 Conclusions

The general conclusions of the thesis are:

- (1) The evaluation and analysis of eight different cases reveal that, if the load demand of Laverton is supplied by only a diesel generator, the cost of energy is at its maximum value (i.e., 34.8 ¢/kWh), although the customers of the town are currently charged at 25.7 ¢/kWh. This analysis validates the fact that the local electrical utility does not gain financial benefit when supplying the customers of this town.
- (2) Based on the economic analysis of different hybrid system combinations, it is evident that if a combination of a suitable diesel generator, photovoltaic system, wind turbines and a battery energy storage system along with a power electronics-based converter is utilized, the cost of energy can be reduced by approximately 30% (to 24.6 ¢/kWh) and will match closely with the current electrical tariff. The analysis illustrates that the suggested hybrid microgrid system is feasible in meeting the demand of the town, and the cost of energy is comparable to existing electricity tariff for this remote off-grid town.

- (3) From the sensitivity analysis, it can be seen that the cost of energy is linearly related to the diesel generator's fuel cost; however, it can also be seen that the life length of the project when varied from 20 to 30 years does not affect the cost of energy.
- (4) To reduce the percentage of the electricity generated by a diesel generator in the remote town, a sustainable system consisting of wind turbines, a PV system and a battery storage system on top of a diesel generator and a converter, has been selected as the most economical solution for Laverton. The study illustrates that the net present cost and the cost of energy of the selected system are barely affected considering even a 3% demand increase over a 25-year period for this remote town. This study yields that by selecting this economical solution, the cost of energy will be 23.7-23.8 ¢/kWh which will closely match the current electricity tariffs defined by the local electricity utility.
- (5) The analysis illustrates that when the remote town of Mount Magnet is supplied by a diesel generator of 750 kW, the cost of energy is 38 ¢/kWh; however, when supplied by a combination of a 400 kW diesel generator, a 500 kW PV system, four 275 kW wind turbines, 300 batteries of 1,231 Ah, and a 350 kW converter, the cost of energy reduced to 26.3 ¢/kWh over the project life of 25 years. Moreover, in comparison to the current system the emissions and the diesel generator operating hours of proposed system reduced to 55 % and 40 % respectively.
- (6) Nowadays, the Australian government, utilities, and research communities are trying all together to increase the use of renewable energies. This study uses HOMER simulation software to investigate the prospects of renewable

energy, and particularly the wind and solar energies, for WA's remote towns, for which the local utility is not gaining benefit for supplying electricity by an existing diesel generator. The COE, the NPC, the initial capital cost, the O&M cost, and the emissions are assessed to compare the performances of different type of hybrid models. This study utilized the real data of the electrical demand of the town, its historical wind speed, and solar radiation as well as the price of each electrical component from the Australian market.

5.2 Recommendations for future research

Some future research topics in the area of this thesis are presented below:

- (1) BSS is the only utilized energy storage system in this research; however, in order to control and minimize the access electricity of proposed HPSs, applications of flywheels can be considered as a probable energy storage system in future analyses.
- (2) In this research, only the remote towns of Laverton and Mount Magnet are analysed. Similar analysis can also be performed for other remote areas of Australia, to define a nationally-acceptable economical HPS for small remote towns.

Appendix

Table A.1 Technical parameters and costs of the components.

PV System		BSS	
ICC [53]	1.3 \$/W	ICC [46, 56]	1500 \$
OMC [46]	40 \$/kW/Year	OMC [46]	30 \$/year
Lifetime	25 Years	Nominal capacity	1,231 Ah
Derating factor	80 %	Nominal voltage	6 V
Ground reflectance	20 %	Initial state of charge	100 %
Nominal operating cell temperature	47 °C	Float life	20 years
Converter		WT	
ICC [46, 54]	1000 \$/kW	Rated capacity	275 kW

OMC [46]	25 \$/kW/year	ICC [55]	350 k\$
Lifetime	10 years	OMC	1.5 k\$/year
Efficiency	96 %	Lifetime	20 years
DG		Starting wind speed	4 m/s
ICC [46]	400 \$/kW	Cut-off wind speed	12.5 m/s
OMC [46]	0.01 \$/hour	Hub height	55 m
Operational lifetime [46]	60,000 hours		
Diesel fuel price	1.1 \$/liter		
Slope coefficient [60]	0.2798 liter/hour/kW		
Intercept coefficient [60]	0.0114 liter/hour/kW		

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Publications arising from this Thesis

Journal papers

- 1) L. Ali, and F. Shahnia, "Determination of an Economically-Suitable and Standalone Power System for an off-grid town in Australia," reviewed by *International Journal of Renewable Energy*, Elsevier 2016.

Conference papers

- 2) L. Ali and F. Shahnia, "Selection of a suitable standalone power supply system for an off-grid town in Western Australia," *2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)*, Florence, 2016, pp. 1-6.
- 3) L. Ali and F. Shahnia, "Impact of annual load growth on selecting the suitable sustainable standalone system for an off-grid town in Western Australia," *2016 IEEE International Conference on Power System Technology (POWERCON)*, Wollongong, NSW, 2016, pp. 1-5.
- 4) L. Ali, F. Shahnia, H.I.T Fernando and A. Arefi, "Feasibility Analysis of a Sustainable System for an Australian Remote Town," *2017 IEEE 3rd International Conference on Power Generation System and Renewable Energy Technology (PGSRET2017)*, Johor Bahru, Malaysia, 2017.