Operations and investment modelling of an energy microgrid with mixed-integer linear programming

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Abstract

The increase in electricity demand worldwide is driven by economic growth and a rising population. The traditional power system, which is based on a centralised network, is facing many challenges and is not capable of meeting the demand. As a result, the advancement towards a smarter grid has occurred, and the concept of Microgrids has gained a lot of attention. Microgrids are seen as the building blocks of Smart Grid and can be defined as local small-scale grids which enable the integration of Distributed Energy Resources (DER), storage systems and various loads. The microgrid system can operate collaboratively or independently from the main power grid.

The adoption of a microgrid with alternative energy options is being considered by numerous individuals and investors. The investment in microgrids is especially considered by those who lack access to the traditional grid or when the main power grid cannot provide sufficient and reliable power to end-users. However, the planning and implementation of a microgrid are not simple, and the investment in alternative energy sources and storage can be costly. The individual needs to know whether the investment is feasible and what to invest in, considering multiple options.

A Mixed-Integer Linear Programming (MILP) model is proposed to minimise the total cost of an energy microgrid while addressing the operational and investment aspects. The model can minimise the total cost of a microgrid while determining the optimal operation, configuration and investment time for the technologies. The model examines a grid-connected system which supports the integration of DERs and battery storage options. The proposed model considers the daily operation and technical aspects of each technology, and based on that, determines the optimal design and investment plan over a long-term period.

The verification process proves that the formulation and implementation of the proposed model are correct. The model complies with all constraints, and the model results are as expected during each evaluation. Furthermore, the model is validated by showing that it provides a feasible solution to several real-life scenarios. During the model validation, changing economic factors are incorporated to show the effect thereof on the model results.

The proposed optimisation model aims to provide individuals that are considering an investment in a microgrid with alternative energy sources and storage with a planning and decision-making framework. The operational and investment components are closely connected and are therefore addressed in a single model. An important contribution of this study is to provide a way for investors to determine the optimal time to invest when considering a changing economic environment.

Keywords: Smart grid; Microgrid planning; Distributed energy sources; Energy scheduling; Optimisation; Mixed-integer linear programming.

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AC	Alternating Current
AMI	Advanced Metering Infrastructure
AMR	Automated Meter Reading
BESS	Battery Energy Storage System
CHP	Combined Heat and Power
CPP	Critical Peak Pricing
DC	Direct Current
DER	Distributed Energy Resource
DG	Distributed Generation
DP	Dynamic Programming
DR	Demand Response
DSM	Demand-Side Management
EMS	Energy Management System
EPRI	Electric Power Research Institute
ESS	Energy Storage System
EV	Electric Vehicle
GA	Genetic Algorithm
HEM	Home Energy Management
ILP	Integer Linear Programming
LP	Linear Programming
MILP	Mixed-Integer Linear Programming
PCC	Point of Common Coupling
PV	Photovoltaic
RES	Renewable Energy Source
SOE	State-of-Energy
STC	Standard Test Conditions
TOU	Time-of-Use
VAT	Value-Added Tax
VPP	Virtual Power Producer

Chapter 1

Introduction

1.1 Background and rationale

The world's current electric power system is undergoing a period of important transformation. These changes are a result of the development in technology and the increasing demand for electricity across the globe (Kucuksari et al., 2014). Some of the main reasons for the increase in power demand include population growth and continuous economic development.

The traditional power system consists of a centralised network where electricity is generated at large power plants and is distributed to end-users (Derakhshan et al., 2016). This system has been in place for many years, but due to ageing infrastructure, the lack of system upgrades and development, and the ability to incorporate additional energy sources, the traditional power grid is reaching its limit and is not capable of meeting the rising demand.

The evolution of a more intelligent electric system, also known as a "Smart Grid", provides a solution to the challenges faced by the traditional power grid. The smart grid is expected to enable the two-way flow of information and electrical power, which can significantly improve the generation, transmission and distribution of electricity (Ataul et al., 2014). This system will allow the integration of Renewable Energy Sources (RES), and it can be described as a mixture of distributed and centralised power generation. Along with other factors, such as the participation of electrical markets and an increase in consumer involvement and awareness, this type of system will lead to a more dependable, resilient and environmentally friendly electrical grid (Salkuti, 2020).

The advancement towards a smarter grid has also led to the concept of microgrids. Microgrids play an important role in smart grids and are defined as local and small-scale energy systems. The microgrid system is a collection of Distributed Energy Resources (DER), Energy Storage Systems (ESS), and loads. It can operate independently from the grid or be connected to the main grid, enabling grid exchange. With the use of smart control, monitoring and self-healing technologies, the microgrid aims to provide electricity to its end-users in an efficient, sustainable and reliable manner (Garg and Sharma, 2018). An article by Savic et al. (2019) states that microgrids are one of the latest and most effective technological solutions in the power industry.

Over the past few years, there has been an increasing interest and growth in RESs as an alternative option for power generation. As a result, the idea of microgrids is becoming more attractive since they can be powered by various DERs including RESs. The continuous development and improvement of new technologies have also led to a decrease in capital costs. Chedid et al. (2020) states that there is a decrease, particularly in the capital cost of Battery Energy Storage Systems (BESS) and Photovoltaic (PV) systems, which makes the combination of a PV system and BESS more appealing to users.

The investment in a microgrid with alternative energy options has gained much attention, especially in countries such as South Africa. Many problems have led to the energy crisis in South Africa, and the national utility company cannot meet the country's power demand. The rapid increase in energy prices and the implementation of scheduled power outages, known as load-shedding, have a negative impact on economic growth and the daily lives of individuals.

According to Chedid et al. (2020), the dependence on diesel generators and scheduled blackouts form part of the electrical power system in many developing countries. Therefore, the installation of additional energy sources is considered by many organisations and consumers and can help to improve the security of energy supply and to lower energy costs. Microgrids can come in various types and sizes. Microgrid applications can vary from a single building or facility to whole communities with many customers. Microgrids can, for example, be incorporated into large business parks, residential estates or university campuses.

Recent studies indicate that many university campuses experience problems with energy efficiency and the security of energy supply. Administrative and academic activities, along with campus accommodation, consume substantial amounts of energy (Ma et al., 2019). Some university campuses rely heavily on the use of diesel generators since the power system experiences regular blackouts and scheduled load-shedding (Chedid et al., 2020). A possible solution for solving these problems includes the implementation of a campus microgrid with DERs (Ma et al., 2019). However, many elements must be considered when adopting a microgrid with DERs for university campuses or other microgrid designs.

Microgrid systems can become very complex since power is supplied by several DERs. This, along with integrating a BESS and connecting to the main grid, increases the complexity. Therefore, microgrid planning and design are essential to ensure the system's reliability and that the consumers' power requirements are met. Many planning techniques focus on operating the microgrid at minimum cost and usually consider the optimal sizing and operation of the system. Several technical and investment factors are considered, such as technology availability, investment and operating costs, and the balance between supply and demand.

Furthermore, customers and potential investors are unsure whether they can afford such an investment. It is important to determine if the investment is feasible over a long-term period while considering the development in technologies, cost trends, and the effect of other economic factors.

1.2 Research problem

Individuals and organisations that are considering an investment in a microgrid system with supplementary alternative electricity sources do not have a reliable framework or guide for assessing the financial viability of such an investment. This includes, amongst other factors, determining how much to invest and the optimal time for the investment of the technology solutions given a changing economic environment.

1.3 Research aim

The aim of the study was to develop a mathematical optimisation model that will be able to determine the optimal configuration of alternative electricity sources in a microgrid while minimising the total cost. The model must consider both the operational and investment factors of the system. Cost trends and changing economic factors need to be considered to determine when the optimal point in time would be to invest.

1.4 Research objectives

The following objectives describe how the research aim was achieved and were important for the successful completion of the research project. The research objectives were to:

(i) Gain an understanding of the research focus areas, namely the traditional power grid and smart grid concept, alternative electricity sources, and the components and operations associated with microgrids. And to also obtain knowledge on mathematical modelling and optimisation to help identify a suitable algorithm for optimising an energy microgrid.

(ii) Gain insight into how microgrid optimisation can be achieved and determine which approaches have been followed in literature with a specific focus on Mixed-Integer Linear Programming (MILP) models.

(iii) Formulate and implement an optimisation model that can minimise the cost of an energy microgrid while addressing the operational and investment aspects of the system. The model determines the optimal configuration of generation and storage technologies as well as the optimal time to invest.

(iv) Obtain data that is satisfactory for the testing and evaluation of the proposed model.

(v) Prove that the model formulation and implementation are correct and accurately represent the proposed microgrid system.

(vi) Validate that the model performs as intended and that it can be used to optimise real-world microgrid scenarios. Evaluate the influence of changing costs on the final solution of the MILP model.

(vii) Identify the limitations of the proposed model and provide recommendations for improvements and future work.

1.5 Research methods

The following research methods were applied to reach the objectives specified in Section 1.4.

(i) A literature study was undertaken to obtain background on the research focus areas. From the information gathered on mathematical optimisation, it was determined that a MILP model is most suitable for solving the research problem.

(ii) To determine which approaches have been followed to solve microgrid optimisation problems, a literature review was carried out. Summaries of the most relevant studies are provided, followed by a discussion on possible gaps that are not addressed in the current literature. Each summary provides insight into how the problem was approached by examining the objective function, decision variables and constraints associated with the operational or financial aspects of the microgrid.

(iii) A MILP model was formulated for the optimisation of an energy microgrid. From the knowledge obtained in the background and literature review section, it was determined which elements form a part of the microgrid system for this study. The parameter and decision variable notations are described, followed by the mathematical expressions used for the objective function. Lastly, the constraints required for the operational and investment aspects of the microgrid are specified. IBM ILOG CPLEX Optimization Studio was installed, and the model was implemented in Python with the use of the DOcplex library.

(iv) The data required by the model parameters were obtained. The data consists of real-world data, which is essential for the testing of the model. The data structures required by the model were created, and the data was processed accordingly.

(v) The verification of the model consisted of testing the proposed model with smaller and simplified datasets. The model verification was further simplified by examining the constraints of each technology and the grid separately. The goal was to determine whether the constraints and expressions work as intended by investigating the effects thereof.

(vi) During the validation process, large real-world datasets and scenarios were considered. It is shown that the model can obtain an optimal solution to various scenarios. A change in technology and grid prices was implemented, and the model results were analysed.

(vii) From the scenarios and results obtained by the model, the areas in need of improvement were identified. A summary of possible improvements and future work is provided.

1.6 Project scope

The project scope is used to specify the extent to which the research topic will be investigated and identifies the boundaries of the study. The project scope is as follows:

- For this study, the focus will be on organisations operating large business parks, residential areas, campuses, etc. It is assumed that large industrial organisations require other focus areas and are therefore excluded.
- The energy resources considered by this study include the grid, diesel generators, PV panels, a wind turbine system and batteries. The incorporation of other alternative energy sources is excluded. It is, however, possible to expand the model by adding additional energy options.
- This study comprises the development and implementation of an optimisation model. The proposed model is verified and validated with the energy profile of a university campus. However, the model testing only consists of running different scenarios and analysing the results. The installation of an actual microgrid is not considered in this study.

1.7 Chapter overview

This dissertation consists of seven chapters, followed by an appendix. Chapter 1 provides an introduction to the study. In Chapter 2, background on power generation, alternative energy sources and microgrids is provided. The mathematical programming and optimisation field is also explored, followed by a literature review section. In this section, existing literature with a focus on microgrid optimisation is assessed. The goal is to determine which approaches have been followed and to identify possible gaps in the literature.

The formulation of the proposed MILP model is presented in Chapter 3. The model aims to address the operational and investment aspects of an energy microgrid. This chapter discusses the model parameters, decision variables, objective function and constraints. In Chapter 4, the input data required for the testing of the model is provided.

The verification process aims to prove that the formulation of the mathematical model is correct. In Chapter 5, each technology is assessed separately to demonstrate that the model adheres to the constraints. Chapter 6 comprises the model validation and determines whether the model performs as intended with large datasets and realistic microgrid scenarios. Chapter 7 summarises the work completed in each chapter, followed by suggestions for future research and improvements on the topic of energy microgrid optimisation.

Chapter 2

Literature study

2.1 Introduction

In Chapter 1, the background and motivation for this study were provided, followed by a description of how the research problem is approached. Chapter 2 consists of two parts. Section 2.2 provides background and context on the topics covered in this dissertation. The goal is to obtain knowledge on relevant subjects, to address the research problem successfully. An overview is provided on the history of electricity and how that has led to the power system of the modern world. The structure and operation of the traditional power grid are discussed, followed by the challenges faced by the current system. The concepts known as Smart Grid and Microgrid are explored in depth, followed by an overview of mathematical optimisation. In Section 2.3, existing research is examined to determine how microgrid optimisation has been approached and what factors should be considered for the accurate modelling of such a system.

2.2 Background

This section provides a discussion and background on the history of electricity, the traditional power grid and the concepts known as Smart Grid and Microgrid. Lastly, an overview of mathematical optimisation is provided.

2.2.1 Electricity

Electricity is defined as the flow of electric charge (Hart-Davis et al., 2009). This charge can be negative or positive, and according to Hart-Davis et al. (2009), an electric current is produced when electrons move from one atom to another in most cases.

During ancient times people started to observe the effects of static electricity (Hart-Davis et al., 2009). Thales of Miletus, a philosopher from ancient Greece, discovered that after rubbing amber on fur, it would attract feathers and other lightweight materials (Hart-Davis et al., 2009).

Hesla and Pendergrass (2020) explained that the understanding of electricity began to evolve quickly during the Age of Enlightenment in the 1700s. During this time, Benjamin Franklin carried out an experiment involving a kite which he flew into a thunderstorm. He discovered that lightning was a form of electricity and that electricity could be defined as positive or negative. From this experiment, he was able to develop the lightning rod (Hesla and Pendergrass, 2020).

The Italian physicist Luigi Galvani placed much of his focus on the theory of "animal electricity" in the 1780s (Hart-Davis et al., 2009). In his experiments, he introduced a spark of static electricity to frogs' legs and that would cause the legs to twitch and move. While performing these experiments, he discovered that when the frog's leg was attached to an iron hook and the exposed nerves were touched by a copper hook, the leg would also twitch (Hart-Davis et al., 2009). These movements were not caused by static electricity but by a new phenomenon (Hart-Davis et al., 2009).

Alessandro Volta directed his attention to the same phenomenon and suggested that the presence of two different metals caused the generation of electricity (Hart-Davis et al., 2009). This led to his invention of the world's first battery, the "Voltaic pile", in 1799. This invention was able to produce a constant electric current (Hart-Davis et al., 2009).

In 1820, the discovery was made that there is a link between electricity and magnetism (Hart-Davis et al., 2009). According to Hesla and Pendergrass (2020), Danish physicist Hans Christian Ørsted noticed the movement of a compass needle while an electric current flowed through a wire near the compass. He concluded that a magnetic field was being produced by the electric current, thus resulting in the discovery of electromagnetism.

This opened the door to many life-changing discoveries, and other scientists began their investigations in the field of electromagnetism (Hart-Davis et al., 2009). André-Marie Ampère showed that depending on the direction of current flow within a wire, two wires can either attract or repel each other. The relationship between electricity and magnetism led to the development of the world's first electric motor. This discovery was made by Michael Faraday, but many others contributed to the development of the electric motor over the years (Hart-Davis et al., 2009).

Hart-Davis et al. (2009) discussed the significant contribution of James Clerk Maxwell in the 1860s and how his equations describe the properties of electromagnetism. According to Hesla and Pendergrass (2020), other major inventions that followed include not only the electric motor but also the dynamo, the telegraph, the telephone, the radio and electric lights.

Thomas Edison was one of the first people to see the potential of electricity and how it could be utilised in our homes (Hart-Davis et al., 2009). Edison is especially known for the incandescent light bulb and the phonograph, and he brought moving pictures into people's homes. Although he was not the first person to invent the electric light bulb or power station, he was able to visualise how all the components would fit together. According to Hart-Davis et al. (2009), Thomas Edison established the first commercial power station in 1882.

One of the challenges Edison faced was the transmission of electricity over long distances (Hesla and Pendergrass, 2020). During this time, he became involved in a debate with George Westinghouse and Nikola Tesla, known as the "war of the currents". Thomas Edison believed in a Direct Current (DC) system, but it was proven unsuccessful, and Nikola Tesla made a huge breakthrough with the invention of generators and motors that worked on Alternating Current (AC), which was able to transmit electricity over long distances (Hesla and Pendergrass, 2020). Thus, he made a massive contribution to the development of the AC power system and how the modern world is powered today (Hart-Davis et al., 2009).

2.2.2 The traditional power grid

The role of a power grid is to deliver electricity from power plants to end-users (Melhem, 2018). The standard structure of a traditional power grid includes the generation, transmission, distribution and consumption of electricity (Savic et al., 2019). Electricity is generated at a central power plant and transported through a transmission and distribution grid (Colak, 2016). The electricity is transmitted at a high voltage, and with the use of substations, the voltage is gradually reduced to meet consumer requirements. This type of flow is characterised as one-directional flow (Colak, 2016). In Figure 2.1, it is shown how electricity is delivered from the top of the chain, namely the central power generation, to the consumers of electricity at the bottom of the chain (Farhangi, 2010). This is classified as a hierarchical system according to the author, Farhangi (2010).

As previously mentioned, the electric power grid is divided into four subsystems, namely generation, transmission, distribution and consumption. Each subsystem is associated with specific voltage levels, and according to Shawkat Ali (2013), the generation, transmission and distribution systems are connected by transformers. Transformers are required for the step-down or step-up of voltages (Shawkat Ali, 2013). Figure 2.2 is described by Shawkat Ali (2013) as a single-line diagram used to represent a simple power grid system with transformers and busbar (*Bus*). The diagram was adapted to show the different subsystems. Consumption is not indicated on the diagram but takes place after distribution and includes the customers listed.

The following section provides a more detailed discussion of each subsystem and its voltage level:

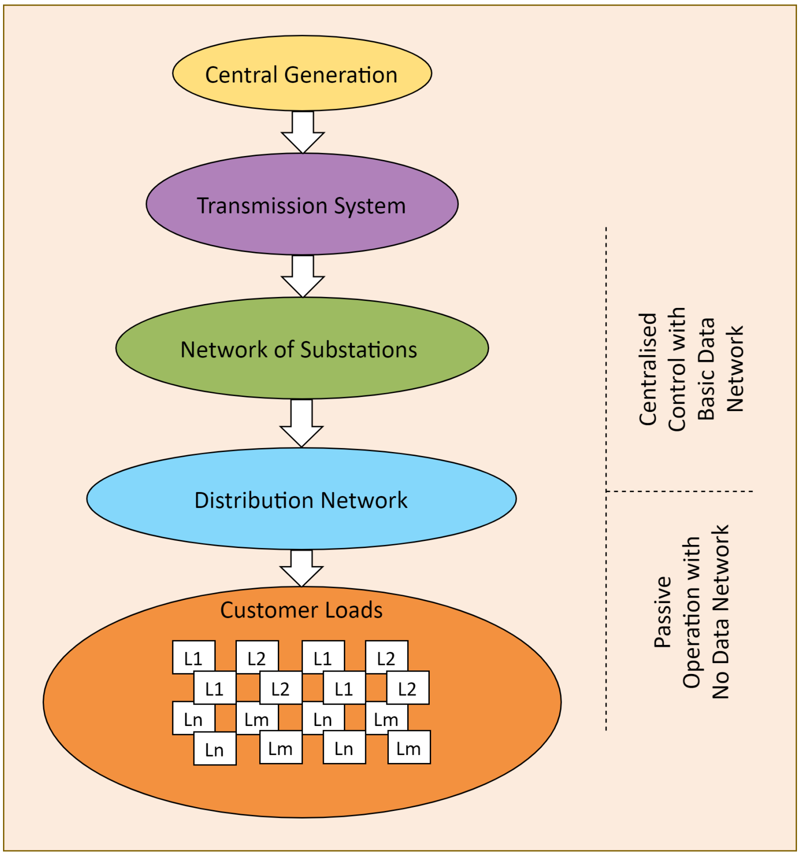

Figure 2.1: The traditional power grid: A hierarchical system (Replicated from Farhangi (2010))

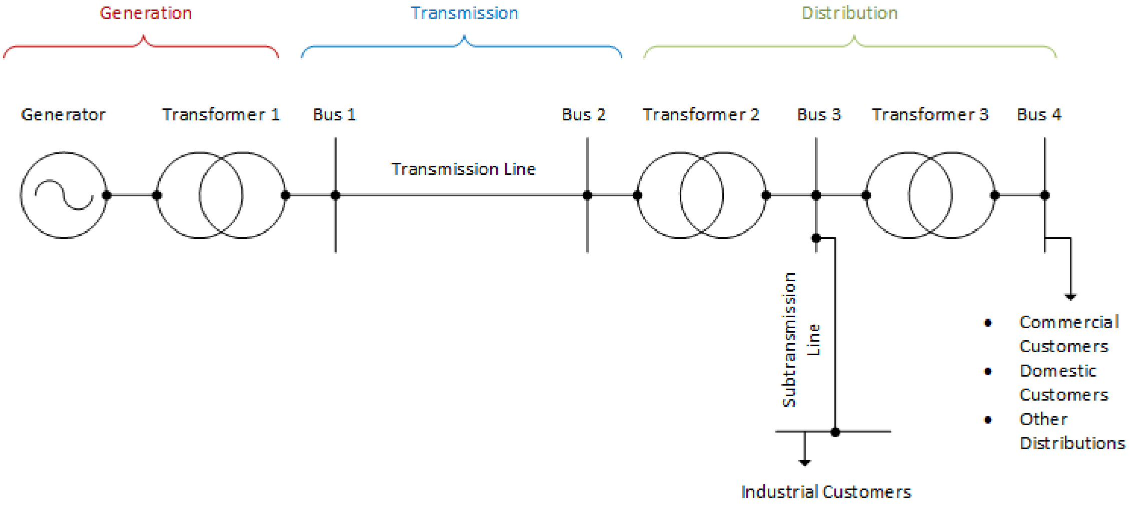

Figure 2.2: Single-line diagram of a simple power grid system with transformers and busbar (*Bus*) (Adapted from Shawkat Ali (2013))

Generation

The generation of electricity can be defined as the conversion of energy from different sources into electric power (Shawkat Ali, 2013). Primary energy sources can be divided into two groups, namely non-renewable and RESs. Coal, oil, natural gas and nuclear power are classified as non-renewable sources, and RESs include wind, solar, geothermal, hydro and biomass (Melhem, 2018). The traditional power system typically utilises fossil fuels. Electricity is generated at a medium voltage and enters the generation plant substation where the voltage is increased (Melhem, 2018).

Transmission

According to Shawkat Ali (2013), the generated electricity is delivered over long distances through transmission lines. During the transmission process, power losses occur due to the Joule effect, where energy is lost in the form of heat when it passes through a conductor (Melhem, 2018). To reduce the power losses and to ensure that the long-distance transmission of power is feasible, the voltage levels are increased (Melhem, 2018). This is the reason why generated power enters the plant step-up transformer and is increased to a very high voltage.

Distribution and consumption

The distribution subsystem is the final part of the delivery of electricity and transports power from the transmission subsystem to the consumers (Shawkat Ali, 2013). Voltage levels are step-down by distribution transformers to meet specific power requirements of consumers (Shawkat Ali, 2013).

Electricity consumers can be grouped as follows (Shawkat Ali, 2013; Melhem, 2018):

- Domestic customers
- Commercial customers
- Industrial customers
- Other distributions such as transportation.

The current electrical system has been in place for almost a hundred years, and it worked well for that time (Ataul et al., 2014). Access to relatively affordable electricity was available at that time due to the centralisation of power generation. However, only minor upgrades have been made, and the system is reaching its technical and physical limit (Savic et al., 2019).

The result is an inefficient system that requires a solution to several challenges. These challenges include ageing infrastructure, system overload due to a lack of network planning, and the use of fossil fuels as the primary source of electricity generation (Aziz et al., 2020). The problem with these sources is the rapid depletion rates and the negative impact it has on the environment (Aziz et al., 2020). The traditional power grid is also not well suited for the integration of distributed RESs and Electric Vehicles (EVs) (Shawkat Ali, 2013).

Farhangi (2010) and Paul et al. (2014) describe the traditional power system as a one-directional channel which cannot provide real-time information on electricity supply and usage at a given point and time. Therefore the system was designed to withstand the maximum expected peak demand across its total load (Farhangi, 2010). This results in an inefficient system since peak demand only occurs during certain periods (Farhangi, 2010). The traditional power system also fails to provide a communication network between the consumer and supplier for effective energy management (Paul et al., 2014).

Since there is no effective way of monitoring electricity usage, the system is vulnerable and it is possible to steal electricity from the power grid (Paul et al., 2014). Further challenges include the need to improve system reliability and the security of supply. With the increase in population and continuous economic growth, the current system may not meet the future demand (Shawkat Ali, 2013).

According to Shawkat Ali (2013), power outages expose new challenges in terms of the reliability of the traditional power grid. With limited safety instruments, it makes it difficult to identify and fix any faults. When a fault occurs, entire areas can black out and remain without power until the problem is solved (Paul et al., 2014).

The various challenges with the traditional power grid can be addressed with the evolution of a next-generation power grid known as the "Smart Grid" (Farhangi, 2010).

2.2.3 Smart Grid

A Smart Grid is a collection of concepts and technologies and does not have a single definition or description. According to Shawkat Ali (2013), the Smart Grid can be described as:

"the transparent, seamless, and instantaneous two-way delivery of energy information, enabling the electricity industry to better manage energy delivery and transmission and empowering consumers to have more control over energy decisions. A Smart Grid incorporates the benefits of advanced communications and information technologies to deliver real-time information and enable the near-instantaneous balance of supply and demand on the electrical grid" (Shawkat Ali, 2013).

Smart Grid characteristics

From the literature, it is evident that the following characteristics are associated with the Smart Grid. The Smart Grid can support various generation types, from centralised power plants to Distributed Generation (DG) (Farhangi, 2010). According to Ackermann et al. (2001), DG refers to electricity generation units that are directly connected to the distribution grid, which is closer to the point of consumption or is located on the consumer's side of the electricity meter. It accommodates but is not limited to, the integration of RESs and energy storage options (Ackermann et al., 2001).

Based on the above definition of the Smart Grid, it can be said that the Smart Grid is an electricity network that uses advanced digital technologies for the two-way communication and flow of electricity between suppliers and customers. The demand side of the power system plays an important role in the Smart Grid concept, and the aim is to increase customer participation (Shawkat Ali, 2013). Based on the electricity information received by the customer, they can adjust their consumption pattern and purchases to reduce energy costs (Farhangi, 2010). In doing this, customers will also help to balance the supply and demand. This is where the concept of Demand Response (DR) and Demand-Side Management (DSM) is introduced by the Smart Grid (Shawkat Ali, 2013).

The self-healing feature of the Smart Grid allows the system to be more resilient during natural disasters, attacks or other disturbances (Shawkat Ali, 2013). The power system can detect and isolate the problem area while the rest of the power system is returned to its normal operation by re-routing the electricity supply. With this, it is possible to reduce the number of consumers affected by the disturbance. This feature improves system reliability and the capability of the system to supply safe and secure energy to the consumers (Shawkat Ali, 2013).

According to Farhangi (2010), the Smart Grid aims to operate more efficiently through asset management. The power system optimises the use of its assets while minimising costs. This can include maintenance and operational costs (Farhangi, 2010). For example, the adoption of predictive maintenance can reduce energy and maintenance costs by predicting the need for equipment maintenance with data analysis methods and tools before it fails (Moamin A. et al., 2021).

Smart Grid technologies help to improve power quality by meeting the specific power requirements of each customer (Shawkat Ali, 2013). With the use of smart meters and advanced technologies, it is possible for utility companies to optimise the voltage specific to each customer and can support sensitive equipment in a way that is suitable for the operation of that equipment (Shawkat Ali, 2013). Lastly, the Smart Grid creates a platform for new markets, services and products in the industry (Fang et al., 2012). New market participants will be able to join and benefit from these opportunities.

It is important to note that the evolution toward a smarter grid does not mean that the existing grid should be replaced, but rather that the Smart Grid should complement and add to the current electricity grid's functionality and performance (Farhangi, 2010).

Demand-side management

An important goal of the Smart Grid is the efficient utilisation of energy. The concept of DSM was introduced in the 1980s by the Electric Power Research Institute (EPRI) and is a crucial part of the Smart Grid (Ibrahim et al., 2020). Gelazanskas and Gamage (2014) and Nasir et al. (2021), define DSM as techniques or activities that are used to encourage customers to adjust their consumption pattern to optimise their electricity usage. This allows customers to help improve energy efficiency and to reduce their energy costs. These techniques also benefit utility companies since customers are motivated to lower energy consumption during peak demand periods or to shift their load to off-peak hours (Gelazanskas and Gamage, 2014).

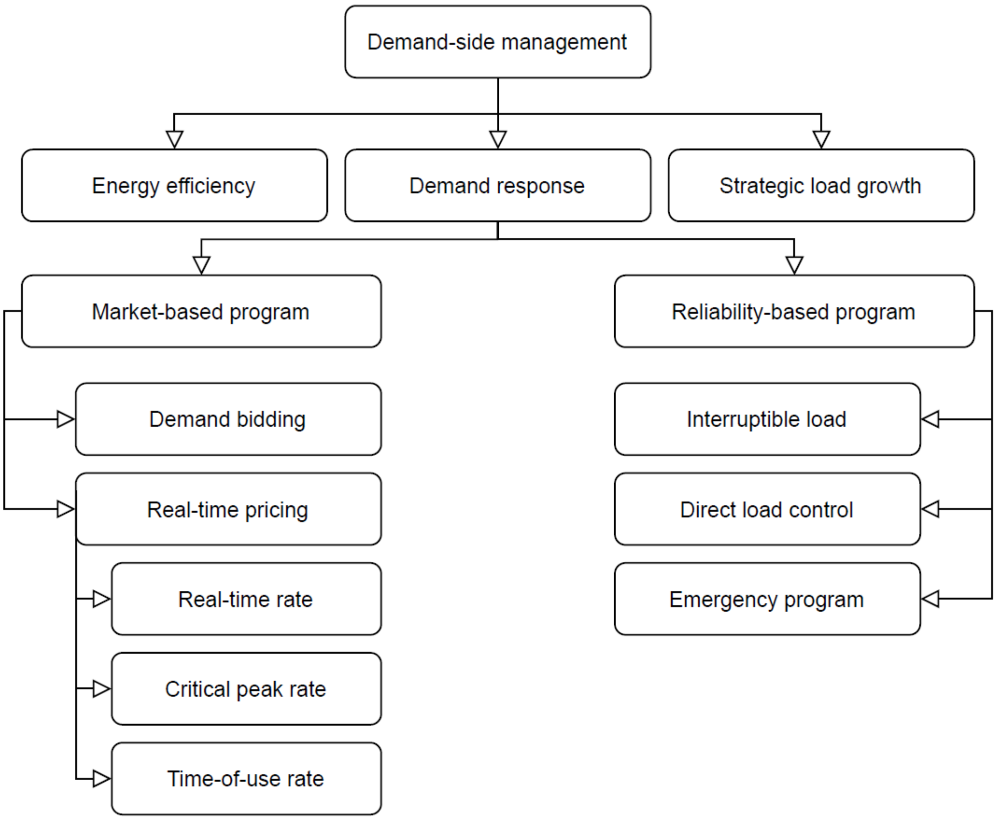

Figure 2.3: Demand-side management techniques (Replicated from Jabir et al. (2018))

Figure 2.3 as presented by Jabir et al. (2018) shows that DSM is divided into three categories, namely energy efficiency, DR and strategic load growth. Energy efficiency is a long-term strategy to utilise energy-efficient processes to help save energy. DR is defined by Jabir et al. (2018) as a short-term strategy to change energy consumption patterns. DR activities can be carried out through peak clipping, which aims to lower consumption and load during peak periods, valley filling focuses on increasing load during off-peak hours, and load shifting is a combination of these activities. Strategic load growth aims to increase energy sales or consumption of specific types of customers or time periods (Jabir et al., 2018).

According to Figure 2.3, DR programs are classified as market-based programs or reliability-based programs. Jabir et al. (2018) defines demand bidding, which falls under market-based programs, as a technique which enables consumer participation in the energy market. Bidding takes place on specific load curtailments, and the consumer can receive a reward or compensation if they do not consume power during the selected time period.

Fixed energy rates do not consider changes in the energy system or variations in production costs. Real-time pricing is introduced to resolve these issues (Jabir et al., 2018). Time-of-Use (TOU) tariffs are predetermined rates based on specific periods, for example, the season, month or day (Jabir et al., 2018). Critical peak rate or Critical Peak Pricing (CPP) is a time-varying rate where the cost of electricity is especially high during critical peak periods. CPP allows customers to help reduce energy demand during emergencies or when energy demand is very high. Real-time rates reflect actual rates and are provided ahead of time to consumers (Jabir et al., 2018).

Reliability-based programs compensate consumers who participate in the programs and are divided into an interruptible load program, direct load control program and emergency program (Jabir et al., 2018). Big industrial consumers who can switch off their load for a short time are an example of consumers who can participate in the interruptible load program. They are compensated when they participate and penalised when they do not meet the requirements. During the direct load control program, consumers are informed of power interruptions during peak demand periods, and the utility can directly reduce the power. According to Jabir et al. (2018), the emergency program offers consumers compensation for reducing power usage during power system emergencies.

Evolution of Smart Grid

Most power blackouts and interruptions originate from the distribution network (Farhangi, 2010). According to Farhangi (2010), it is, therefore, important that the evolution towards the Smart Grid begins at the bottom of the chain, namely the distribution grid. Alongside this, other factors, such as utility companies being unable to increase generation capacity to meet the growing demand and the rise of fossil fuel costs, have created the need to update and improve the distribution system. This can be achieved using technologies for revenue protection and DSM (Farhangi, 2010).

Figure 2.4 shows the metering aspect of the distribution system as the electrical power system evolves toward the Smart Grid. Automated Meter Reading (AMR) systems provide the energy provider with a way to collect and read consumption records and status data from the customers remotely. However, this technology only has a one-way communication system and is unsuitable for DSM (Farhangi, 2010).

According to Farhangi (2010), AMR systems only allow the reading of meter data and utility companies cannot act on information received from meters. In other words, AMR cannot support a smart grid system where pervasive control is possible at all levels. The

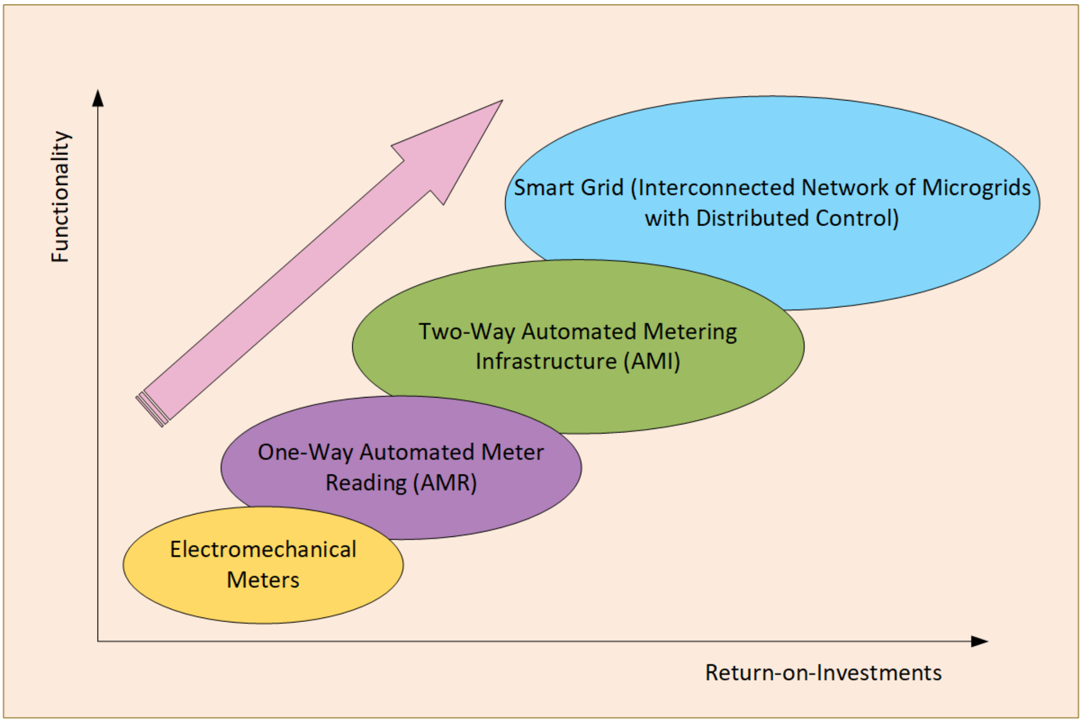

Figure 2.4: Evolution of the Smart Grid (Replicated from Farhangi (2010))

restrictions of the AMR system led to the development and investment in Advanced Metering Infrastructure (AMI) (Farhangi, 2010).

AMI enables two-way communication between customers and utility companies and is composed of smart meters, data management systems and communication networks (Faisal et al., 2012). The system provides information on electricity usage to the utility company and the customers regularly and is responsible for obtaining, measuring and investigating the data. Faisal et al. (2012) says that this enables DSM, self-healing features and adaptive power pricing.

Farhangi (2010) states that the next step in the evolution toward a Smart Grid would be to use AMI and to build on that infrastructure, implementing further strategies required by the Smart Grid. As shown in Figure 2.4, the integration of smart microgrids will play an important role in the further development and growth of the Smart Grid. Table 2.1 provides a comparison between the traditional power grid and the Smart Grid.

2.2.4 Microgrid

Microgrids are recognised as key building blocks of Smart Grid, especially when it comes to the improvement of power quality and reliability, providing a chance for individual end-user locations to become more independent from the grid and for an increase in energy efficiency (Ton and Smith, 2012).

A microgrid is defined by The U.S. Department of Energy as, “a group of interconnected

Table 2.1: Comparison between the traditional power grid and the Smart Grid (Adapted from Farhangi (2010))

Traditional Power Grid	Smart Grid
One-way communication	Two-way communication
One-way flow of energy	Two-way flow of energy
Centralised generation	Distributed generation
Hierarchical	Network
Electromechanical	Digital
Manual monitoring	Self-monitoring
Manual repair	Self-healing
Few sensors	Many sensors throughout the system
Power failures and blackouts	Adaptive protection
Limited control	Pervasive control
Few customers choices	Many customer choices

loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode" (Ton and Smith, 2012).

A microgrid carries out all power system operations, including generation, distribution and regulation of the flow of electricity to end users (Aslam et al., 2018). Aslam et al. (2018) describes a microgrid as a small version of the future electrical power grid. This type of system is a small-scale power supply system consisting of DG, devices used for monitoring and protection, loads, energy storage and energy conversion devices (Xu et al., 2018). A microgrid can include a variety of small power-generating sources consisting of RESs, such as wind turbines and solar panels. These sources are usually situated near consumer sites (Ataul et al., 2014).

An article by Lazar et al. (2017) also states that power-generating sources such as solar panels and low-power wind turbines are widely used in microgrids. However, due to irregularities in these RESs, they are not able to produce constant power, and this is seen as a drawback. Solar panels cannot generate energy at night time, and wind turbines depend heavily on the weather. This means that the power generated might not be sufficient to meet the demand during certain periods of the day (Tutkun, 2014).

Possible solutions include the installation of additional generators or backup generators to help prevent load-shedding and to complement the low amount of power generated. The use of ESSs can prove useful since excess energy can be stored in batteries, and they can also supply the lacking energy when consumption exceeds power generation. Factors such as generator capacity and electricity demand will determine the number of batteries required for the system (Lazar et al., 2017). According to Aslam et al. (2018), the microgrid can automatically switch to utilise electricity stored in the ESS when the power demand is higher than the amount of electricity generated by the system. Another possibility is that the system can import electricity from the external grid.

A microgrid can operate in two modes, namely grid-connected mode or “island” mode (Lu and Li, 2013). A single connection point, known as the Point of Common Coupling (PCC), connects the microgrid with the main power grid and is used to switch between different modes. Normally the microgrid operates in grid-connected mode, but the system can become independent and generate power with its local DG when it is separated from the main grid. This mode is referred to as island mode, and the change can be made in case of emergencies such as power outages, ageing infrastructure and natural disasters (Lu and Li, 2013).

Based on the power demand of consumers and the availability of generated electricity within the microgrid, the microgrid can sell surplus energy back to the main grid (Ataul et al., 2014). Figure 2.5 shows a typical microgrid model integrating different power-generating sources, EVs, local loads, a battery storage system and the utility grid.

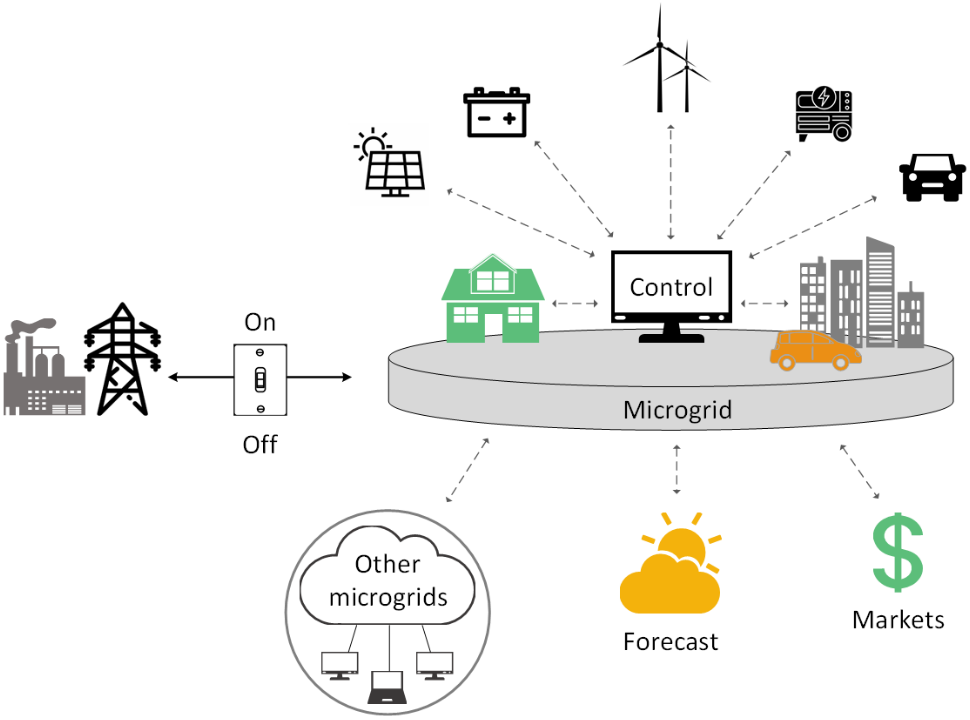

Figure 2.5: Example of a microgrid system (Replicated from Stadler and Nasle (2019))

A microgrid can be characterised as follows (Zhou et al., 2015):

1. Unique: A microgrid can be seen as unique since it is composed of small power generation sources and loads. The main difference between this system and the main grid is its scheduling flexibility.
2. Diverse: Microgrids can be described as diverse since they consist of various types of loads, both RESs and traditional power, and include energy storage devices.
3. Controllable: A microgrid can switch between different operating modes according to the operating conditions. Security and reliability can be improved with the use of good control strategies.

4. Interactive: The microgrid can receive power from the main power grid or provide support to the main grid by selling excess power.
5. Independent: In certain situations, the microgrid can become independent and provide electricity to local consumers to some extent.

These characteristics make the evolution of microgrids promising and have the following advantages as a result (Ton and Smith, 2012; Souza and Castilla, 2019; Zhou et al., 2015; Yang et al., 2019):

- It allows the integration of various Smart Grid technologies, which enables the modernisation of the power grid.
- Microgrids enable the integration of DG, which is usually located near demand. Therefore, there is a limited distance between loads, generation and power redispatch. As a result, the transmission and distribution system will experience a reduction in power losses.
- Peak load can be reduced with the integration of RESs.
- The improvement of the reactive power support of the system enables the microgrid to ensure voltage stability.
- Microgrids help to encourage the use of RESs for electrical power generation. This can lead to a reduction in the emission of greenhouse gasses compared to a system using sources such as coal, diesel, oil and other fossil fuels.
- The microgrid can support the main grid by providing auxiliary services. When the microgrid is in grid-connected mode, it can provide services such as voltage control, reactive power, and operating reserve.
- Power supply in remote locations, where the construction of the power grid is unsuitable, is a problem that can be solved with the implementation of a microgrid consisting of DERs. This solution aids in the economic development of these parts.
- When large area blackouts occur, the microgrid can ensure the power supply of essential loads. Thus, reducing power losses due to accidents or emergencies. It also makes up for the shortcomings of the main grid when it comes to stability and safety. Microgrid characteristics such as flexibility and the use of distributed sources have made this a possibility.
- Costs associated with power outages are taken into account for the price of electrical energy. With the improved system reliability of a microgrid, this can be reduced. For example, industrial loads within a microgrid can have costs associated with a power interruption, such as the loss of raw materials and operating expenses related to downtime. Therefore, the security of power supply is important since it can reduce some of these costs and will result in an increase in revenue.

- From a consumer point of view, the microgrid meets power needs by controlling power reliability and quality, guarantees energy supply for essential loads, and encourages consumer participation through DSM.

2.2.5 Optimisation techniques

To obtain an understanding of mathematical programming and optimisation techniques, it is helpful to first look at optimisation in general. Typical optimisation problems can be defined in terms of the following (Albright and Winston, 2016):

- Objective function: The objective function is the goal of the optimisation problem and can be maximised or minimised. Objective functions typically include the optimisation of profit, costs, environmental impacts etc.
- Decision variables: The values of the decision variables are controlled by the decision-maker to solve the problem.
- Constraints: Constraints are restrictions that must be met by the obtained solutions.

Optimisation problems are solved by finding values of the decision variables that maximise or minimise the objective function (Albright and Winston, 2016). The values determined by the decision-maker must satisfy all of the constraints (Albright and Winston, 2016). Some terms provided by Albright and Winston (2016) include:

- Feasible solution: This occurs when the values of the decision variables meet all of the constraints.
- Feasible region: This is the set of all the values that will meet the constraints and provide a feasible solution.
- Infeasible solution: A solution is classified as infeasible if at least one of the constraints is not satisfied.
- Optimal solution: This is obtained when a feasible solution optimises the objective function.

Optimisation problems can be solved through mathematical programming (Jain, 2013). To obtain the values of the decision variables that can optimise the objective function while meeting all of the constraints, a mathematical model that represents the problem is required (Jain, 2013). The mathematical model determines the appropriate values of the decision variables (Jain, 2013).

The use of mathematical programming for solving optimisation problems involves the creation of a mathematical framework and the application of an optimisation technique (Silvente Saiz, 2016). The appropriate optimisation technique is determined based on the type of problem to be solved and its characteristics (Silvente Saiz, 2016). Different approaches for the optimisation of an Energy Management System (EMS) in Smart Grids and microgrids are discussed by Melhem (2018). The approaches include (Melhem, 2018):

1. Rule-based techniques
2. Optimisation-based techniques
3. Hybrid techniques

However, this dissertation is focused on the application of optimisation-based techniques, and a discussion is provided thereof. As previously mentioned, optimisation problems involve the maximisation or minimisation of the objective function while adhering to all the constraints. According to Melhem (2018), optimisation-based techniques aim to find the best global or local solutions. This technique can include the use of exact methods or approximate methods (Melhem, 2018). One of these methods can be applied based on how complex and hard the problem is to solve (Melhem, 2018). Williamson and Shmoys (2011) states that approximation methods can determine near-optimal solutions.

Exact methods can provide a proven optimal solution from within the problem's feasible region and are further divided into two groups, namely linear and non-linear models (Melhem, 2018). Non-linear models are used for problems where the objective function or some of the constraints are non-linear, whereas linear model conditions or requirements have linear relationships. Linear models are further divided according to the type of variables they have. Linear models are divided into Linear Programming (LP), Integer Linear Programming (ILP) and MILP (Melhem, 2018). LP is composed of continuous variables, integer programming of integer variables, and MILP consists of both types of variables (Melhem, 2018).

The objective function and constraints of the proposed model are linear, and both continuous and integer variables are present in the formulation. Therefore, MILP is the chosen optimisation technique used to solve the problem, as defined in Chapter 1. Muqeet and Ahmad (2020) provides a general formulation of MILP:

$$\min_{x} f^t x \tag{2.1}$$

$$\text{Subject to} \begin{cases} A.x \leq b \\ A_{eq}.x = b_{eq} \\ lb \leq x \leq ub \\ \text{x(intcon) are integers} \end{cases} \tag{2.2}$$

The formulation aims to find a minimum and is subjected to equation (2.2). Where A and A_{eq} are matrices, and f, x, $(intcon)$, b, b_{eq}, lb and ub are vectors.

According to Silvente Saiz (2016), various methods have been created to solve ILP problems. Some of the main methods used to solve MILP problems include the branch-and-bound, cutting-plane, and branch-and-cut methods (Silvente Saiz, 2016). The branch-and-bound method aims to break the problem down into sub-problems which create a tree structure. According to Silvente Saiz (2016), the problem is represented by the root node, followed by nodes that represent the different sub-problems. The sub-problems are solved, compared, and eliminated if an optimal solution cannot be found. This continues until the optimal solution is obtained by growing the branches that will be able to obtain the best value.

The cutting-plane method iteratively cuts off parts from the feasible regions obtained from the LP relaxation process by adding additional constraints, known as cutting planes (Silvente Saiz, 2016). The simplex method can then be used to find the extreme point, which has now become integer-valued. The branch-and-cut method is a combination of these two methods. According to Silvente Saiz (2016), the LP problem is first solved with the simplex method. The obtained optimal solution does not have an integer value, and the cutting-plane method is applied until an optimal integer solution is obtained or until no cutting planes are found.

2.3 Existing research

According to Husein and Chung (2018), previous literature shows that microgrid planning is carried out through optimisation techniques and mathematical models or by utilising commercial software tools. To use commercial software tools for microgrid planning, it is important to have a thorough understanding of their capabilities, characteristics and restrictions (Husein and Chung, 2018). Husein and Chung (2018) describes iHOGA, DER-CAM, HOMER, RETScreen and SAM as the most commonly used tools.

iHOGA is defined by Ganguly et al. (2018) as an optimisation model which makes use of a Genetic Algorithm (GA). The algorithm computes the optimal configuration and sizes of DERs for microgrid systems. Stadler et al. (2014) utilises the optimisation tool DER-CAM. The tool uses MILP and aims to reduce CO_2 emissions or to minimise the total annual costs. DER-CAM is used to provide support when making investment decisions in terms of DERs.

The study by Iqbal and Siddiqui (2017) discusses the implementation and optimisation of a sustainable campus microgrid, placing focus on CO_2 emission, energy resources availability, and the cost analysis. The microgrid optimisation is carried out with the simulation tool HOMER. HOMER is defined as an optimisation tool used for the planning and design of microgrids which support the integration of RESs. The simulation tool analyses optimal combinations of different types of energy storage options, power sources and loads. The tool considers certain design topologies and parameters, such as wind speed and fuel prices, to find the optimal solution (Iqbal and Siddiqui, 2017).

RETScreen and SAM are defined by Husein and Chung (2018) as financial and performance models used to make decisions concerning RESs. The economic models take taxes, tax benefits and incentives into account. However, limitations of both tools include that the operation of energy systems cannot be modelled and that they cannot be used as sizing tools (Husein and Chung, 2018). Due to the restrictions of these commercial tools, an opportunity exists for researchers to use different optimisation techniques when creating their microgrid models. The following paragraphs discuss how microgrid planning has been approached through mathematical modelling and optimisation techniques, especially with a focus on MILP.

In Muqeet and Ahmad (2020), the authors aimed to minimise the total operating cost and to increase the use of RESs in an institutional microgrid. The study considered energy data from a university campus that only imported power from the main grid. The problem has been formulated as a MILP model. The paper considered the development of an EMS for a microgrid that consists of DG, including a PV system, a diesel generator, as well as an ESS. The optimisation model managed the exchange of energy between the grid and microgrid optimally and considered constraints that were necessary for energy storage scheduling in terms of charging and discharging (Muqeet and Ahmad, 2020).

To determine an optimal solution, the EMS required inputs such as weather data, price data, power demand and information from the ESS, for example, the initial status of the battery system (Muqeet and Ahmad, 2020). In Muqeet and Ahmad (2020), the operational costs included the cost associated with energy storage degradation, diesel generator cost and grid import and export cost. As previously mentioned, the paper focussed on the reduction of the operational cost, and that was accomplished by considering a price-based DR and by using the ESS as a DR system that can be scheduled to charge and discharge during different periods. The life cycle of the ESS was also taken into consideration. The authors concluded that during summer, daily savings of 35% were achieved, and during the winter months, savings of 29% were obtained. These savings were a result of the integration of the ESS, PV system and diesel generator (Muqeet and Ahmad, 2020).

The optimal design of energy microgrids, as well as the operational scheduling thereof, is addressed by Koltsaklis et al. (2018). The authors formulated the problem as a MILP model to reduce the total cost of the system. Operational costs, investment costs for various technologies, and the energy exchange cost with the utility grid form part of the total annual cost of the microgrid. The proposed model studies a microgrid made up of different zones that can sell and purchase energy from the utility grid. The microgrid consists of energy storage options, such as batteries, renewable energy technologies, and utilises natural gas fuel for thermal power generating units.

They investigated the effects of certain parameters, namely the exchange price of electricity from and to the utility grid and the maximum acceptable level of CO_2 release into the atmosphere. The effects of the parameters on the energy balance of the system, the number and capacity of the utilised technologies, as well as the influence on economic aspects, were studied (Koltsaklis et al., 2018). To incorporate these parameters into the model, certain constraints were considered, namely economic constraints such as technology installation options and technical constraints, including the balance of energy demand, discharging and charging limits, the balance of energy storage and the limits of power capacity. Environmental constraints with regards to the maximum allowable level of CO_2 release were also considered (Koltsaklis et al., 2018).

Yang et al. (2019) considered a MILP model for the cost minimisation of a community microgrid. The article aimed to optimally plan the configuration of the microgrid and considered a microgrid system consisting of wind turbines, fuel cells, a PV system, and a BESS to meet the power demand of the community. For this article, the popular idea of grouping a cluster of loads and multi-bus distributed systems within a location was incorporated into the model (Yang et al., 2019).

The proposed model by Yang et al. (2019) considered the real-time exchange of electricity with the main power grid, DSM, and the costs required for operating the power generation sources. The model also aimed to find the optimal installation number and location of renewable resources in the microgrid. The results indicated that the daily electricity cost had been reduced with the design of such a microgrid (Yang et al., 2019).

Chedid et al. (2020) investigated a scenario where a microgrid receives power from an unreliable and unstable grid, thus resulting in a system which heavily relies on diesel generators. The authors proposed a microgrid design that incorporates a BESS and a PV system, therefore creating a hybrid energy system which will replace the diesel generators. To achieve the optimal flow of power and to determine the optimal sizing of the system in terms of PV and BESS capacities, a combination of optimisation approaches, namely Dynamic Programming (DP) and GA, was utilised. The utilisation of a GA, DP and rule-based algorithm has led to a decrease in the computation time required for sizing the components of the microgrid (Chedid et al., 2020).

The ability to meet load demand, reduce the use of diesel generators, and minimise the amount of energy procured from the main grid during peak hours, are some of the goals of the new design. A university campus was used as a case study for creating the new microgrid design. The final results indicated that the implementation of the hybrid system, and through almost completely replacing the diesel generators and reducing energy obtained from the main grid during peak hours, resulted in minimised operational cost. A 10-year bank loan was used to finance the system, but it was determined that the payback period would be six years. This proved the economic feasibility of the hybrid system (Chedid et al., 2020).

In the article by Morais et al. (2010), the authors focused on the optimal operation of a small renewable power system. According to the authors, the performance of generation units can be maximised if the right timing is applied. Therefore, the economic scheduling of the generators was addressed, and the dispatch was formulated as a MILP problem. They also incorporated the use of a Virtual Power Producer (VPP), which has the task of optimally operating the generation units.

The developed model aimed to minimise the generation cost for one day, which consisted of 24 hours, and the time for storage charging and discharging is optimised while adhering to all constraints. Budapest University of Technology and Economics was used as a real case study to demonstrate how effective and useful the proposed program is. The case study focused on the operation of an isolated system with solar units, a wind turbine, a storage battery and a fuel cell. The problem was able to converge in 0.09 seconds and 30 iterations (Morais et al., 2010).

Microgrids and smart homes were investigated by Zhang et al. (2011). It is possible to reduce the cost of energy for homes and to have a local energy supplier with the implementation of a microgrid. Alongside this, the concept of smart homes offers a more secure environment to individuals, as well as the opportunity to lower power consumption costs and peak demand. This can be achieved with the optimal scheduling of energy consumption activities within these smart homes.

The authors used MILP to address the optimal scheduling where the objective was to minimise the total energy cost of homes one day ahead and to shave the peak demand. Based on the electricity price from the grid, the forecasted output of renewable generation, constraints such as the starting and ending time for tasks, and the operation of appliances and generation units, the microgrid operation was scheduled. This paper considered a case study of a smart building that has thirty homes. The smart building has a microgrid with resources, including a Combined Heat and Power (CHP) generator, a boiler, thermal storage, electrical storage, wind generation and a grid connection. Fixed technology capacities were provided since the model only computed the optimal schedule for one day (Zhang et al., 2011).

The results, from when tasks were scheduled to operate within their given time window, were compared to the current living scenario, where appliances are switched on at their earliest starting time. They found an 18.7% savings for a winter day compared to the scenario of the earliest starting time. They also concluded that this type of scheduling increased the utilisation of assets (Zhang et al., 2011).

In Zhang et al. (2013), the authors expanded and added to their previous work in Zhang et al. (2011). The article still focused on the reduction of energy costs and peak demand through the scheduling of energy consumption activities across multiple smart homes. Changes introduced in the study included the use of two pricing schemes, namely real-time pricing and peak demand pricing. The goal of peak demand pricing was to lower the electricity peak demand from the main grid. When the electricity demand exceeded the agreed-upon threshold, additional costs were charged depending on the amount over the threshold. If the demand did not exceed the threshold, real-time pricing was applied.

In this article, two examples were used. The first considered a smart building with 30 homes, where residents had similar living routines and the second, a building with 90 homes where residents had different living routines. The two pricing schemes were deployed in both examples. The results from the examples indicated remarkable savings in peak demand and energy cost. The authors also mentioned that the peak demand was lowered with the use of the peak demand pricing scheme (Zhang et al., 2013).

In the article by Erdinc et al. (2015), the authors focused on the application of DR strategies within a smart home. The proposed smart household was controlled by a Home Energy Management (HEM) system that operated based on a DR strategy, namely dynamic pricing. DR activities influence the daily load profile of a home (Erdinc et al., 2015). Considering DR, the authors created a model that determined the optimal size of additional energy storage and distributed generation. In this article, they included the sizing of ESS and PV system for a smart home. They considered a system with PV panels, an EV and an ESS.

Erdinc et al. (2015) mentioned that the sizing of the units over a long-term period affected the daily operation, while the varying load profile also affected the results from the technical and economical sizing procedure. The sizing procedure and the modelling of the HEM system were undertaken with the development of a MILP framework. The authors also considered the impact on cost as a result of increased capacity. This was investigated with a step-by-step decreasing cost function. Three scenarios were evaluated where households had different size families and different living patterns. The results indicated the impact of DR on the sizing of additional units and showed the importance thereof. During the experimental phase, they also studied the effects of different economic inputs on the proposed model with sensitivity analyses (Erdinc et al., 2015).

2.4 Chapter summary

In this chapter, the research focus areas were explored to gain knowledge on this topic, followed by a literature review on the optimisation approaches that have been applied in this field. Many studies have focused on the optimal operation or sizing of a microgrid system. This study also aims to provide an optimisation model that can determine the optimal operation and configuration of a microgrid. But the main contribution is to provide a way to determine the optimal investment time while incorporating changing economic factors over multiple years. Chapter 3 presents the proposed mathematical model that aims to address the problem specified in Chapter 1.

Chapter 3

Operations and investment model

3.1 Introduction

In Chapter 3, the problem defined in Chapter 1 is formulated as a MILP model. This chapter aims to present a mathematical model for the optimisation of an energy microgrid. The operations and investment aspects of a microgrid are combined into one model. The main components of the proposed microgrid system are discussed, followed by the model formulation. The model formulation consists of the model parameters, decision variables, objective function and constraints to which the objective function is subjected.

3.2 Microgrid description

The energy microgrid considered in this study takes large residential customers, business parks or university campuses into consideration. Therefore, the microgrid components are selected based on the needs of these consumers. The microgrid operates in grid-connected mode. In other words, the microgrid is connected to the power grid and can import electricity from the grid. The goal of the optimisation model is to meet the energy demand of the microgrid at the minimum cost. Therefore, the export of electricity back to the main grid is not incorporated into the model.

Supplementary alternative electricity sources are considered. The integration of a PV system and medium-sized wind system is proposed as RESs, which are used to complement each other and the grid power. The installation of a BESS can be used to store excess power generated by the different electricity sources and can be discharged when needed. The BESS can be charged by all generation technologies, including the main grid, if necessary. Furthermore, backup diesel generators are considered in the case of load-shedding or power outages.

3.3 Mathematical model formulation

This section contains the formulation for the proposed mathematical model.

3.3.1 Sets and indices

The following sets and indices are used within the mathematical model. Let $t \in T = \{1, 2, 3 \ldots, |T|\}$ represent the set of time. Time consists of hourly intervals. Let $d \in D = \{1, 2, 3 \ldots, |D|\}$ and $y \in Y = \{1, 2, 3 \ldots, |Y|\}$ denote the set of representative days and the set of years in the project horizon, respectively.

3.3.2 Parameters

This section defines the parameters used by the model and can be divided into different categories, namely cost parameters, technical parameters and constraint parameters.

Cost parameters

The cost parameters are listed below and each parameter is followed by a description. The unit of measure is enclosed in brackets, next to each parameter description.

c_{td}^{Im} - import cost of grid at time $t \in T$ for day $d \in D$ (R/kWh)
c_{op}^{Diesel} - operating cost of diesel generator (R/kWh)
c_{fuel}^{Diesel} - cost of fuel per litre (R/l)
c_{y}^{Diesel} - capital cost of diesel generator in year $y \in Y$ $(R/unit)$
c_{y}^{PV} - capital cost of PV panel in year $y \in Y$ $(R/unit)$
c_{y}^{BESS} - capital cost of BESS in year $y \in Y$ $(R/unit)$
c_{y}^{Wind} - capital cost of wind turbine in year $y \in Y$ $(R/unit)$
m_{y}^{Diesel} - maintenance cost of diesel generator in year $y \in Y$ $(R/unit)$
m_{y}^{PV} - maintenance cost of PV panel in year $y \in Y$ $(R/unit)$
m_{y}^{BESS} - maintenance cost of BESS in year $y \in Y$ $(R/unit)$
m_{y}^{Wind} - maintenance cost of wind turbine in year $y \in Y$ $(R/unit)$

Technical parameters

The technical parameters required by the generation and storage technologies are defined and followed by a description. The technical parameters are specific to each technology and the operation thereof. The unit of measure is indicated in brackets next to each parameter.

Im_t^{max} - maximum power import limit of grid at time $t \in T$ (kW)
$fuel_{kWh}$ - fuel consumption (l/kWh)
Dg_{max} - diesel generator capacity (kW)
PV_{td}^{max} - PV panel output power at time $t \in T$ for day $d \in D$ (kW)
A_{PV} - PV panel area (m^2)
e_{PV} - efficiency of PV panel (%)
I_{td} - solar irradiance at time $t \in T$ for day $d \in D$ (kW/m^2)
I_{rate} - solar irradiance under Standard Test Conditions (STC) (kW/m^2)
P_{rate}^{PV} - rated power of PV panel (kW)
$Bs_{initial}$ - initial state of battery (kWh)
Bs_{max} - storage battery maximum limit (kWh)
Bs_{min} - storage battery minimum limit (kWh)
Bd_{max} - maximum discharge rate of battery (kWh)
Bc_{max} - maximum charge rate of battery (kWh)
e_{Bd} - battery discharge efficiency (%)
e_{Bc} - battery charge efficiency (%)
N_1 - modelling constant (large value)
N_2 - modelling constant (large value)
$Wind_{td}^{max}$ - wind turbine output power at time $t \in T$ for day $d \in D$ (kW)
v_{td}^{Wind} - wind speed at time $t \in T$ for day $d \in D$ (m/s)
v_{ci} - cut-in wind speed (m/s)
v_{co} - cut-out wind speed (m/s)
v_{rate} - rated wind speed (m/s)
P_{rate}^{Wind} - rated power of wind turbine (kW)

Constraint parameters

The following list represents the constraint parameters. This includes the energy demand parameter and parameters for the sizing of energy technologies. All sizing parameters will take on integer values. Each parameter has a description and the unit of measure is indicated, if applicable.

L_{td} - load demand in time $t \in T$ for day $d \in D$ (kWh)

n_{max}^{Diesel} - maximum number of diesel generators allowed to be purchased each year

n_{max}^{PV} - maximum number of PV units allowed to be purchased each year

n_{max}^{BESS} - maximum number of battery units allowed to be purchased each year

n_{max}^{Wind} - maximum number of wind turbines allowed to be purchased each year

n_{total}^{Diesel} - total number of diesel generators allowed over entire project lifetime

n_{total}^{PV} - total number of PV units allowed over entire project lifetime

n_{total}^{BESS} - total number of battery units allowed over entire project lifetime

n_{total}^{Wind} - total number of wind turbines allowed over entire project lifetime

3.3.3 Decision variables

This section describes the decision variables to be determined by the model while solving the MILP problem. The decision variables include continuous variables, integer variables and binary integer variables. The list of symbols used to represent the variables is given in each subsection and the notations are followed by a short description.

Continuous variables

u_{tdy}^{Im} - power imported from grid at time $t \in T$ for day $d \in D$ in year $y \in Y$ (kWh)

u_{tdy}^{Diesel} - power from diesel generators at time $t \in T$ for day $d \in D$ in year $y \in Y$ (kWh)

u_{tdy}^{PV} - power from PV system at time $t \in T$ for day $d \in D$ in year $y \in Y$ (kWh)

u_{tdy}^{s} - battery storage power at time $t \in T$ for day $d \in D$ in year $y \in Y$ (kWh)

u_{tdy}^{Bd} - battery discharge power at time $t \in T$ for day $d \in D$ in year $y \in Y$ (kWh)

u_{tdy}^{Bc} - battery charge power at time $t \in T$ for day $d \in D$ in year $y \in Y$ (kWh)

u_{tdy}^{Wind} - power from wind turbines at time $t \in T$ for day $d \in D$ in year $y \in Y$ (kWh)

Integer variables

n_y^{Diesel} - number of diesel generators purchased in year $y \in Y$
n_y^{PV} - number of PV units purchased in year $y \in Y$
n_y^{BESS} - number of battery units purchased in year $y \in Y$
n_y^{Wind} - number of wind turbines purchased in year $y \in Y$
z_y^{Diesel} - total number of diesel generators in year $y \in Y$
z_y^{PV} - total number of PV units in year $y \in Y$
z_y^{BESS} - total number of battery units in year $y \in Y$
z_y^{Wind} - total number of wind turbines in year $y \in Y$

Binary variables

$y_{tdy}^{Bd} = 1$ if BESS is discharging at time $t \in T$ for day $d \in D$ in year $y \in Y$, 0 otherwise.
$y_{tdy}^{Bc} = 1$ if BESS is charging at time $t \in T$ for day $d \in D$ in year $y \in Y$, 0 otherwise.

3.3.4 Objective function

The objective function (3.1) minimises the total cost of the microgrid over a long-term horizon while determining the optimal configuration of generation and storage technologies. The model aims to determine which technologies to invest in, when to invest, and the optimal size of each alternative. The total cost of the microgrid is composed of operating costs (O_{total}), capital costs (C_{total}) and maintenance costs (M_{total}).

$$minimise(O_{total} + C_{total} + M_{total}) \tag{3.1}$$

The total operating cost of the microgrid is represented by equation (3.2) and consists of the cost of purchasing electricity from the grid and the cost of operating the diesel generator during each period.

$$O_{total} = \sum_{y \in Y} \sum_{d \in D} \sum_{t \in T} (c_{td}^{Im} u_{tdy}^{Im} + c_{op}^{Diesel} u_{tdy}^{Diesel}) \tag{3.2}$$

The operating cost of the diesel generator is calculated using equation (3.3) by multiplying the price of fuel per litre with the fuel consumption per kWh.

$$c_{op}^{Diesel} = c_{fuel}^{Diesel} fuel_{kWh} \tag{3.3}$$

The capital cost of all technologies over the project horizon is described by equation (3.4), and the cost includes the capital required for each alternative and the installation cost. It is assumed that technologies will be procured at the beginning of a year and will therefore be utilised starting from the year of purchase.

$$C_{total} = \sum_{y \in Y} (c_y^{Diesel} n_y^{Diesel} + c_y^{PV} n_y^{PV} + c_y^{BESS} n_y^{BESS} + c_y^{Wind} n_y^{Wind}) \tag{3.4}$$

The final part of the objective function, the total maintenance cost, is given by equation (3.5). It is assumed that maintenance will commence when the equipment is operational, therefore, in the same year of purchase. As equipment gets older, it starts to wear down, resulting in higher maintenance costs. For the purpose of this study, the degeneration of equipment will not be considered. It is assumed that the maintenance and operating cost of the technologies will remain the same regardless of when it was purchased.

$$M_{total} = \sum_{y \in Y} (m_y^{Diesel} z_y^{Diesel} + m_y^{PV} z_y^{PV} + m_y^{BESS} z_y^{BESS} + m_y^{Wind} z_y^{Wind}) \tag{3.5}$$

A discount rate will be considered for the capital cost and maintenance cost of all technologies. Formula (3.6) determines the future discounted value of an investment. FV represents the future value, PRV the present value, i is the discount rate per year, and n the number of years.

$$FV = PRV(1 - i)^n \tag{3.6}$$

3.3.5 Model constraints

The objective function (3.1) is subjected to the following constraints.

Energy balance

Constraint (3.7) is essential for the balance between supply and demand. To achieve this balance, the electricity consumed during each period cannot exceed the electricity supplied by the power generation technologies. In other words, the electricity demand in each time period is equal to the electricity imported from the grid, electricity provided by the diesel generators and the PV system, electricity received from electrical storage minus electricity sent to electrical storage, and electricity supplied by the wind generators in each period. Energy losses and self-consumption are not considered in this equation, and it is assumed that the losses are incorporated into the efficiency of each individual technology.

$$L_{td} = u_{tdy}^{Im} + u_{tdy}^{Diesel} + u_{tdy}^{PV} - u_{tdy}^{Bc} + u_{tdy}^{Bd} + u_{tdy}^{Wind}, \quad \forall t \in T, \forall d \in D, \forall y \in Y \tag{3.7}$$

Grid exchange

The amount of electricity purchased from the grid during each period can be limited by constraint (3.8).

$$u_{tdy}^{Im} \leq Im_t^{max}, \quad \forall t \in T, \forall d \in D, \forall y \in Y \tag{3.8}$$

Diesel generator

Equation (3.9) calculates the total number of diesel generators available in each year. It is assumed that when a diesel generator is purchased, it will remain available for the entire project duration. The replacement of units within the project lifetime will not be considered, and the same can be expected from the rest of the technologies. Therefore, the number of diesel generators available in year y is calculated by adding the number of diesel generators purchased prior to year y, starting from the first year of the project, to the number of diesel generators purchased in year y.

$$z_y^{Diesel} = \sum_{k=1}^{y} n_k^{Diesel}, \quad \forall y \in Y \tag{3.9}$$

Constraint (3.10) ensures that the output from the diesel generators does not exceed the designed capacity. The degeneration of the technologies will not be incorporated into this study. In other words, it is assumed that all equipment will operate at the same level regardless of when it was purchased during the project's lifetime.

$$u_{tdy}^{Diesel} \leq Dg_{max} z_y^{Diesel}, \quad \forall t \in T, \forall d \in D, \forall y \in Y \tag{3.10}$$

To restrict the number of diesel generators purchased per year, constraint (3.11) is enforced. The constraint allows the model to incorporate real-life scenarios where budget or other restrictions must be considered by the buyer.

$$n_y^{Diesel} \leq n_{max}^{Diesel}, \quad \forall y \in Y \tag{3.11}$$

Constraint (3.12) ensures that the sum of all diesel generators purchased does not exceed the maximum number of diesel generators allowed over the entire project lifetime. This can be due to space limitations on the microgrid premises.

$$\sum_{y \in Y} n_y^{Diesel} \leq n_{total}^{Diesel} \tag{3.12}$$

PV system

Formula (3.13) is used for calculating the output of a single PV panel. For this study, it is assumed that the panel performance is not affected by changes in panel temperature and that the PV panel output is calculated only considering solar irradiance.

$$PV_{td}^{max} = \begin{cases} A_{PV} e_{PV} I_{td}, & I_{td} < I_{rate} \\ P_{rate}^{PV}, & I_{td} \geq I_{rate} \end{cases}, \forall t \in T, \forall d \in D \tag{3.13}$$

Equation (3.14) calculates the total number of PV panels available for each year. To determine how many panels are available in year y, the PV panels purchased in previous years and the current year y are summed together.

$$z_y^{PV} = \sum_{k=1}^{y} n_k^{PV}, \quad \forall y \in Y \tag{3.14}$$

Constraint (3.15) is used to calculate the total output of the PV system within each period and ensures that it does not exceed the system's capacity. The maximum capacity is obtained by multiplying the power output of a single PV panel by the total number of PV panels available at that time.

$$u_{tdy}^{PV} \leq PV_{td}^{max} z_y^{PV}, \quad \forall t \in T, \forall d \in D, \forall y \in Y \tag{3.15}$$

The number of PV panels allowed to be purchased per year is limited by constraint (3.16).

$$n_y^{PV} \leq n_{max}^{PV}, \quad \forall y \in Y \tag{3.16}$$

Constraint (3.17) is the sizing constraint and ensures that the total number of PV panels procured over all years does not exceed the maximum number of PV panels allowed on the microgrid premises.

$$\sum_{y \in Y} n_y^{PV} \leq n_{total}^{PV} \tag{3.17}$$

Battery energy storage system

Equation (3.18) calculates the total number of BESSs available in each year. The number of BESSs available in year y is the sum of all BESSs purchased in previous years and the current year y.

$$z_y^{BESS} = \sum_{k=1}^{y} n_k^{BESS}, \quad \forall y \in Y \tag{3.18}$$

Constraints (3.19) and (3.20) represent the State-of-Energy (SOE) of the battery storage system. Constraint (3.19) ensures that the amount of energy in the BESS at time t is equal to the stored amount in the previous period $t-1$ minus the electricity that is subtracted when the battery is discharged plus the amount of electricity consumed by the BESS when charged during that period. Constraint (3.20) represents the initial state of the battery.

$$u_{tdy}^{s} = u_{t-1,dy}^{s} - \frac{u_{tdy}^{Bd}}{e_{Bd}} + e_{Bc}u_{tdy}^{Bc}, \quad \forall t \in T, \forall d \in D, \forall y \in Y \tag{3.19}$$

$$u_{t=0,dy}^{s} = Bs_{initial} z_y^{BESS}, \quad \forall d \in D, \forall y \in Y \tag{3.20}$$

To maximise battery life, it must always function within its designed limits. Constraints (3.21) and (3.22) ensure that the battery system does not exceed the maximum limit or drop below the minimum operating limit.

$$u_{tdy}^{s} \leq Bs_{max} z_y^{BESS}, \quad \forall t \in T, \forall d \in D, \forall y \in Y \tag{3.21}$$

$$u_{tdy}^{s} \geq Bs_{min} z_y^{BESS}, \quad \forall t \in T, \forall d \in D, \forall y \in Y \tag{3.22}$$

Constraints (3.23), (3.24) and (3.25) are used to ensure that discharging and charging does not take place at the same time.

$$u_{tdy}^{Bd} \leq N_1 y_{tdy}^{Bd}, \quad \forall t \in T, \forall d \in D, \forall y \in Y \tag{3.23}$$

$$u_{tdy}^{Bc} \leq N_2 y_{tdy}^{Bc}, \quad \forall t \in T, \forall d \in D, \forall y \in Y \tag{3.24}$$

$$y_{tdy}^{Bd} + y_{tdy}^{Bc} \leq 1, \quad \forall t \in T, \forall d \in D, \forall y \in Y \tag{3.25}$$

The power taken from the battery during discharging operations is limited by a maximum discharge rate in constraint (3.26). Similarly, constraint (3.27) enforces the limit on charging operations with a maximum charge rate for each period.

$$u_{tdy}^{Bd} \leq Bd_{max} z_y^{BESS}, \quad \forall t \in T, \forall d \in D, \forall y \in Y \tag{3.26}$$

$$u_{tdy}^{Bc} \leq Bc_{max} z_y^{BESS}, \quad \forall t \in T, \forall d \in D, \forall y \in Y \tag{3.27}$$

The number of BESSs purchased per year is restricted by constraint (3.28).

$$n_y^{BESS} \leq n_{max}^{BESS}, \quad \forall y \in Y \tag{3.28}$$

Constraint (3.29) ensures that the sum of all BESSs purchased over the years, does not exceed the maximum number of BESSs allowed for the project.

$$\sum_{y \in Y} n_y^{BESS} \leq n_{total}^{BESS} \tag{3.29}$$

Wind system

The output power from the wind turbine is variable since wind generators work on variable speed. The mathematical function (3.30) is used to calculate the capacity of the wind turbine in each time period.

$$Wind_{td}^{max} = \begin{cases} 0, & 0 \leq v_{td}^{Wind} < v_{ci} \\ P_{rate}^{Wind} \dfrac{(v_{td}^{Wind} - v_{ci})}{(v_{rate} - v_{ci})}, & v_{ci} \leq v_{td}^{Wind} < v_{rate} \\ P_{rate}^{Wind}, & v_{rate} \leq v_{td}^{Wind} \leq v_{co} \\ 0, & v_{co} < v_{td}^{Wind} \end{cases} \quad \forall t \in T, \forall d \in D \tag{3.30}$$

The number of available wind turbines in year y is the sum of all the wind turbines acquired in previous years and the wind turbines purchased in the current year y. This is calculated by equation (3.31).

$$z_y^{Wind} = \sum_{k=1}^{y} n_k^{Wind}, \quad \forall y \in Y \tag{3.31}$$

Constraint (3.32) is the maximum capacity constraint and ensures that the output from the wind turbine system does not exceed its capacity for each period. The maximum capacity is obtained by multiplying the generated output from a single turbine by the total number of wind turbines available in that specific time frame.

$$u_{tdy}^{Wind} \leq Wind_{td}^{max} z_{y}^{Wind}, \quad \forall t \in T, \forall d \in D, \forall y \in Y \tag{3.32}$$

The number of wind turbines purchased per year is limited by constraint (3.33).

$$n_{y}^{Wind} \leq n_{max}^{Wind}, \quad \forall y \in Y \tag{3.33}$$

Constraint (3.34) is the sizing constraint that ensures that the sum of all the wind turbines purchased over time does not go above the maximum limit of wind turbines for the entire project horizon.

$$\sum_{y \in Y} n_{y}^{Wind} \leq n_{total}^{Wind} \tag{3.34}$$

3.4 Chapter summary

In this chapter, a mathematical model was introduced for the optimisation of an energy microgrid. In Chapter 4, the input data required by the model parameters and notations are presented. The acquired data is essential for the testing of the proposed model.

Chapter 4

Data characterisation

4.1 Introduction

In Chapter 3 the proposed mathematical model was described and the purpose of Chapter 4 is to provide the input data required by the model parameters, as defined in Section 3.3. The data characterised in this chapter is used for both the verification and validation of the model.

4.2 Location and time

For this study, the focus of the proposed model will be on organisations operating large business parks, estates or campuses. Therefore, the North-West University, Potchefstroom campus, was selected and the necessary data was obtained from the university and surrounding area. The North-West University is located in Potchefstroom, South Africa, having a latitude of "26.6906° S" and a longitude of "27.0929° E".

The proposed model considers different time periods as defined in Chapter 3, Section 3.3. The set of time, represented by $T = \{1, 2, 3 \ldots, |T|\}$, consists of hourly intervals with each day having 24 hours. The set of representative days denoted by $D = \{1, 2, 3 \ldots, |D|\}$, includes 84 representative days in a year. This was introduced to reduce computational time and help simplify the model's testing. The 84 representative days are obtained by taking the days of the week, from Monday through Sunday, for each month of the year, January through December. The calculation $7 \times 12 = 84$ shows how the number of representative days was obtained. To scale the input data down to 84 representative days, the average hourly values of each month, averaged on each day of the week (Monday through Sunday), are obtained.

Lastly, $Y = \{1, 2, 3 \ldots, |Y|\}$ defines the set of years. The number of project years can vary and will be specified for each scenario. But, to ensure the feasibility of the alternatives, it is necessary to consider periods of 10 to 20 years.

4.3 Demand data

This section describes the demand data required by parameter L_{td}. The electricity demand of 10 campus buildings was obtained from the North-West University, Potchefstroom campus. Many departments, buildings and facilities form part of the campus, but for this study, only a few buildings are considered. The data includes the energy demand for the year 2019 and provides hourly consumption readings on each building.

Obtaining 84 representative days from an entire year's energy data involves getting the average hourly usage of each month, averaged on each day of the week (Monday through Sunday). By doing this, it is possible to incorporate the variation in demand associated with different hours of the day, days in the week, and months of the year. The energy demand of 10 campus buildings is combined and used by parameter L_{td} over the entire project duration. It is assumed that the energy demand will remain the same over all years. The total combined demand over the 84 representative days of the year amounts to $1\,438\,390 kWh$.

Figure 4.1 shows the total combined demand of the campus buildings per month in hourly intervals. As expected, the consumption pattern is affected by the time of day and by the seasons of the year. In Figure 4.1, it is evident that more power is consumed during daytime than during the night. Since the data was obtained from a university campus, there is a visible change in demand during months when the campus is fully active and when it closes at the end of a term, for example, during the December holiday.

Figure 4.2 shows the total demand as mentioned above but is grouped per day of the week in hourly intervals. This demonstrates the change in consumption over different days of the week. There is an increase in consumption over weekdays when academics and other campus activities occur.

4.4 Grid specifications

The parameters required by the model for grid exchange include the maximum power import limit, Im_t^{max}. A maximum limit will not be placed on the amount of power that can be imported from the grid unless specified otherwise.

Parameter c_{td}^{Im} denotes the grid price for different time periods. For this study, the electricity tariffs were obtained from JB Marks Local Municipality for the financial year 2019/2020. The prices provided are Value-Added Tax (VAT) excluded, and to ensure that the technologies are compared equally, VAT will be excluded from the prices of all the technologies considered. The tariff selected is suited for large business, residential and

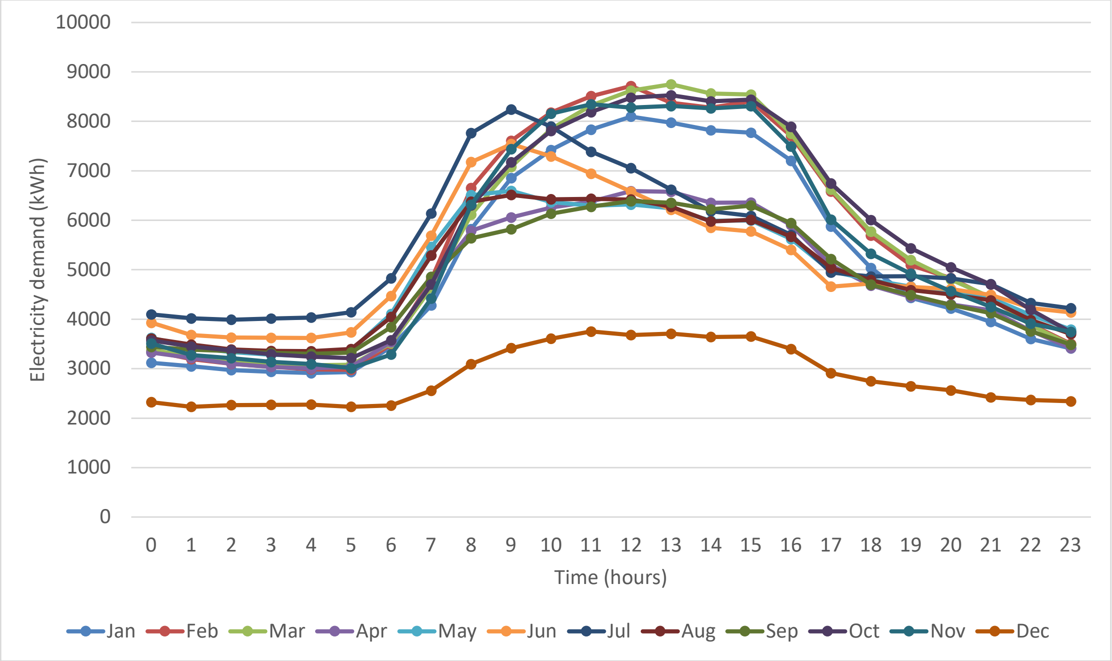

Figure 4.1: Electricity demand per month

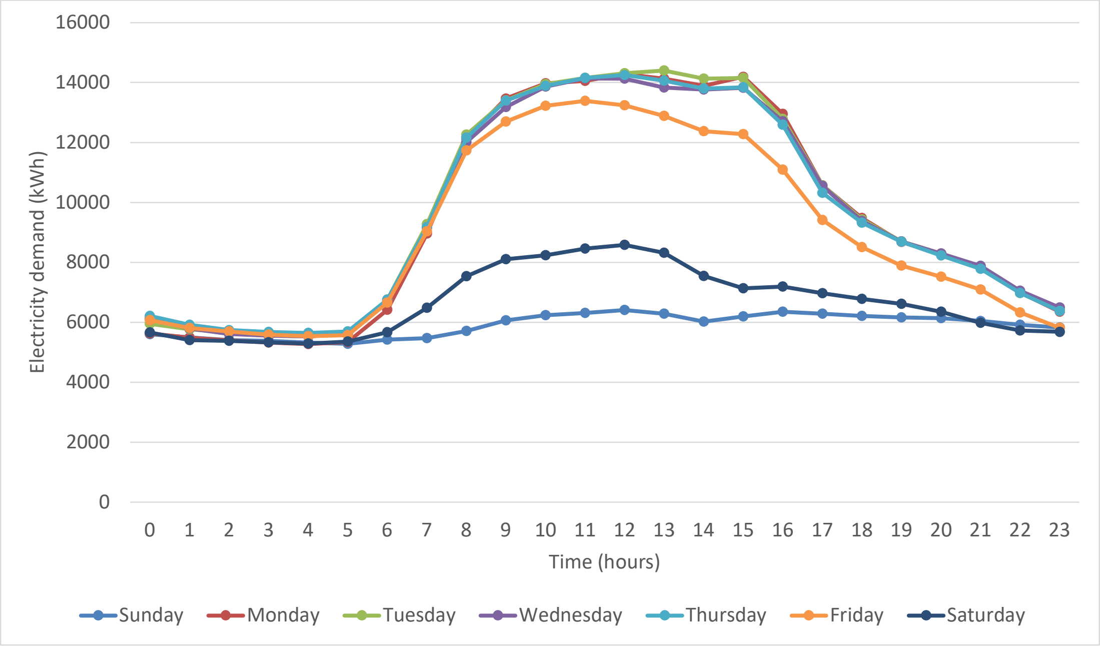

Figure 4.2: Electricity demand for days of the week

industrial customers. Therefore, the selected tariff is ideal for the microgrid considered in this dissertation. Only the price per kWh will be considered, and all other costs associated with grid exchange will be excluded. The tariff consists of TOU categories which include:

- Peak hour
- Standard hour
- Off-peak hour

The grid price therefore depends on the time of day and the day of the week. The grid price over weekdays is usually higher than at weekends, and the price on Saturdays differs from Sundays. Lastly, the cost of energy depends on the season of the year. The winter months, June through August, are categorised as the high demand season and the months from September to May as the low demand season. Figure 4.3 represents the grid price per kWh on weekdays. The grid prices of the high demand season and low demand season are compared.

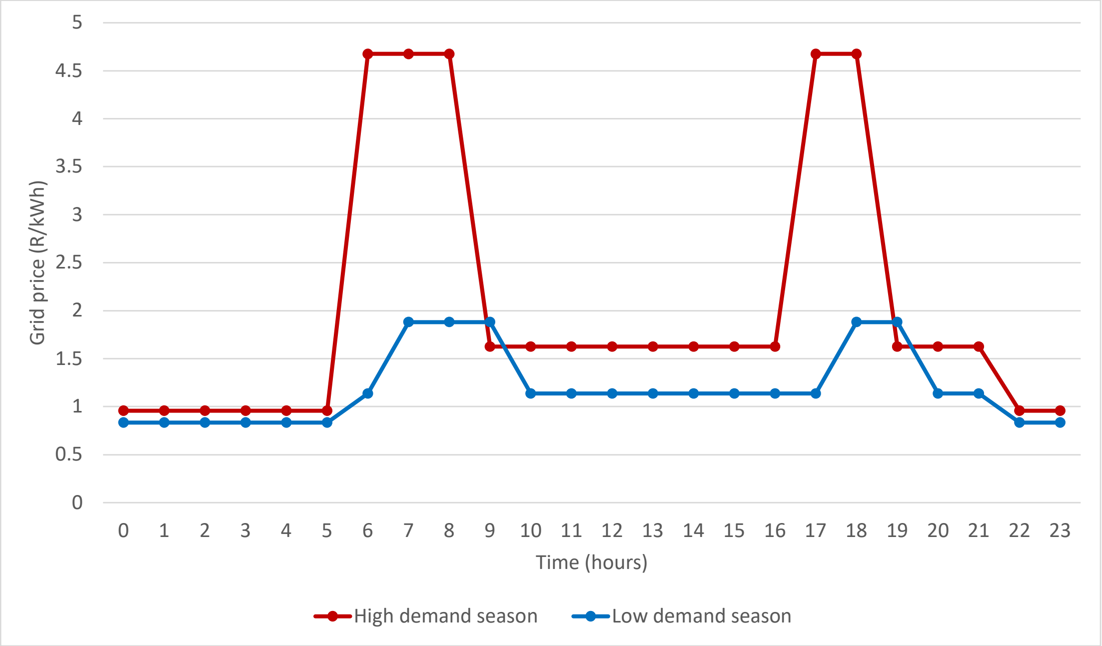

Figure 4.3: Grid price on weekdays

In Figure 4.4, the grid price on Saturdays is shown for the high demand season and low demand season. Figure 4.5 represents the grid price per kWh on Sundays, and it can be seen that only the off-peak prices are charged on Sundays.

The 24 hours and 84 representatives days required by the model are populated with the obtained grid prices.

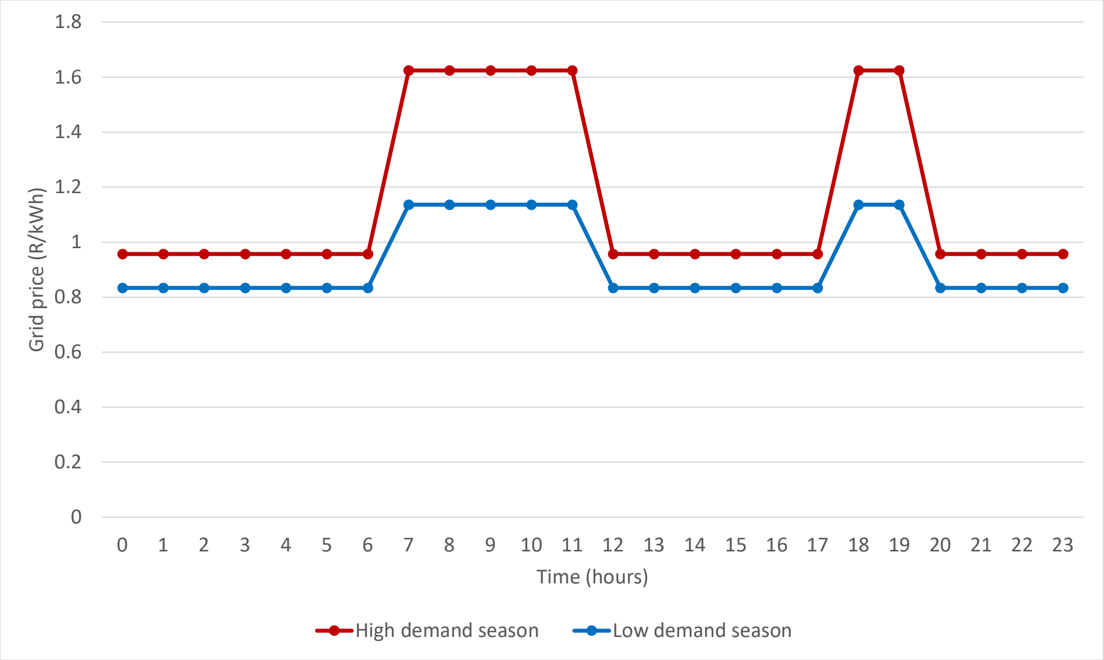

Figure 4.4: Grid price on Saturdays

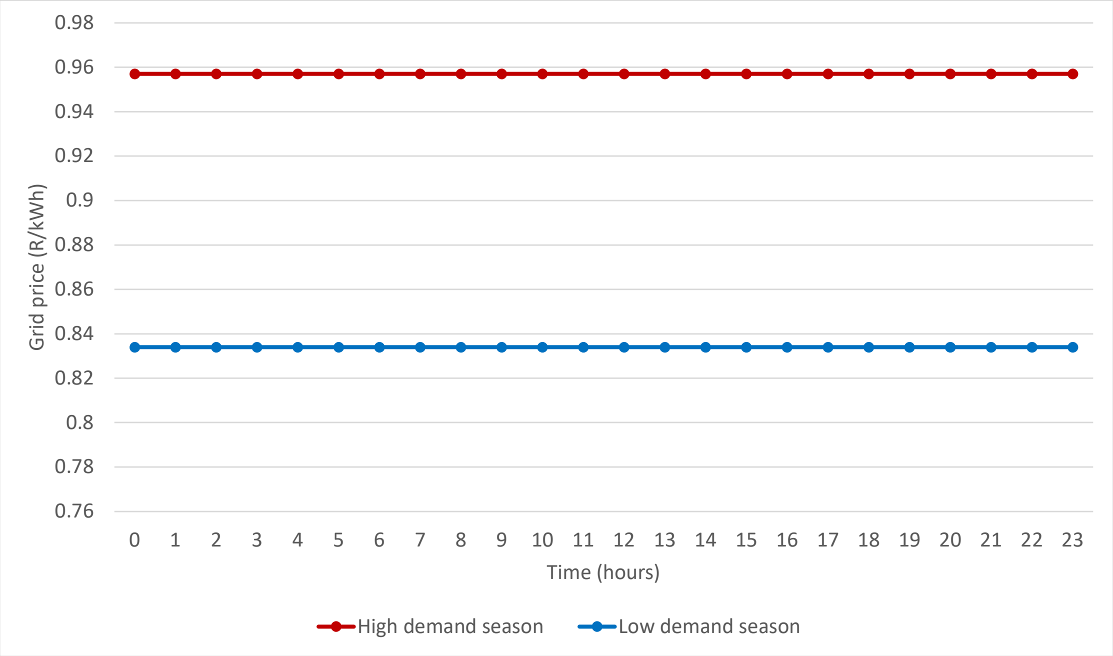

Figure 4.5: Grid price on Sundays

4.5 Diesel generator specifications

The diesel generator cost and technical parameters are provided in this section. The parameter values are shown in Table 4.1. A 320kVA industrial diesel generator was selected as an example generator for this study. This generator was selected since it is common for the size of the microgrid in consideration.

Table 4.1: Diesel generator parameters

Parameter	Value	Unit
c_{op}^{Diesel}	5.32	R/kWh
c_{fuel}^{Diesel}	24.16	R/l
c_{y}^{Diesel}	1 125 683.85	$R/unit$
m_{y}^{Diesel}	20 000	$R/unit$
$fuel_{kWh}$	0.22	l/kWh
Dg_{max}	320	kW

Table 4.2 represents the adapted cost parameters of the diesel generator. The capital and maintenance costs are adjusted since the years do not consist of 365 days but of 84 representative days, as described in Section 4.2. It is necessary to adjust the costs of all the generation and storage technologies since they are not used for an entire year, and the cost per kWh is more expensive than it would be when considering a normal year. The prices are obtained by dividing each cost by 4.345. This ensures that the costs represent the considered period of 84 days. The value is calculated by dividing 365 by the number of representative days. This is also applied to the rest of the technologies in this chapter.

Table 4.2: Adapted cost parameters for diesel generator

Parameter	Value	Unit
c_{y}^{Diesel}	259 076	$R/unit$
m_{y}^{Diesel}	4603	$R/unit$

The input data and assumptions of all cost and technical parameters are discussed. The sizing parameters of each technology are specified in Chapter 5 and Chapter 6, depending on the scenario.

4.6 PV system specifications

The specifications and data for the PV system are described in this section. Solar irradiance data required by the parameter I_{td} was obtained for the Potchefstroom area. Hourly solar irradiance was downloaded from power.larc.nasa.gov (2021) for one year. The historical data incorporates all-sky conditions, meaning that the readings include weather factors such as cloud coverage. The data obtained for the entire year is transformed into 84 representative days. The average hourly solar irradiance (kW/m^2) was calculated for each day of the week within each month of the year. Solar irradiance is assumed to remain the same for all project years.

Figure 4.6 represents the solar irradiance of an average day for each month. It shows how different seasons of the year impact solar irradiance. During autumn and winter, from April to May and June to August, the average solar irradiance is less than that of the summer months. Weather factors such as cloud coverage also play a role in the average solar irradiance, depending on the location and season of the year. As expected, there is no solar irradiance during the night, only during the day. The availability of solar irradiance is also greater during summer months compared to winter months since summer days are longer than winter days, as seen in Figure 4.6.

It is assumed that the data, as represented in Figure 4.6, is the irradiance that the PV panel cells are subjected to. The angle of incidence and panel orientation is assumed irrelevant for this study.

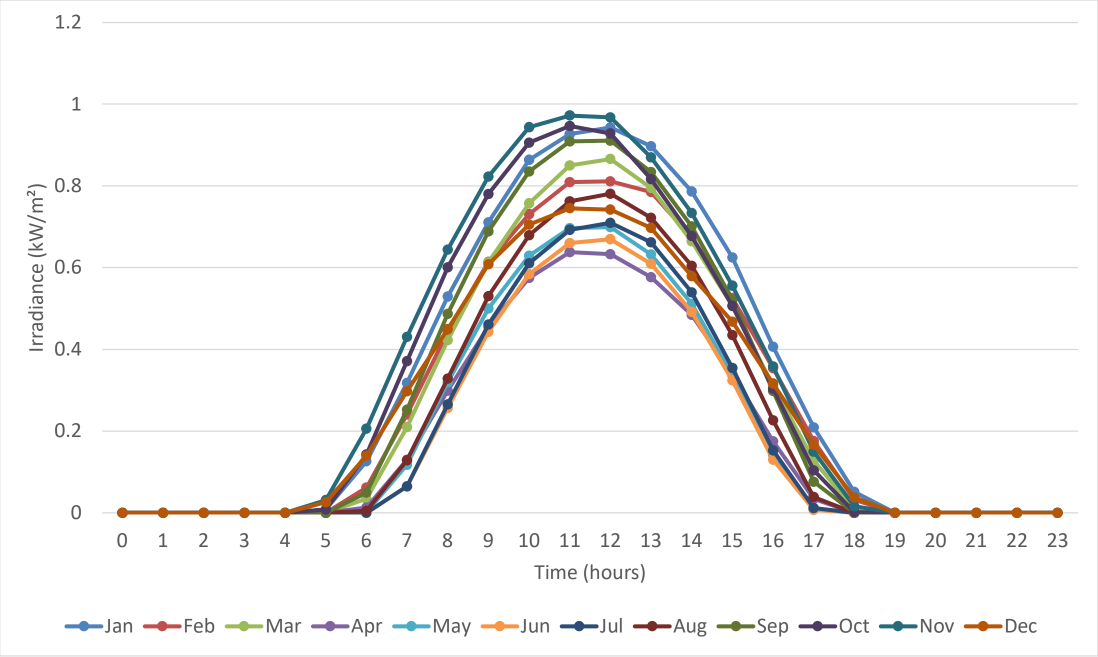

Figure 4.6: Average solar irradiance per month

A mono percium PV panel was selected for this study, and the parameters are shown in Table 4.3. This PV panel was chosen since the technology is one of the larger contenders in the current market. It gives a higher output per panel, therefore a higher rated power per area of PV cells. The efficiency is also higher than previous PV cell technologies. Table 4.4 represents the adapted cost parameters of the PV system.

Parameter PV_{td}^{max} is defined in Chapter 3, Section 3.3, as the output power of a single PV panel in each time period. There is variation in the output power of the PV panel during each time period because the PV cells are subjected to time-varying solar irradiance data. The output power of the PV panel is therefore calculated with equation (3.13) using the

Table 4.3: PV panel parameters

Parameter	Value	Unit
c_y^{PV}	2865.22	$R/unit$
m_y^{PV}	200	$R/unit$
A_{PV}	2.174	m^2
e_{PV}	20.7	%
I_{rate}	1	kW/m^2
P_{rate}^{PV}	0.45	kW

Table 4.4: Adapted cost parameters for PV system

Parameter	Value	Unit
c_y^{PV}	660	$R/unit$
m_y^{PV}	46	$R/unit$

parameters and data discussed in this section. It is assumed that the same output power will be provided by the PV panel each year.

4.7 BESS specifications

This section describes the parameters required by the BESS. A lithium iron phosphate BESS was chosen, and the parameters are shown in Table 4.5. The selected lithium iron phosphate battery is considered a type of lithium-ion technology. It provides longer life cycles, improved efficiency, safe and reliable power delivery, and is maintenance-free. It is assumed that the battery discharge and charge efficiency is 95% and that the initial state of the BESS ($Bs_{initial}$) should be equal to the battery's minimum storage limit (Bs_{min}). Table 4.6 represents the adapted cost parameters of the BESS.

Table 4.5: BESS parameters

Parameter	Value	Unit
c_y^{BESS}	24 943.61	$R/unit$
m_y^{BESS}	0	$R/unit$
$Bs_{initial}$	0.178	kWh
Bs_{max}	3.552	kWh
Bs_{min}	0.178	kWh
Bd_{max}	1.776	kWh
Bc_{max}	1.776	kWh
e_{Bd}	95	%
e_{Bc}	95	%

Table 4.6: Adapted cost parameters for BESS

Parameter	Value	Unit
c_y^{BESS}	5740	$R/unit$
m_y^{BESS}	0	$R/unit$

4.8 Wind turbine specifications

To calculate the output power of a wind turbine, the following inputs are required. Firstly, the weather data required by a wind turbine is discussed. Parameter v_{td}^{Wind} is defined in Chapter 3, Section 3.3. It denotes the wind speed in m/s for a specific time period. The historical wind speed for Potchefstroom is gathered from power.larc.nasa.gov (2021) for one year in hour intervals. The data is also converted to the 84 representative days required by the model. For this study, all weather data will remain the same each year.

Figure 4.7 shows the average hourly wind speed per month. The average wind speed varies during different months of the year. From Figure 4.7, it can be seen how the wind speed alters between night and day. During the daytime, the sun heats the earth's surface, and this causes convection and turbulence. At night, the wind continues its usual direction and speed since the surface air is colder, meaning there is less turbulence.

It is assumed that the wind data, as represented in Figure 4.7, is the wind speeds that the wind turbine is subjected to. It is also assumed that angle and direction factors are irrelevant since the wind turbine directs its head perpendicular to the wind stream to ensure the highest power output.

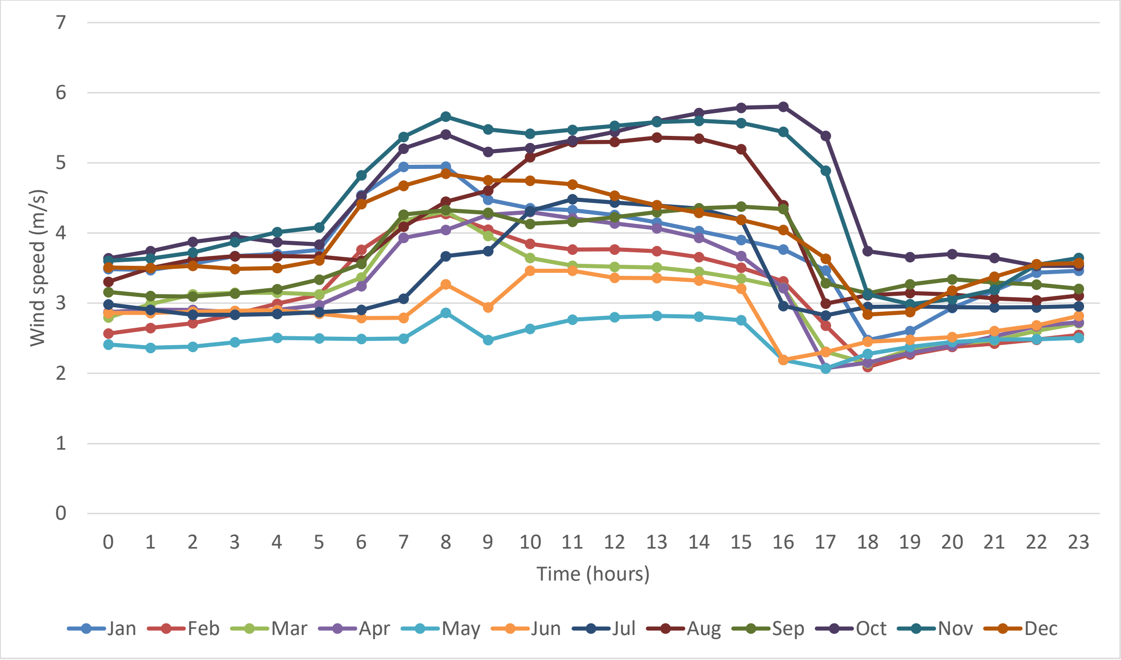

Figure 4.7: Average wind speed per month

A medium-sized wind turbine was selected, and the parameters are shown in Table 4.7. This wind turbine was selected since the technology is more suited for the microgrid considered in this study, namely large business parks or campuses. A medium wind turbine allows for the installation of multiple wind turbines if deemed necessary by the model. A wind turbine with a higher solidity (with more blades) is used as an example since the average wind speed of the considered location, Potchefstroom, is lower than what is required by standard 3-blade turbines that are currently available. Table 4.8 represents the adapted cost parameters of the wind turbine system.

Table 4.7: Wind turbine parameters

Parameter	Value	Unit
c_y^{Wind}	49 812.17	$R/unit$
m_y^{Wind}	2000	$R/unit$
v_{ci}	2	m/s
v_{co}	50	m/s
v_{rate}	12	m/s
P_{rate}^{Wind}	3	kW

Table 4.8: Adapted cost parameters for wind turbines

Parameter	Value	Unit
c_y^{Wind}	11 464	$R/unit$
m_y^{Wind}	460	$R/unit$

Parameter $Wind_{td}^{max}$ is defined as the output power of a single wind turbine in each time period. The variation in wind speed influences the output power of the wind turbine. The generated power of the wind turbine is therefore calculated with the mathematical function (3.30) using the input data discussed in this section. The output power of the wind turbine is calculated for 24 hours for 84 representative days, and it is assumed that the output power will remain the same for each year.

4.9 Chapter summary

In Chapter 4, the input data required by the model parameters were presented. The data described in this chapter is essential for the testing of the model. Chapter 5 represents the scenarios used to evaluate and verify the proposed model.

Chapter 5

Model verification

5.1 Introduction

Chapter 3 represented the MILP model used for the optimisation of an energy microgrid. In Chapter 5, the verification of the model is presented. The goal is to prove that the formulation of the mathematical model is correct and that the implementation accurately represents the model. There are various ways to ensure that the model is implemented correctly. In this chapter, the model is verified by demonstrating that the model adheres to all constraints and that the obtained results are as expected. The implementation, data and assumptions of the verification process are discussed, followed by the verification of the model.

5.2 Implementation, data and assumptions

The implementation of the model, for both the verification and validation process, is done with IBM Decision Optimization CPLEX Modeling for Python (DOcplex) on a local computer with IBM ILOG CPLEX Optimization Studio. The installation of the full edition CPLEX Optimization Studio is required for solving the model. The Pandas and NumPy libraries are compatible with the DOcplex library and are used for data processing and creating data structures required by the model.

The input data described in Chapter 4 is considered but is simplified for the verification of the model. The model considers 24 hours for each day, but only a single representative day is considered instead of 84 representative days, as described in Section 4.2. The project lifetime consists of 5 years. The power demand data, weather data and grid prices of the single representative day are incorporated into the model. However, the demand data is simplified, and the power demand of only a single building is considered. It is assumed that the data will remain the same over all years. Figure 5.1 presents the grid prices. The values of the technical parameters of all generation and storage technologies, defined in

Chapter 4, are considered.

The cost parameters for each technology are discussed in the sections below. The considered costs do not represent the actual prices associated with each technology. Low costs are randomly selected to ensure that the model chooses the technology to be evaluated in each section. The sizing parameters of each technology are specified in the relevant sections.

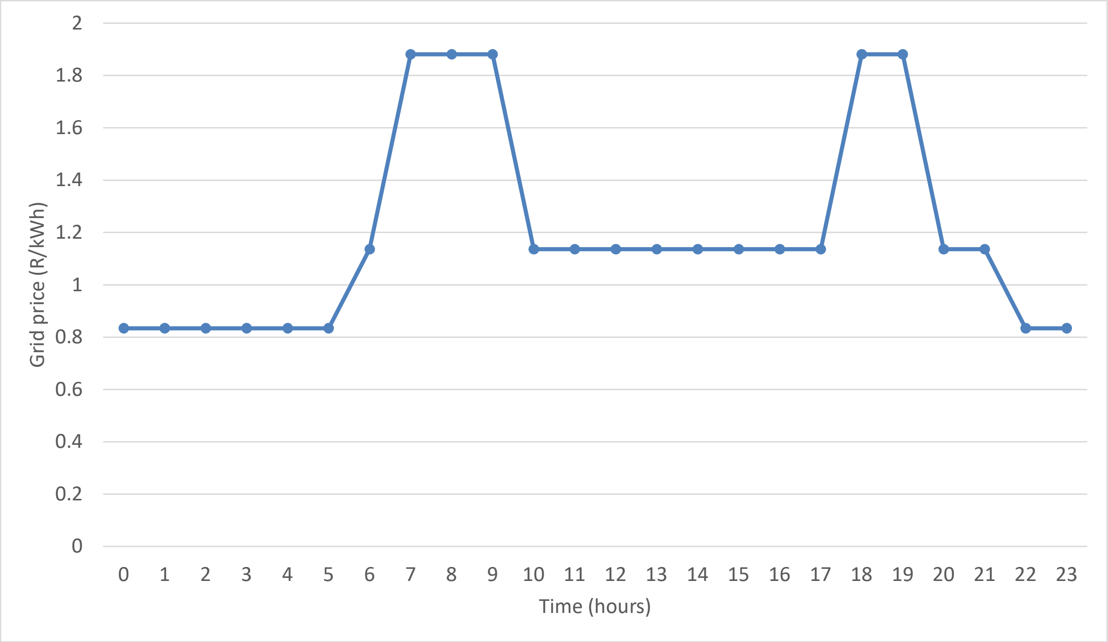

Figure 5.1: Grid price for model verification

5.3 Model verification

In the following sections, it is demonstrated that a solution is obtained by the model while satisfying all constraints. The verification process is simplified by assessing the constraints associated with each technology separately. The import of grid power is considered in each scenario since a grid-connected microgrid was proposed in this study.

5.3.1 Diesel generator and grid

In this section, a diesel generator system and a connection to the grid is considered. The model is verified by evaluating the constraints associated with the diesel generator and with grid exchange. The constraints related to the diesel generator system include constraints (3.9) to (3.12), and constraint (3.8) represents the maximum capacity limit of the grid. The impact of the energy balance, represented by constraint (3.7), is also assessed in each section.

The following input data and assumptions are considered:

- The model considers the use of diesel generators and exchange with the grid.
- The grid prices shown in Figure 5.1, are considered by the model.
- A limit will be placed on the amount of power imported from the grid. Im_t^{max} will be set to 0 for hours 6 and 7.
- The capital cost of the diesel generator c_y^{Diesel} is selected to be $R1$ and a yearly maintenance cost m_y^{Diesel} of $R0.10$. The costs will remain the same for all years.
- The operating cost of the diesel generator c_{op}^{Diesel} is set to $R2$.
- The maximum number of diesel generators allowed to be purchased each year n_{max}^{Diesel} is 1.
- The total number of diesel generators allowed over the entire project duration n_{total}^{Diesel} is 2.

The aim of the objective function (3.1) is to minimise the total cost while determining the optimal configuration of generation and storage technologies. Table 5.1 shows the microgrid costs determined by the model for this scenario. The total cost of $R5884.38$ consists of the grid import cost and diesel generator costs over the entire project duration.

The goal of the optimisation model is to find the power generation mix that will result in minimal cost while adhering to the constraints. Therefore, power is imported from the grid because the operating costs associated with the diesel generator make it very expensive. But, since a limit is placed on the amount of power received from the grid, the model is forced to use a single diesel generator to meet the demand. The diesel generator is only used during hours 6 and 7 when power cannot be imported from the grid.

Table 5.1: Cost of diesel generator and grid

Cost	Value (R)
Grid cost	5039.92
Diesel generator operating cost	842.96
Diesel generator capital cost	1
Diesel generator maintenance cost	0.50
Total cost	5884.38

The results in Table 5.2 show the number of diesel generators purchased and the number of generators available for each year. Constraint (3.11) restricts the number of diesel generators purchased per year. Similarly, constraint (3.12) ensures that the total number of purchased generators does not exceed the specified limit. From Table 5.2, it can be seen that the results adhere to the constraints and do not exceed the maximum limits. The results also prove that the number of available diesel generators each year is calculated correctly by constraint (3.9).

Table 5.2: Number of diesel generators chosen by model

Year	Number purchased	Number available
0	1	1
1	0	1
2	0	1
3	0	1
4	0	1

Figure 5.2 represents the results produced by the model. The demand and the power received from the grid and diesel generator over the 5 years are shown. From Figure 5.2, it is clear that the power demand is met at all times and that the energy balance constraint (3.7) is satisfied. Constraint (3.10) ensures that the output from the diesel generator does not exceed its capacity. The generated output from the diesel generator during hours 6 and 7 does not exceed the maximum capacity of $320kW$.

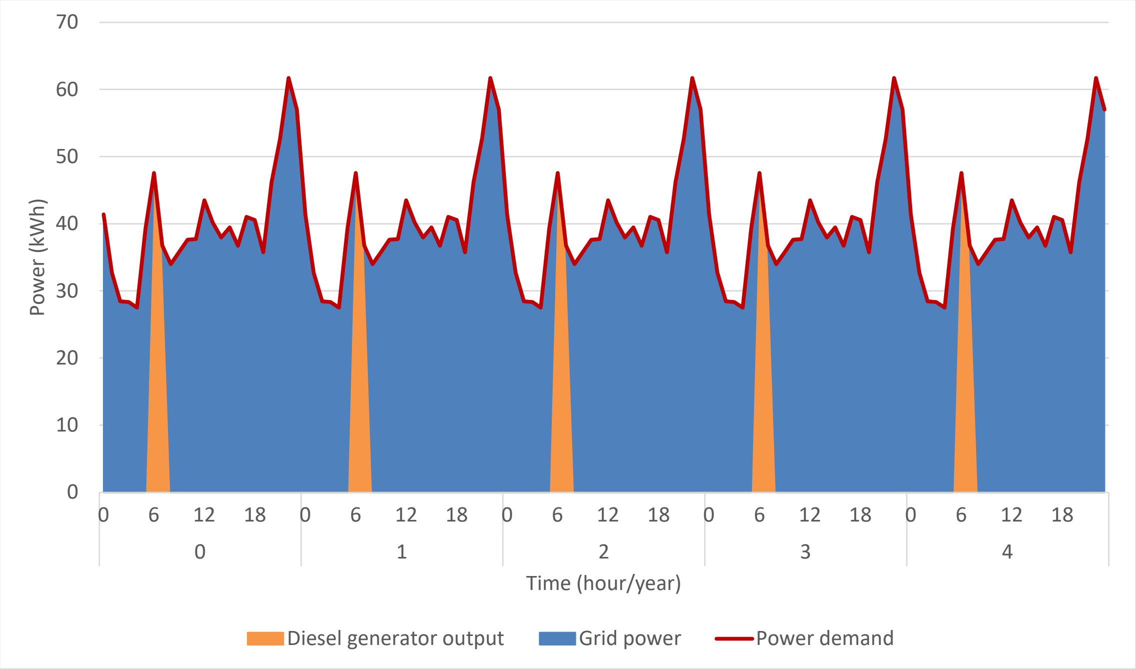

Figure 5.2: Output power from the diesel generator and grid

5.3.2 PV system and grid

In this section, the model considers PV panels and a connection to the grid. The model is verified by evaluating the constraints associated with the PV system and with grid exchange. The constraints related to the PV system include constraints (3.13) to (3.17).

The following input data and assumptions are considered:

- The model considers the use of a PV system and exchange with the grid.

- The grid prices described in Figure 5.1 are considered by the model and no maximum limit is placed on the power imported from the grid.
- The capital cost of a PV panel c_y^{PV} is selected to be $R1$ and a yearly maintenance cost m_y^{PV} of $R0.10$. The costs will remain the same for all years.
- The maximum number of PV panels allowed to be purchased each year n_{max}^{PV} is 15.
- The total number of PV panels allowed over the entire project duration n_{total}^{PV} is 60.

Table 5.3 shows the microgrid costs for this scenario. The total cost of $R4857.65$ consists of the grid import cost and the PV system's capital and maintenance cost over the entire project duration. As expected, the model selects the maximum number of allowed PV panels since they are less expensive compared to the grid prices. However, the PV system alone cannot satisfy the total demand, and the remaining power is imported from the grid.

Table 5.3: Cost of PV system and grid

Cost	Value (R)
Grid cost	4776.65
PV system capital cost	60
PV system maintenance cost	21
Total cost	4857.65

Table 5.4 contains the results from the model and shows the number of PV panels purchased per year and the number of available PV panels. The number of PV panels purchased per year is limited by constraint (3.16). The sum of all PV panels purchased over the project lifetime is restricted by constraint (3.17). From the results, it is visible that the number of purchased PV panels each year does not exceed 15. The total number of PV panels is 60, which is equal to the specified limit but does not exceed it. The results also prove that the number of available PV panels each year is calculated correctly by constraint (3.14). The number of PV panels from previous years and the current year is summed together.

Table 5.4: Number of PV panels chosen by model

Year	Number purchased	Number available
0	15	15
1	15	30
2	15	45
3	15	60
4	0	60

Figure 5.3 represents the capacity of a single PV panel. The PV_{td}^{max} values are obtained with equation (3.13) for the representative day. It is assumed that the capacity of a single PV panel will remain the same for all years.

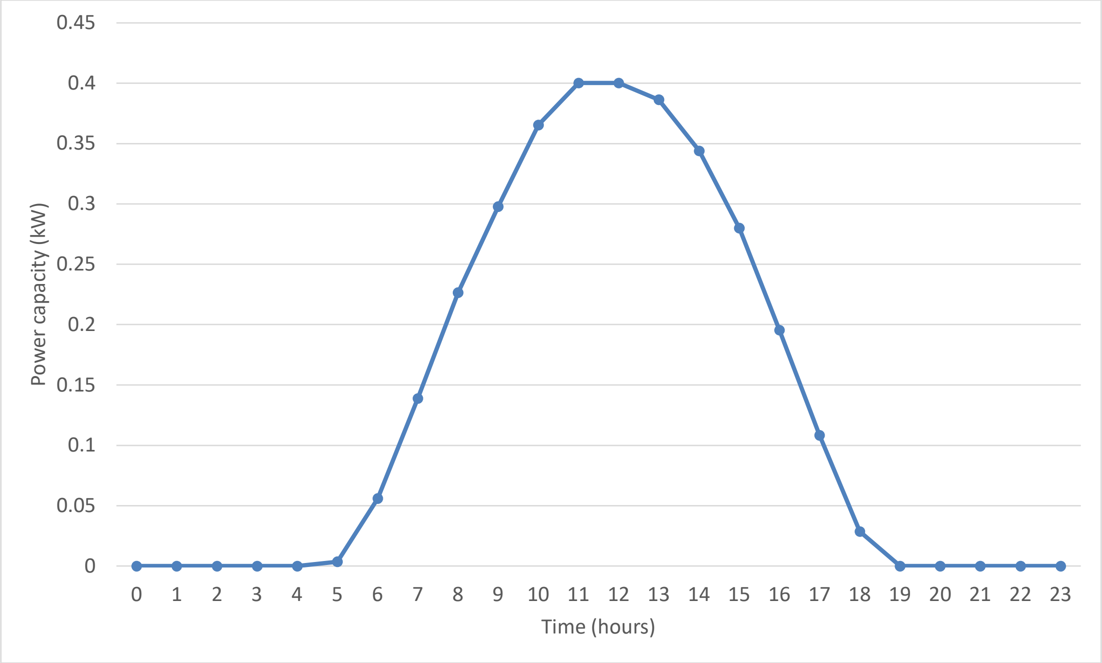

Figure 5.3: Power capacity of PV panel for model verification

Figure 5.4 represents the power provided by the grid and PV system over the 5 years, along with the demand. It is clear that the power demand is met and that the energy balance constraint (3.7) is satisfied. Constraint (3.15) ensures that the output from the PV system does not exceed its capacity. The system's maximum capacity is obtained by multiplying the number of available PV panels within each period by the values from Figure 5.3. From Figure 5.4, it can be seen that the PV system's output increases over time as more PV panels are purchased. It is also evident that the model adheres to the capacity constraint and that the output does not exceed the total capacity.

5.3.3 BESS and grid

The model considers a BESS and power exchange with the grid in this section. The model is verified by evaluating the constraints associated with the BESS and with grid exchange. The constraints related to the BESS include constraints (3.18) to (3.29).

The following input data and assumptions are considered:

- The model considers the installation of a BESS and a connection with the grid.
- The grid prices represented in Figure 5.1 are considered by the model, and no maximum limit is placed on the power imported from the grid.
- The capital cost of a BESS c_y^{BESS} is selected to be $R1$ and a yearly maintenance cost m_y^{BESS} of $R0.10$. The costs will remain the same for all years.
- The maximum number of BESSs allowed to be purchased each year n_{max}^{BESS} is 4.

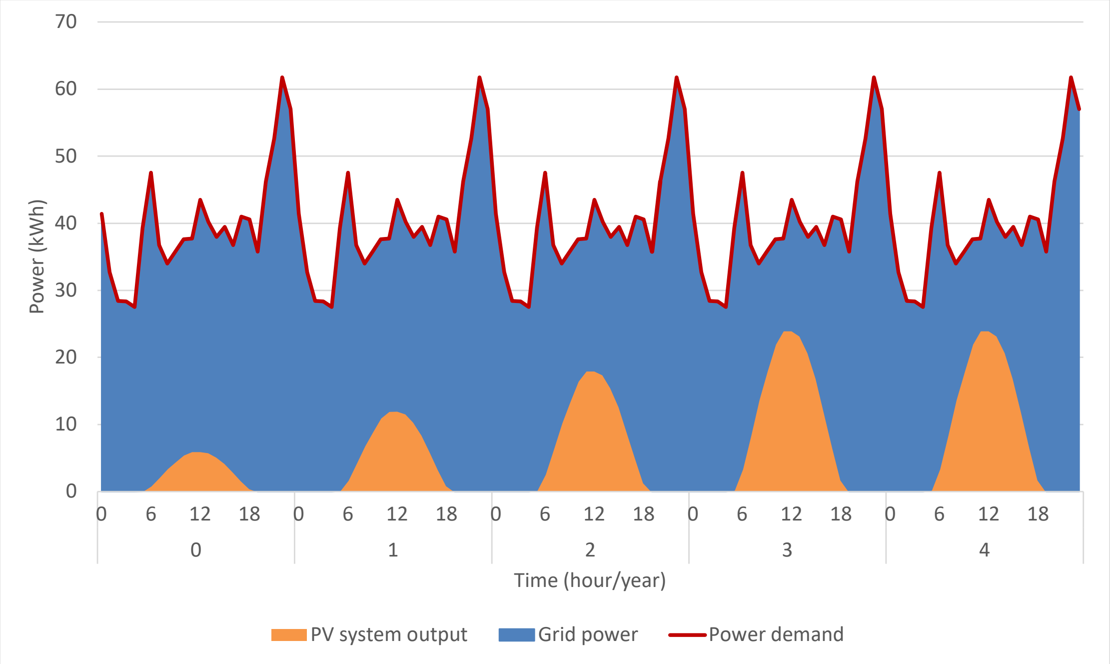

Figure 5.4: Output power from the PV system and grid

- The total number of BESSs allowed over the entire project duration n_{total}^{BESS} is 15.

In Table 5.5, a total cost of $R5402.66$ is obtained by the model. In this scenario, the model considers the implementation of a BESS and power exchange with the grid. From the results, it can be seen that the model decides to use a BESS while power is imported from the grid. The maximum number of battery units is selected because of the low capital and maintenance cost considered in this scenario. Figure 5.1 represents the grid prices. The BESS is charged with grid power during periods when the grid prices are low. To help minimise the total cost, the BESS can supply power during peak hours when the grid prices are expensive, namely hours 7 to 9 and 18 to 19.

Table 5.5: Cost of BESS and grid

Cost	Value (R)
Grid cost	5382.26
BESS capital cost	15
BESS maintenance cost	5.40
Total cost	5402.66

The results in Table 5.6 show the number of procured BESSs and the number of storage units available for each year. Constraint (3.28) restricts the number of BESSs purchased per year, and constraint (3.29) ensures that the total number of BESSs does not exceed the limit. From Table 5.6, it can be seen that the model adheres to the constraints and does not exceed the maximum limits. The table shows that 4 battery units are purchased each year, except during year 3, when only 3 BESSs are purchased. This is due to the limit on the total number of allowed BESSs. The total number of battery units is reached during year 3, and the procurement of more units is not possible. Constraint (3.18) determines the number of available storage units per year.

Table 5.6: Number of BESS chosen by model

Year	Number purchased	Number available
0	4	4
1	4	8
2	4	12
3	3	15
4	0	15

Figure 5.5 represents the results generated by the model. The demand and the power imported from the grid are represented. The figure also indicates when the BESS's charging and discharging operations occur. From Figure 5.5, it can be seen that the power imported from the grid meets the demand and that the energy balance constraint (3.7) is satisfied. During certain hours, the grid power exceeds the demand since additional power is required by charging operations. This is indicated in red on Figure 5.5. The power is discharged during peak hours to reduce costs. The BESS's charging and discharging power has increased over the years since more battery units are purchased.

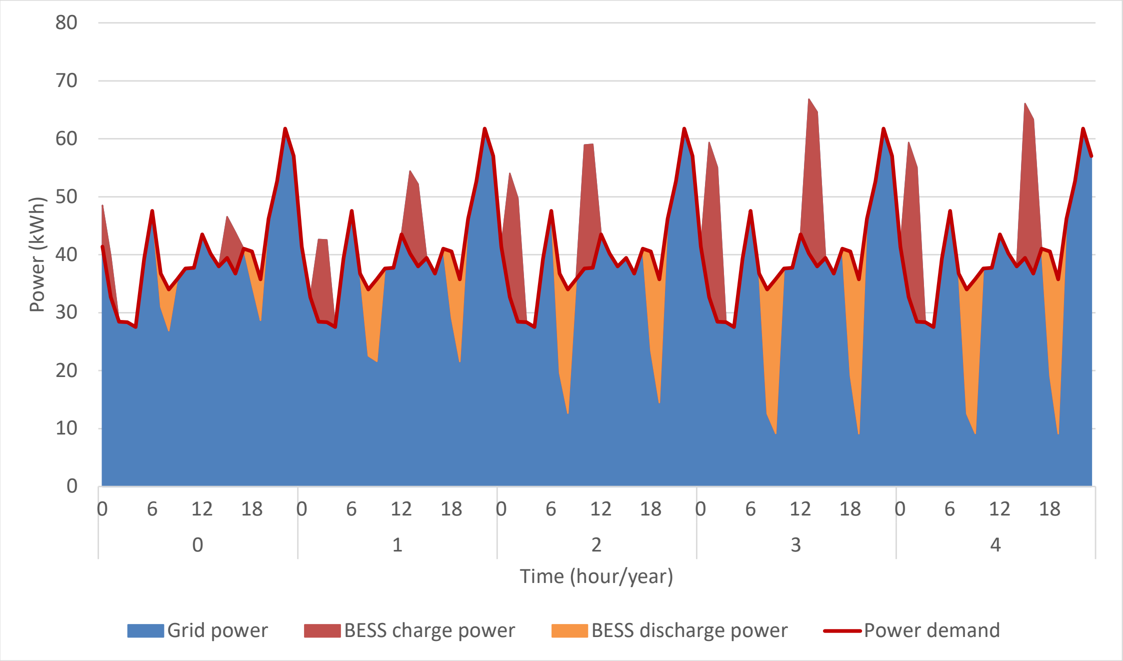

Figure 5.5: Power from the BESS and grid

The model result of the BESS for the single representative day in year 0 is represented by Table 5.7. The aim is to prove that the model satisfies the constraints associated with the battery storage units. The values of the BESS parameters are defined in Chapter 4, Section 4.7, and are multiplied by the number of available battery units during each period to obtain the system's overall limits. The energy within the battery storage system adheres to constraint (3.19), and the total storage capacity of the BESS does not exceed the maximum or minimum amount, limited by constraints (3.21) and (3.22). The discharging and charging operations do not take place at the same time, which is enforced by constraints (3.23) to (3.25). It is also clear that the discharging and charging rates, as specified by constraints (3.26) and (3.27), are met.

Table 5.7: Model results of BESS for year 0

Hour	Battery power	Battery charge power	Battery discharge power
0	7.459	7.102	0
1	14.208	7.104	0
2	14.208	0	0
3	14.208	0	0
4	14.208	0	0
5	14.208	0	0
6	14.208	0	0
7	8.190	0	5.717
8	0.712	0	7.104
9	0.712	0	0
10	0.712	0	0
11	0.712	0	0
12	0.712	0	0
13	0.712	0	0
14	0.712	0	0
15	7.461	7.104	0
16	14.208	7.102	0
17	14.208	0	0
18	8.190	0	5.717
19	0.712	0	7.104
20	0.712	0	0
21	0.712	0	0
22	0.712	0	0
23	0.712	0	0

5.3.4 Wind system and grid

In this section, the model considers wind turbines and a connection to the grid. The model is verified by assessing the constraints associated with the wind system and with the grid. The constraints related to this generation technology include constraints (3.30) to (3.34).

The following input data and assumptions are considered:

- The model considers the use of wind turbines and exchange with the grid.
- The grid prices described in Figure 5.1 are considered by the model and no maximum limit is placed on the power imported from the grid.

- The capital cost of a wind turbine c_y^{Wind} is selected to be $R1$ and a yearly maintenance cost m_y^{Wind} of $R0.10$. The costs will remain the same for all years.
- The maximum number of wind turbines allowed to be purchased each year n_{max}^{Wind} is 5.
- The total number of wind turbines allowed over the entire project duration n_{total}^{Wind} is 20.

The model aims to minimise the total cost of the energy microgrid, and Table 5.8 shows the microgrid costs obtained for this scenario. The total cost of $R4461.18$ consists of the grid import cost and the wind system cost over the 5 years. The model selects the maximum number of wind turbines due to the inexpensive capital and maintenance costs. The wind system cannot meet the total power demand, and the remaining power is imported from the grid.

Table 5.8: Cost of wind system and grid

Cost	Value (R)
Grid cost	4434.18
Wind system capital cost	20
Wind system maintenance cost	7
Total cost	4461.18

The number of wind turbines purchased each year is shown in Table 5.9. Constraint (3.33) restricts the number of wind turbines purchased per year. Similarly, constraint (3.34) ensures that the total number of wind turbines does not exceed the given maximum limit. The results in Table 5.9 prove that the model adheres to the constraints and does not exceed the limits. The table also shows the number of available wind turbines each year, which is calculated by constraint (3.31).

Table 5.9: Number of wind turbines chosen by model

Year	Number purchased	Number available
0	5	5
1	5	10
2	5	15
3	5	20
4	0	20

Figure 5.6 represents the capacity of a wind turbine. The wind turbine capacity $Wind_{td}^{max}$ during each time period is obtained with the mathematical function (3.30). It is assumed that the capacity of a single wind turbine will remain the same for each year.

Figure 5.7 shows the demand and the power supplied by the grid and wind turbines over the project lifetime. It is clear that the power demand is met and that the energy balance constraint (3.7) is satisfied. Constraint (3.32) ensures that the output from the

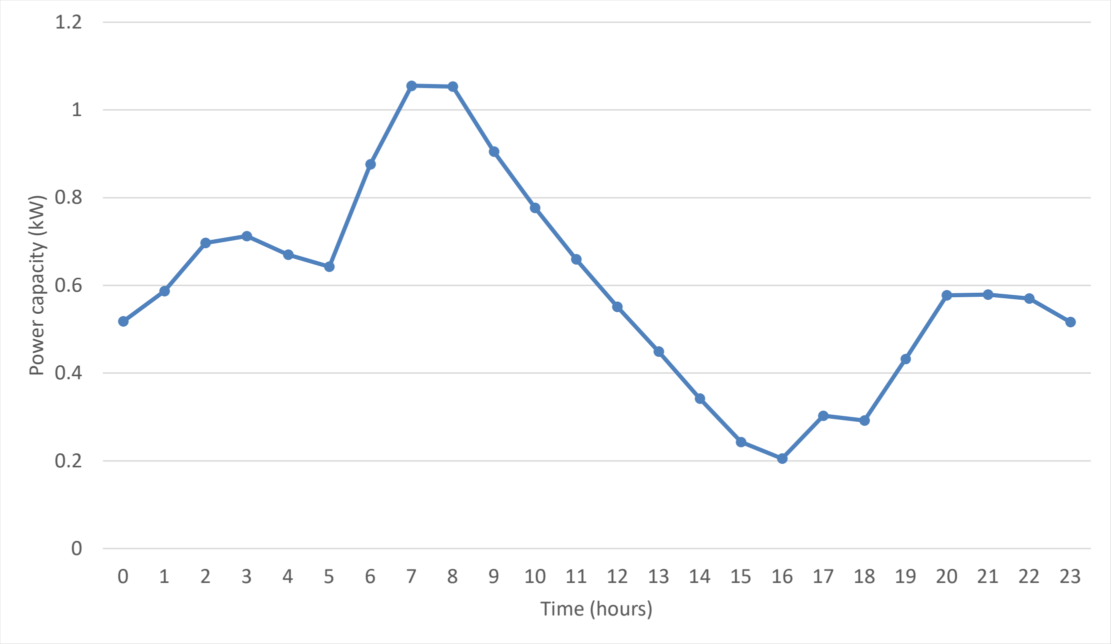

Figure 5.6: Power capacity of wind turbine for model verification

wind system does not exceed its capacity. From Figure 5.7, it can be seen how the wind system's output increases over the years. The system's maximum capacity is obtained by multiplying the number of available wind turbines within each year by the values from Figure 5.6. It is also evident that the model adheres to the capacity constraint and that the output does not exceed the total capacity of the wind turbines.

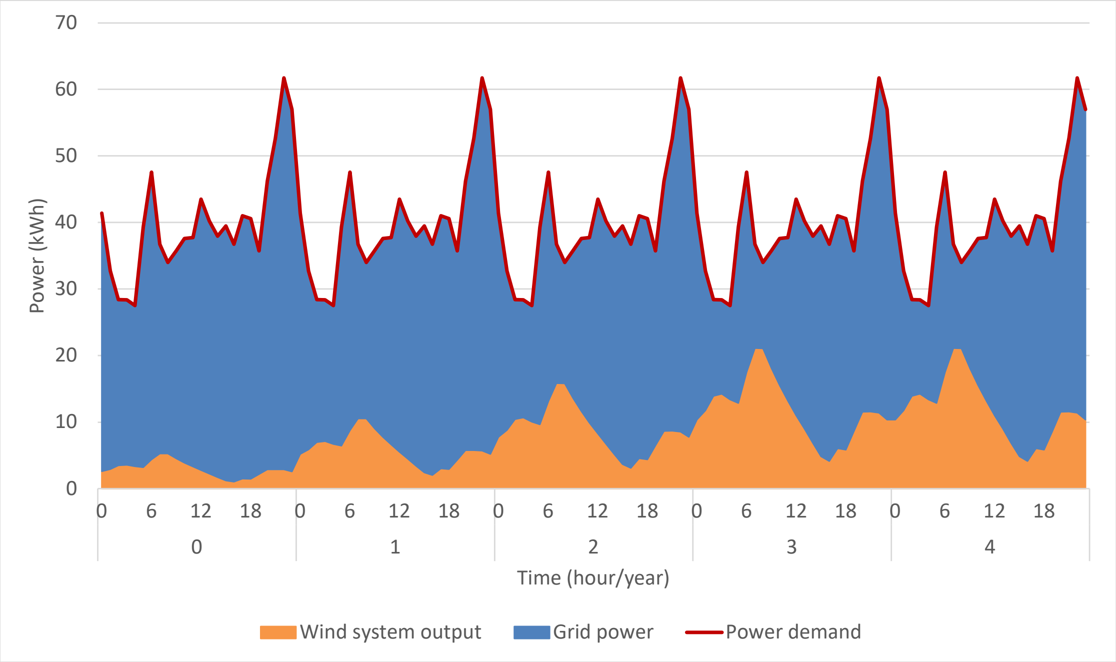

Figure 5.7: Output power from the wind system and grid

5.4 Chapter summary

The verification of the mathematical model was undertaken in Chapter 5. It is proven that the model formulation is correct and that the implementation accurately represents the proposed model. The model validation takes place in Chapter 6.

Chapter 6

Model validation

6.1 Introduction

In Chapter 5, the scenarios for model verification are presented and verify that the optimisation model was correctly formulated and built. Therefore the next step is the validation of the model, as presented in Chapter 6. Model validation is necessary to ensure that the model performs as intended. The validation process considers the use of large and real-world datasets, as described in Chapter 4, to ensure that the proposed model represents a real microgrid system to the greatest extent possible. The data and assumptions considered in this chapter are discussed, followed by the various scenarios for the model validation.

6.2 Data and assumptions

The location, time and data described in Chapter 4 are considered for the validation of the model. The model considers a period of 24 hours and 84 representative days. A project lifetime of 15 years is selected. The size parameters considered for the model validation are shown in Table 6.1. The maximum number of units allowed to be purchased each year and the total number allowed over the project lifetime are represented in Table 6.1 for each generation and storage technology.

Table 6.1: Size parameters for model validation

Technology	Limit per year	Limit over project lifetime
Diesel generators	5	10
PV system	400	4000
BESS	50	400
Wind system	50	250

6.3 Constant costs

The model validation is divided into two main sections. This section considers different scenarios while assuming that all cost parameters remain the same for each year. The effect of variable costs is examined in Section 6.4.

6.3.1 Scenario 1: Grid exchange with no technology limits

In this section, the model considers a scenario where the microgrid has a grid connection. No limits are placed on the number of units purchased per year or on the number of units allowed over the entire project duration. This allows the model to obtain the optimal configuration of generation and storage technologies without any restrictions.

Table 6.2 represents the results obtained by the model. The number of units purchased and available each year is shown for each technology. From Table 6.2, it can be seen that the model chooses PV panels and BESSs. No limit is placed on the number of units purchased per year, and the model decides to purchase all required units during year 0. The technologies can therefore be fully utilised for the entire project duration. The procurement of diesel generators and wind turbines is not feasible since these generation technologies are not selected by the model.

Table 6.2: Number of technologies purchased and available for Scenario 1

Year	Diesel generators purchased	Diesel generators available	PV panels purchased	PV panels available	BESS purchased	BESS available	Wind turbines purchased	Wind turbines available
0	0	0	4908	4908	490	490	0	0
1	0	0	0	4908	0	490	0	0
2	0	0	0	4908	0	490	0	0
3	0	0	0	4908	0	490	0	0
4	0	0	0	4908	0	490	0	0
5	0	0	0	4908	0	490	0	0
6	0	0	0	4908	0	490	0	0
7	0	0	0	4908	0	490	0	0
8	0	0	0	4908	0	490	0	0
9	0	0	0	4908	0	490	0	0
10	0	0	0	4908	0	490	0	0
11	0	0	0	4908	0	490	0	0
12	0	0	0	4908	0	490	0	0
13	0	0	0	4908	0	490	0	0
14	0	0	0	4908	0	490	0	0

Figure 6.1 shows that power is imported from the grid along with the use of PV panels

and BESSs. In Figure 6.1, it can be seen that the power demand is satisfied by the PV system and grid. The total amount used for charging and discharging operations during each year is also shown. It can be noted that the power each year slightly exceeds power demand. This is a result of the power lost during battery operations due to battery efficiency. Constraint (3.19) ensures that battery efficiency is taken into account. The optimal number of PV panels and BESSs are purchased during year 0. Therefore the power composition remains the same during all years.

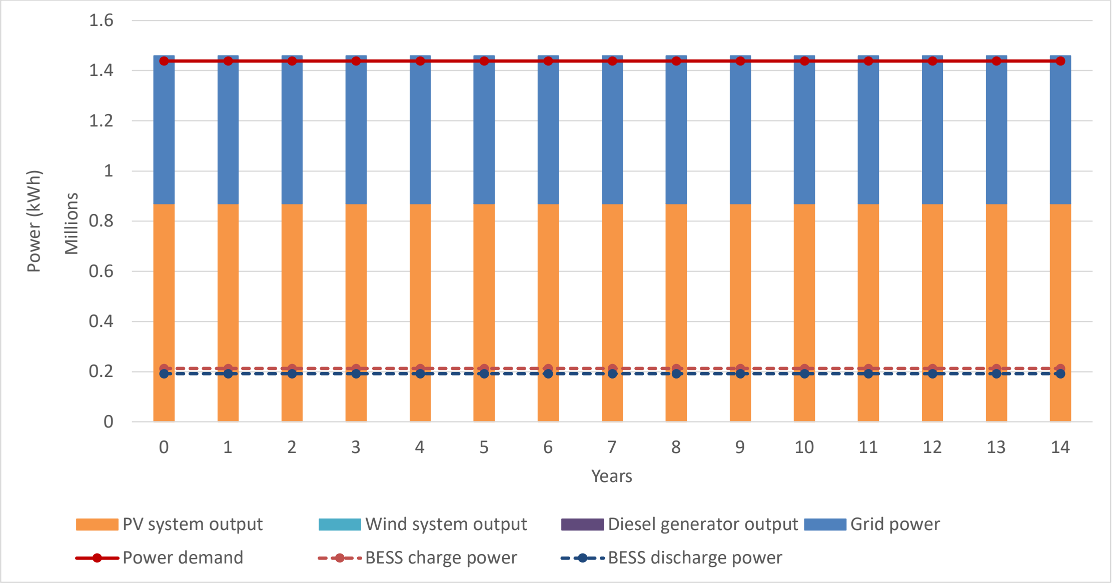

Figure 6.1: Model results of the entire project duration for Scenario 1

The model results of a single day are shown in Figure 6.2. The aim is to demonstrate the typical daily operation of the microgrid in this scenario. Figure 6.2 represents the results from a single day in March in the final year of the project. The same day is selected and examined for all of the scenarios. It can be seen how the grid and output power from the PV system is used to meet the demand. During certain hours, additional power from the grid and surplus power from the PV system is used for BESS charging operations. The power is discharged for later use.

The objective function value calculated by the model amounts to $R18\,519\,163$. This is the total power cost of the microgrid over 15 years. Figure 6.3 shows the cost composition for Scenario 1.

6.3.2 Scenario 2: Grid exchange with technology limits

This scenario also considers exchange with the grid, but the model has to adhere to the technology size limits. The size parameters are shown in Table 6.1 and are used to represent a real-life scenario where it is necessary to incorporate budget and space limitations into the microgrid design.

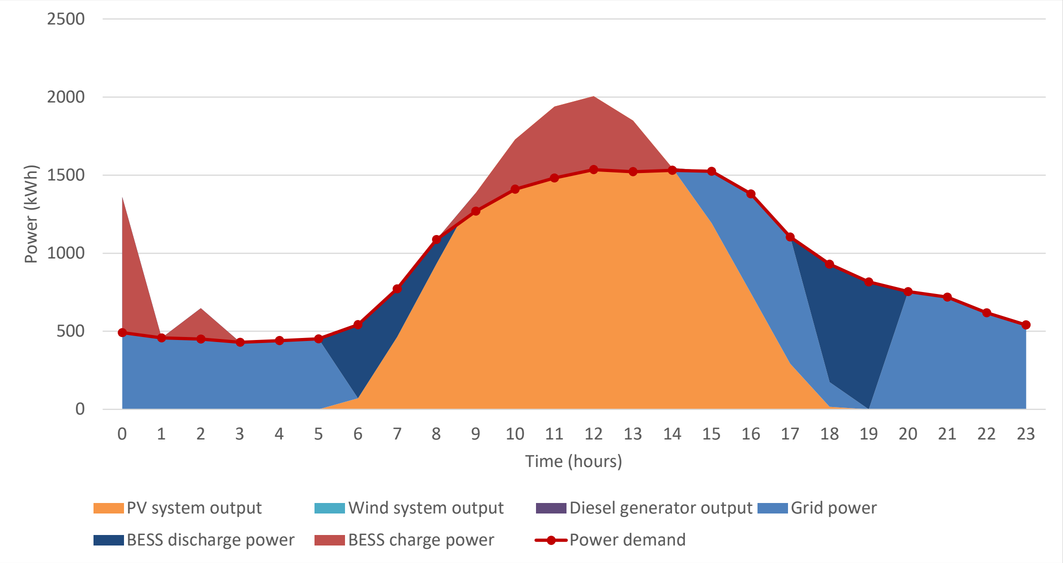

Figure 6.2: Model results of a single day for Scenario 1

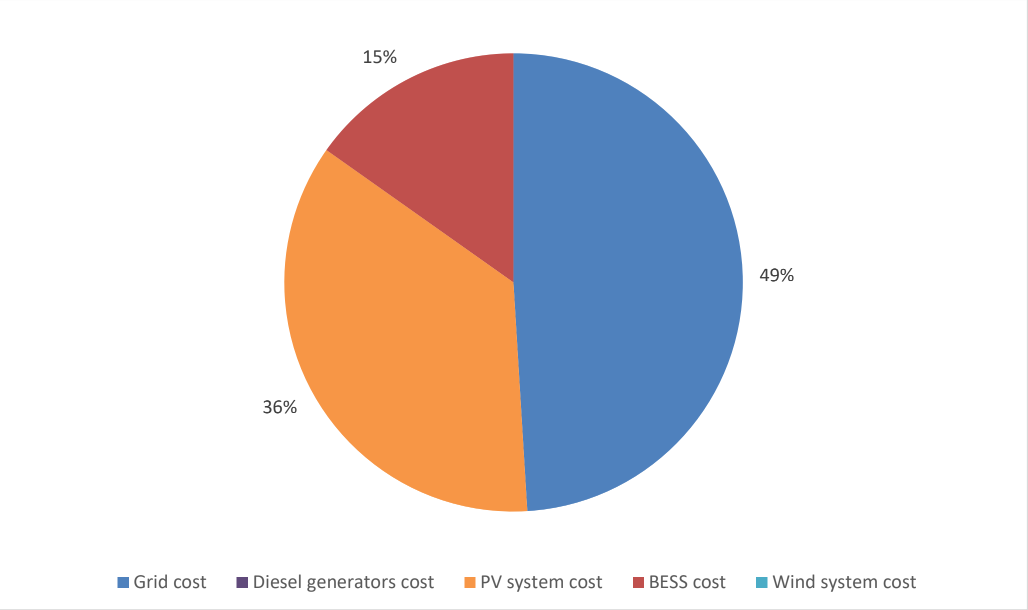

Figure 6.3: Cost composition for Scenario 1

The number of generation and storage units purchased and available each year are shown in Table 6.3. The optimal combination consists of PV panels, BESSs and power imported from the grid. Diesel generators and wind turbines are not selected because of the high costs associated with these technologies. From Table 6.3, it can be seen that the model adheres to the limits as specified in Table 6.1. The maximum number of PV panels and BESSs allowed on the microgrid premises are 4000 and 400, respectively. The optimal number of PV panels and BESSs for this scenario does not reach the maximum limit. The model reaches a point in time where it is more expensive to purchase additional PV panels and BESSs compared to importing the remaining power from the grid.

Table 6.3: Number of technologies purchased and available for Scenario 2

Year	Diesel generators purchased	Diesel generators available	PV panels purchased	PV panels available	BESS purchased	BESS available	Wind turbines purchased	Wind turbines available
0	0	0	400	400	50	50	0	0
1	0	0	400	800	50	100	0	0
2	0	0	400	1200	50	150	0	0
3	0	0	400	1600	50	200	0	0
4	0	0	400	2000	50	250	0	0
5	0	0	400	2400	50	300	0	0
6	0	0	400	2800	0	300	0	0
7	0	0	400	3200	0	300	0	0
8	0	0	400	3600	0	300	0	0
9	0	0	226	3826	0	300	0	0
10	0	0	0	3826	0	300	0	0
11	0	0	0	3826	0	300	0	0
12	0	0	0	3826	0	300	0	0
13	0	0	0	3826	0	300	0	0
14	0	0	0	3826	0	300	0	0

Figure 6.4 shows that the total power is supplied by a combination of power from the PV system and grid while considering the operation of the BESS. It can be seen how the output power from the PV system and power from the BESS operations increase over the years as more units are purchased. As a result, the amount of power imported from the grid decreases over the project's lifetime.

Figure 6.5 represents the results of a single day during the final year of the project. The hourly power demand is satisfied by power from the grid, the PV system and the BESS discharge power. Power is discharged from the battery system during hours when the PV system cannot meet the total demand and when the grid prices are the most expensive. On this specific day, the BESS is mostly charged with power from the grid since the bulk of the PV system power is consumed by the load.

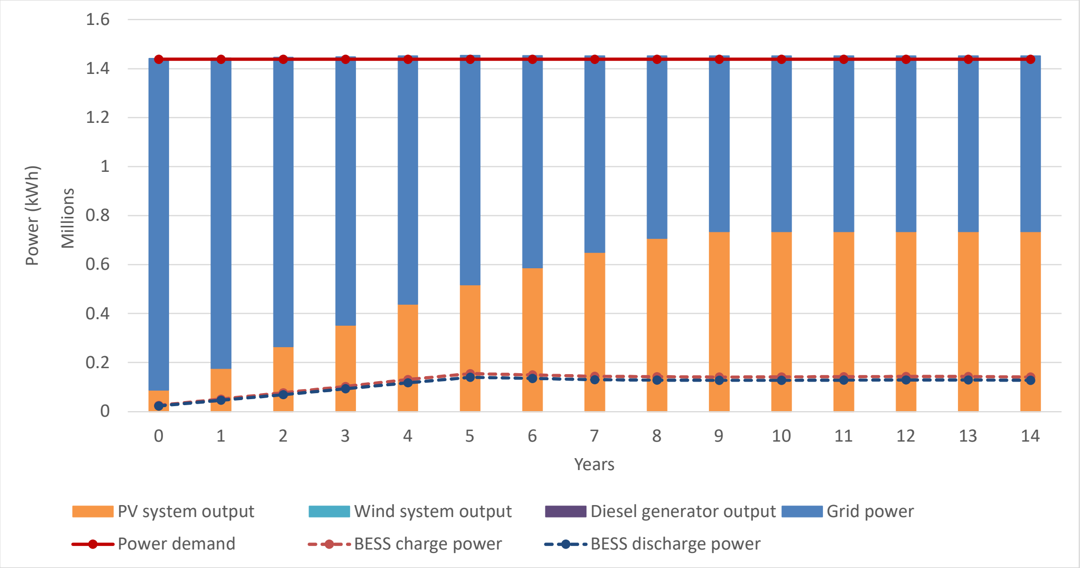

Figure 6.4: Model results of the entire project duration for Scenario 2

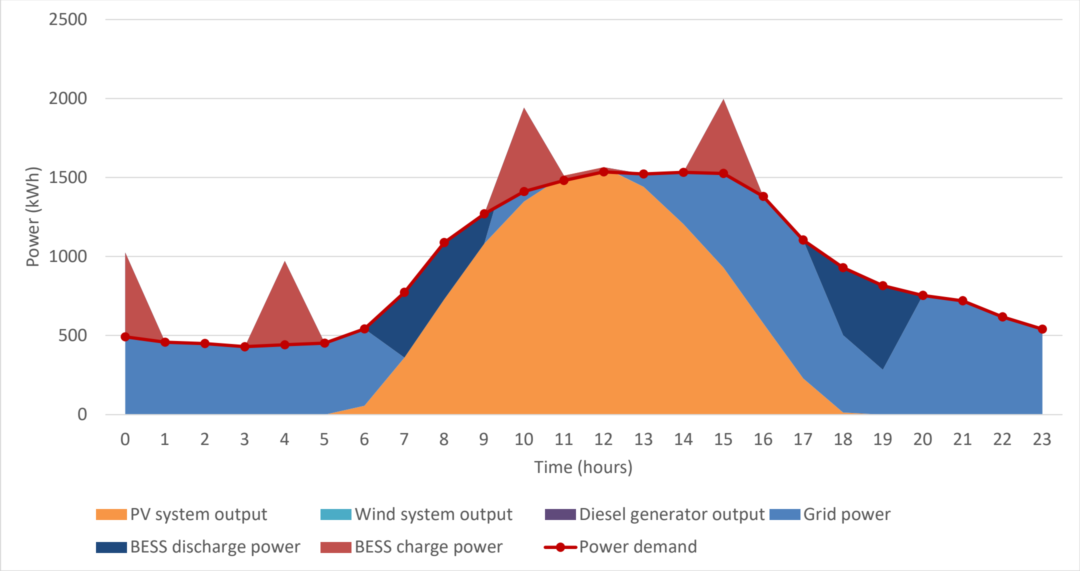

Figure 6.5: Model results of a single day for Scenario 2

The total cost calculated by the model amounts to $R22\,856\,349$ for the entire project lifetime. Figure 6.6 represents the cost composition for Scenario 2.

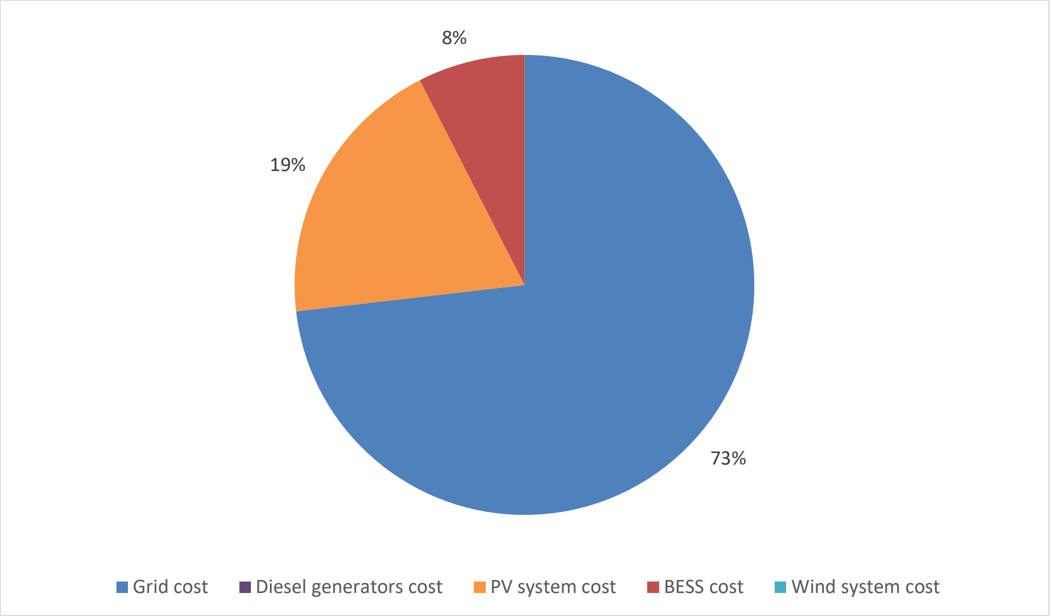

Figure 6.6: Cost composition for Scenario 2

6.3.3 Scenario 3: No grid exchange or technology limits

A grid-connected microgrid is considered by the model, but a microgrid can also operate in island mode. This scenario determines the optimal mix of technologies while the microgrid operates independently from the grid. No limit is placed on the number of units allowed to be purchased or on the total number of units allowed to be integrated with the microgrid.

In this scenario, no power can be imported from the grid. To meet the power demand, the model determines that the optimal configuration of generation and storage technologies must consist of diesel generators, PV panels, BESS and wind turbines. The results are shown in Table 6.4. There are no limits placed on the numbers to be purchased per year. Therefore, the optimal time to invest is at the beginning of the project.

Figure 6.7 shows the total power supplied by the generation technologies during each year. The total amount of power used for BESS charging and discharging is also indicated per year. The demand and the power required by the BESS are supplied by a combination of power from diesel generators, the PV system and the wind system. The capacity of each technology remains the same over all the years since the optimal number of units, as determined by the model, was obtained in year 0.

The model results shown in Figure 6.8 are used to demonstrate how the microgrid operates in a single day during the last year. It can be seen which technology, or combination of technologies, supplies power during each hour of the day. Surplus power from the PV

Table 6.4: Number of technologies purchased and available for Scenario 3

Year	Diesel generators purchased	Diesel generators available	PV panels purchased	PV panels available	BESS purchased	BESS available	Wind turbines purchased	Wind turbines available
0	2	2	6103	6103	1157	1157	612	612
1	0	2	0	6103	0	1157	0	612
2	0	2	0	6103	0	1157	0	612
3	0	2	0	6103	0	1157	0	612
4	0	2	0	6103	0	1157	0	612
5	0	2	0	6103	0	1157	0	612
6	0	2	0	6103	0	1157	0	612
7	0	2	0	6103	0	1157	0	612
8	0	2	0	6103	0	1157	0	612
9	0	2	0	6103	0	1157	0	612
10	0	2	0	6103	0	1157	0	612
11	0	2	0	6103	0	1157	0	612
12	0	2	0	6103	0	1157	0	612
13	0	2	0	6103	0	1157	0	612
14	0	2	0	6103	0	1157	0	612

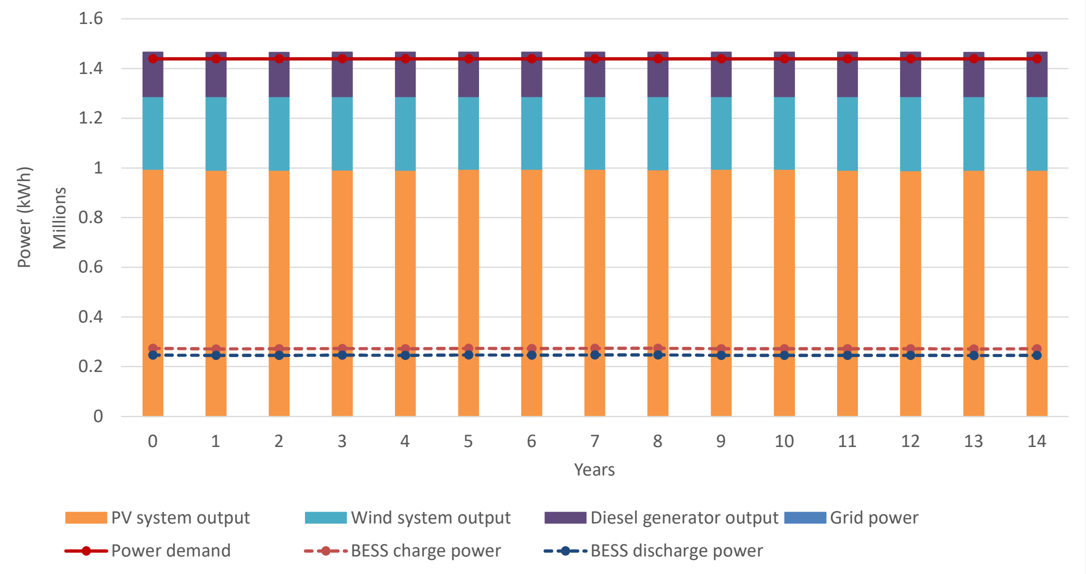

Figure 6.7: Model results of the entire project duration for Scenario 3

panels and wind turbines is used for charging the BESS. The model determines the amount of power required for the charging and discharging operations.

The objective function value for Scenario 3 is equal to $R40\,971\,548$. In Figure 6.9, it can be seen how the total cost is divided between the generation and storage technologies.

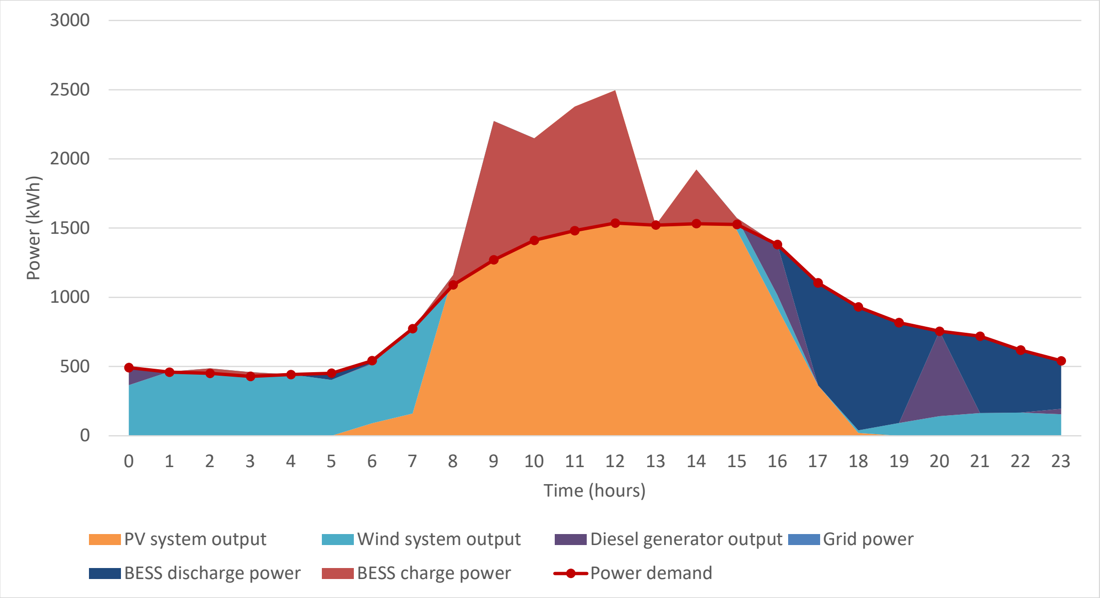

Figure 6.8: Model results of a single day for Scenario 3

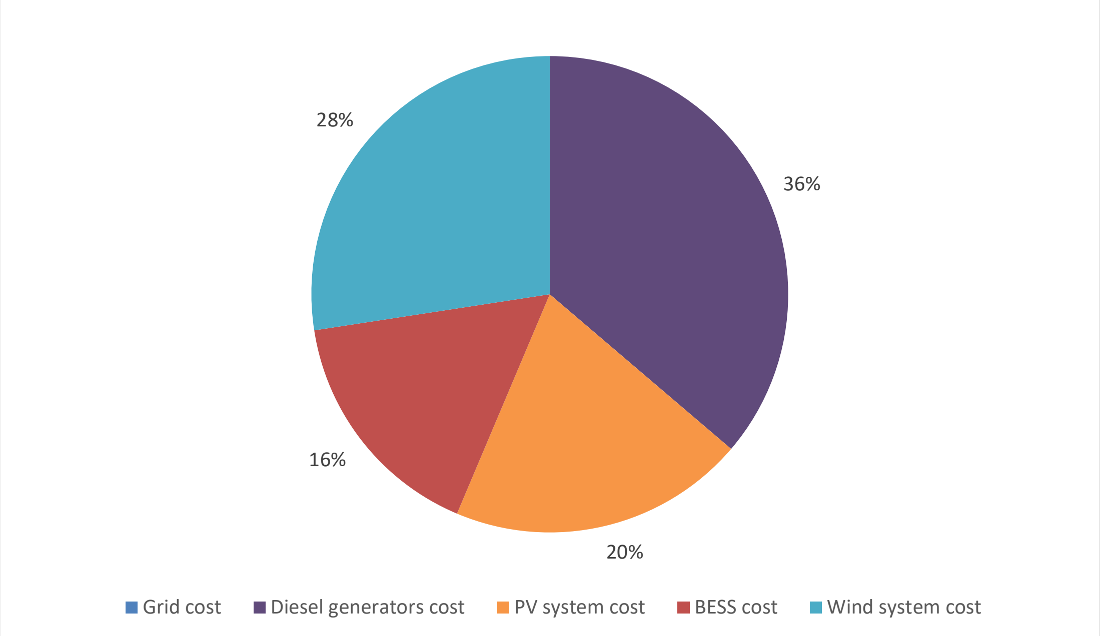

Figure 6.9: Cost composition for Scenario 3

6.3.4 Scenario 4: No grid exchange but with technology limits

In this section, the model evaluates a scenario without grid exchange and with limits placed on the number units for each technology.

Table 6.5 represents the results for Scenario 4. The model calculates which technologies to invest in, when to invest, and the number of units required. The import of grid power is not considered and therefore the optimal mix consists of all of the technologies. From Table 6.5 it is evident that the model adheres to the limits specified in Section 6.2. The model selects the maximum number of PV panels, BESSs and wind turbines allowed on the microgrid site. It is determined that only 5 diesel generators are required.

Table 6.5: Number of technologies purchased and available for Scenario 4

Year	Diesel generators purchased	Diesel generators available	PV panels purchased	PV panels available	BESS purchased	BESS available	Wind turbines purchased	Wind turbines available
0	5	5	400	400	50	50	50	50
1	0	5	400	800	50	100	50	100
2	0	5	400	1200	50	150	50	150
3	0	5	400	1600	50	200	50	200
4	0	5	400	2000	50	250	50	250
5	0	5	400	2400	50	300	0	250
6	0	5	400	2800	50	350	0	250
7	0	5	400	3200	50	400	0	250
8	0	5	400	3600	0	400	0	250
9	0	5	400	4000	0	400	0	250
10	0	5	0	4000	0	400	0	250
11	0	5	0	4000	0	400	0	250
12	0	5	0	4000	0	400	0	250
13	0	5	0	4000	0	400	0	250
14	0	5	0	4000	0	400	0	250

Figure 6.10 shows the total amount of power generated by the technologies in each year. The BESS power and demand are met with the combined output from the diesel generators, PV panels and wind turbines. In this scenario, it is clear how the output from the PV system and wind turbines increases over time as more units are purchased. The amount of power generated by the diesel generators decreases as a result. The diesel generators were mainly purchased to meet the demand during the earlier years when only a few PV panels and wind turbines were available. Diesel generators also supply power in the last couple of years since a limit is placed on the number of PV panels and wind turbines allowed.

The model results of a single day are shown in Figure 6.11. The amount of power supplied by the technologies is shown. It is evident that the demand is satisfied during each hour

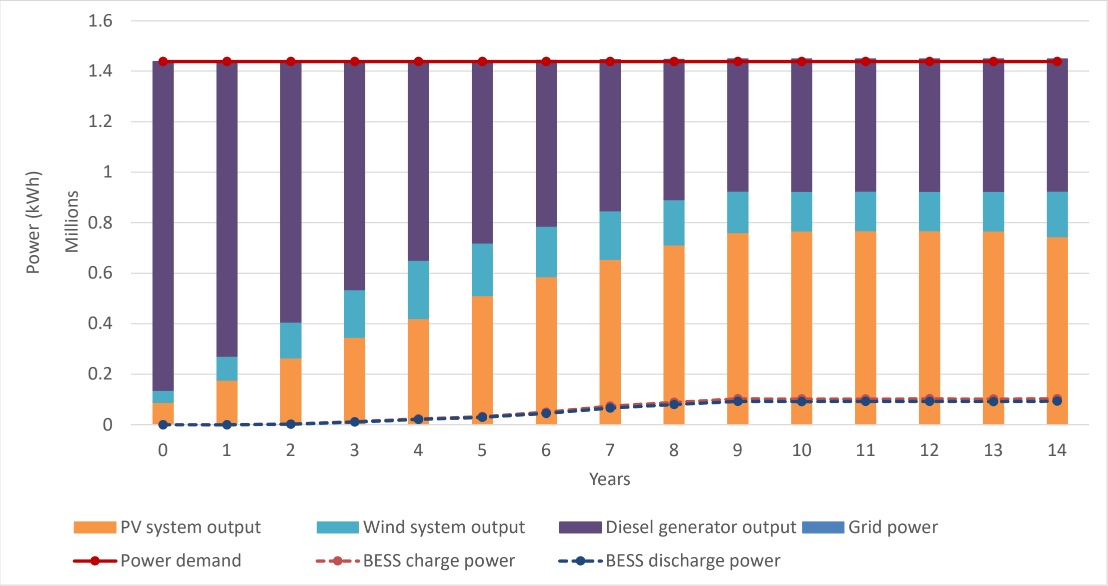

Figure 6.10: Model results of the entire project duration for Scenario 4

and that the excess power from the renewable technologies is used for BESS charging.

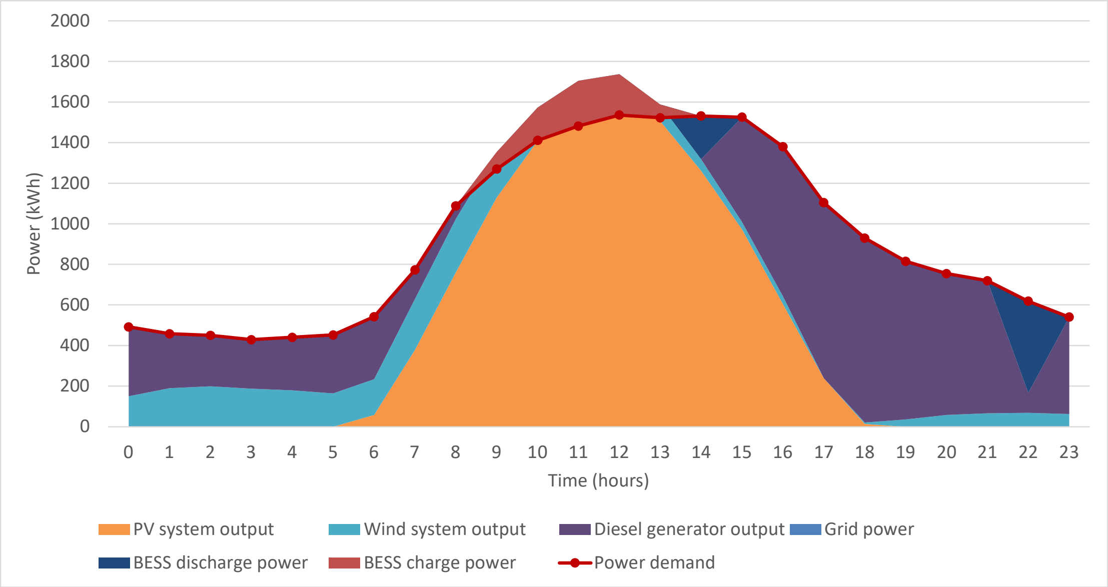

Figure 6.11: Model results of a single day for Scenario 4

The total cost calculated by the model amounts to $R70\,689\,600$ for the entire project lifetime. Figure 6.12 represents the cost composition for Scenario 4 and consists of costs from the diesel generators, PV system, BESS and wind turbines.

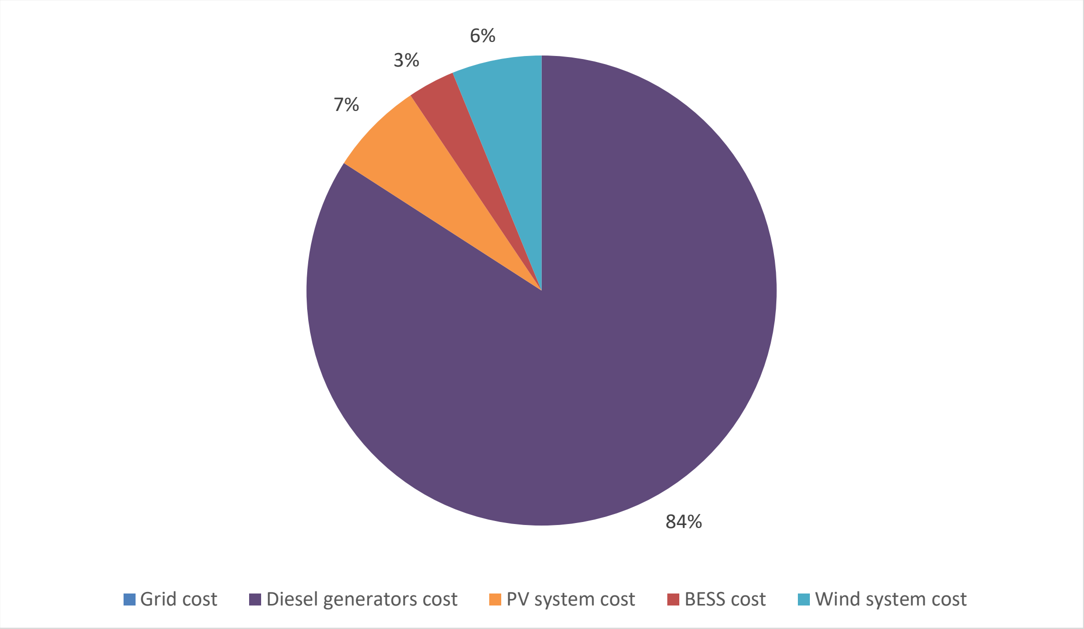

Figure 6.12: Cost composition for Scenario 4

6.4 Variable costs

The effect of changing prices is incorporated into this section to represent a real-world microgrid as much as possible. Different scenarios are also examined to show how the results are impacted by factors such as technology limits and load-shedding. For this section, it is assumed that there is a yearly increase of 15% in grid prices.

The rise of a more competitive market and the advancement of technologies can lead to a decrease in prices. Therefore, it is assumed that the capital cost of PV panels and batteries will be driven down each year. A yearly decrease of 7% and 3% is selected for PV panels and batteries, respectively. It is assumed that the price of diesel generators and wind turbines will remain constant over the years. However, the price of diesel is expected to increase by 10% per year. The values are selected based on the average price trends over the last few years in South Africa.

In Chapter 3, Section 3.3, the discount in capital cost and maintenance cost was discussed. In this section, the discounted costs are incorporated into each scenario. The discounted values are calculated for each technology over a period of 15 years. A discount rate of 3% per year is considered.

6.4.1 Scenario 5: Grid exchange with no technology limits

In this section, the model considers a scenario where the microgrid can import power from the grid. No limits are placed on the number of units purchased per year or on the number of units allowed over the entire project duration. Variable cost values are considered to show how the model results are affected by the change in prices over time.

Table 6.6 shows the number of units purchased and available in each year. No limits are placed on the size of the technologies therefore the model determines that the optimal configuration is comprised of grid power, a PV system and a BESS. Since no limit is placed on the number of units to be purchased per year, it is expected that the optimal number of PV panels and BESSs will be procured during year 0. However, this is not the case. The model obtains a large number of PV panels and batteries during the first year, followed by the procurement of additional units over several years. This is a result of the changing prices over time in both grid prices and technology prices. With the rapid increase in grid price and the discount in technology costs, the model determines that it is feasible to procure some of the units later in time, instead of purchasing all units during year 0.

Table 6.6: Number of technologies purchased and available for Scenario 5

Year	Diesel generators purchased	Diesel generators available	PV panels purchased	PV panels available	BESS purchased	BESS available	Wind turbines purchased	Wind turbines available
0	0	0	4484	4484	510	510	0	0
1	0	0	637	5121	138	648	0	0
2	0	0	225	5346	43	691	0	0
3	0	0	611	5957	327	1018	0	0
4	0	0	400	6357	149	1167	0	0
5	0	0	403	6760	94	1261	0	0
6	0	0	257	7017	87	1348	0	0
7	0	0	397	7414	66	1414	0	0
8	0	0	127	7541	0	1414	0	0
9	0	0	177	7718	0	1414	0	0
10	0	0	192	7910	0	1414	0	0
11	0	0	0	7910	0	1414	0	0
12	0	0	0	7910	0	1414	0	0
13	0	0	0	7910	0	1414	0	0
14	0	0	0	7910	0	1414	0	0

Figure 6.13 shows the model results for Scenario 5. For this scenario, the model determines that power should be imported from the grid and supplied by the PV system. The use of a BESS is also considered and Figure 6.13 shows the total charge and discharge power in each year. As previously mentioned, power is lost during BESS operations, therefore the power supplied each year exceeds the demand. From the graph, it can be seen that the BESS charge power is greater than the discharge power each year. In other words, more power has to be put into the battery to get the desired amount when discharging. It is clear how the total capacity of the PV system and BESS increases over the years until the

optimal number of units is reached.

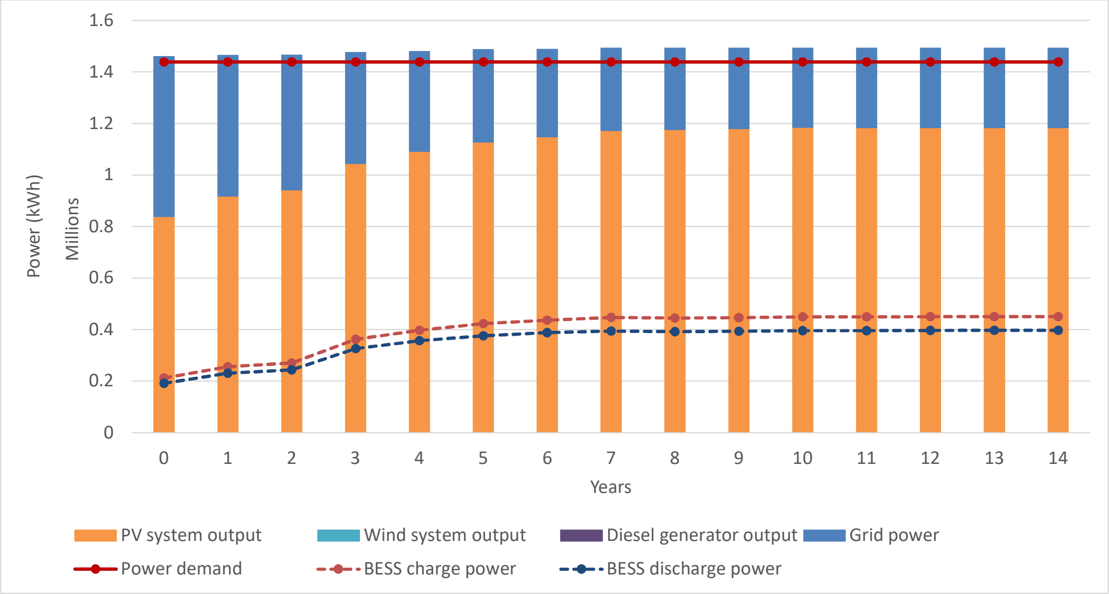

Figure 6.13: Model results of the entire project duration for Scenario 5

Figure 6.14 represents the results of a single day in March in the final year. The demand is satisfied by the power imported from the grid, PV system and BESS discharge power. During certain hours, additional power from the grid and surplus power from the PV system is used for BESS charging operations. The power is discharged during times when the grid prices are expensive or when the PV system cannot meet the demand.

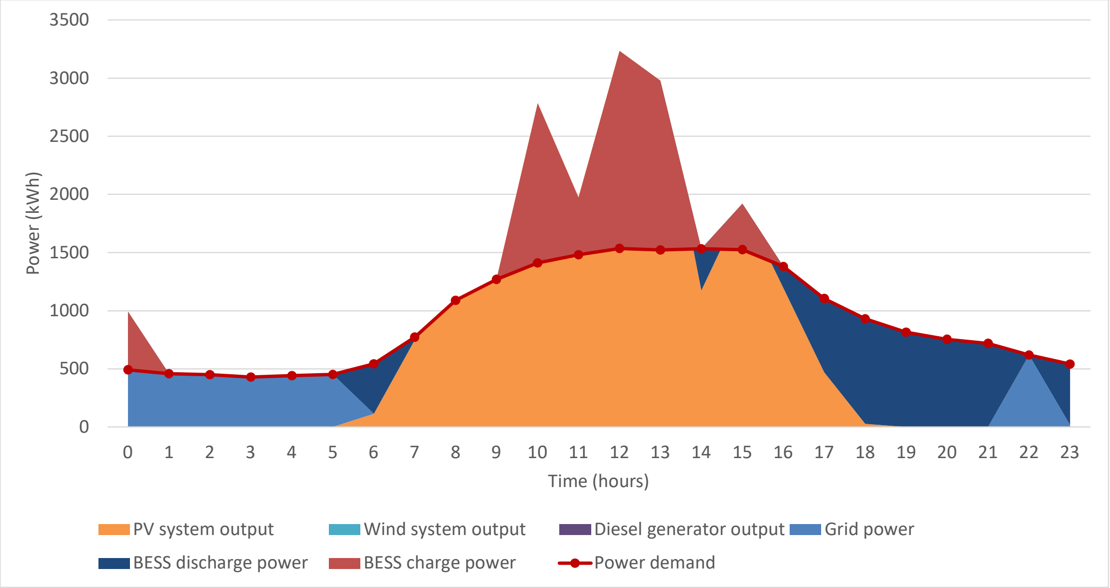

Figure 6.14: Model results of a single day for Scenario 5

The objective function value calculated by the model amounts to $R29\,658\,153$. This is the total cost of the microgrid over 15 years. Figure 6.15 shows the cost composition for

Scenario 5, consisting of the grid, PV system, and BESS costs.

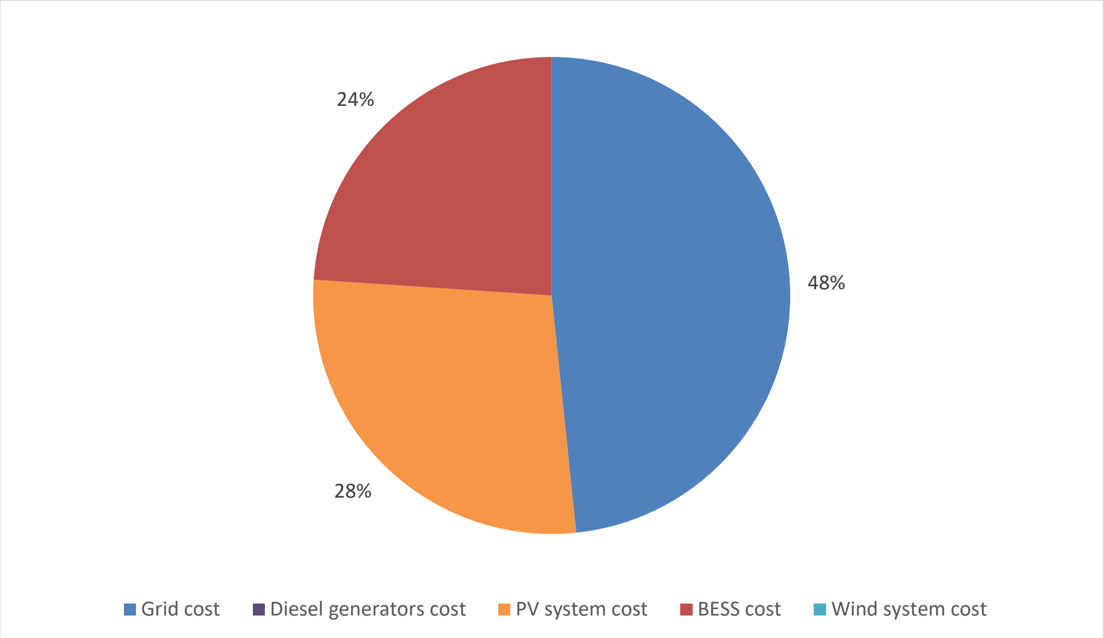

Figure 6.15: Cost composition for Scenario 5

6.4.2 Scenario 6: Grid exchange with technology limits

This scenario considers a connection to the grid, but the number of technology units purchased per year is limited, as well as the total number of units allowed over the project lifetime. The change in grid and technology prices are also considered in this scenario.

The results for Scenario 6 are shown in Table 6.7. The model determines that the procurement of a diesel generator, PV system, wind system and BESS is the optimal mixture for this scenario. The model cannot select a large number of PV panels and batteries as seen in Scenario 5, because of the limit placed on the size of the technologies. Therefore, the model selects the maximum number of units allowed for both the PV system and BESS. It is also determined that the maximum number of wind turbines allowed per year and over the project lifetime should be purchased. The remaining demand is met with power imported from the grid.

From Table 6.7 it can be seen that the procurement of a single diesel generator occurs in year 5. When considering the change in prices, the model determines that it is worth investing in a diesel generator. The diesel generator is utilised during peak hours of the high-demand season when the price of grid power is extremely high. As a result of the increase in grid prices, it is more economical to run the diesel generator during those hours than to purchase power from the grid.

In this scenario, the demand is satisfied through the combination of power from all generation and storage technologies, as shown in Figure 6.16. It can be seen how the amount of

Table 6.7: Number of technologies purchased and available for Scenario 6

Year	Diesel generators purchased	Diesel generators available	PV panels purchased	PV panels available	BESS purchased	BESS available	Wind turbines purchased	Wind turbines available
0	0	0	400	400	50	50	50	50
1	0	0	400	800	50	100	50	100
2	0	0	400	1200	50	150	50	150
3	0	0	400	1600	50	200	50	200
4	0	0	400	2000	50	250	50	250
5	1	1	400	2400	50	300	0	250
6	0	1	400	2800	50	350	0	250
7	0	1	400	3200	50	400	0	250
8	0	1	400	3600	0	400	0	250
9	0	1	400	4000	0	400	0	250
10	0	1	0	4000	0	400	0	250
11	0	1	0	4000	0	400	0	250
12	0	1	0	4000	0	400	0	250
13	0	1	0	4000	0	400	0	250
14	0	1	0	4000	0	400	0	250

power increases over the years as more units are purchased for the PV system, the wind system and BESS. A limit is placed on the number of units to be purchased, therefore the remaining power is imported from the grid. The single diesel generator generates a small portion of the required power from year 5, when it was purchased, until the last year.

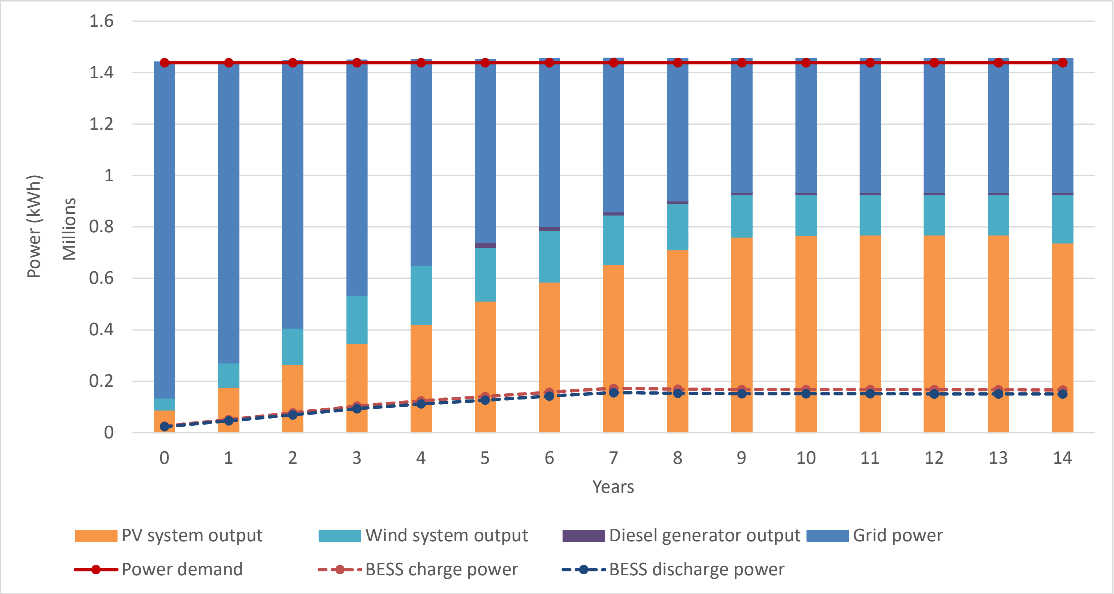

Figure 6.16: Model results of the entire project duration for Scenario 6

The model results of a single day are shown in Figure 6.17. The demand is satisfied during each hour by a combination of power from the grid, PV system, wind turbines and BESS. The excess power from the renewable technologies and additional power purchased from the grid, at the beginning of the day, is used for BESS charging and discharging operations.

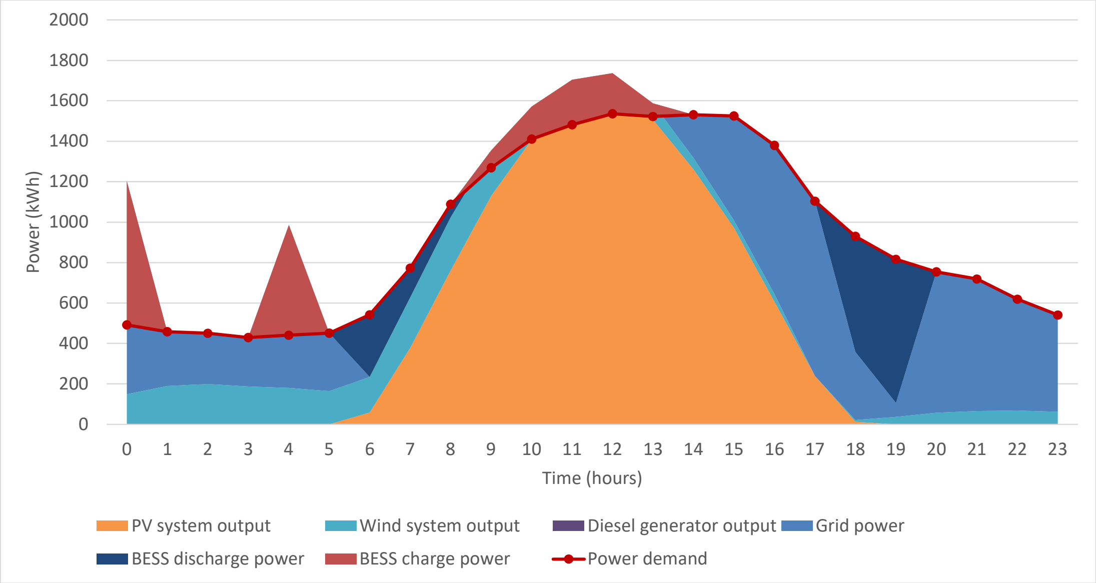

Figure 6.17: Model results of a single day for Scenario 6

The total cost calculated by the model is $R42\,430\,803$ for the entire project lifetime. Figure 6.18 represents the cost composition for Scenario 6 and consists of costs from all generation and storage technologies, as well as the grid.

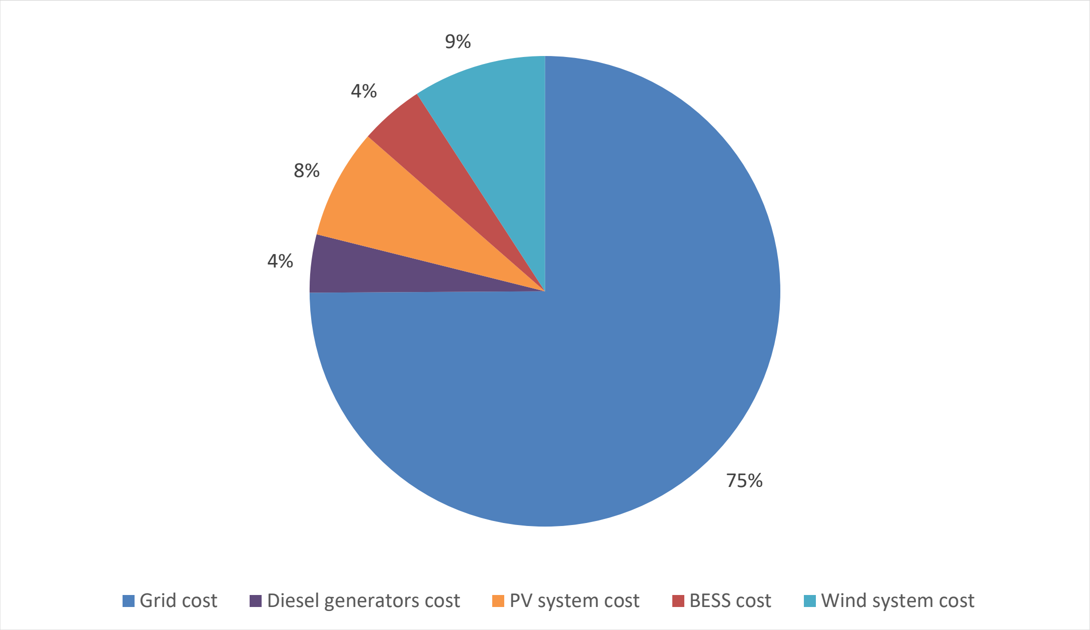

Figure 6.18: Cost composition for Scenario 6

6.4.3 Scenario 7: Grid exchange with load-shedding and technology limits

In this section, the aim is to consider a scenario that would represent a real-world situation. It is assumed that the microgrid has a grid connection and can import power from the grid. However, load-shedding is incorporated into this scenario to represent the current situation in South Africa, where load-shedding is frequently implemented by the electricity utility company, Eskom. It is assumed that load-shedding takes place during hours 7 to 8 and 18 to 19 and that no power can be imported from the grid during this time. For this study, it is also assumed that the load-shedding times are implemented during each day for the entire project lifetime. The number of units is limited by the values shown in Table 6.1. Limits are placed on the size of each technology to consider budget and space restrictions. The change in costs over time is considered by the model.

In this scenario, the model selects a combination of generation and storage technologies. As seen in Table 6.8, the maximum number of units allowed per technology is selected, except for the diesel generators. Only 4 diesel generators are purchased over the entire project duration. The additional diesel generators are utilised during the hours when load-shedding takes place and the other technologies cannot meet the demand.

Table 6.8: Number of technologies purchased and available for Scenario 7

Year	Diesel generators purchased	Diesel generators available	PV panels purchased	PV panels available	BESS purchased	BESS available	Wind turbines purchased	Wind turbines available
0	4	4	400	400	50	50	50	50
1	0	4	400	800	50	100	50	100
2	0	4	400	1200	50	150	50	150
3	0	4	400	1600	50	200	50	200
4	0	4	400	2000	50	250	50	250
5	0	4	400	2400	50	300	0	250
6	0	4	400	2800	50	350	0	250
7	0	4	400	3200	50	400	0	250
8	0	4	400	3600	0	400	0	250
9	0	4	400	4000	0	400	0	250
10	0	4	0	4000	0	400	0	250
11	0	4	0	4000	0	400	0	250
12	0	4	0	4000	0	400	0	250
13	0	4	0	4000	0	400	0	250
14	0	4	0	4000	0	400	0	250

Figure 6.19 shows the total power supplied by the generation technologies and the grid during each year while considering the load-shedding implemented by the utility company. The total amount of power used for BESS charging and discharging is also indicated per

year. The number of units purchased each year is also limited and it can be seen how the output from the PV system, the wind system and BESS grows over time. As a result, the amount of power generated by the diesel generators and grid decreases. The generation and storage technologies supply power during the times when load-shedding takes place.

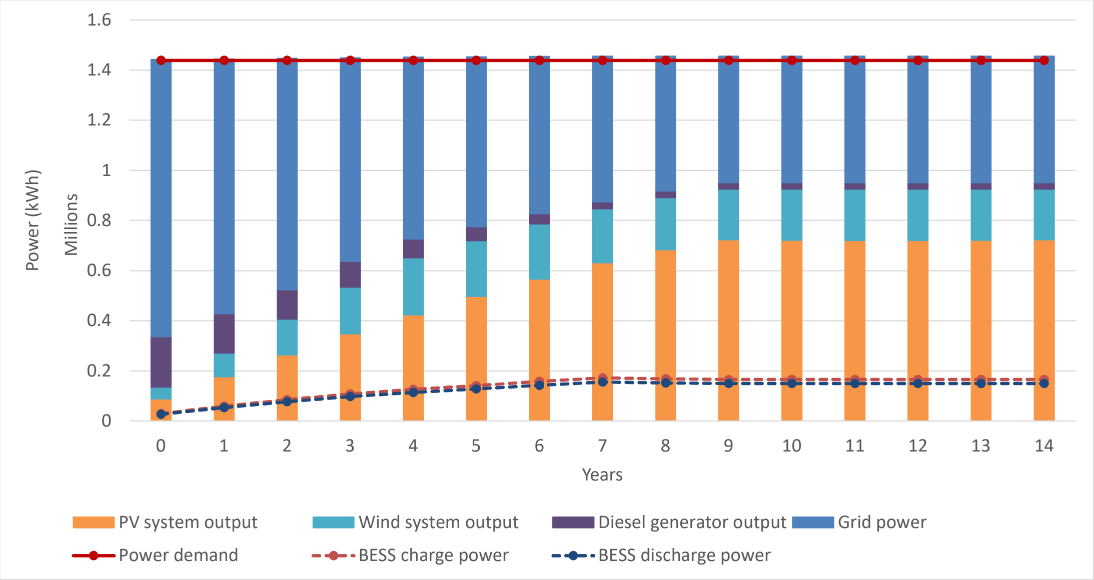

Figure 6.19: Model results of the entire project duration for Scenario 7

The model results presented in Figure 6.20 are used to show how the microgrid operates in a single day during the last year. It can be seen which technology, or combination of technologies, supplies power during each hour of the day. In this scenario, power is supplied by all generation technologies and the grid, to meet the demand. Surplus power from the PV panels and wind turbines is used for charging the BESS. Additional power is also purchased from the grid during hours 0 and 1, which is used for BESS charging. Load-shedding occurs during hours 7 to 8 and 18 to 19, and it is clear that the power is supplied by the PV system, and wind system and power is discharged from the BESS during hours 7 and 8. It can be seen that the diesel generators are utilised during hours 18 and 19 along with the other technologies.

The objective function value for Scenario 7 is equal to $R46\,678\,323$. In Figure 6.21, it can be seen how the total cost is divided between the grid and all of the technologies.

6.5 Results discussion

In Section 6.3, four scenarios were evaluated while assuming that all costs remain constant over the years. This was done to simplify the validation process. The total cost of each scenario is compared to the cost of supplying power only from the grid. The objective function value obtained for a grid-only scenario amounts to $R29\,340\,077$.

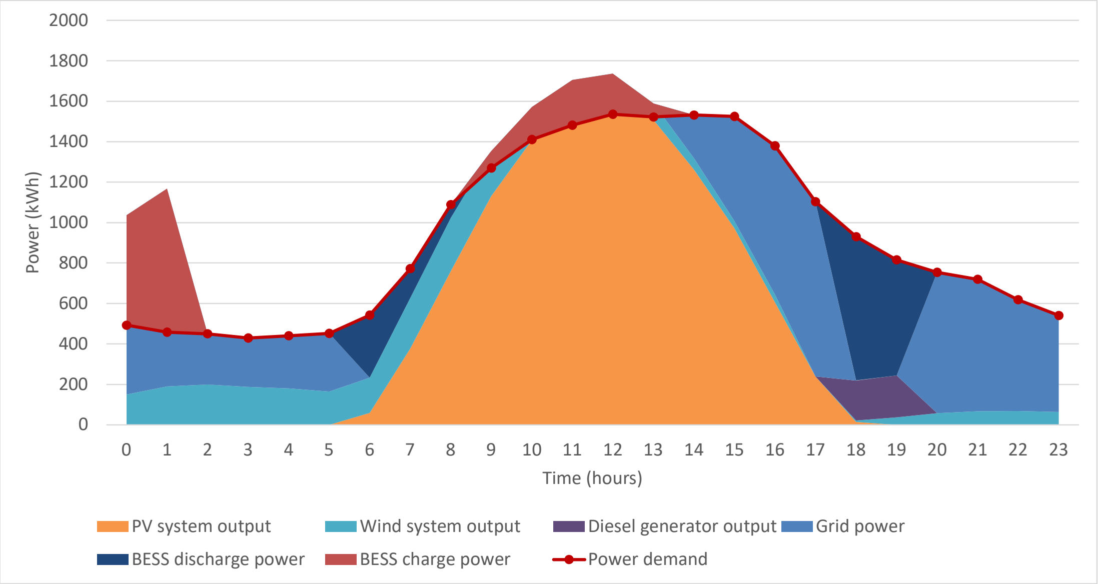

Figure 6.20: Model results of a single day for Scenario 7

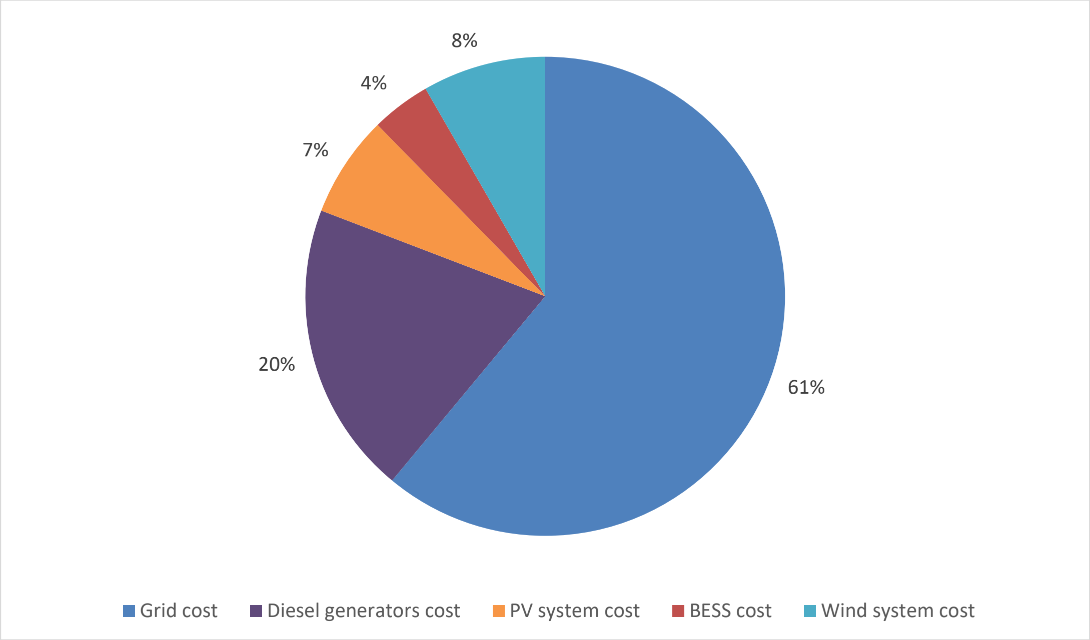

Figure 6.21: Cost composition for Scenario 7

In Scenario 1, it was assumed that the microgrid can obtain power from the grid and that the number of technologies is not restricted by any limits. Scenario 2 also considers the import of grid power, but the number of technologies allowed is limited. In Scenario 3, it was assumed that no grid exchange takes place and that no limits are placed on the technologies. Lastly, Scenario 4 also considers a microgrid with no grid connection and limits are placed on the size of the generation and storage units. In Table 6.9, the objective function value of each scenario is provided. The objective function values represent the total cost of energy over 15 years.

Table 6.9: Results of constant cost scenarios

Scenario	Objective function value
Grid	R29 340 077
Scenario 1	R18 519 163
Scenario 2	R22 856 349
Scenario 3	R40 971 548
Scenario 4	R70 689 600

From the results, it can be seen that the costs from Scenario 1 and Scenario 2 decreased by 37% and 22%, respectively. The percentages are obtained by comparing the scenarios to the grid-only scenario. The investment in a PV system and BESS is feasible and minimises the total energy cost. It should be noted that the PV system and BESS operate alongside the grid in both scenarios. The investment in diesel generators and wind turbines is very expensive and was not selected by the model. Scenarios 3 and 4 determine the optimal configuration of generation and storage units when no power can be imported from the grid. From Table 6.9, it can be seen how the total cost of Scenarios 3 and 4 exceeds the other scenarios. The PV system and BESS are not capable of meeting the total demand during all hours, therefore, the use of diesel generators and wind turbines is considered by the model.

In Section 6.4, the validation process was broadened by considering the effect of changing prices on the model results. Therefore, three additional scenarios were examined, which incorporate the change in grid and technology prices. These scenarios were selected to represent real-life scenarios as much as possible. When considering variable costs, the objective function value obtained for a grid-only scenario amounts to R93 067 528.

Scenario 5 considers exchange with the grid, and there are no technology limits. This allows the model to determine the optimal configuration for an energy microgrid without any restrictions. Scenario 6 considers a grid connection and enforces the specified technology limits. Finally, Scenario 7 represents a microgrid with a grid connection while incorporating load-shedding and the limits placed on the number of generation and storage units. Table 6.10 shows the total cost of each scenario over the entire project duration.

From the results shown in Table 6.10, it can be seen that the grid-only scenario yields an extremely high cost compared to Scenarios 5 to 7. The high cost is a result of the 15%

Table 6.10: Results of variable cost scenarios

Scenario	Objective function value
Grid	*R*93 067 528
Scenario 5	*R*29 658 153
Scenario 6	*R*42 430 803
Scenario 7	*R*46 678 323

increase in grid price each year. In Scenario 5, the model determines that the optimal microgrid configuration consists of grid power, a PV system and BESS. This scenario results in a 68% decrease compared to the grid scenario. Scenario 6 achieves a decrease of 54% and Scenario 7 a decrease of 50% in total costs. In Scenarios 6 and 7, the model adheres to the limits placed on the technologies, and it is determined that the maximum number of PV panels and BESS should be purchased. The model also determines that the total cost will also be minimised with the procurement of wind turbines and a small number of diesel generators.

From the results obtained in Chapter 6, it can be seen that the proposed model is capable of providing the optimal configuration of generation and storage technologies while minimising the total cost of an energy microgrid. The model determines the right time to invest, as well as the optimal number of units required by the microgrid, over a long-term period. This occurs while the daily operation of the microgrid system is considered and optimised by the model.

6.6 Chapter summary

In Chapter 6, the validation of the model was undertaken. The goal was to prove that the model can perform as intended while considering various microgrid scenarios. The model can provide results that are beneficial for the planning, investment and operation of a real microgrid. The impact of constant costs were evaluated in Section 6.3. An important part of this study is to determine the optimal configuration and investment time of technologies while considering a change in grid and technology prices. Different scenarios were examined while considering variable costs in Section 6.4. In Chapter 7, a study conclusion is provided, followed by a recommendation for future work.

Chapter 7

Conclusion and recommendations

7.1 Conclusion

In Chapter 1, the need for the study was justified through the background and rationale. Thereafter, the problem was described, followed by the research aim, objectives and methods. The research objectives and methods were set out to ensure the successful fulfilment of the project aim. As stated in Chapter 1, individuals and investors require a framework for the optimal planning and operation of a microgrid with alternative energy sources and storage. This study also aimed to address the need to assess the financial feasibility of the investment and to determine what the best investment time would be considering changing economic factors over the long-term period.

Chapter 2 was divided into two main sections. Section 2.2 provided an overview of the topics in this dissertation. Background on the traditional power grid was presented, followed by a detailed overview of the Smart Grid and how the evolution towards a smarter grid occurred. The building blocks of a smart grid, known as microgrids, were studied, and the main components and characteristics were identified. An overview of supplementary generation and storage technologies was provided, with a description of how they fit into a microgrid system. Furthermore, the field of mathematical programming and optimisation was researched to obtain knowledge on methods that can be applied to the problem. In Section 2.3, a literature review was undertaken to examine previous research on the topic of microgrid optimisation. This was carried out to get an understanding of what has been done and how the study should move forward by addressing possible gaps in the field.

The operations and investment modelling of an energy microgrid was addressed in Chapter 3 with the formulation of a single MILP model. This chapter aimed to design an optimisation model that considers a microgrid's operational and investment aspects while minimising the total cost. The model considered alternative electricity sources, storage options, and a grid connection. The technical, cost and constraint parameters were discussed, followed by a detailed section on the model's decision variables, objective function and constraints.

In Chapter 4, the input data required by the model parameters were discussed. To show that the model can be applied to large business parks, residential areas or campuses, data was obtained from the North-West University in Potchefstroom. The collected data was essential for the verification and validation of the proposed model. The model was critically assessed in Chapter 5. The goal was to prove that the model was developed and implemented correctly. This was achieved by testing each technology separately and ensuring that the model adheres to all constraints associated with that technology. From this chapter, it was evident that the model performed as expected in each scenario. Thus, proving that the model formulation and implementation were accurate.

In Chapter 6 the model was validated. The scenarios and data presented for the validation process aimed to replicate a real-world microgrid as much as possible. The first four scenarios examined a microgrid operating under constant cost values. The following scenarios considered changing economic factors. The change in grid and technology prices had a significant impact on the model results. From this chapter, it could be seen that the proposed model was able to minimise the total cost of an energy microgrid while addressing various investment and operational aspects of a microgrid, simultaneously.

The model provided the optimal mixture of generation and storage technologies over a long-term period, for each scenario. The final results presented the optimal number of units and the amount of power supplied by the technologies and grid. Changing economic factors were analysed and it was possible to determine the optimal investment time while considering these factors. It should also be noted that the model was able to solve various scenarios successfully. Therefore, it was determined that the model can be used for the planning and investment of real-world microgrid scenarios, from university campuses and business parks to residential areas.

In conclusion, the problem formulated in Chapter 1 was addressed by the proposed MILP model, the model can minimise the total energy cost over a long-term horizon while considering changing economic factors. The model provides individuals with a framework for the investment and operation of a microgrid and shows the financial viability of different generation and storage options. It is evident that the objectives as specified in Chapter 1, were addressed by the content of the chapters in this dissertation. The recommendations for future work are discussed in Section 7.2.

7.2 Recommendations for future work

The following aspects were identified for future research and improvements in the field of microgrid optimisation:

- The physical validation of the model to evaluate the accuracy against a real-world implementation.

- To simplify this study, the model only considers the daily operation of technologies. Therefore, the energy states of the previous day are not transferred to the next day. In other words, the proposed model considers the energy storage and operations of the BESS for each day separately. The battery returns to its initial state or minimum limit by the end of each day. To ensure more accurate modelling of a microgrid system, the transfer of energy states from the previous days to the following should be investigated. It is important to note that these changes should be implemented before the physical validation of the model can take place.
- Consider a scenario for model validation where different levels of load-shedding are incorporated.
- Expand the model to consider more variants of a certain technology. This can be done to evaluate different sizing options while considering the cost, capacity and other technical factors of each alternative.
- Improvements can be made to provide a more accurate PV model in terms of output and costs. Changes to panel performance as a result of changes in panel temperature should be investigated, along with factors such as panel orientation and angle of incidence.
- As previously mentioned, the model considers a microgrid system consisting of diesel generators, a PV system, wind turbines, a BESS and a connection to the grid. The model can be broadened by including other alternative energy sources. This study also focuses on microgrid adoption for large business parks, residential estates and university campuses. It is assumed that industrial organisations have other energy requirements, it is, however, an area that can be considered for future work.

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Appendix A

Results extract

A.1 Validation: Scenario 7

An extract of the results obtained during the validation of the proposed model is presented in this appendix. The extract contains the results from Scenario 7 in Chapter 6, Section 6.4, and shows data from the first few days during year 0. All of the results from the verification and validation scenarios are obtained and presented similarly.

Year	Day	Hour	Demand	Grid prices	Grid import	Diesel generator	Number Diesel Purchased	Number Diesel Total	PV system	Number PV Purchased	Number PV Total	Battery power	Battery charge power	Negative charge power	Battery discharge power	Battery charge binary	Battery discharge binary	Number BESS Purchased	Number BESS Total	Wind turbine	Number Wind Purchased	Number Wind Total
0	0	0	439.14	0.83	413.23	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	25.91	50	50
0	0	1	426.21	0.83	396.85	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	29.36	50	50
0	0	2	421.87	0.83	387.03	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	34.84	50	50
0	0	3	415.36	0.83	379.73	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	35.63	50	50
0	0	4	413.90	0.83	469.19	0.00	4	4	0.00	400	400	93.24	88.78	-88.78	0.00	1	0	50	50	33.49	50	50
0	0	5	420.49	0.83	475.69	0.00	4	4	1.47	400	400	177.60	88.80	-88.80	0.00	1	0	50	50	32.14	50	50
0	0	6	514.23	1.14	448.01	0.00	4	4	22.42	400	400	177.60	0.00	0.00	0.00	1	0	50	50	43.80	50	50
0	0	7	715.35	1.88	0.00	518.26	4	4	55.53	400	400	84.13	0.00	0.00	88.80	0	1	50	50	52.76	50	50
0	0	8	1064.71	1.88	0.00	849.95	4	4	90.62	400	400	8.90	0.00	0.00	71.47	0	1	50	50	52.69	50	50
0	0	9	1247.45	1.88	1083.02	0.00	4	4	119.17	400	400	8.90	0.00	0.00	0.00	0	1	50	50	45.26	50	50
0	0	10	1318.73	1.14	1133.68	0.00	4	4	146.20	400	400	8.90	0.00	0.00	0.00	1	0	50	50	38.85	50	50
0	0	11	1370.31	1.14	1177.27	0.00	4	4	160.08	400	400	8.90	0.00	0.00	0.00	1	0	50	50	32.96	50	50
0	0	12	1457.73	1.14	1270.05	0.00	4	4	160.11	400	400	8.90	0.00	0.00	0.00	1	0	50	50	27.56	50	50
0	0	13	1470.90	1.14	1293.89	0.00	4	4	154.54	400	400	8.90	0.00	0.00	0.00	1	0	50	50	22.46	50	50
0	0	14	1439.53	1.14	1284.87	0.00	4	4	137.57	400	400	8.90	0.00	0.00	0.00	1	0	50	50	17.10	50	50
0	0	15	1447.22	1.14	1323.09	0.00	4	4	111.98	400	400	8.90	0.00	0.00	0.00	1	0	50	50	12.15	50	50
0	0	16	1352.81	1.14	1353.13	0.00	4	4	78.19	400	400	93.24	88.78	-88.78	0.00	1	0	50	50	10.28	50	50
0	0	17	1042.53	1.14	1072.86	0.00	4	4	43.32	400	400	177.60	88.80	-88.80	0.00	1	0	50	50	15.15	50	50
0	0	18	858.81	1.88	0.00	743.97	4	4	11.45	400	400	84.13	0.00	0.00	88.80	0	1	50	50	14.59	50	50
0	0	19	710.94	1.88	0.00	617.88	4	4	0.00	400	400	8.90	0.00	0.00	71.47	0	1	50	50	21.60	50	50
0	0	20	675.38	1.14	646.51	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	28.88	50	50
0	0	21	631.98	1.14	603.03	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	28.95	50	50
0	0	22	563.20	0.83	534.70	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	28.50	50	50
0	0	23	525.54	0.83	499.70	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	25.84	50	50
0	1	0	413.74	0.83	389.47	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	24.27	50	50
0	1	1	431.40	0.83	407.52	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	23.88	50	50
0	1	2	422.97	0.83	400.65	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	22.32	50	50
0	1	3	421.85	0.83	399.53	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	22.32	50	50
0	1	4	416.23	0.83	483.32	0.00	4	4	0.00	400	400	93.24	88.78	-88.78	0.00	1	0	50	50	21.69	50	50
0	1	5	423.43	0.83	487.05	0.00	4	4	1.57	400	400	177.60	88.80	-88.80	0.00	1	0	50	50	23.61	50	50
0	1	6	499.19	1.14	439.59	0.00	4	4	22.40	400	400	177.60	0.00	0.00	0.00	1	0	50	50	37.20	50	50
0	1	7	636.00	1.88	0.00	451.31	4	4	55.51	400	400	84.13	0.00	0.00	88.80	0	1	50	50	40.38	50	50
0	1	8	864.45	1.88	0.00	663.88	4	4	89.24	400	400	8.90	0.00	0.00	71.47	0	1	50	50	39.87	50	50
0	1	9	1036.58	1.88	883.95	0.00	4	4	114.38	400	400	8.90	0.00	0.00	0.00	0	1	50	50	38.25	50	50
0	1	10	1091.82	1.14	916.95	0.00	4	4	137.84	400	400	8.90	0.00	0.00	0.00	1	0	50	50	37.02	50	50
0	1	11	1140.29	1.14	961.51	0.00	4	4	143.65	400	400	8.90	0.00	0.00	0.00	1	0	50	50	35.13	50	50
0	1	12	1180.55	1.14	997.50	0.00	4	4	149.87	400	400	8.90	0.00	0.00	0.00	1	0	50	50	33.18	50	50
0	1	13	1179.78	1.14	1000.65	0.00	4	4	147.90	400	400	8.90	0.00	0.00	0.00	1	0	50	50	31.23	50	50
0	1	14	1184.85	1.14	1028.74	0.00	4	4	127.58	400	400	8.90	0.00	0.00	0.00	1	0	50	50	28.53	50	50
0	1	15	1163.52	1.14	1037.88	0.00	4	4	100.35	400	400	8.90	0.00	0.00	0.00	1	0	50	50	25.29	50	50
0	1	16	1085.58	1.14	1083.19	0.00	4	4	69.87	400	400	93.24	88.78	-88.78	0.00	1	0	50	50	21.30	50	50
0	1	17	886.61	1.14	929.18	0.00	4	4	34.61	400	400	177.60	88.80	-88.80	0.00	1	0	50	50	11.61	50	50
0	1	18	742.93	1.88	0.00	645.85	4	4	8.28	400	400	84.13	0.00	0.00	88.80	0	1	50	50	0.00	50	50
0	1	19	644.44	1.88	0.00	572.97	4	4	0.00	400	400	8.90	0.00	0.00	71.47	0	1	50	50	0.00	50	50
0	1	20	610.04	1.14	610.04	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	0.00	50	50
0	1	21	566.34	1.14	566.34	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	0.00	50	50
0	1	22	503.10	0.83	495.57	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	7.53	50	50
0	1	23	468.74	0.83	460.52	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	8.22	50	50
0	2	0	439.71	0.83	432.54	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	7.17	50	50
0	2	1	424.13	0.83	417.95	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	6.18	50	50
0	2	2	412.31	0.83	406.46	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	5.85	50	50
0	2	3	414.41	0.83	407.51	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	6.90	50	50
0	2	4	409.21	0.83	492.04	0.00	4	4	0.00	400	400	93.24	88.78	-88.78	0.00	1	0	50	50	5.94	50	50
0	2	5	410.41	0.83	491.60	0.00	4	4	1.67	400	400	177.60	88.80	-88.80	0.00	1	0	50	50	5.94	50	50
0	2	6	502.71	1.14	463.83	0.00	4	4	23.04	400	400	177.60	0.00	0.00	0.00	1	0	50	50	15.84	50	50
0	2	7	661.40	1.88	0.00	502.04	4	4	54.09	400	400	84.13	0.00	0.00	88.80	0	1	50	50	16.47	50	50

0	2	8	910.08	1.88	0.00	730.02	4	4	92.66	400	400	8.90	0.00	0.00	71.47	0	1	50	50	15.93	50	50
0	2	9	1087.16	1.88	944.63	0.00	4	4	130.11	400	400	8.90	0.00	0.00	0.00	0	1	50	50	12.42	50	50
0	2	10	1173.71	1.14	1007.56	0.00	4	4	153.19	400	400	8.90	0.00	0.00	0.00	1	0	50	50	12.96	50	50
0	2	11	1249.14	1.14	1066.30	0.00	4	4	168.44	400	400	8.90	0.00	0.00	0.00	1	0	50	50	14.40	50	50
0	2	12	1293.01	1.14	1106.28	0.00	4	4	171.94	400	400	8.90	0.00	0.00	0.00	1	0	50	50	14.79	50	50
0	2	13	1287.44	1.14	1112.03	0.00	4	4	159.93	400	400	8.90	0.00	0.00	0.00	1	0	50	50	15.48	50	50
0	2	14	1316.18	1.14	1153.44	0.00	4	4	146.18	400	400	8.90	0.00	0.00	0.00	1	0	50	50	16.56	50	50
0	2	15	1327.21	1.14	1192.95	0.00	4	4	116.86	400	400	8.90	0.00	0.00	0.00	1	0	50	50	17.40	50	50
0	2	16	1221.78	1.14	1213.14	0.00	4	4	79.09	400	400	93.24	88.78	-88.78	0.00	1	0	50	50	18.33	50	50
0	2	17	975.57	1.14	1002.02	0.00	4	4	42.64	400	400	177.60	88.80	-88.80	0.00	1	0	50	50	19.71	50	50
0	2	18	804.07	1.88	0.00	694.64	4	4	11.21	400	400	84.13	0.00	0.00	88.80	0	1	50	50	9.42	50	50
0	2	19	691.28	1.88	0.00	604.42	4	4	0.00	400	400	8.90	0.00	0.00	71.47	0	1	50	50	15.39	50	50
0	2	20	637.82	1.14	616.94	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	20.88	50	50
0	2	21	594.09	1.14	570.78	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	23.31	50	50
0	2	22	527.40	0.83	502.62	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	24.78	50	50
0	2	23	505.22	0.83	483.14	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	22.08	50	50
0	3	0	471.30	0.83	451.29	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	20.01	50	50
0	3	1	452.63	0.83	431.09	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	21.54	50	50
0	3	2	438.91	0.83	414.85	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	24.06	50	50
0	3	3	433.60	0.83	407.71	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	25.89	50	50
0	3	4	429.56	0.83	489.78	0.00	4	4	0.00	400	400	93.24	88.78	-88.78	0.00	1	0	50	50	28.56	50	50
0	3	5	425.54	0.83	482.76	0.00	4	4	1.49	400	400	177.60	88.80	-88.80	0.00	1	0	50	50	30.09	50	50
0	3	6	523.63	1.14	461.64	0.00	4	4	21.61	400	400	177.60	0.00	0.00	0.00	1	0	50	50	40.38	50	50
0	3	7	681.54	1.88	0.00	490.15	4	4	58.04	400	400	84.13	0.00	0.00	88.80	0	1	50	50	44.55	50	50
0	3	8	982.66	1.88	0.00	768.23	4	4	97.91	400	400	8.90	0.00	0.00	71.47	0	1	50	50	45.06	50	50
0	3	9	1146.15	1.88	975.41	0.00	4	4	134.56	400	400	8.90	0.00	0.00	0.00	0	1	50	50	36.18	50	50
0	3	10	1243.60	1.14	1053.43	0.00	4	4	160.77	400	400	8.90	0.00	0.00	0.00	1	0	50	50	29.40	50	50
0	3	11	1317.48	1.14	1119.26	0.00	4	4	169.74	400	400	8.90	0.00	0.00	0.00	1	0	50	50	28.47	50	50
0	3	12	1374.49	1.14	1176.24	0.00	4	4	171.57	400	400	8.90	0.00	0.00	0.00	1	0	50	50	26.67	50	50
0	3	13	1363.90	1.14	1180.49	0.00	4	4	158.72	400	400	8.90	0.00	0.00	0.00	1	0	50	50	24.69	50	50
0	3	14	1336.38	1.14	1179.39	0.00	4	4	133.29	400	400	8.90	0.00	0.00	0.00	1	0	50	50	23.70	50	50
0	3	15	1266.74	1.14	1134.41	0.00	4	4	109.71	400	400	8.90	0.00	0.00	0.00	1	0	50	50	22.62	50	50
0	3	16	1129.19	1.14	1135.38	0.00	4	4	61.68	400	400	93.24	88.78	-88.78	0.00	1	0	50	50	20.91	50	50
0	3	17	858.86	1.14	902.14	0.00	4	4	29.71	400	400	177.60	88.80	-88.80	0.00	1	0	50	50	15.81	50	50
0	3	18	720.70	1.88	0.00	622.63	4	4	7.17	400	400	84.13	0.00	0.00	88.80	0	1	50	50	2.10	50	50
0	3	19	652.17	1.88	0.00	575.33	4	4	0.00	400	400	8.90	0.00	0.00	71.47	0	1	50	50	5.37	50	50
0	3	20	618.19	1.14	605.02	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	13.17	50	50
0	3	21	582.87	1.14	564.18	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	18.69	50	50
0	3	22	538.81	0.83	515.29	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	23.52	50	50
0	3	23	503.87	0.83	480.95	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	22.92	50	50
0	4	0	460.61	0.83	433.58	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	27.04	50	50
0	4	1	453.55	0.83	429.89	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	23.66	50	50
0	4	2	435.15	0.83	411.30	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	23.85	50	50
0	4	3	420.60	0.83	393.75	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	26.85	50	50
0	4	4	414.79	0.83	473.26	0.00	4	4	0.00	400	400	93.24	88.78	-88.78	0.00	1	0	50	50	30.30	50	50
0	4	5	419.57	0.83	474.79	0.00	4	4	1.55	400	400	177.60	88.80	-88.80	0.00	1	0	50	50	32.03	50	50
0	4	6	510.37	1.14	439.43	0.00	4	4	23.17	400	400	177.60	0.00	0.00	0.00	1	0	50	50	47.78	50	50
0	4	7	663.11	1.88	0.00	455.37	4	4	57.36	400	400	84.13	0.00	0.00	88.80	0	1	50	50	61.58	50	50
0	4	8	933.65	1.88	0.00	701.64	4	4	96.68	400	400	8.90	0.00	0.00	71.47	0	1	50	50	63.86	50	50
0	4	9	1115.61	1.88	920.54	0.00	4	4	135.33	400	400	8.90	0.00	0.00	0.00	0	1	50	50	59.74	50	50
0	4	10	1242.75	1.14	1018.22	0.00	4	4	167.42	400	400	8.90	0.00	0.00	0.00	1	0	50	50	57.11	50	50
0	4	11	1320.82	1.14	1086.51	0.00	4	4	177.61	400	400	8.90	0.00	0.00	0.00	1	0	50	50	56.70	50	50
0	4	12	1340.68	1.14	1104.32	0.00	4	4	180.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	56.36	50	50
0	4	13	1314.61	1.14	1085.31	0.00	4	4	173.87	400	400	8.90	0.00	0.00	0.00	1	0	50	50	55.43	50	50
0	4	14	1273.55	1.14	1064.60	0.00	4	4	155.77	400	400	8.90	0.00	0.00	0.00	1	0	50	50	53.18	50	50
0	4	15	1285.29	1.14	1116.39	0.00	4	4	118.54	400	400	8.90	0.00	0.00	0.00	1	0	50	50	50.36	50	50
0	4	16	1110.76	1.14	1080.35	0.00	4	4	72.96	400	400	93.24	88.78	-88.78	0.00	1	0	50	50	46.24	50	50
0	4	17	882.15	1.14	898.29	0.00	4	4	34.71	400	400	177.60	88.80	-88.80	0.00	1	0	50	50	37.95	50	50
0	4	18	749.01	1.88	0.00	642.54	4	4	8.89	400	400	84.13	0.00	0.00	88.80	0	1	50	50	8.78	50	50
0	4	19	644.73	1.88	0.00	562.72	4	4	0.00	400	400	8.90	0.00	0.00	71.47	0	1	50	50	10.54	50	50

0	4	20	604.51	1.14	588.54	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	15.98	50	50
0	4	21	564.23	1.14	541.66	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	22.58	50	50
0	4	22	500.06	0.83	472.65	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	27.41	50	50
0	4	23	463.36	0.83	433.17	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	30.19	50	50
0	5	0	451.68	0.83	421.64	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	30.04	50	50
0	5	1	433.06	0.83	409.14	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	23.93	50	50
0	5	2	421.23	0.83	397.16	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	24.08	50	50
0	5	3	416.49	0.83	388.97	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	27.53	50	50
0	5	4	414.09	0.83	385.33	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	28.76	50	50
0	5	5	428.62	0.83	484.74	0.00	4	4	1.65	400	400	93.24	88.78	-88.78	0.00	1	0	50	50	31.01	50	50
0	5	6	471.25	0.83	493.83	0.00	4	4	23.10	400	400	177.60	88.80	-88.80	0.00	1	0	50	50	43.13	50	50
0	5	7	498.22	1.14	0.00	295.95	4	4	58.20	400	400	84.13	0.00	0.00	88.80	0	1	50	50	55.28	50	50
0	5	8	619.41	1.14	0.00	391.46	4	4	95.84	400	400	8.90	0.00	0.00	71.47	0	1	50	50	60.64	50	50
0	5	9	736.91	1.14	566.32	0.00	4	4	122.14	400	400	8.90	0.00	0.00	0.00	0	1	50	50	48.45	50	50
0	5	10	819.55	1.14	608.54	0.00	4	4	160.27	400	400	8.90	0.00	0.00	0.00	0	1	50	50	50.74	50	50
0	5	11	876.53	1.14	645.47	0.00	4	4	176.76	400	400	8.90	0.00	0.00	0.00	0	1	50	50	54.30	50	50
0	5	12	880.15	0.83	643.34	0.00	4	4	180.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	56.81	50	50
0	5	13	797.56	0.83	566.59	0.00	4	4	175.32	400	400	8.90	0.00	0.00	0.00	1	0	50	50	55.65	50	50
0	5	14	730.04	0.83	526.03	0.00	4	4	150.76	400	400	8.90	0.00	0.00	0.00	1	0	50	50	53.25	50	50
0	5	15	716.26	0.83	543.97	0.00	4	4	120.70	400	400	8.90	0.00	0.00	0.00	1	0	50	50	51.60	50	50
0	5	16	724.16	0.83	684.53	0.00	4	4	79.39	400	400	93.24	88.78	-88.78	0.00	1	0	50	50	49.01	50	50
0	5	17	690.76	0.83	700.44	0.00	4	4	42.38	400	400	177.60	88.80	-88.80	0.00	1	0	50	50	36.75	50	50
0	5	18	641.48	1.14	0.00	529.29	4	4	9.07	400	400	84.13	0.00	0.00	88.80	0	1	50	50	14.33	50	50
0	5	19	597.38	1.14	0.00	513.73	4	4	0.00	400	400	8.90	0.00	0.00	71.47	0	1	50	50	12.19	50	50
0	5	20	580.25	0.83	565.33	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	14.93	50	50
0	5	21	527.65	0.83	510.14	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	17.51	50	50
0	5	22	496.01	0.83	474.07	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	21.94	50	50
0	5	23	475.90	0.83	453.21	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	22.69	50	50
0	6	0	440.88	0.83	508.06	0.00	4	4	0.00	400	400	93.24	88.78	-88.78	0.00	1	0	50	50	21.60	50	50
0	6	1	428.47	0.83	491.39	0.00	4	4	0.00	400	400	177.60	88.80	-88.80	0.00	1	0	50	50	25.88	50	50
0	6	2	419.36	0.83	390.30	0.00	4	4	0.00	400	400	177.60	0.00	0.00	0.00	1	0	50	50	29.06	50	50
0	6	3	415.36	0.83	384.99	0.00	4	4	0.00	400	400	177.60	0.00	0.00	0.00	1	0	50	50	30.38	50	50
0	6	4	412.58	0.83	382.73	0.00	4	4	0.00	400	400	177.60	0.00	0.00	0.00	1	0	50	50	29.85	50	50
0	6	5	406.44	0.83	374.66	0.00	4	4	1.58	400	400	177.60	0.00	0.00	0.00	1	0	50	50	30.19	50	50
0	6	6	415.14	0.83	352.87	0.00	4	4	23.87	400	400	177.60	0.00	0.00	0.00	1	0	50	50	38.40	50	50
0	6	7	421.16	0.83	0.00	232.09	4	4	62.17	400	400	84.13	0.00	0.00	88.80	0	1	50	50	38.10	50	50
0	6	8	445.70	0.83	0.00	238.84	4	4	104.13	400	400	8.90	0.00	0.00	71.47	0	1	50	50	31.28	50	50
0	6	9	484.70	0.83	414.53	0.00	4	4	139.59	400	400	93.26	88.80	-88.80	0.00	1	0	50	50	19.39	50	50
0	6	10	528.54	0.83	433.15	0.00	4	4	163.10	400	400	177.60	88.78	-88.78	0.00	1	0	50	50	21.08	50	50
0	6	11	555.54	0.83	362.06	0.00	4	4	171.40	400	400	177.60	0.00	0.00	0.00	1	0	50	50	22.09	50	50
0	6	12	570.29	0.83	382.28	0.00	4	4	166.59	400	400	177.60	0.00	0.00	0.00	1	0	50	50	21.41	50	50
0	6	13	558.82	0.83	377.92	0.00	4	4	160.01	400	400	177.60	0.00	0.00	0.00	1	0	50	50	20.89	50	50
0	6	14	538.76	0.83	378.83	0.00	4	4	139.46	400	400	177.60	0.00	0.00	0.00	1	0	50	50	20.48	50	50
0	6	15	562.08	0.83	432.11	0.00	4	4	109.72	400	400	177.60	0.00	0.00	0.00	1	0	50	50	20.25	50	50
0	6	16	577.39	0.83	487.24	0.00	4	4	70.58	400	400	177.60	0.00	0.00	0.00	1	0	50	50	19.58	50	50
0	6	17	540.66	0.83	487.83	0.00	4	4	36.06	400	400	177.60	0.00	0.00	0.00	1	0	50	50	16.76	50	50
0	6	18	519.94	0.83	0.00	418.19	4	4	9.09	400	400	84.13	0.00	0.00	88.80	0	1	50	50	3.86	50	50
0	6	19	493.94	0.83	0.00	416.40	4	4	0.00	400	400	8.90	0.00	0.00	71.47	0	1	50	50	6.08	50	50
0	6	20	487.95	0.83	477.12	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	10.84	50	50
0	6	21	477.83	0.83	463.58	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	14.25	50	50
0	6	22	471.22	0.83	454.15	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	17.06	50	50
0	6	23	467.84	0.83	446.05	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	21.79	50	50
0	7	0	469.27	0.83	459.78	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	9.49	50	50
0	7	1	448.85	0.83	441.65	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	7.20	50	50
0	7	2	432.52	0.83	427.31	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	5.21	50	50
0	7	3	423.16	0.83	421.43	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	1.73	50	50
0	7	4	406.94	0.83	494.93	0.00	4	4	0.00	400	400	93.24	88.78	-88.78	0.00	1	0	50	50	0.79	50	50
0	7	5	411.46	0.83	498.87	0.00	4	4	0.00	400	400	177.60	88.80	-88.80	0.00	1	0	50	50	1.39	50	50
0	7	6	519.22	1.14	496.45	0.00	4	4	12.26	400	400	177.60	0.00	0.00	0.00	1	0	50	50	10.50	50	50
0	7	7	764.86	1.88	0.00	617.40	4	4	46.51	400	400	84.13	0.00	0.00	88.80	0	1	50	50	12.15	50	50

0	7	8	1117.03	1.88	0.00	956.77	4	4	78.03	400	400	8.90	0.00	0.00	71.47	0	1	50	50	10.76	50	50
0	7	9	1299.14	1.88	1187.55	0.00	4	4	103.12	400	400	8.90	0.00	0.00	0.00	0	1	50	50	8.48	50	50
0	7	10	1369.87	1.14	1220.58	0.00	4	4	132.90	400	400	8.90	0.00	0.00	0.00	1	0	50	50	16.39	50	50
0	7	11	1365.66	1.14	1183.52	0.00	4	4	160.62	400	400	8.90	0.00	0.00	0.00	1	0	50	50	21.53	50	50
0	7	12	1465.53	1.14	1271.11	0.00	4	4	170.24	400	400	8.90	0.00	0.00	0.00	1	0	50	50	24.19	50	50
0	7	13	1318.32	1.14	1128.21	0.00	4	4	164.61	400	400	8.90	0.00	0.00	0.00	1	0	50	50	25.50	50	50
0	7	14	1349.75	1.14	1195.48	0.00	4	4	129.06	400	400	8.90	0.00	0.00	0.00	1	0	50	50	25.20	50	50
0	7	15	1430.62	1.14	1307.15	0.00	4	4	99.74	400	400	8.90	0.00	0.00	0.00	1	0	50	50	23.74	50	50
0	7	16	1264.20	1.14	1266.72	0.00	4	4	65.22	400	400	93.24	88.78	-88.78	0.00	1	0	50	50	21.04	50	50
0	7	17	1070.41	1.14	1116.68	0.00	4	4	30.76	400	400	177.60	88.80	-88.80	0.00	1	0	50	50	11.78	50	50
0	7	18	907.53	1.88	0.00	812.88	4	4	5.85	400	400	84.13	0.00	0.00	88.80	0	1	50	50	0.00	50	50
0	7	19	804.40	1.88	0.00	731.36	4	4	0.00	400	400	8.90	0.00	0.00	71.47	0	1	50	50	1.58	50	50
0	7	20	770.60	1.14	768.39	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	2.21	50	50
0	7	21	705.65	1.14	704.19	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	1.46	50	50
0	7	22	583.59	0.83	582.76	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	0.82	50	50
0	7	23	521.83	0.83	519.88	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	1.95	50	50
0	8	0	488.96	0.83	484.61	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	4.35	50	50
0	8	1	452.66	0.83	448.16	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	4.50	50	50
0	8	2	431.06	0.83	431.02	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	0.04	50	50
0	8	3	425.98	0.83	422.80	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	3.19	50	50
0	8	4	423.94	0.83	501.77	0.00	4	4	0.00	400	400	93.24	88.78	-88.78	0.00	1	0	50	50	10.95	50	50
0	8	5	414.92	0.83	485.12	0.00	4	4	0.00	400	400	177.60	88.80	-88.80	0.00	1	0	50	50	18.60	50	50
0	8	6	513.97	1.14	473.47	0.00	4	4	10.06	400	400	177.60	0.00	0.00	0.00	1	0	50	50	30.45	50	50
0	8	7	772.89	1.88	0.00	611.03	4	4	40.99	400	400	84.13	0.00	0.00	88.80	0	1	50	50	32.06	50	50
0	8	8	1117.23	1.88	0.00	933.19	4	4	77.36	400	400	8.90	0.00	0.00	71.47	0	1	50	50	35.21	50	50
0	8	9	1264.63	1.88	1130.18	0.00	4	4	106.86	400	400	8.90	0.00	0.00	0.00	0	1	50	50	27.60	50	50
0	8	10	1394.59	1.14	1238.51	0.00	4	4	135.34	400	400	8.90	0.00	0.00	0.00	1	0	50	50	20.74	50	50
0	8	11	1439.45	1.14	1269.30	0.00	4	4	151.54	400	400	8.90	0.00	0.00	0.00	1	0	50	50	18.60	50	50
0	8	12	1506.40	1.14	1333.58	0.00	4	4	151.14	400	400	8.90	0.00	0.00	0.00	1	0	50	50	21.68	50	50
0	8	13	1517.88	1.14	1347.63	0.00	4	4	146.17	400	400	8.90	0.00	0.00	0.00	1	0	50	50	24.08	50	50
0	8	14	1483.11	1.14	1326.52	0.00	4	4	132.48	400	400	8.90	0.00	0.00	0.00	1	0	50	50	24.11	50	50
0	8	15	1511.38	1.14	1391.70	0.00	4	4	98.09	400	400	8.90	0.00	0.00	0.00	1	0	50	50	21.60	50	50
0	8	16	1390.46	1.14	1397.74	0.00	4	4	62.87	400	400	93.24	88.78	-88.78	0.00	1	0	50	50	18.64	50	50
0	8	17	1127.76	1.14	1174.67	0.00	4	4	32.36	400	400	177.60	88.80	-88.80	0.00	1	0	50	50	9.53	50	50
0	8	18	951.32	1.88	0.00	856.31	4	4	6.21	400	400	84.13	0.00	0.00	88.80	0	1	50	50	0.00	50	50
0	8	19	840.96	1.88	0.00	769.49	4	4	0.00	400	400	8.90	0.00	0.00	71.47	0	1	50	50	0.00	50	50
0	8	20	770.89	1.14	770.89	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	0.00	50	50
0	8	21	696.59	1.14	694.42	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	2.18	50	50
0	8	22	603.17	0.83	598.59	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	4.58	50	50
0	8	23	522.92	0.83	515.60	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	7.31	50	50
0	9	0	492.46	0.83	483.01	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	9.45	50	50
0	9	1	456.61	0.83	445.74	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	10.88	50	50
0	9	2	436.74	0.83	424.03	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	12.71	50	50
0	9	3	429.70	0.83	415.56	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	14.14	50	50
0	9	4	421.80	0.83	495.73	0.00	4	4	0.00	400	400	93.24	88.78	-88.78	0.00	1	0	50	50	14.85	50	50
0	9	5	423.55	0.83	494.95	0.00	4	4	0.00	400	400	177.60	88.80	-88.80	0.00	1	0	50	50	17.40	50	50
0	9	6	526.62	1.14	484.33	0.00	4	4	11.65	400	400	177.60	0.00	0.00	0.00	1	0	50	50	30.64	50	50
0	9	7	793.43	1.88	0.00	624.97	4	4	45.98	400	400	84.13	0.00	0.00	88.80	0	1	50	50	33.68	50	50
0	9	8	1127.74	1.88	0.00	938.48	4	4	86.21	400	400	8.90	0.00	0.00	71.47	0	1	50	50	31.58	50	50
0	9	9	1290.54	1.88	1140.96	0.00	4	4	119.12	400	400	8.90	0.00	0.00	0.00	0	1	50	50	30.45	50	50
0	9	10	1441.18	1.14	1269.00	0.00	4	4	143.80	400	400	8.90	0.00	0.00	0.00	1	0	50	50	28.39	50	50
0	9	11	1515.93	1.14	1328.18	0.00	4	4	160.18	400	400	8.90	0.00	0.00	0.00	1	0	50	50	27.56	50	50
0	9	12	1483.65	1.14	1303.68	0.00	4	4	153.23	400	400	8.90	0.00	0.00	0.00	1	0	50	50	26.74	50	50
0	9	13	1358.81	1.14	1191.42	0.00	4	4	141.66	400	400	8.90	0.00	0.00	0.00	1	0	50	50	25.73	50	50
0	9	14	1461.60	1.14	1319.63	0.00	4	4	116.92	400	400	8.90	0.00	0.00	0.00	1	0	50	50	25.05	50	50
0	9	15	1474.05	1.14	1358.26	0.00	4	4	91.90	400	400	8.90	0.00	0.00	0.00	1	0	50	50	23.89	50	50
0	9	16	1355.89	1.14	1358.78	0.00	4	4	64.41	400	400	93.24	88.78	-88.78	0.00	1	0	50	50	21.49	50	50
0	9	17	1179.75	1.14	1227.34	0.00	4	4	32.32	400	400	177.60	88.80	-88.80	0.00	1	0	50	50	8.89	50	50
0	9	18	983.48	1.88	0.00	888.52	4	4	5.45	400	400	84.13	0.00	0.00	88.80	0	1	50	50	0.71	50	50
0	9	19	844.46	1.88	0.00	770.14	4	4	0.00	400	400	8.90	0.00	0.00	71.47	0	1	50	50	2.85	50	50

0	9	20	790.34	1.14	785.54	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	4.80	50	50
0	9	21	725.43	1.14	719.73	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	5.70	50	50
0	9	22	612.21	0.83	604.90	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	7.31	50	50
0	9	23	535.90	0.83	527.28	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	8.63	50	50
0	10	0	508.48	0.83	499.22	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	9.26	50	50
0	10	1	490.32	0.83	480.01	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	10.31	50	50
0	10	2	469.88	0.83	458.60	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	11.29	50	50
0	10	3	453.43	0.83	442.33	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	1	0	50	50	11.10	50	50
0	10	4	444.05	0.83	522.78	0.00	4	4	0.00	400	400	93.24	88.78	-88.78	0.00	1	0	50	50	10.05	50	50
0	10	5	447.16	0.83	528.76	0.00	4	4	0.00	400	400	177.60	88.80	-88.80	0.00	1	0	50	50	7.20	50	50
0	10	6	554.94	1.14	535.78	0.00	4	4	11.07	400	400	177.60	0.00	0.00	0.00	1	0	50	50	8.10	50	50
0	10	7	805.63	1.88	0.00	654.74	4	4	47.39	400	400	84.13	0.00	0.00	88.80	0	1	50	50	14.70	50	50
0	10	8	1149.25	1.88	0.00	966.65	4	4	86.68	400	400	8.90	0.00	0.00	71.47	0	1	50	50	24.45	50	50
0	10	9	1345.97	1.88	1192.28	0.00	4	4	119.91	400	400	8.90	0.00	0.00	0.00	0	1	50	50	33.79	50	50
0	10	10	1460.65	1.14	1295.95	0.00	4	4	131.47	400	400	8.90	0.00	0.00	0.00	1	0	50	50	33.23	50	50
0	10	11	1501.59	1.14	1321.65	0.00	4	4	148.59	400	400	8.90	0.00	0.00	0.00	1	0	50	50	31.35	50	50
0	10	12	1494.66	1.14	1320.14	0.00	4	4	144.22	400	400	8.90	0.00	0.00	0.00	1	0	50	50	30.30	50	50
0	10	13	1476.96	1.14	1309.18	0.00	4	4	138.60	400	400	8.90	0.00	0.00	0.00	1	0	50	50	29.18	50	50
0	10	14	1478.89	1.14	1324.90	0.00	4	4	126.16	400	400	8.90	0.00	0.00	0.00	1	0	50	50	27.83	50	50
0	10	15	1517.73	1.14	1394.40	0.00	4	4	97.08	400	400	8.90	0.00	0.00	0.00	1	0	50	50	26.25	50	50
0	10	16	1375.42	1.14	1379.11	0.00	4	4	61.43	400	400	93.24	88.78	-88.78	0.00	1	0	50	50	23.66	50	50
0	10	17	1117.82	1.14	1165.70	0.00	4	4	26.41	400	400	177.60	88.80	-88.80	0.00	1	0	50	50	14.51	50	50
0	10	18	952.20	1.88	0.00	852.04	4	4	4.12	400	400	84.13	0.00	0.00	88.80	0	1	50	50	7.24	50	50
0	10	19	836.34	1.88	0.00	753.03	4	4	0.00	400	400	8.90	0.00	0.00	71.47	0	1	50	50	11.85	50	50
0	10	20	782.20	1.14	769.30	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	12.90	50	50
0	10	21	684.95	1.14	672.50	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	12.45	50	50
0	10	22	593.38	0.83	582.13	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	11.25	50	50
0	10	23	509.81	0.83	499.16	0.00	4	4	0.00	400	400	8.90	0.00	0.00	0.00	0	1	50	50	10.65	50	50