OPTIMAL ENERGY MANAGEMENT IN A SMART HOME, BASED ON PHOTOVOLTAIC SYSTEMS ENERGY FEED-IN TARIFF: CASE OF SOUTH AFRICA

By

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DECLARATION

I, STEPHAN MARAIS, student number , do hereby declare that this research project, which has been submitted to the Central University of Technology Free State, for the degree: Master of Engineering in Electrical Engineering, is my own independent work and complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of the Central University of Technology, Free State. This project has not been submitted before by any person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

S. Marais

Date: 1st December 2019

DEDICATION

I dedicate this dissertation to the memory of my Father, Victor George Marais. To my Mother, Getrude Marais, who delivered everything she could, to give us the best. Further, to all my siblings and friends, for their continuous support. To my girlfriend for her support and patience during this process, love you.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank our Almighty Heavenly Father, for making everything possible for me, by strengthening me throughout this study. Eternal Glory to our Almighty Father, His Son Jesus Christ and the Holy Spirit! Amen!

To my supervisors, Prof. Kanzumba Kusakana and Dr. S.P Koko.

To Mr. Percy Andrew Hohne, for always lending a helping hand and ear. Your office is always open to provide guidance and understanding.

Furthermore, I would like to acknowledge the support and assistance provided to me by the Central University of Technology, Free State (CUT). CUT has been tremendously generous in supporting my academic pursuits and many of my colleagues have contributed with ideas, feedback and advice.

Thank You.

LIST OF ABBREVIATIONS

BCR	Benefits-to-Cost Ratio
BEP	Break-Even Point
COE	Cost of Energy
DR	Demand Response
DC	Direct Current
DER	Demand-side Energy Resources
DES	Distributed Energy Storage systems
DG	Distributed Generators
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance
DSM	Demand Side Management
EBT	Energy-Based Tariffs
EMS	Energy Management System
Eskom	South African Electric Utility Company
ESS	Energy Storage System
FFPPs	Fossil Fuel Power Plants
FIT	Feed-in-Tariff
GHGs	Concentration of Greenhouse Gases
GHI	Global Horizontal Irradiance
GDP	Gross Domestic Product
HEM	Home Energy Management
HOMER	Hybrid Optimization Model for Electric Renewable
HPWH	Heat Pump Water Heater
IRR	Initial Rate of Return
IEA	International Energy Agency
LLC	Life Cycle Cost
LCOE	Levelized Cost of Electricity
MHK	Micro-Hydrokinetic River System
MPC	Model Predictive Control

MILP	Mixed Integer Linear Programming
MPC	Model Predictive Control
NPC	Net Present Cost
O&M	Operation & Maintenance
PBP	Beyond the Payback Period
PCC	Point of Common Coupling
SoC	State of Charge
SOCP	Second-Order Cone Programming
SPP	Simple Payback Period
SCIP	Solving Constraint Integer Programming
SOC	State of Charge
TOU	Time-of-Use
PHS	Pumped-Hydro Storage
PTR	Peak-Time-Rebates
PV	Photovoltaic
RCGA	Real-Coded Generic Algorithm
RTP	Real-Time-Pricing
RE	Renewable Energy

Nomenclature

C_t	TOU tariff price at time t [ZAR/kWh]
C_o	Off-peak tariff rates [ZAR/kWh]
C_p	Peak tariff rates [ZAR/kWh]
C_s	Standard tariff rates [ZAR/kWh]
$E_{deferrable}$	Energy for the deferrable load [kWh/year]
E_{grid}	Total energy grid sales [kWh/year]
$E_{primary}$	Energy of primary load [kWh/year]
j	Sampling interval
N	Total number of sampling intervals
p	TOU electricity tariff
P_{BC}	Electrical power flow [kW] from the DB to battery
P_{BD}	Electrical power flow [kW] from the battery to DB
P_{EXP}	Electrical power flow [kW] from the DB to the utility grid
P_i^{rated}	Rated power of the component[kW]
P_i^{max}	Maximum generated power [kW]
P_{IMP}	Electrical power flow [kW] from the utility grid to the DB
P_{LOAD}	Electrical power flow [kW] from DB to the load
P_{PV}	Electrical power flow [kW] from the PV the DB
RP	Residential premises
$SoC(j\text{-}1)$	Previous sampling interval
$SoCj$	SoC at the current sampling interval
t_s	Sampling time
η_C	Charging efficiency of the battery
η_D	Discharging efficiency of the battery

ABSTRACT

In recent years, concern over environmental problems, such as the increase of atmospheric temperatures and destruction of the ozone layer, have amplified on a global scale. In the future, increased efficiency of energy systems and reduced end-use energy demand will be significant in attaining the 6% curtailment of greenhouse gases, targeted by the Kyoto Protocol. Although the energy research and development has been known over an extended period in large buildings, it has recently been applied at household level.

In South Africa, there are approximately 9 million homes that have access to electricity. Approximately 27% of the generated energy in South Africa was consumed by the residential sector in 2015. This making the residential sector the second largest energy consumer in the economy.

In South Africa, electricity is solely supplied by Eskom, a state-owned enterprise. For the last decade, Eskom have experienced challenges in meeting the national demand. The issue of the supply being less than the demand, has led to the requirement of additional fossil fuel plants, which resulted in financial challenges. These financial challenges have resulted in harsh tariff increases for consumers. With the aim to reduce the load-demand of the grid during peak periods, the electricity supply commission (ESKOM), implemented the time-of-use (TOU) tariff structure, billing consumers at a higher tariff rate during certain periods of the day. These tariff increases are compelling consumers to search for alternative ways in meeting their energy demand. Currently, many countries are permitting residential consumers to install renewable forms of energy sources.

With Eskom contending to meet the load demand, load shedding was introduced, in order to reduce the load demand during certain periods of the day. If load shedding was never introduced, the load demand may have resulted in the grid collapsing. As a result of the electricity challenge in South Africa, a few municipalities have begun revising the regulations on small scale embedded generators, permitting consumers, under strict regulations, to feed-back excess energy into the grid. This study used a solar photovoltaic (PV) system, combined with battery storage. The mathematical modelling of the grid-interactive PV, with battery storage system, has been developed to allow for optimal energy storage and sales, while ensuring that the consumer load demand is met at all times,

considering variable time-of-use (TOU) tariffs and load demand uncertainties, that may take place in real-time context.

The aim is to develop a model for optimal operation of a residential grid-interactive PV system with battery storage, operating under TOU and FIT tariffs. The research will further assess the potential of energy cost saving and cost effectiveness that the system may achieve, under the new residential feed-in tariff; along with the impact the battery storage system will have on the profitability of the grid-interactive solar PV system.

Additionally, the second aim is to maximize the energy sales into the grid, if the system is grid-interactive. The MATLAB optimization toolbox was used to evaluate the cost effectiveness of the grid-interactive system, in terms of money spent.

The baseline system was established, consisting solely of energy supplied by the grid. The optimal operation of the proposed system was simulated and compared to the baseline system.

A life cycle cost (LCC) analysis was conducted for a period of 20 years, for both the baseline and the optimally controlled grid-interactive PV with battery storage system scheme. Results from the analysis indicated that the proposed system would break-even in 11.5 years, with an approximate saving of 35%, translating into savings of R 270 022.83. The results clearly illustrated that the consumer could save a significant amount if the system is implemented correctly, including the parameters of the desired system. The model showed that it could be used for different operating conditions, as long as the user incorporates the new environment. The model clearly shows that managing the power flow in a proposed system could be beneficial for electricity consumers in South Africa and not merely for residential consumers.

CONTENTS

List of Figures

List of Tables

CHAPTER 1: INTRODUCTION

1.1. BACKGROUND

South Africa is the main power generator in Africa, of which 83% of the power is generated from coal-fired power plants [1]. In 2015, Eskom experienced challenges in supplying the demanded load. Various attempts were implemented to prevent the grid from being overloaded, as this could result in a national blackout. There are approximately 9 million homes in South Africa that have access to electricity [2]. The energy provider, in an attempt to reduce the load consumption during peak times of the day, implemented load shedding. To encourage consumers in urban-residential areas to reduce their power usage during certain times of the day, a time-of-use (TOU) tariff was introduced [3]. This tariff billed consumers at a higher rate for electricity, during the peak energy usage periods of the day. Eskom further introduced a low demand season and a high demand season. The high demand season occurred during the winter periods, when the consumption of electricity by consumers is higher [4].

Traditionally, in the majority of urban-residential homes, the energy consumption peaks twice a day, typically from 07:00-10:00 in the mornings and 18:00-21:00 in the evenings [3]. During these periods, the national grid nears peak capacity [6]. The majority of the urban-residential consumers found it challenging to relocate their load from the peak times, avoiding off-peak times to avoid the higher tariff billing.

Consumers generally prepare for work in the mornings during the peak period and in the afternoons, use energy extensively.

For most of the consumers, an increase in their electricity costs was unavoidable and they had no choice but to settle the extra costs every month, along with the expected increase in the electricity price by Eskom [3].

With the stress on the national grid, the National Energy Regulator of South Africa (NERSA), has encouraged electricity consumers and independent power producers (IPPs) to generate power, using alternative energy resources. Focus was placed on those sources, which are renewable and sustainable [4].

South Africa is ideally positioned to generate solar energy, with a few provinces reaching isolation of up to 4, 5-6, 5 kWh/m² [4]. This makes solar photovoltaic (PV) an ideal energy to implement and has the added benefit of being non-polluting, eco-friendly and a viable source of energy [5]. Small-scale renewable energy has been implemented successfully internationally, promoting sustainable energy use, as well as reducing the demand on the national energy supplier. During the last decade, research and development has moved to photovoltaic based solar cells, to increase the efficiency of these solar cells [5].This has made it possible for consumers to implement photovoltaic systems at their places of residence.

The majority of electricity consumers may solely make use of the TOU tariff structure to reduce their overall monthly electricity bill, by installing a battery storage system to store the power. However, the battery storage system increases the overall cost of the project. Currently, four municipalities have procedures in place to facilitate connection of small-scale embedded generators to their networks. These cities include the City of Cape Town [9], eThekwini [3], the City of Johannesburg [10] and Ekurhuleni [11]. These municipalities allow consumers to connect to the grid and sell electricity back under the feed-in tariff (FIT), or the PBI (price-based incentive). The FIT allows customers to reduce their electricity bill by feeding the excess power back to the grid and recompensed by the local municipality. This allows for consumers to generate revenue with the excess power, which is fed back into the grid. This may be an incentive for customers to boost the PV market in residential sectors.

1.2. PROBLEM STATEMENT

Municipalities in Cape Town allow residential consumers to sell electricity back to the grid, under the residential FIT tariff. Consumers using solar PV with battery systems in Cape Town, make use of the grid-interactive system, selling electricity back to the utility. The challenge is that the various power flows from the PV, grid and battery, are not optimised to take advantage of the TOU and FIT, therefore reducing the cost effectiveness and making the payback period longer.

1.3. OBJECTIVES OF THE STUDY

The main aim is to develop a model for optimal operation of a residential grid-interactive PV system, with battery storage operating under TOU and FIT tariff. The research will further assess the potential of energy cost saving and cost effectiveness that the system may achieve under the new residential feed-in tariff, along with the impact that the battery storage system may have on the profitability of the grid-interactive solar PV system.

The objective of the study is as follows:

- To review literatures related to grid interactive PV systems, with a specific focus on the South African energy sector.
- To determine the optimal size of the system using HOMER software.
- To develop a model for optimal operation of a residential grid-interactive PV system, with battery storage operating under TOU and FIT tariff.
- Simulate the proposed PV systems, to analyse the potential of energy cost saving, under the new residential feed-in-tariff (FIT).
- To conduct an economic analysis on the impact battery storage will have on the profitability of the systems.

1.4. EXPECTED OUTCOMES OF STUDY:

The scientific outcomes are as follows:

- A mathematical model for optimal energy management of a grid-interactive PV system.
- A master's dissertation and publications.

The social impact are as follows:

- The consumers will be provided with the ability of controlling the bi-directional power flow between the grid and their building.
- The consumers may be able to benefit from time-based pricing.

1.5. RESEARCH METHODOLOGY

To achieve the objectives of the study, the methodology is as follows:

1.5.1 Literature Review

Literature on Grid interactive PV systems were reviewed. The literature covered all the key aspects, such as the design of the PV to the various forms of energy storage devices. The literature further covered the relative regulation, particularly for residential consumers, under the FIT and time-of-use tariff. A few of the reviews further covered the economic analyses of the PV systems.

1.5.2 Data collection

- The residential load consumption of a house in Cape Town was recorded over a period of one year, from January 2017 to December 2017.
- The TOU and FIT tariff structures retrieved from the electricity supplier brochure of the year 2017/2018.
- The solar radiance for the year 2017 was retrieved from the Southern African Universities Radiometric Network (SAURAN) website.

1.5.3 Optimal sizing

Optimal sizing of the proposed grid interactive PV with battery storage system, will be determined through the use of HOMER (hybrid optimization model for electrical renewable energy) software. The recorded load demand, as well as the solar radiance extracted from SAURAN, will be used as input parameters.

1.5.4 System modelling

Following the study of operation of the various components in the proposed system, a mathematical model of a grid interactive PV system with battery storage, under the residential TOU and FIT tariff for optimal energy management, will be developed.
The model will comprise of the following:

1.5.4.1 The objective function

The control objective to be minimized, is the net electricity cost (drawn from the grid), while maximizing the profit generated by selling energy to the grid under a given period.

1.5.4.2 System Constraints

- Power balance: At any given time, the load demand should be met. However, the combination of the power from the grid, the renewable source and the storage system should be used.
- Dynamics of battery state of charge: During charging and discharging, the state of charge (SoC) of the battery bank, should be maintained between its minimum and maximum values.
- Power flow limitations: For equipment safety purposes, all power flows (from PV, battery, inverters), should be maintained within the minimum and maximum limits, according to the design specifications, provided by the manufacturer.
- Exclusive power flow: Power cannot be exported and imported from the grid at the same time. Furthermore, the battery cannot be charged and discharged simultaneously.
- Fixed final state: To ensure that the simulation allows for repeated implementation of the optimally controlled system, the battery energy remaining at the end of a control horizon should be equal to the amount at the start of the control horizon.

1.5.5 Simulation

After developing the mathematical model, real input data, such as TOU tariffs, recorded residential load and the solar radiance, will be used in MATLAB software for a specific case study in Cape Town, South Africa.

1.5.6 Economic Analysis

Economic analysis will be analysed from the results of the simulation. In the simulation, the baseline results for a day, in both the winter and summer period, will be compared with the results from the optimized system for the same day. A break-even point analyses, followed by a life cycle cost (LLC), will be conducted for a period of 20 years.

1.6. PUBLICATIONS DURING THE STUDY

Conference papers:

- Marais S., Kusakana K., Koko S.P. "Techno-economic feasibility analysis of a grid-interactive solar PV system for South African residential load." In *2019 International Conference on the Domestic Use of Energy (DUE)*, pp. 163-168. IEEE, 2019.
- Marais S., Kusakana K., Koko S.P. "Prospective implementation of grid-interactive photovoltaic systems in the South African residential sector." In *2018 Open Innovations Conference (OI)*, pp. 62-67. IEEE, 2018.
- Marais S., Kusakana K., Koko S.P. "Energy Monitoring for Potential Cost Saving in a Typical South African Household." In *2019 Open Innovations (OI)*, pp. 122-126. IEEE, 2019.
- Marais S., Kusakana K., "Optimal sizing of a residential grid-interactive PV with battery storage using HOMER." Accepted to be presented at the *12th International Energy, Energy and Enviroment Symposium 2020.*

Journal article:

- Marais S., Kusakana K., Koko S.P "Optimal energy management and economic analysis of a grid-interactive PV with battery storage system: A case study of Cape Town, South Africa" (submitted).

1.7. DISSERTATION LAYOUT

This dissertation is structured as follows:

Chapter 1 is an introduction to the dissertation, which presents background, problem statement, objectives, methodology of the study and research outputs.

Chapter 2 provides a comprehensive review on the optimization studies, based on grid-connected systems with specific focus on the residential sector applying the TOU and FIT tariff strategy. Followed by a thorough survey on the operation principle of grid connected PV systems and their components.

Chapter 3 develops an optimal size of the proposed grid-interactive PV with battery storage system, using HOMER software.

Chapter 4 covers the development of the mathematical model for a Grid interactive PV system. The MATLAB library has been used to develop the model. The simulated results are presented and discussed.

Chapter 5 evaluates the economic feasibility and presents the break-even point and life cycle cost analysis of the grid interactive PV system, compared the systems baseline.

Chapter 6 concludes the work of this dissertation and indicates the next level, for future studies to be made.

CHAPTER 2: LITERATURE REVIEW

2.1. INTRODUCTION

This chapter presents a brief introduction of the state of renewable energy in South Africa (SA). Followed by an overview on the various forms of grid connected systems used in the residential sector and the operating principles, thereof.

This chapter further outlines the state of renewable energy (RE) in SA, followed by municipal policies and regulations of grid interactive renewable energy systems.

From the literature reviewed, various optimal energy management studies have been undertaken, to develop energy optimization models. The main aim of the developed models, is to minimize the grid electricity consumption costs. The majority of studies are based on off-grid systems, while a few studies have been carried out on grid interactive systems in the South African context. Due to the high initial cost of the system, grid intergration is becoming the sole way to make the system viable in the residential sector. Therefore, this chapter further focuses on the review of recent optimal energy management studies of grid interactive RE systems, applying the TOU and FIT tariff scheme.

2.2. SOUTH AFRICAN ENERGY SECTOR

The Republic of South Africa is the southernmost country on the continent of Africa [6]. Energy is the vital force that powers business, manufacturing, the transportation of goods and the delivery of services to the nation. It is the lifeblood of modern living, as it has an impact on everything we do and affects our very existence.

South Africa currently produces 85% of its electricity demand through coal-fired power plants [3, 7]. The coal-fired power plants are responsible for approximately 7.7 (tonnes) of C02-eq emission per capita per annum [8, 9].

Currently, almost all of South African electricity is produced by Eskom, a state-owned enterprise [2]. This is by far the largest emitter of carbon emissions in South Africa [10].

Electrical services are shared between Eskom and local municipalities [11]. Municipalities provide electricity services to the commercial, industrial and residential sectors [12].

Overall, municipalities are often dependent on Eskom for the provision of electricity services in their areas of jurisdiction and have no direct control regarding timing for service delivery purposes.

In 1997, South Africa joined the Kyoto Protocol. This protocol aims to reduce the amount of carbon emission, caused by coal-fired power stations worldwide [3, 13]. The Department of energy is working towards achieving 30% of clean energy by 2025 [14]. For the government to achieve this goal, significant changes in the infrastructure should take place. Replacing coal fired power plants with energy generated from renewable sources, will significantly reduce green house gases (GHG) emission levels, or the rate at which greenhouse gases are increasing [10, 15].

Along with reducing GHG gases, renewable energy could be an effective solution in reducing grid instability problems, faced by Eskom [16, 17].

South Africa is currently rated among the top twelve most attractive investments for renewable energy [18]. Studies from the International Energy Agency (IEA), show that African total energy consumption per gross domestic product (GDP,) is twice the global average. The available renewable resources in South Africa will contribute immensely to the energy sector, society and economy, at large [10].

South Africa has a high radiation area of approximately 194,000km^2. Studies have shown that the Northern Cape is one of the optimal solar resources, globally [2, 19].

Figure. 2.1, indicates the potentials of solar energy resources in South Africa.

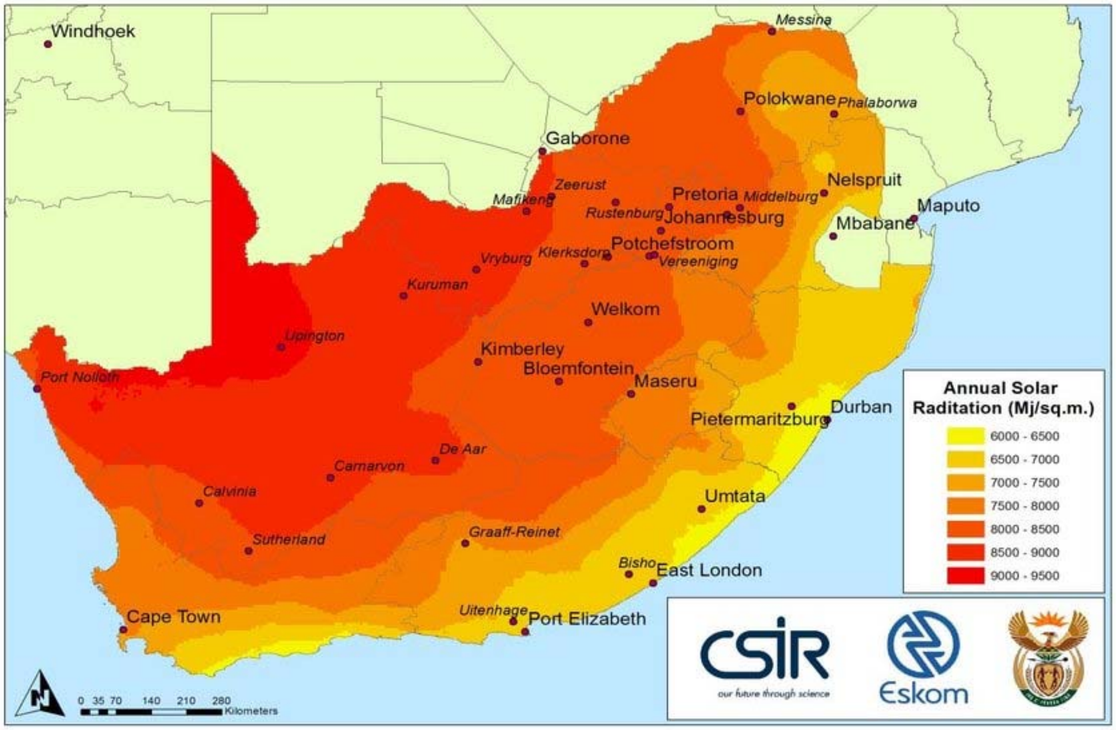

Figure 2.1: Annual solar radiation of South Africa [19]

The dramatic decline in the cost of solar PV technology, since 2010 [20], has resulted in unsubsidized solar PV-generated electricity cost-competitive with fossil fuels [21, 22]. The reduced cost of the rooftop PV installations and the levelised cost of electricity of these systems, reaches parity with the domestic and commercial tariffs. There has been a growing interest from South African electricity customers to install rooftop PV systems, in order to reduce their electricity bill and supplement their consumption [23, 24, 25].

Records of rooftop Solar PV installed in the Nelson Mandela Bay Municipality (NMBM) [26] and City of Cape Town (COCT), reveal this trend, wherein the numbers of solar systems have increased, as indicated in Figure. 2.2.

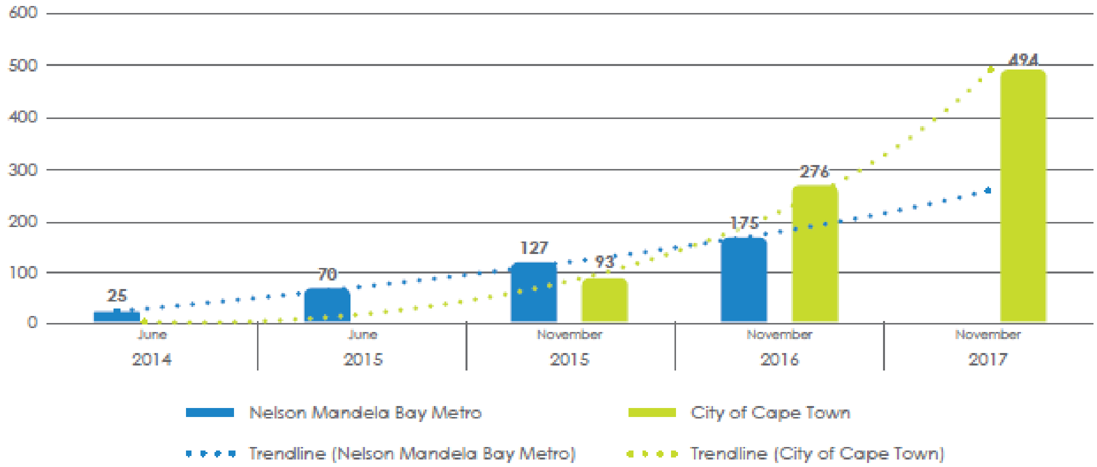

Figure 2.2: Number of solar PV systems registered in NMBM and Cape Town, respectively (cumulative) [12]

While available data does not support a growth analysis in other cities or towns, installed capacities have reached significant levels in a number of them. Johannesburg has 32 commissioned installations on their database [12]. In Western Cape towns, Drakenstein and George, each have more than 100 installations, while Langeberg, Mossel Bay and Cederberg have more than 5024 each [12]. Data is further being gathered for Swartland, Stellenbosch, Beaufort West, Overstrand, Theewaterskloof, Breede Valley and Oudtshoorn. Growth rates should become available once an additional year's worth of data has been aggregated.

A report published by PQRS25, a privately held database of non-utility Solar PV installations in Africa, reflected 120 MW [12, 27] installed capacity in South Africa, at the time of reporting, in November 2016 (Figure. 2.3). It was highlighted that the data point for 2016 was preliminary, pending completion of the data collection process.

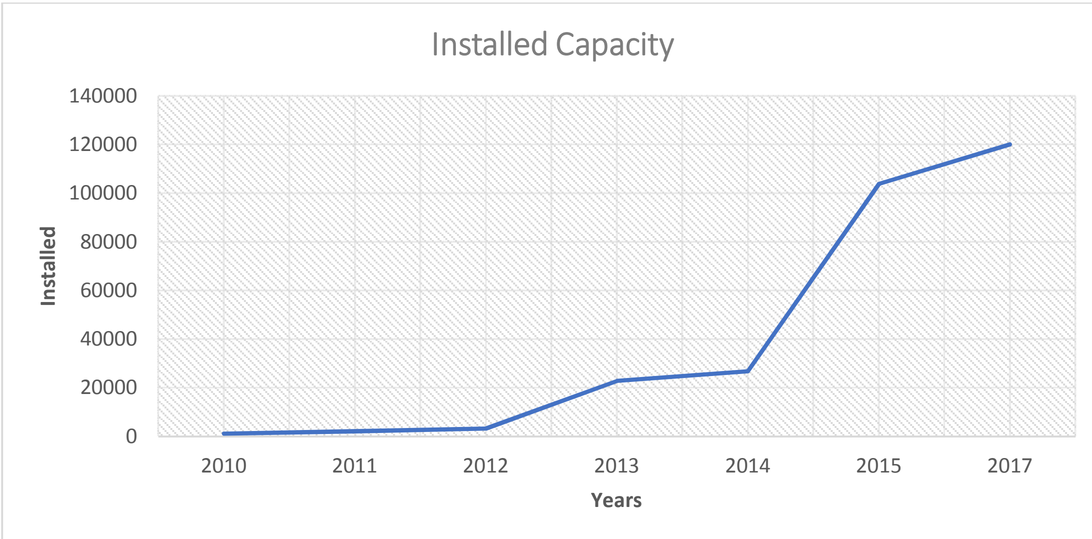

Figure 2.3: Installed capacity of rooftops solar PV in South Africa (Cumulative kWp) [12]

Installation data is reported voluntarily to this database, however, data is subjected to a verification process to confirm existence, location, installation data and to ensure that double counting occurs. Considering their data collection and verification process and methodology, the average lag experienced with data reporting and capturing into the database, combined with Solar PV sales figures for 2016, PQRS estimated the total installed capacity by the end of 2016 to be approximately 280 MW [27]. This estimation was confirmed by industry, placing the country-wide installed capacity at approximately 300 MW by August 2017, a near seven-fold increase, from May 2015.

In August 2017, the PQRS dataset recorded 183 MW of rooftop PV installations that had been allocated to specific provinces [12, 28]. Figure. 2.4 shows that the Growth in Gauteng appears to have outpaced the remainder of the country, with 44 percent of registered rooftop Solar PV installations in this province [12]. The Western Cape, Northern Cape and Eastern Cape provinces contribute a further 32% of the recorded installations [12].

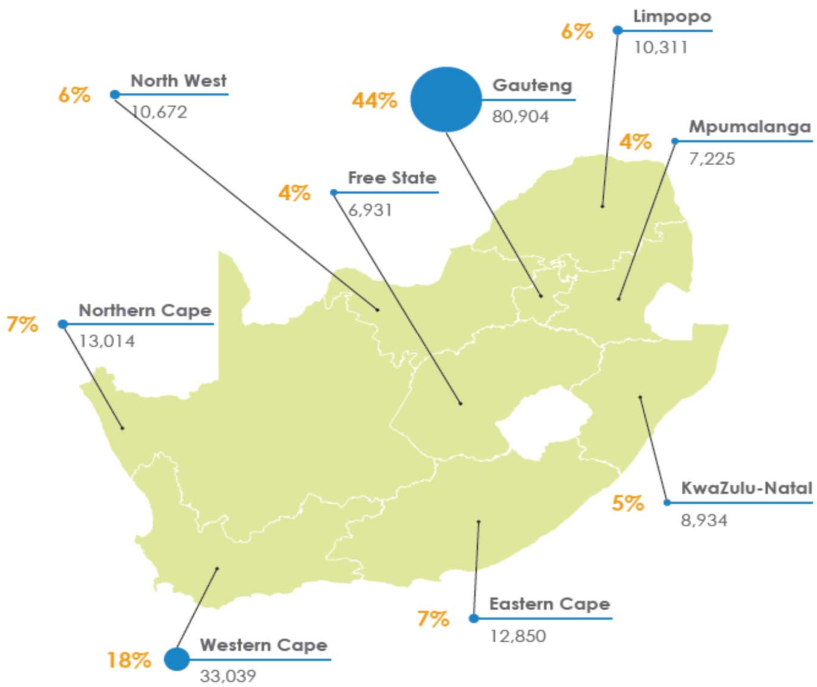

Figure 2.4: Provincial share of recorded small-scale (rooftops) solar PV installations [12]

Lower prices are making rooftop Solar PV increasingly attractive to electricity consumers as part of their supply solution. Market uptake may further accelerate, as technology prices continue to drop, including the resolution of the regulatory environment. The total rooftop space available in the country for Solar PV has been estimated at 73 GW [12], presenting an enormous remaining opportunity for market uptake in this area. If coordinated into a national initiative, this market potential could be developed with optimal economic benefit to South Africa.

2.3. SOUTH AFRICAN ENEGRY USAGE

2.3.1 Energy sectors

South Africa's energy consumption is divided into six sectors, namely: industry, transport, agriculture, residential, commerce and public services [29]. The percentage contribution of energy consumed by various sectors, are presented in Figure. 2.5. The sector "non-specified (other)", refers to unaccounted energy (energy that has not been classified into a specific sector).

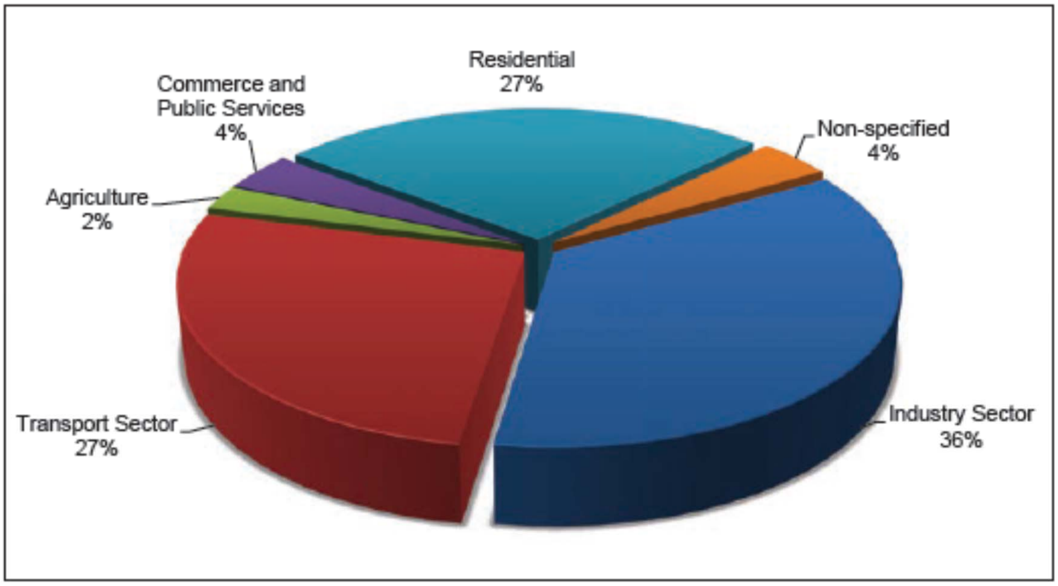

Figure 2.5: Energy demand by sectors, 2015 [56]

2.3.2 Residential load consumption

Approximately 27% of the generated energy in South Africa was consumed by the residential sector, in 2015 [10, 31]. This resulted in the residential sector, the second largest energy consumer in the economy.

In 2015, due to incompleted power plants, Eskom was unable to suppy the demanded load. Various attempts were carried out by the management of Eskom, avoiding total grid collaption [2]. Load shedding was implemented by the energy provider, as an attempt to reduce the load consumption during peak times of the day [32]. To encourage consumers in urban-residential areas to reduce their power usage during certain times of the day, a time-of-use (TOU) tariff was introduced [17, 32, 33]. The TOU tariff pricing strategy involves a variable price over various periods [34, 35]. The electricity price is costly during peak periods and affordable during off-peak periods, due to higher electricity generation costs driven by the higher consumption level [35, 36]. Eskom further introduced a low demand season and a high demand season. The high demand season was during the winter periods, when the consumption of electricity by consumers is higher [37, 38]. Traditionally, in these urban-residential homes, the energy consumption peaks twice a day [39, 40], typically from 07:00-10:00 in the mornings and 18:00-21:00 in the evenings, as illustrated in Figure. 2.6.

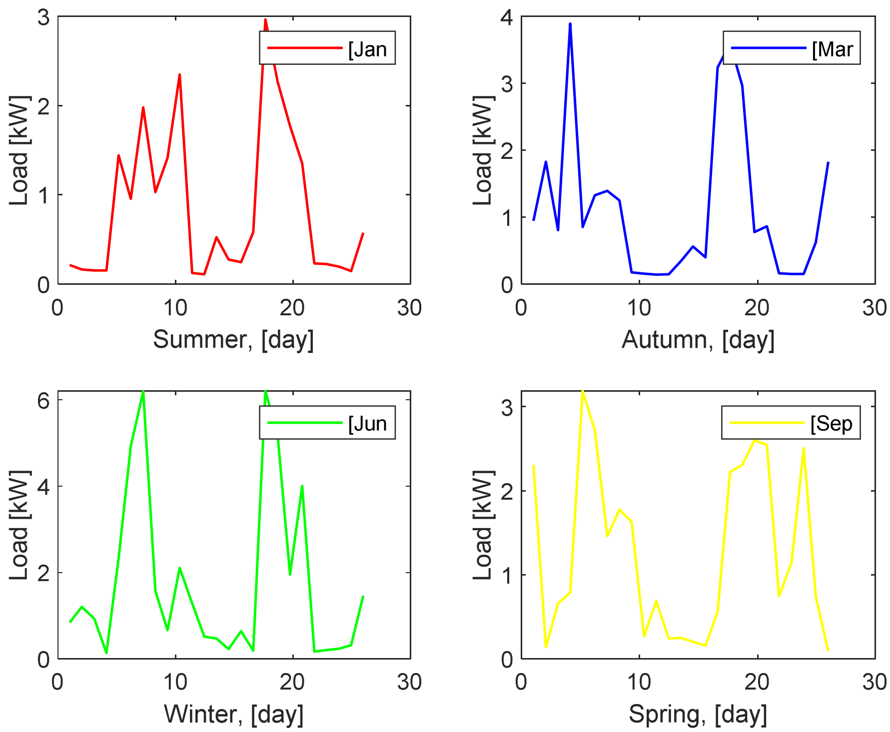

Figure 2.6: Typical residential load [41]

During these time periods, the national grid nears peak capacity [42]. The majority of the urban-residential consumers found it challenging to shift their load from the peak times, to the off-peak times, avoiding the higher tariff billing. Consumers generally prepare for work in the mornings, during the peak period and in the afternoons, use energy extensively [41, 43]. For most of the consumers, an increase in their electricity costs was unavoidable and they would were required to settle the additional amount monthly [3].

2.3.3 Electricity increases

The cost of electricity has been rising significantly over the past decades, being a direct consequence of Eskom's recent building programs and the costs of essential plant maintenance [2, 15].

Eskom, over the past decade, has requested a harsh tariff increase, as seen in Figure. 2.7, thus compelling the residential consumer to identify ways in reducing the electricity usage.

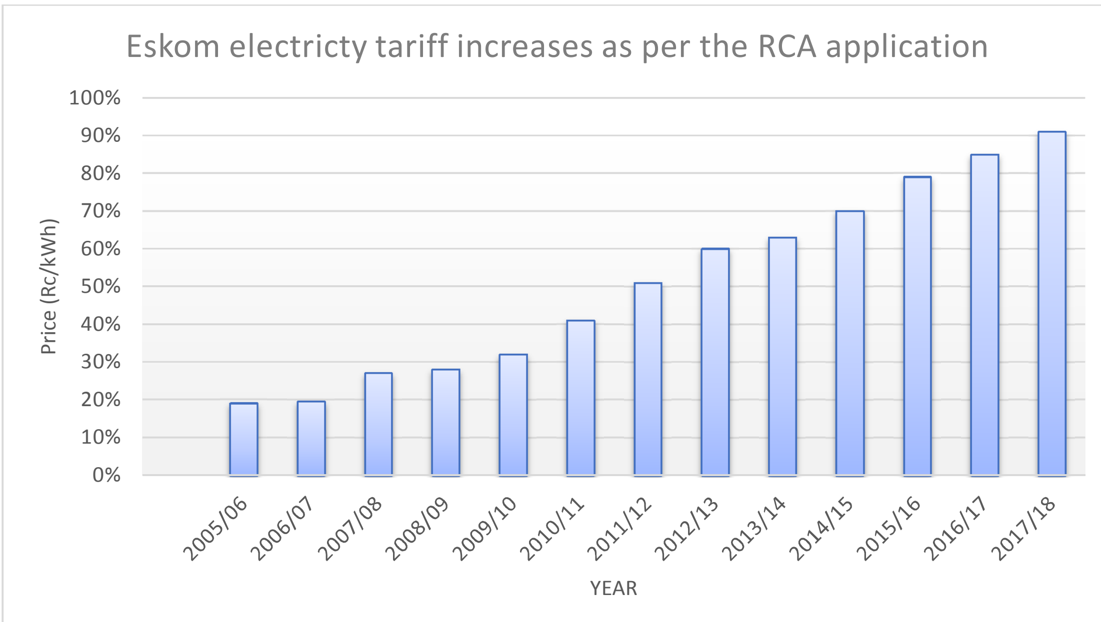

Figure 2.7: Eskom electricity tariff increases [41]

The constant increase in the cost of electricity, coupled with marked pressures for cleaner energy sources, is peaking an interest in residential consumers to generate their own energy [16, 44].

The National Energy Regulator of South Africa (NERSA), has encouraged electricity consumers and independent power producers (IPPs), to generate power using alternative energy resources. Focus was placed on those sources, which are renewable and sustainable [45].

2.3.4 Introduction to SSEG

Households in South Africa have increasingly begun to invest in PV systems [46]. Due to the increase in installations, the need to develop a policy framework for both national and municipal level is required. The minister of Energy published the small scale embedded generation (SSEG) policy for public comment, on the 2nd of December 2016. The result of this, was that SSEG below 1 MW, would be able to proliferate in a reasonably free, legal, yet controlled manner. In time, the cap of 1 MW may be reassessed, as required [26].
An estimated 100 000+ systems are installed throughout South Africa [47]. Residential consumers, currently generating energy, are encouraged to obtain grid-tie PV systems. This system could be favourable towards the consumer and grid operator. The customer could lower the cost of purchasing energy from the grid during peak periods, by using energy stored in the battery storage system. A few of the municipalities, such as Cape Town, Johannesburg, eThekwini and Ekurhuleni, have started to implement regulations, allowing residential consumers to feed excess energy back into the grid [49, 50], under the residential feed-in tariff scheme. Table 2.1, indicated the status of SSEG in South African municipalities. Table 2.2, shows the documented installations of SSEG in South African Municipalities in 2016.

Table 2.1: Status of small embedded generation (SSEG) in South African municipalities Aug 2016 [51]

Province	Existing installations	Official applications	Approved SSEG tariffs	Number of installations	kWp installed	Ave size (in kWp)
Eastern Cape	2	2	1	154	1302	8
Gauteng	3	2	1	9	4505	501
Limpopo	2	0	0	3	265	88
Western Cape	13	11	9	301	8887	30
North West	1	0	0	10	2000	200

Mpumalanga	0	0	0	-	-	-
Nothern Cape	1	0	0	4	183	46
Free State	1	0	0	3	400	133
Total (Aug 2016)	23	16	12	465	17029	34

Table 2.2: List of municipalities active on SSEG [51]

Province	Municipality	List of installation	Approved SSEG application process	Allows feed back into grid?	Status of SSEG tariff
Eastern Cape	Nelson Mandela Bay	Yes	Yes	Yes	Approved and operational
Eastern Cape	Buffalo City	Yes	Yes		No SSEG tariff
Free State	Mangaung	Yes	Under development	No	Under development
Gauteng	Johannesburg	Yes	Yes	Yes	Approved and operational
Gauteng	Tshwane	Under development	Under development	No	No SSEG tariff
Kwazulu Natal	eThekwini	Yes	Yes	Yes	Approved and being rolled out
Limpopo	Ephrain Mogale	Yes	No	Yes(pilot)	Under development
Limpopo	Polokwane	Yes	No	Under development	No SSEG tariff
Nothern Cape	Khara Hais	Yes	No	No	No SSEG tariff
North West	Tlokwe	Yes	No	No	No SSEG tariff
Western Cape	Beaufort West	Yes	Yes	Yes	Approved and operational
Western Cape	Bergriver	Yes	Under development	Yes	No SSEG tariff
Western Cape	Breede Valley	Yes	Yes	Yes	No SSEG tariff
Western Cape	Drakenstein	Yes	Yes	Yes	Approved and operational

Western Cape	George	Yes	Yes	Yes	Approved and operational
Western Cape	Langeberg	Yes	Yes	Yes with out compensation	No SSEG tariff
Western Cape	Mossel Bay	Yes	Yes	Yes	Approved and operational
Western Cape	Oudtshoorn	Yes	Under development	Yes	Under development
Western Cape	Overstrand	Yes	Yes	Yes	Approved and rolled out
Western Cape	Stellenbosch	Yes	Yes	Yes	Approved and rolled out
Western Cape	Cape Town	Yes	Yes	Yes	Approved and rolled out
Western Cape	Saldanha Bay	Yes	Under development	No	Under development
Western Cape	Threewaterskloof	Yes	Yes	Yes	Approved and rolled out
Western Cape	Swartland	Yes	Yes	Yes	Approved and operational

By allowing consumers to feed energy back to the grid, it reduces the load demand from the grid during peak hours, enabling the grid to operate closer to the base load [35].

However, adoption of grid-connected PV systems is a challenge for consumers, with the requirement of designing an optimal home energy management system. This management system should focus on reducing the dependence on grid energy and maximize the export of energy back to the grid, taking into consideration the various billing periods and the intermittent nature of PV energy.

2.4. REVIEW OF POLICIES ON SMALL-SCALE EMBEDDED GENERATORS IN SOUTH AFRICA

2.4.1 Eskom regulations for grid connected systems

Eskom does not allow for synchronization of small-scale embedded generation to its LV network. Voltage levels up to and not exceeding 1000V, is referred to as the LV network. The reason connection on LV networks are not permitted, is to ensure safety for technicians working on the network [52, 53].

It is of utmost importance to understand the principle of "synchronization". This is the use by the Solar PV system, the frequency supplied by the utility and does not imply reverse flow of power.

Because of the above mentioned, Eskom does not allow for embedded generators to be installed at its clients' premises, when utilizing a LV connection.

Clients may convert from an LV to MV connection. However, this convertion is significantly costly [53].

2.4.2 Municipalities regulations of grid connected systems

For municipalities to avoid unregulated proliferation of installations, they should be proactive in developing appropriate procedures and standards for SSEG integration [53, 54].

In July 2016, the National Energy Regulator of South Africa (NERSA), agreed to approve municipal Small Scale Embedded Generator tariffs, as an interim solution and should be on a case-by-case basis, while awaiting the final regulations to be finalized [55]. Currently, four municipalities have procedures in place to facilitate connection of small-scale embedded generators to their networks.

The municipalities that as of yet have these procedures in place, will ultimately disconnect clients from the grid that connect such a system, in disregard to the municipality's principles [57].

In instances where municipalities do allow for connections:

- Each municipality has its own rules, by-laws and processes to follow.
- Generally, the large Metropolitan municipalities have processes in place for embedded generation to connect to the system.
- Municipalities should witness and inspect these installations, before permitting them to be commissioned.
- Solely a few municipalities accept excess generation back onto their networks.
- Some municipalities do accept excess generation, however, do not compensate the client for the energy [53].

Municipalities currently differ on whether they allow reverse feed from solar PV SSEG systems, or whether they merely allow SSEG generation to offset 'own use'. Nelson Mandela Bay Municipality intends to allow for full reverse feed. Cape Town does not permit reverse feed on average (averaged over a financial year), however they intend to do so in the future. City Power, in Johannesburg and eThekwini Municipality, will further allow for reverse feed in the future [58].

2.4.3 Requirement for connecting to the grid

Firstly, under the Electricity Regulation Act (Act No. 4 of 2006), all generators connected to the national grid require a generation licence, issued by NERSA [59]. Municipal electricity companies and Eskom distribution, are required to play a major role in supporting and facilitating the implementation of the program at a grass roots level, in particular, in terms of connections, metering and implementing payments to power producers [58].

All residential consumers willing to invest in embedded generating, would be required to be on the TOU tariff. If they are currently on the pre-paid structure, they would be required to migrate to the time-of-use tariff. The Small Scale Embedded Generator (SSEG) tariff, is solely available for net consumers [48].

When connecting to the grid, residential customers may adopt one of two approaches:

- Customers wanting to connect SSEG to the grid, without compensation for the reverse power. These customers are required by the municipality to install reverse power flow blocking protection; this will prevent power flow into the grid [48].

- Residential consumers with installed SSEG, who wish to participate in the SSEG tariff, should have a bi-directional credit meter installed. These meters will be provided and installed by the city at the consumers' cost [60].
- In order to qualify for the SSEG tariff, customers will have excess generation, to regularly require the facility to feed excess power back into the municipal electrical grid. Small Scale Embedded generators will require to be licensed or registered as per act, since they are operated for commercial purpose [61].

2.5. SOLAR PV OPERATING WITH THE GRID

In recent years, the number of residential consumers, with solar powered homes connected to the grid, has increased. Grid connected PV systems provide some or even most of the energy, during the day and night, using the grid when solar irradiance is low [62]. Grid connected PV systems are designed with several components, such as inverter and PV module. The PV module being the main component; converting natural solar energy into direct electricity. The inverter converts the direct current (DC), into alternating current (AC), making it available to the consumer [63, 64].

2.5.1 Grid-tie system (battery free)

Grid-tie systems without batteries, are simple to design and are substantially cost effective, as they possess relatively few components. The main objective of a grid-tied system, is to lower the energy bill and benefit from solar incentives.
This system does not use battery or related battery equipment. It has one function only: it feeds all electric power generated by the solar panels through a DC-AC inverter, supplying the residential load.

A few of the disadvantages of this system, is that it provides no form of backup power during power outage, although the sun is available [65] . This system is mostly used in areas where the grid power is reliable [65]. The schematic diagram of a typical grid connected PV system is presented in Figure. 2.8.

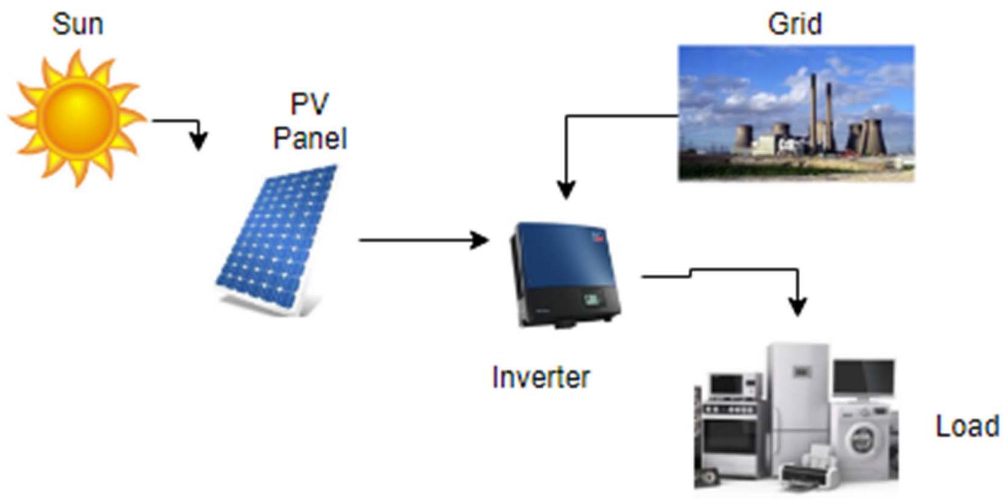

Figure 2.8: Grid-tie PV system without battery storage

2.5.2 Grid-tie with battery backup

Observed above, a PV system with battery storage is fundamentally the same, as with the previous grid tie connected PV system, with the addition of the batteries and charge controller.

Electricity produced by solar panels may be stored in batteries within the design and, furthermore, works in conjunction with local a electricity company to power a household, while electricity from the grid supplements power shortfalls when the solar panels are not producing energy.

The battery charge controller determines whether the power generated by the solar panels is required for home use, to run low voltage equipment and lighting, or whether it will charge the deep-cycle backup batteries, to be used at a later stage [66].

The schematic diagram of a typical grid connected PV system is presented in Figure. 2.9

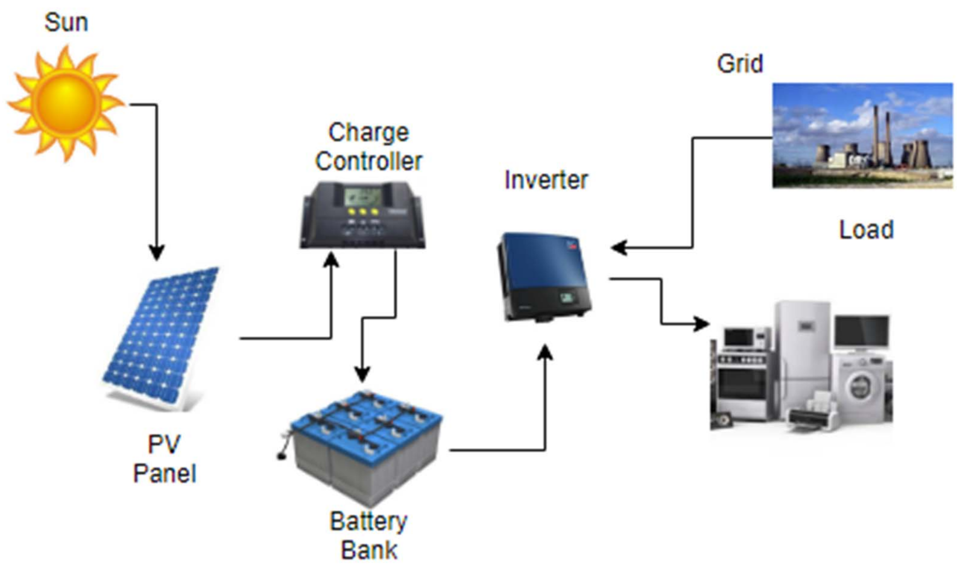

Figure 2.9: Grid-tie PV system with battery storage

2.5.3 Grid Interactive

In grid connected PV systems, electricity flows to and from the main grid, according to sunlight conditions and the actual electrical demand at that time [62].

Feed-In Tariff (FIT), enables customers to reduce their bill by feeding excess usage to the grid at the retail cost. A FIT pays the customer a further rate for selling energy, than the retail rate for consuming energy. Feed-in tariffs require an extra power meter, in order to measure the outflow of electricity from a household independently. This enables electricity consumption and electricity generation, to be priced separately [61].

The considered PV system is a combination of photovoltaic panels and battery banks. By combining a solar PV with a battery storage system, it increases the efficiency and the reliability of the supply. The reliability issues may be overcome by the energy storage system, with accurate power flow management. The energy generated from the solar PV should be regulated and converted from direct current (DC), to alternating current (AC).

This is implemented so that the energy generated by the PV may be utilized in the household and connection to the grid [65, 67].

The schematic diagram of a typical grid connected PV/battery system is presented in Figure. 2.10. The battery bank may be used to provide energy to the load, when the renewable source is absent. The battery bank may be charged from the excess energy, after the load has been satisfied, or it may be charged during the off-peak periods, when the cost of energy is affordable. To respect the protections standards from the municipality, an AC inverter is used to sync the output power to the grid characteristics [68] .

The advantages of installing a grid connected PV system is the straightforward, relatively low operating and maintenance costs and reducing the electricity cost. One of the disadvantages is that the consumer should install a number of solar panels, to generate a required amount of excess power [62].

The schematic diagram of a typical grid connected PV system is presented in Figure. 2.10.

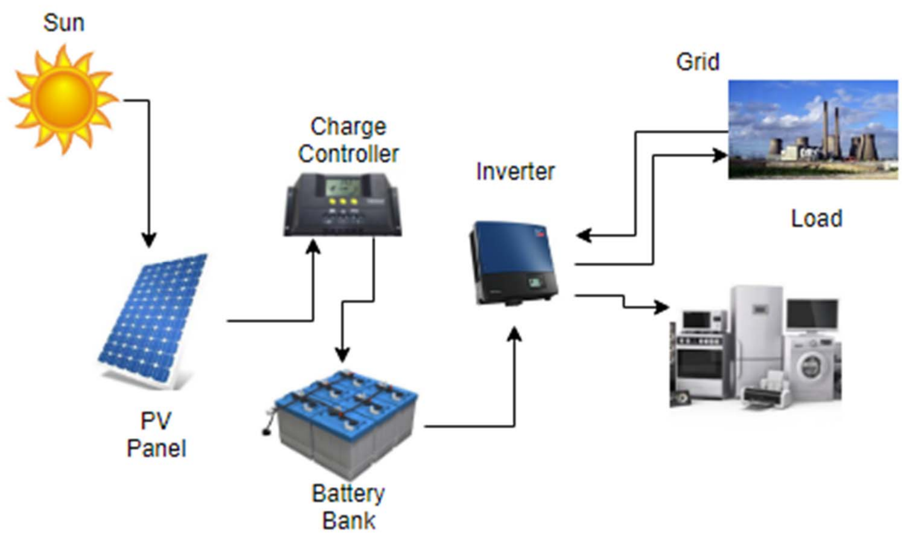

Figure 2.10: Grid-interactive PV system

2.6. RECENT STUDIES ON OPTIMAL ENERGY MANAGEMENT OF GRID CONNECTED SYSTEMS

Various studies have been carried out to develop an optimal energy management model for various electrical systems (renewable or non-renewable). A few studies are based on off-grid systems, while others are based on grid-connected systems. Hence, the following studies focus on the review of recent optimal energy management studies of grid-connected PV systems, applying the TOU and the Feed-in tariff scheme.

2.6.1 Literature on Grid-interactive renewable systems (Internationally)

Below, is a review of recent optimal energy management studies of grid-interactive PV systems conducted. Table. 2.3 focuses on the studies conducted internationally on grid-interactive RE systems and the significant progress made. From Table. 2.3, the majority of the reviewers focused on reducing the consumers electricty bill, by designing an optimal system that takes advantage of the TOU and FIT tariff structure. In most of the reviews, SSEG's have been approved by the local government, with a few of the governments giving incentives to consumers.

Below, Table 2.3 is focused on research being conducted, based on SSEG, followed by Table 2.4, focusing more on the research conducted under the South African SSEG policies.

Table 2.3: International literature

Title	Highlights/Contributions	Tarrif	Technology
Techno-economic feasibility of grid-independent residential roof-top solar PV systems in Muscat, Oman [69]	Implemented roof-top solar PV/battery technologies using a house in Muscat. Results indicated that grid-independent PV systems are not feasible.	Grid-independent PV	PV/battery technologies
Comparative analysis of different grid-independent hybrid power generation systems for a residential load [70]	Examined the techno-economic feasibility of hybrid power generation systems applied to off-grid residence.	Off-Grid	PV-DG,PV-WT,WT-DG, WT-FC.
Pleasure is the profit - The adoption of solar PV systems by	The study focused on implementing PV systems in households.		PV

households in Finland [71]	The results showed that with appropriate information, the consumers are willing to adopt PV systems.		
Performance simulation of grid-connected rooftop solar PV system for small households: A case study of Ujjain, India [72]	Feasibility of grid-connected rooftop solar photovoltaic systems for small households was investigated. The results show that there is an acceptable power generation potential.	Grid-Connected	PV
Residential PV-BES Systems: Economic and Grid impact analysis [73]	Residential PV-BES systems in terms of both technical and economic metrics was investigated. Results shows that the battery systems enabled a much higher self-sufficiency rate, particulary under the time-of-use tariff.	FIT	PV/battery technologies
Residential solar PV policy: An analysis of impacts, successes and failures in the Australian case [74]	The paper presented a deeper analysis of available data focused on residential PV system. With a focus on employment, market maturity, FiT settings and environmental outcomes.	FIT	PV
An optimization-based approach to scheduling residential battery [75] storage with solar PV: Assessing customer benefit	The authors presented a QP-based algorithm for day ahead scheduling of residential battery storage co-located with solar PV.	FIT	PV/battery technologies

Residential consumers' experiences in the adoption and use of solar PV [76]	This paper explores consumer experiences in acquiring solar PV under different feed-in tariffs.	FIT	PV
Optimal battery storage operation for PV systems with tariff incentives [77]	An optimisation model was developed to optimise FiT revenue streams for an existing and new PV generation system, coupled with battery storage. Results showed that the model becomes feasible when the battery charges from the grid when the electricity tariffs are low and discharge at high electricity tariff periods.	FIT, TOU	PV/battery technologies
Techno-Economic Simulation of a Grid-Connected PV System Design as Specifically Applied to Residential in Surabaya, Indonesia [78]	Technical, economic and environmental aspects of PV system for supplying of household electricity energy needs were evaluated. Present time grid-connected PV system not financially viable.	FIT	PV

Dynamic modeling of hybrid energy storage systems coupled to photovoltaic generation in residential applications [21]	PV powered residence in stand-alone configuration was developed and evaluated. The choice of control strategy for a hybrid energy storage system is found to have a significant impact on system efficiency, hydrogen production and component utilization.	Stand-Alone	Fuel cells (RFC), batteries, and ultra-capacitors (UC) both individually, and in combination, as hybrid energy storage devices

2.6.2 Literature on Grid-Interactive renewables energy systems in South Africa

Table. 2.4 presents the available studies conducted in South Africa on grid-interactive renewable energy systems, where authors incorporated the TOU and FIT tariff structures. When comparing the two tables, it is observed that a few of the South African reviewed optimal management studies are grid-interactive, meaning, they allow the energy to be sold into the utility grid and to be purchased from the utility grid, whenever it is economical to do so, based on the TOU rates. Further studies considered in this review, are said to be solely grid-connected and not grid-interactive. This simply implies that they solely allow the purchase of energy from the utility grid, when charges are inexpensive or there is insufficient energy from the RE system. Hence, the energy sales into the utility grid are not permitted.

Table 2.4: South African focused literature

Title	Highlights/Contributions	Tarrifs	Technology
Optimal power dispatch of a grid tied-battery-photovoltaic system supplying heat pump water heaters [50]	An optimal scheduling strategy for a grid-tie PV system with heat pump water heater. The results showed that incorporating the feed-in-tariff it is more economical than solar thermal heaters.	Feed-in-tariff (FIT)	Photovoltaic (PV) system to power a heat pump water heater (HPWH)
Optimal power dispatch of a grid tied-battery-photovoltaic system supplying heat pump water heaters [32]	Presented an optimal management strategy for hybrid systems, that supply an electrical load and a heat pump water heater (HPWH). The objective function of the model was to minimize energy and fuel cost, while maximizing the PV output. The model was investigated under the TOU tariff. The simulations confirmed the effectiveness of the proposed control strategy as it increased the supply reliability of the system.	Time-of-use (TOU) tariff,	Fuel cell/wind/PV /grid hybrid
Optimal energy control of grid tied PV–diesel–battery hybrid system powering heat pump water heater [79]	An optimal scheduling strategy for a grid-tied PV/battery, system to power the HPWH and the domestic load under the TOU tariff scheme.	TOU	PV–diesel–battery hybrid

	The model possessed more economic benefits than solar thermal heaters, as it had the possibility to turn the building into an energy-positive building with the attractiveness of the feed-in tariff.		
Optimal energy management for a jaw crushing process in deep mines [80]	Two optimal control techniques for the TOU based optimal energy management system. Scheduling the hoist under the TOU tariff leads to energy cost saving.	TOU	Compressive crushers
Techno-economic and environmental optimization of a household photovoltaic-battery hybrid power system within demand side management [81]	Power management systems may be applied in a PV-BT hybrid. Demand management, under the TOU tariff was considered. The proposed strategies reduced energy cost and energy consumption from the grid.	TOU	PV-BT hybrid
Optimal scheduling of household appliances for demand response [44]	Residential demand response may be used to minimize electricity cost and earn relevant incentives.	TOU	

	The consumer could realize an electrical cost saving of up to 25%.		
An optimal control model for load shifting – With application in the energy management of a colliery [1]	Optimal control model may be applied, to improve the efficiency through the control of conveyor belts. To minimize the electrical costs, the TOU tariff was utilized. Promising results were obtained from the model.	TOU	
Demand Side Management of Photovoltaic-Battery Hybrid System [82]	Optimal scheduling of small-scale PV-battery systems may benefit the customer on the demand side, under the TOU tariff. The customer reduced the monthly cost.	TOU	PV/battery technologies
Optimal energy cost and economic analysis of a residential grid-interactive solar PV system-case of eThekwini municipality in South Africa [3].	Optimal energy model for a grid-interactive solar PV. For a higher feed-in tariff, the need to have a battery bank became less, however, for lower FIT, the battery bank provided improvements on the cost effectiveness of the system. Profitability of the system increased with an increase in grid electricity price.	FIT	PV/battery technologies
Energy management of a grid-connected hydrokinetic	Optimal power scheduling may be used to benefit the customers.	TOU, FIT	PV/battery technologies

system under Time of Use tariff [83].	Investigated grid-connected PV-batteries, under the TOU tariff. Operational costs are reduced and customers may generate revenue by selling back to the grid.		
Demand Side Management of a grid connected PV-WT-Battery hybrid system [83].	Hybrid system may be operated efficiently under the TOU tariff in South Africa. Consumers may reduce the operational cost and generate an income by selling power to the grid under the FIT tariff.	FIT, TOU	
Optimal energy mix of a microhydro-wind-grid system powering a dairy farm in Western CAPE TOWN [84].	Optimal control strategy of a grid-tied micro hydro-wind power system for a rural dairy farm in South Africa. Minimise grid imported energy cost under Time of Use Tariff (TOU), while at the same time maximizing revenue, generated under the feed-in tariff. Huge energy and cost saving potential of the proposed model, under TOU tariff.	TOU, FIT	WIND , HYDRO
Impact of different South African demand sectors on grid-connected PV systems' optimal energy dispatch under time of use tariff [85].	Analysing the impact of by residential, commercial and industrial load profiles on the daily operational cost and scheduling of grid-connected	FIT	PV/battery technologies GRID

	hybrid systems, with the time-of-use tariff in Bloemfontein, South Africa. Using the proposed set-up in this work, more savings or income is generated from the industrial and commercial sectors than from the residential sector		
The impact of residential rooftop solar PV on municipal finances: An analysis of Stellenbosch [23].	Financial impact that grid-connected rooftop PV at a household level might have on local governments in South Africa. The outcome indicated a financial reduction in total electricity revenue of 0.6–2.4%, depending on the approach followed.	TOU	PV
Novel Intelligent Energy Management System for Residential PV Systems in Non-feed-in Tariff Countries [86].	A new intelligent energy management system was developed for grid-tie residential PV systems. A daily energy saving in the range of $ 2.71 to $ 3.1, making this EMS a feasible solution to implement along with a residential PV system.	FIT, Net Metering	PV

2.7. DISCUSSIONS

From the available literature, various studies based on recent developments of optimal energy management models, under the TOU and the FIT tariff scheme, were considered. These authors used various approaches to solve the challenge, depending on the anticipated outcome. The common goals of the studies were to minimize the electricity imported from the grid. The majority of the authors in the review have focused on the TOU tariff scheme exclusively, not incorporating the FIT tariff. The dominating renewable energies noticed in the studies were PV and wind energy.

- From the research survey carried out on PV policies, considering the FIT applicable to Small-Scale Embedded, it is clear that future research should aim to address the following uncertainties. These uncertainties could be a key factor as to why residential consumers are continuously cautious in making use of the RE systems.
- The FIT incentive should be equal to the price at which the residential consumer purchases electricity.
- A subsidy program, to assist with making the program cost effective, should be initiated by the government.
- Further studies focusing on the pay-back period of the systems, before the consumer begins to make a profit from the system.

2.8. CONCLUSION AND SCOPE OF FUTURE WORKS

Grid-connected renewable energy, implemented by consumers, proves to be beneficial for both the grid and the consumer. The study presented a review, based on recent optimal energy management studies for PV systems integrated with the national grid, under the TOU and FIT tariff schemes, may be beneficial towards the consumer. The energy produced by the solar PV could be boosted by battery capacity, during peak tariff periods, or when solar PV is not sufficient, or does not exist. Alternatively, a battery energy dispatch schedule of the battery will further increase income, by using the stored energy to deliver the loads, since the electricity cost is high during peak hours of the day. Electricity should be imported from the grid throughout off-peak hours to charge the battery. Although there is an additional investment cost for the battery system, by scheduling the battery operation in a smart way, the overall benefits of the system are mainly focused on reducing the reliance on the grid, during costly peak periods. The common goal to be achieved by the optimization studies, is to minimize the customer electricity bills and grid system operation costs.

Based on the review findings, the study has led to the following recommendations for future optimization research:

- Further optimization studies should to be carried out that focus on grid-interactive PV systems, South African based.
- Further studies should to be carried out, to analyze the behaviour of the optimization models, by considering seasonal variability of the load demand and RE resources. The performance of the model should be investigated under both week and weekend days' TOU tariff rates, in order to analyse the effects on the behaviour of the model.

CHAPTER 3: SYSTEM SIZING

3.1. INTRODUCTION

The performance and cost of each component of the PV System are the most crucial parameters to consider before the design process. Hence, an optimal size of the proposed grid-interactive PV with battery storage system should be determined, before developing an optimal energy management model in Chapter 4. With this is mind, HOMER software will be used in this study to determine the system architecture. Input parameters including the recorded load data, solar resource, electricity price structure, as well as on the cost of the different components will be inserted in HOMER software for the sizing of the system [87].

3.2. DATA COLLECTION

3.2.1 Consumer load data

From the demand perspective, the load demand profile is the most significant factor in the optimization process [77]. This is critical for accurately designing an optimal system. The optimal system should satisfy the power demand at any given time and avoid further costs due to oversizing. The household identified for this case study, is in the City of Cape Town, Western Cape. This is a typical South African household with appliances indicated in Table 3.1, that illustrates the power consumption of some of the equipment in the house, along with the number of items and the total consumption expected by each device.

Table 3.1: Load specification for a typical household

Equipment	Power[W]	Number	Total power [W]
Water heating	4300	1	4300
Washing machine	2200	1	2200
Electrical tool	1500	1	1400
Vacuum Cleaner	1400	1	1200
Electric Heather	1200	3	3600
Refrigerator	1000	1	1000
TV	80	2	160
Laptop	65	4	260
Pump	60	1	60
Mixer	20	1	20
Lights	30	8	240
Mobile charger	4	5	20

An energy monitoring device, that measures the energy consumption in real-time, was used to record the load consumption of the house Figure. 3.1 shows various components used by Efergy E2, where: (A) is the current transformer sends through the wireless transmitter; (B) information on the amount of electricity used to a receiver, which has a display monitor; (C) converts this information into kilowatt-hours.

Figure 3.1: Efergy wireless electricity monitor and data logger

Efergy E2 Classic shows real-time usage in Watts and cost per hour. The overall consumption of the household may be viewed by day, week or month. Efergy E2 includes key software features, making it possible to download the recorded data on a regular basis. The software may either be uploaded from the disc or downloaded from the Efergy website.

By installing Efergy E2 in the selected house in Cape Town, the load consumption of the house may be recorded. The energy monitoring device was installed on 01 January 2017 to 31 December 2017, to record the energy variations over a period of one year, including both the summer and winter seasons. The load data will be used in HOMER software to determine the systems sizing. Data collected from Efergy E2 will clearly display the difference in energy usage over the high demand season, and the low demand season when the cost per kWh changes.

Figure. 3.2 shows the annual load data for 2017. It may be noted that the average peak demand usage during the recorded year (2017) was 16.12 kWh/d, with an average peak consumption of 2 kW. During the summer months, the load consumption was significantly less than during winter months, due to the use of heaters.

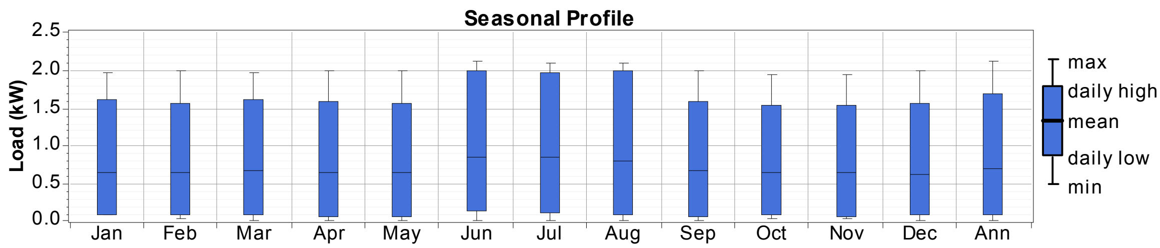

Figure 3.2: Acquired annual residential load demand using Efergy monitoring device

3.2.2 Solar resource data

Solar resource data is typically obtained either by collecting actual ground measurements at the location of interest, or from satellite data. Ground measurements are obtained by using equipment such as pyranometers and silicon sensors, to collect hourly and, at times, sub-hourly data onsite. The other challenges presented by data obtained from ground measurements, include variable standards of calibration, maintenance and measurement periods, as well as uncertainties in the interpolated data. Satellite data sources, on the other hand, typically possess have a wider geographical and historical coverage. They are further not susceptible to the majority of the uncertainties and challenges that ground-measured data sources are prone to.

The solar resource profile for this study has been obtained from the Southern African Universities Radiometric Network (SAURAN) database. Figure. 3.3. shows the solar radiation used in this study. The maximum radiation levels take place during the month of November, December and January. Hence, this reveals that the large amount of PV power may be obtained in the study area.

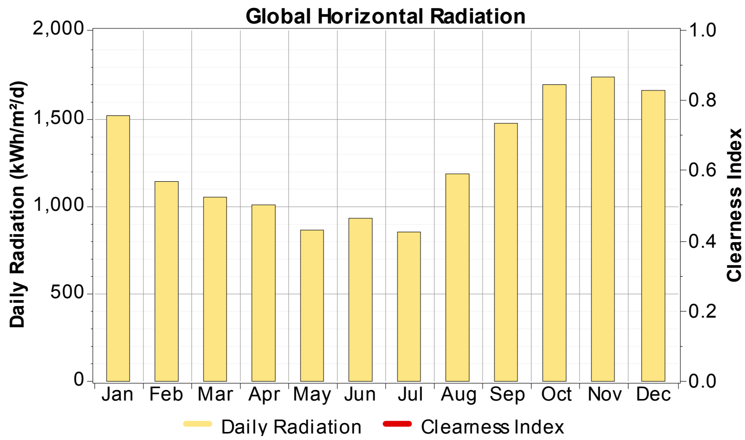

Figure 3.3: Solar radiation data for 2017

3.3. HOMER SOFTWARE

The HOMER software tool developed by the National Renewable Energy Laboratory (NREL) has been selected for sizing a PV with battery storage system. Among different simulation softwares associated with RES sizing, optimal design and planning, HOMER is the simplest and fastest tool to evaluate RES [91, 92]. The HOMER software performs the analysis of the RES systems, by evaluating the system operation and performing cost over the project's lifetime. HOMER software requires cost data for operation and maintenance (O&M), purchasing and replacement. This data is run through the software where it compares all the possible options and gives you the most optimized solution [95].

3.3.1 Economic Methods

The levelized COE, as well as the NPC, are the main economic factors in ranking various system configurations. NPC calculates the present cost of installing and operating the simulated system over the project lifetime, as illustrated in Eq. (1) [96, 97]. The COE computes the average cost per kWh of electrical energy per year, as shown by Eq. (3) [96, 98].

$$NPC = \frac{C_T}{CRF} \tag{3.1}$$

Where: CT is the total annualized costs of the system (ZAR/year) and CRF is the function returning the capital recovery factor, calculated using Eq. (2). ZAR is the South African currency to be used in this study.

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (3.2)$$

Where: *i* is the real interest rate, *N* is the number of years considered for the recovery of the investment.

The levelized cost of energy is calculated as follows:

$$COE = \frac{C_T}{E_{Primary} + E_{Deferrable} + E_{Grid}} \quad (3.3)$$

Where: *Eprimary* is the primary load (kWh/year), *Edeferrable* is the deferrable load (kWh/year) and *Egrid* is the total grid sales (kWh/year).

3.4. SYSTEM SIZING AND COST

Figure. 3.4 presents the schematic diagram for the proposed grid-interactive PV with battery storage system, as used in HOMER software. The following constraints where considered in designing the system:

- The funding available to implement the system,
- The space available on site to implement the system,
- The grid requirement, in terms of power and energy that is permitted to be exported to the grid,
- The energy savings target on the consumer's side.

The proposed system consists of four components, namely, solar PV array, direct current (DC) to alternating current (AC) converter, battery storage bank, primary load, as well as the utility grid. It may be seen that the primary load to be supplied, reaches an average consumption of 14 kWh/day. The solar resource data, along with the load data, was discussed in Section 3.2. The PV specification will be discussed in Section 3.4.1, along with the grid-tie inverter in Section 3.4.2, followed by the battery storage in Section 3.4.3.

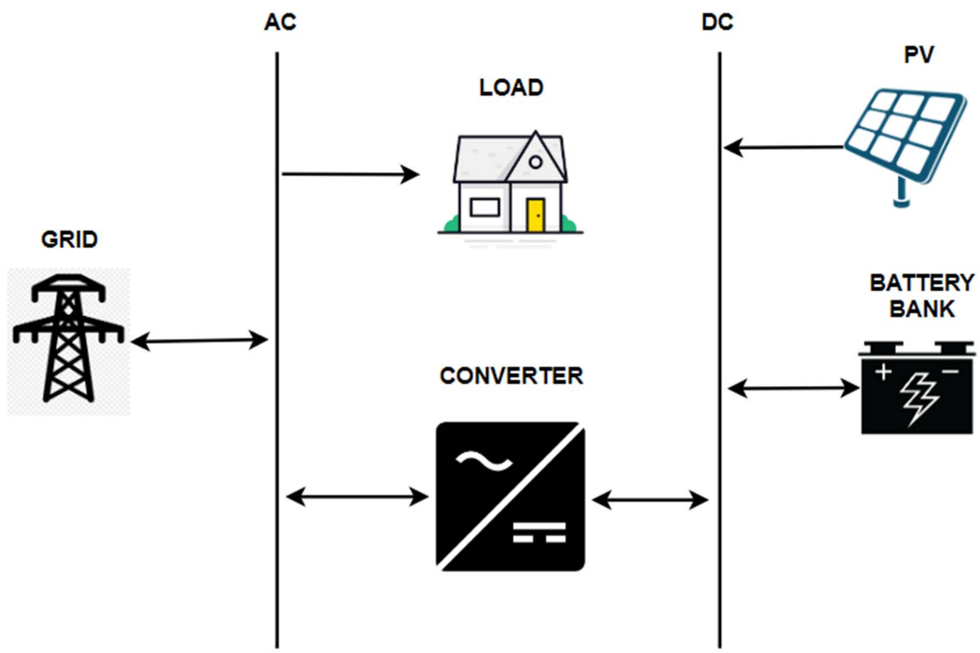

Figure 3.4: Design configuration of PV battery-based grid-interactive system

3.4.1 PV module

The number of PV panels is directly related to the available roof space. The maximum number of panels will be selected in the Homer Software. The PV panel selected based on market price suitable for this study is Renewsys [99]. The average price of a PV panel will be set to ZAR 2000 for a 440W, throughout the simulations [99]. Compared to the capital and installation cost, the O&M cost is minimal. For each kW of PV model, the O&M cost was estimated to be 2% of the installation cost/year [100]. PV lifetime will be set to 20 years throughout the simulations.

3.4.2 Grid-Tie inverter sizing

For this study, the 2 kW Steca single phase grid-interactive inverter is selected. This inverter has a maximum load current of 11.2 A, with an efficiency rate of >94% for PV to battery and >93% for battery to AC [99]. When the load requirement of the residence is observed, it is noticed that the load does not exceed 2 kW peak during summer or winter periods. From the inverter's technical specifications, the inverter has a peak output power of 2.5 kW and a rated output power of 2 kW.

The price of the PV converter used in this study will be set to ZAR 11495 [99]. The converter O&M cost is estimated to be 5% of the total investment per year [95].

3.4.3 Storage batteries

The main aim when sizing a battery bank is the installation of appropriate number of batteries to carry a certain load, particularly when the sunlight is not accessible. The battery storage selected for the design was the Trojan T-105 model. The South African market price of purchasing this battery is ZAR 3195, with a lifespan of 5-7 years [97]. When selecting a battery for a specific application, it is important to consider the amount of amp-hours (AH) that the battery may deliver when discharging at a constant rate. Table 3.2 provides a brief summary of what conditions the user may expect when discharging the battery at a specific temperature for 5, 10, 20 and 100-hours, at peak capacity performance.

It is imperative to note that, in grid interactive PV systems, the size of the battery is mainly determined by the size of the charge controller rating [3]. Based on a number of reviews, the battery bank in a grid-tied system should be sized in such a way that the charging current is between 10% and 20% of the total battery capacity. Trojan T-105 is specifically designed to support renewable energy systems, with large daily loads and its high ampere-hour capacity is ideal for use in large off-grid or grid-interactive PV systems.

Table 3.2: Product specifications [97]

Discharge Rate	Temperature	Amp-Hours (AH)
5-Hr Rate	30^0C	185
10-Hr Rate	30^0C	207
20-Hr Rate	27^0C	225
100-Hr Rate	27^0C	250

3.4.4 Electricity Price

TOU pricing tariff used by South Africa electricity utility (Eskom) will be applied as a case study during simulation [101]. Eskom Ruraflex Gen tariff will be applied as a case study, since it permits the consumer to consume and generate (importers and exporters of electricity) energy at the same point of supply. Table 3.3 shows the Eskom Ruraflex Gen TOU tariff for high and low-demand seasons, as applied to consumers. The high demand season is from June until the end of August, while the remaining months of the year represent the low demand season. The rates include off-peak, standard and peak hours. For this study, the FIT incentive for residential embedded generation used in this municipality will be used as 65% [3].

In this study, all the excess energy, after the load demand has been met, will be sold to the grid. To increase profitability of the system, the FIT and TOU tariff structures will be implemented, as illustrated in figure 3.5. Figure. 3.5 illustrates the different billing periods, as discussed in Table 3.3. The utility grid is the main power supplier, whereas the solar PV system runs in daytime only. Whenever the generated solar PV power is higher than the primary load demand, the excess electric energy may be sold to the utility grid.

Table 3.3: Schedule rates for different times of day

TOU Periods	High-Demand Season (Jun-Aug)	Period Range	Low-Demand Season (Sep-May)	Period Range
Peak Periods	ZAR 3.28 R/kWh	06:00-09:00 17:00-19:00	ZAR 1.07 R/kWh	07:00-10:00 18:00-20:00
Standard Periods	ZAR 0.995 R/kWh	09:00-17:00 19:00-22:00	ZAR 0.7374 R/kWh	06:00-07:00 10:00-18:00 20:00-22:00
Off-Peak Periods	ZAR 0.54 R/kWh	22:00-06:00	ZAR 0.41 R/kWh	22:00-06:00

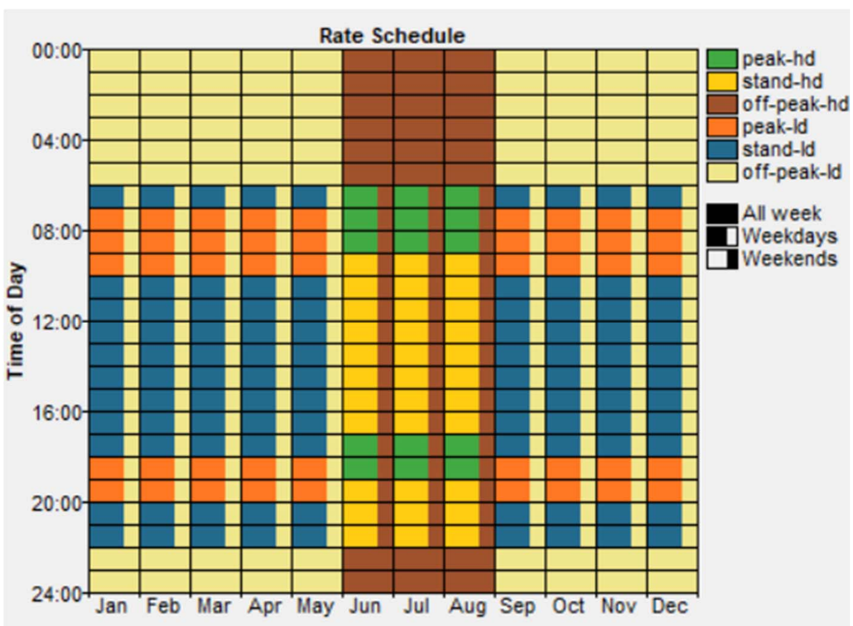

Figure 3.5: TOU schedule for low demand and high demand season as applied by the utility

3.5. SIMULATION RESULTS AND DISCUSSION

HOMER determines the most economical design for the proposed grid-interactive PV with battery storage system, by using the imported data mentioned in Section 3.4 [77]. For this study, the costs related to the installation and labour was excluded. Lastly, in order to improve the accuracy of the results, the simulation was obtained over a period of 1 year, with 8760 hours/year to incorporate the effect the seasonal changes might have. Therefore, the proposed system was simulated to ensure that the load demand is constantly satisfied.

From HOMER optimization results in Table 3.4, represented by a screen shot displaying the summary of outcomes for different sizes of PV with battery storage system combinations. The results in the table are presented from the most affordable option and include values such as the initial capital, operating cost per year and total net present cost.

The chosen optimal system configuration is utilizing a PV system of 2.1 kW, with a 2kW converter and four (TROJAN T-105) batteries.

Table 3.4: Overall optimization results

T-105 Min. Life (yr)		PV (kW)	T-105	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.
4.0		2.1	4	2	1000	$ 2,790	1,477	$ 21,673	0.320	0.56
4.5		2.1	4	2	1000	$ 2,790	1,477	$ 21,673	0.320	0.56
6.0		2.1	4	2	1000	$ 2,790	1,477	$ 21,673	0.320	0.56
7.0		2.1	4	2	1000	$ 2,790	1,477	$ 21,673	0.320	0.56
8.0		2.1	4	2	1000	$ 2,790	1,477	$ 21,673	0.320	0.56
9.0		2.1	4	2	1000	$ 2,790	1,477	$ 21,673	0.320	0.56

The electricity generated by the PV with battery system and the corresponding electricity consumed by the consumer, is shown in Table 3.5. The table shows that the total energy generated by the systems as 9.044 kWh/year, which comprises of 4.444 kWh/year (49%) from the solar PV and 4.6 kWh/year from the grid. The energy generated is utilized as follows: 73% of the energy is used by the consumer and 27% is sold back to the grid.

The monthly average of electricity produced by each component of the system is presented in Figure. 3.6. The monthly and seasonal variations in amount of electricity produced by PV system and contribution from the grid, may be observed from this figure. The amount of solar radiation has a significant effect on the results presented in the figure.

The maximum average monthly power generated by the solar PV during summer periods, is around 0.45 kW and a maximum of 0.4 kW during winter.

Table 3.5: Electricity generated by the solar PV-grid system and end-use consumption pattern.

	Production			Consumption	
	kWh/year	%		kWh/year	%
Solar PV	4.444	49	AC Load	6.022	73
Grid Purchases	4.6	51	Grid Sales	2.252	27
Total	9.044	100	Total	8.274	100

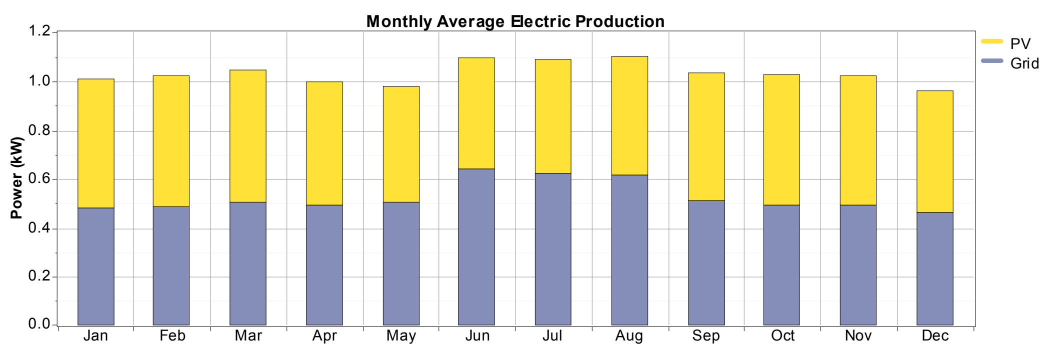

Figure 3.6: Monthly average production from PV and grid

Therefore, the major share of the power during the summer periods is obtained from the PV system with the PV meeting around 49% of the required load. During winter periods, a significant change is seen as the solar resource decreases more of the load is met by the grid. HOMER software utilizes both the grid and the generated PV energy to meet the load requirement and to maintain zero unmet energy by the system.

The yearly scaled data for solar radiation based on hourly load for each day of every month, is shown in Figure. 3.7. The results from figure 3.7, shows that the sun rises at approximately 06h00 in the summer, with the irradiance varying between 0.2 and 0.4 kW/m^2 and sets at approximately 18h00. While the sun rises at 07h30 during winter periods, with the irradiance varying between 0.75 and 0.8 kW/m^2 and sets at approximately

18h00. The peak hours of sunshine are observed to be between 09h00 and 15h00, with irradiance reaching 2 kW/m².

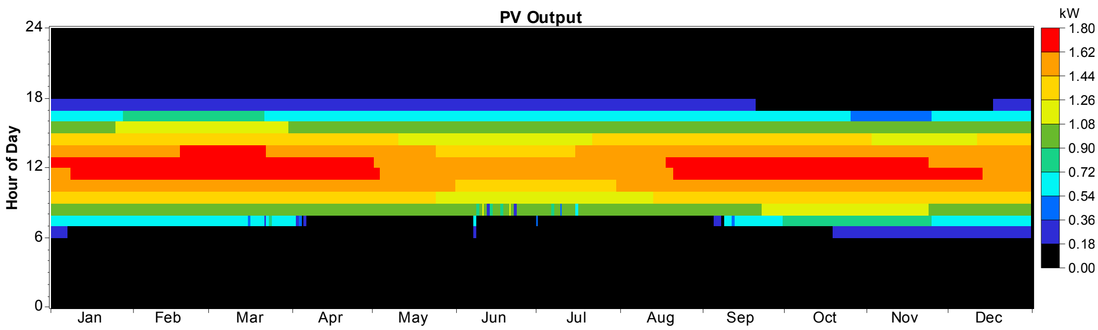

Figure 3.7: PV power output

Figure. 3.8 shows the monthly statistics of the battery state of charge for the entire year and the total amount of energy contained in the battery. Figure. 3.9 presents a detailed, hourly state of charge of the batteries for each month during the simulated period. Figure. 3.9 shows that the battery remains fully charged from 09h00 to 18h00 during summer periods (January to May and September to December), having a minimum state of charge around 18h30. During winter periods (June to August) the batteries are never fully charged, reaching a minimum state of 30% around 07h00 in the morning and 18h30 in the evening.

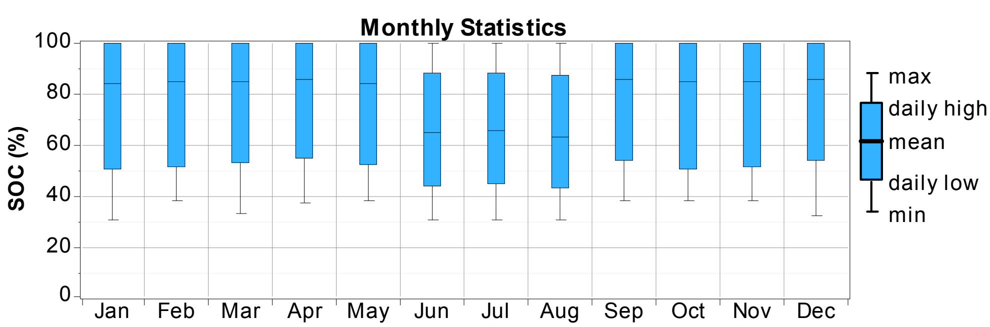

Figure 3.8: Battery state of charge for the year 2017

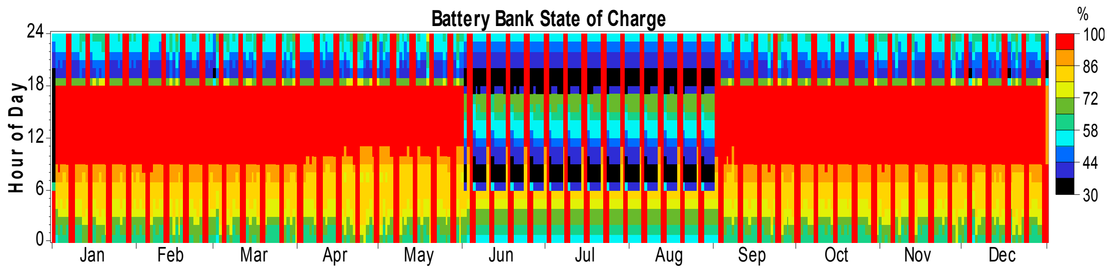

Figure 3.9: Hourly state of charge of the batteries.

Figure. 3.10 and 3.11, represent the inverter output and rectifier output. Figure. 3.10 shows that the majority of the DC to AC power conversion takes place during midday. The opposite may be seen in Figure. 3.11, where the model solely converts AC to DC power in the morning and the evenings.

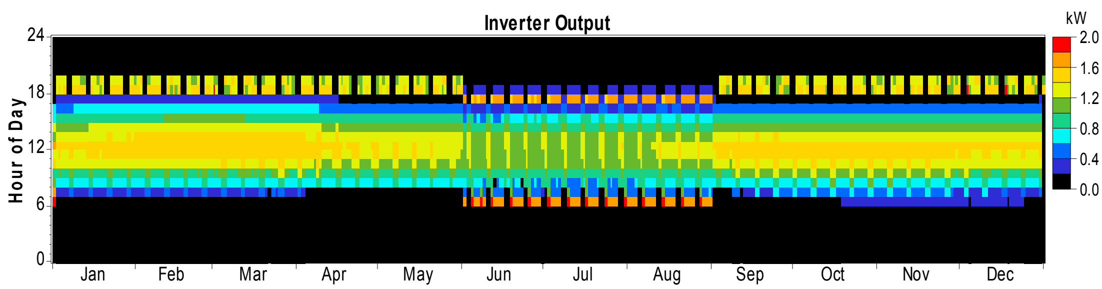

Figure 3.10: Inverter output power

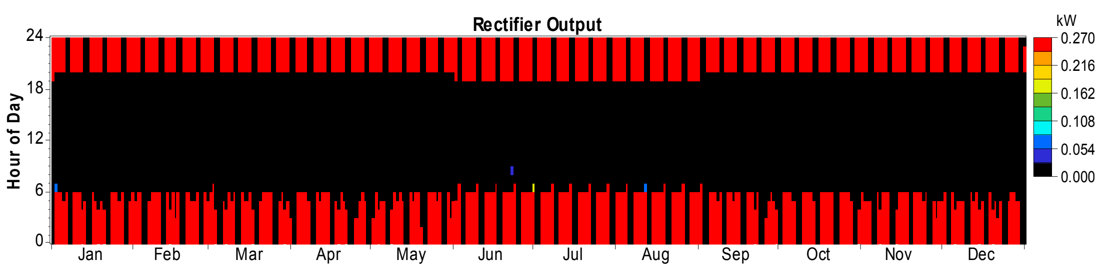

Figure 3.11: Rectifier output power

3.6. Power flow analysis

The following section presents a detailed analysis of the power flow during the simulation. For simplicity, a day in the low demand season and a day in the high demand season was selected.

3.6.1 Low Demand (January 2017)

The simulation results for the low demand season is represented in Figures. 3.12 to 3.15.

- The system behaviour from 00h00 to 06h00

Figure. 3.12, illustrates the load profile and PV output power for 12 January 2017. During this period, the load profile remains constant for the first 3 hours, then rapidly increases, reaching a maximum of 1.48 kW. Figure. 3.13 presents the energy sold to the grid, vs the energy purchased from the grid. Figure. 3.13 shows that no energy is exported, however, that the consumer imported energy from the grid. The battery state of charge in Figure. 3.14, shows that the batteries are charged during this period.

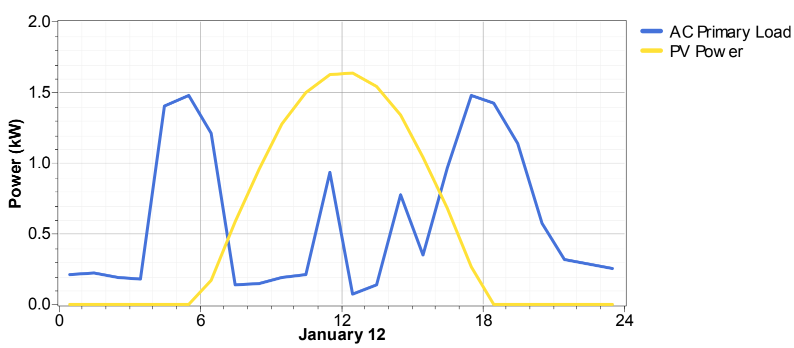

Figure 3.12: PV output power and load profile

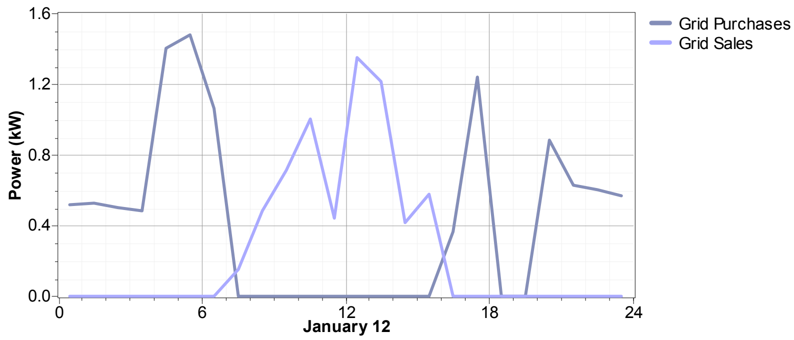

Figure 3.13: Grid purchases vs grid sales

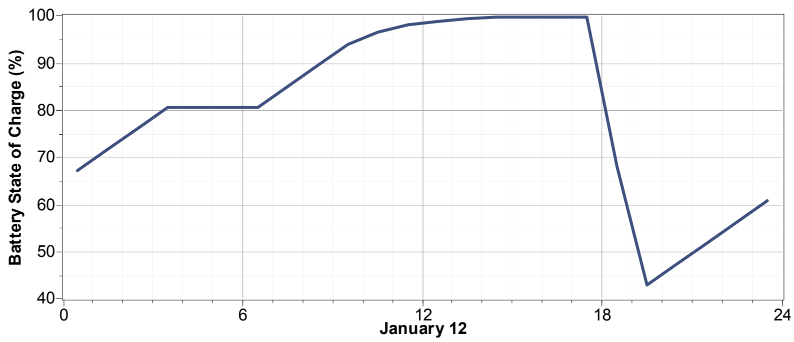

Figure 3.14: Battery state of charge

- The system behaviour from 06h00 to 12h00

Figure. 3.12 shows a rise in solar radiance, as the output power of the PV reaches a peak of 1.7 kW. As the consumer starts preparing for work the load demand reaches a peak of 1.3 kW around 06h00. During this period Figure. 3.13 shows that the amount of energy imported from the grid starts reducing. It may further also be seen that the consumer starts selling energy to the grid. Figure. 3.14 shows that the batteries continue to charge. The power flow of the inverter which converts electricity from DC to AC is presented in Figure 3.15. Figure. 3.15 shows that power is flowing through the inverter, reaching a peak power flow of 1.4 kW. The challenge with the power flow through the inverter, is that it is not possible to determine from where it originated. The inverter may be supplied from the PV or the battery bank.

- The system behaviour from 12h00 to 18h00

Figure. 3.12 shows that during this period, the PV output power starts reducing as the sun sets. Figure. 3.12 further shows that the load remains constant for most of this period and only begins to increase at approximately 17h00. Figure. 3.13 shows a reduction in the amount of energy exported. Figure. 3.14 shows that the batteries continue to charge, reaching 100% state of charge. Figure. 3.15 shows a reduction in the amount of energy flowing through the inverter.

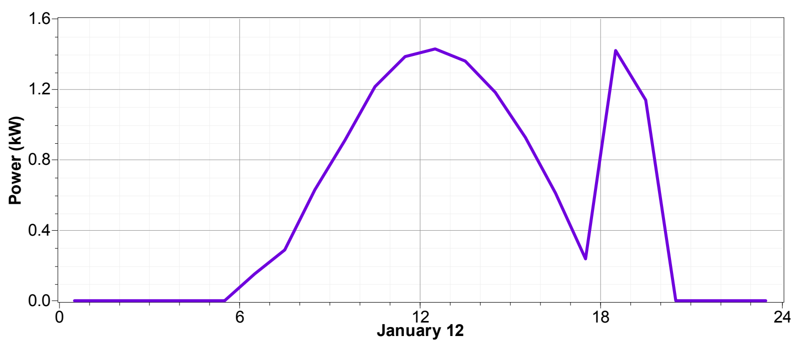

Figure 3.15: Inverter input

- The system behaviour from 18h00 to 24h00

Figure. 3.12; shows that during this period, the PV power flowing remains zero, while the load demand has a significant increase. During this period, Figure. 3.13 shows that the amount of energy imported remains relatively low. The state of charge of the batteries continues to discharge, reaching a minimum of 60% at the end of the day.

3.6.2 High demand (July)

The simulation results for the high demand season are represented in Figure. 3.16 to 3.19.

- The system behaviour from 00h00 to 06h00

Figure. 3.16, illustrates the load profile and PV output power for 1'st June 2017. During the period there is no solar radiation available. Meaning the PV output power remains zero.

Figure. 3.17 presents the energy sold to the grid vs the energy purchased from the grid. Figure. 3.17 shows that the consumer solely imports energy during this period. Figure. 3.18 shows that, during this period, the batteries are charged.

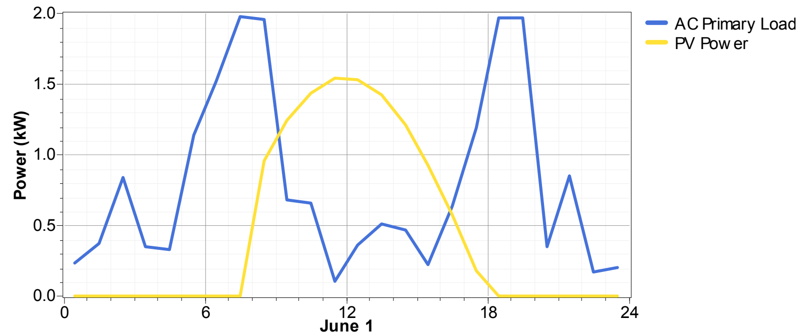

Figure 3.16: PV output power and load profile

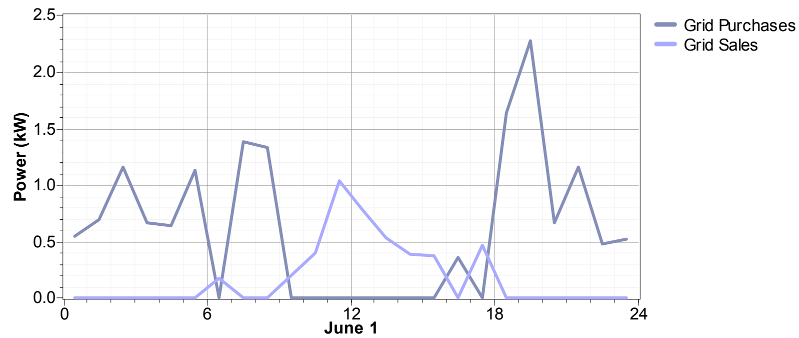

Figure 3.17: Grid purchases vs grid sales

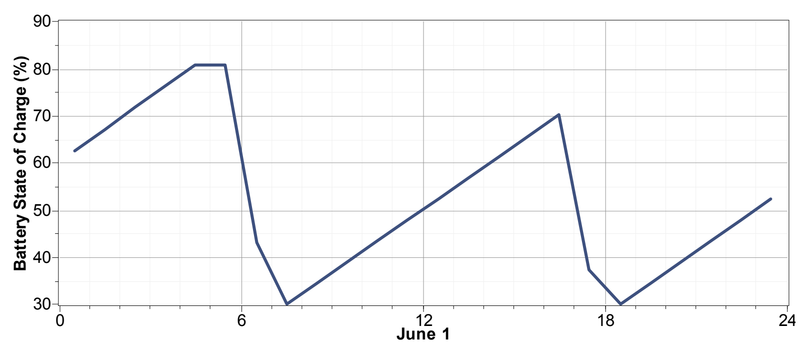

Figure 3.18: Battery state of charge

- The system behaviour from 06h00 to 12h00

Figure. 3.16 shows an increase in the output power of the PV, which reaches a peak of 1.5 kW. As the consumer starts preparing for work, the load demand reaches a peak of 1.93 kW. Figure. 3.17 shows a decrease in the amount of energy imported from the grid. Figure. 3.18 shows that the batteries are used during the first hours, reaching a minimum of 30%, where the batteries start charging again after 07h30. Figure. 3.19 shows that the inverter reaching a peak of 1.7 kW during this period. The inverter converts DC power to AC power and to approximately analyze the behaviour of the system, it is important to know whether the power is converted from the PV or from the battery bank.

- The system behaviour from 12h00 to 18h00

Figure. 3.16 shows that during this period, the PV output power starts reducing as the amount of solar radiance reduces. The load demand increases significantly, reaching a peak of 1.5 kW at 18h00. Figure. 3.17, shows an increase in the amount of energy imported, reaching a peak of 2.3 kW. Figure. 3.18 shows a sharp decrease in the state of charge, from 70% to 35%. Once again, the inverter reaches a peak of 1.7 kW during this period.

- The system behaviour from 18h00 to 24h00

Figure. 3.16 shows that, during this period, the PV power remains at zero, while the load demand starts to reduce. Figure. 3.17 shows that no energy is exported during this period. Figure. 3.18 shows that the batteries are charged.

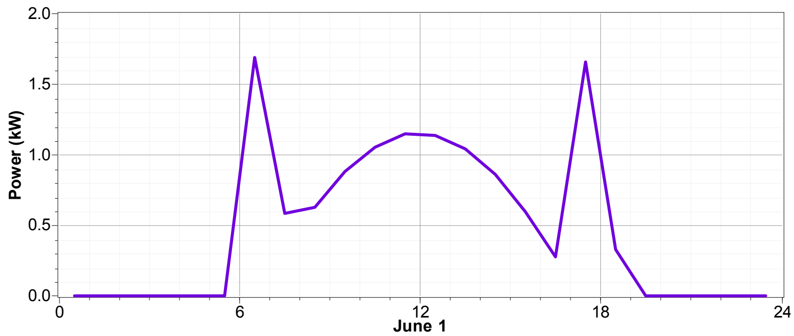

Figure 3.19: Inverter input

3.7. SUMMARY

The main goal of this chapter, was to conduct a sizing and techno economic analysis on the proposed grid-interactive system. Before the start of the design phase, a detailed study on data input collection had to be performed. In this study, the Efergy E2 monitoring device was used to obtain the load data from a residential premise for one year. The simulation, performed with HOMER, required an imported file that contains the annual load profile, with the annual solar resource data covering 8760 points, simulating one year. This file was created using Excel, which was further adapted for HOMER. Solar resource data used in the simulation was gained from SAURAN, which an initiative of the Centre for Renewable and Sustainable Energy studies. For HOMER to perform the economic, evaluation the most available components in the marketplace should be selected. These components include the PV panels, batteries and the grid-tie inverter.

The results from Section 3.5, revealed that the load demand was adequately met at no shortage and incurred levelized cost of energy of ZAR 5/kWh. This section further highlighted that the reliance on the grid went from 100% to 51%, with the PV producing 49% of the required energy. The results further revealed that HOMER avoided importing energy from the grid during peak billing periods, however, the battery state of charge had a vital impact on the amount of energy imported during peak periods. From Figure. 3.9, which presents the battery state of charge, it may be seen that the battery state of charge at the end of each day varies and is not constant. From the inverter output power presented in Figure. 3.10, the majority of power flow takes place during the day, while the inverter power flow graph does not indicate which component supplied the inverter during this time. In order to investigate this challenge, one day was selected in both the summer and winter seasons, for further analyses, presented in Section 3.6.

In Section 3.6, the power flow of each component was presented in the figures. These figures presented the power flow for the selected day. The results from Section 3.6, demonstrated that it is not possible to analyze the power flow of each component at a specific time frame, as Homer does not permit the following specific power flows:

- The power flow from the PV to the load,
- The power flow from the PV to the grid,
- The power flow from the PV to the battery bank,
- The power flow from the battery bank to the load,
- The power flow from the battery bank to the grid,
- The power flow from the grid to battery bank,
- The power flow from the grid to the load.

HOMER solely provides the option of plotting the power flowing through the inverter and rectifier.

Hence, this limitation denoted that there is a continuous need to model an optimal energy management scheme, allowing the consumer to analyze the power flow in each component, allowing the consumer to make an optimal decision. An optimal energy management model should be developed.

CHAPTER 4: OPTIMAL POWER CONTROL FOR A GRID INTERACTIVE PV AND BATTERY STORAGE SYSTEM

4.1. INTRODUCTION

This chapter presents an optimal energy management algorithm for a grid interactive PV and battery storage system. Due to the limitation specified in Chapter 3, this chapter aims to design a model that will provide a greater insight into the power flowing through each component. The proposed model should be able to minimize the energy imported from the grid, while creating revenue for the consumer, based on the TOU and FIT tariffs, respectively. Because of the complexity of the mathematical algorithm, MATLAB software will used to percieve the cost saving benefit of the model. Since the problem consists of non-linear constraints, "fmincon", a function in MATLAB's operational toolbox, will be used.

4.2. MODEL DEVELOPMENT

4.2.1 Description of Grid-Interactive PV with battery storage system

The configuration/power flow layout of the proposed grid-interactive PV with Battery storage system, is as shown in Figure. 4.1. This system consists of the utility grid, PV and battery storage.

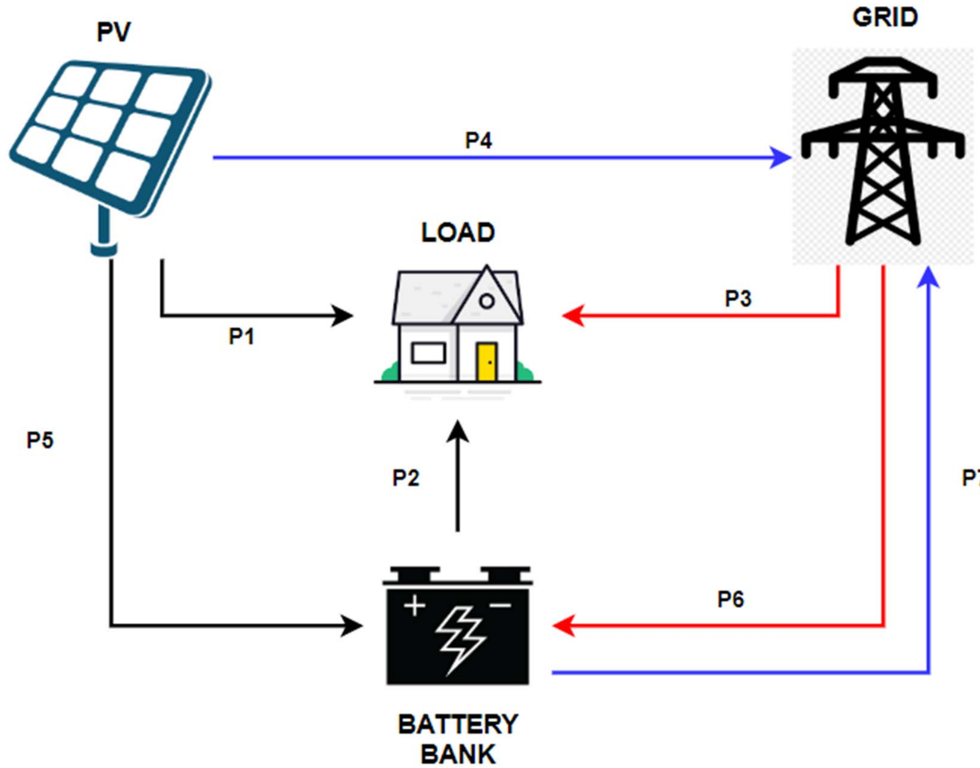

Figure 4.1: Layout of the grid-interactive PV with battery system

As the solar PV (kW) is generating more power than required by the load, the power will be used to charge the battery bank (P5) and the excess power will be sold to the grid through (P4). The load may either be supplied from the PV (P1), or the battery bank (P2). As the load demand is fully met, the exsess energy could be sold to the grid, under the residential FIT, through P7 and P4. The amount of energy imported under the TOU tariff through P6 and P3, will depend on the battery state of charge, power flow from the PV and the load demand shortage.

The objective function and constraints will be formulated through the use of the following variables associated with the system power-flow diagram, shown in figure 4.1:

- P_1: Is the electrical power flow (kW) from the PV to the load;
- P_2: Is the electrical power flow (kW) from batteries to the load;
- P_3: Is the electrical power flow (kW) from the grid to the load;
- P_4: Is the electrical power flow (kW) from the PV to the battery;
- P_5 : Is the electrical power flow (kW) from the PV to the batteries;

- P_6 : Is the electrical power flow (kW) from the grid to the batteries;
- P_7: Is the electrical power flow (kW) from the batteries to the grid.

4.2.1.1 Objective function

The control objective of the grid interactive PV with Battery storage system, will be to minimize the net electricity cost under a given period. This is defined as the difference between the electricity cost, due to the power imported from the grid, (P6+P3) and the electricity revenue, due to the power exported to the grid, (P4+P7). A crucial point for this study will be to determine the optimal time for consuming grid electricity and for selling the onsite generated PV energy to the grid, under the TOU and FIT tariff, respectively. Some of the municipalities have agreed to permit consumers to sell the generated electricity at a pre-determined price per kWh.

In this study, the consumer will be conpensated a fixed percentage of the variable selling price (TOU). This fixed percentage is customarily selected, to allow the selling cost to be less than the utility retail cost. Hence, in this study, a fixed percentage is assumed to be 65% of the utility retail cost [3].

Since the proposed model aims at minimizing the grid cost, while maximizing the energy sales revenue, the objective function (residental premises - RP) is expressed as follows:

$$RP = \sum_{j=1}^{N}(p_j \, P_{IMP_j} - cP_{EXP_j}) \times t_s \quad (1 \leq j \leq N) \tag{4.1}$$

Where:

- j will be the j^{th} sampling interval;
- N is the total number of sampling intervals;
- t_s is the sampling time;
- p is the TOU electricity tariff;
- c is the FIT electricty tariff;
- P_{EXP} (kW) is the power being exported from the grid and P_{IMP} (kW) is the power being imported from the grid.

4.2.1.2 Constraints

The objective function stated above will be subjected to the following constraints:

a) Equality constraint

In electrical circuits, the power balance is a particularly important constraint that should be met. The noted of the system is expressed as follows, by neglecting the losses in the nodes:

$$P_{LOAD_j} = P_{1_j} + P_{2_j} + P_{3_j} \qquad (1 \leq j \leq N) \qquad (4.2)$$

b) Non-Linear equality constraints

The consumer cannot import and export power from and to the grid at the same time. This means the product between P_{IMP} and P_{EXP} should be zero, written as:

$$P_{IMP_j} \times P_{EXP_j} = 0 \qquad (1 \leq j \leq N) \qquad (4.3)$$

The consumer cannot allow the simultaneous charging and discharging of the battery. This means that the product between the power flowing into the battery (charging) and out of the battery (discharging), should be zero.

$$(P_{5_j} \times P_{6_j}) \times (P_{2_j} \times P_{7_j}) = 0 \qquad (1 \leq j \leq N) \qquad (4.4)$$

c) Control variables limits constraints

The optimization problem consists of five control variables, that should be firmly limited to operate within their minimum limits (zero) and maximum operating levels, arrording the design specifications. These power constraints limits (kW), are expressed as follows:

$$\left.\begin{array}{c} P_{PV_j^{MIN}} \leq P_{PV_j} \leq P_{PV_j^{MAX}} \\ P_{B_j^{rated}} \leq P_{B_j} \leq P_{B_j^{rated}} \\ P_{IMP_j^{MIN}} \leq P_{IMP_j} \leq P_{IMP_j^{MAX}} \\ P_{EXP_j^{MIN}} \leq P_{EXP_j} \leq P_{EXP_j^{MAX}} \end{array}\right\} \quad (1 \leq j \leq N) \qquad (4.5)$$

Where:

- j is the j^{th} sampling interval;
- $P_{i_j^{MAX}}$ = is the maximum generated power;
- P_i^{rated} = is the rated power of the component.

d) Fixed final state

To ensure that the simulation allows for repeated implementation of the optimally controlled system, the battery energy remaining at the end of a control horizon should be equal to the amount at the start of the control horizon. This is equivalent to equating the SoC at the last sampling interval, SoC_N, to the initial condition, SoC_0. To ensure this behaviour, the following constraint should to be satisfied:

$$\sum_{j=1}^{N}(P_5 + P_6) - \sum_{j=1}^{N}(P_2 + P_7) = 0 \qquad (1 \leq j \leq N) \qquad (4.6)$$

e) State Variables

The state of charge of the battery should be maintained between its minimum and maximum values. To ensure that the battery does not discharge completely, to minimize the degradation of the battery and maximize the lifespan of the battery:

$$SoC_j = SoC_{(j-1)} + \Delta t. \left[\left(P_{5_j} + P_{6_j}\right). \eta_c - \left(\frac{P_{2_j} + P_{7_j}}{\eta_D}\right)\right] \quad (1 \leq j \leq N) \qquad (4.7)$$

Where:

- j is the j^{th} sampling interval;

- $SoCj$ is the SoC at the current sampling interval;
- $SoC_{(j-1)}$ will be the previous sampling interval;
- η_D is the discharging efficiency of the battery.

4.3. SIMULATION RESULTS AND DISCUSSION

The optimization problem is non-linear due to the constraints. Hence, Fmincon solver in MATLAB will be used to deal with the non-linear nature of the optimization problem.

4.3.1 Baseline: Consumers' demand entirely supplied by the utility company

In order to validate the effectiveness of the derived model, the operating cost from the proposed system is assessed against the one archived as the residential consumer solely relying on the grid.

In Figure. 4.2, the system behaviour achieved during low demand season (summer period), when the grid is used as the main source of energy to supply the consumer's load demand. From the graph it is noticed that the consumer's peak consumption occurs during the high pricing period. Both from 05h00 to 08h00 and again from 17h00 to19h00, is when the price of electricity is highest.

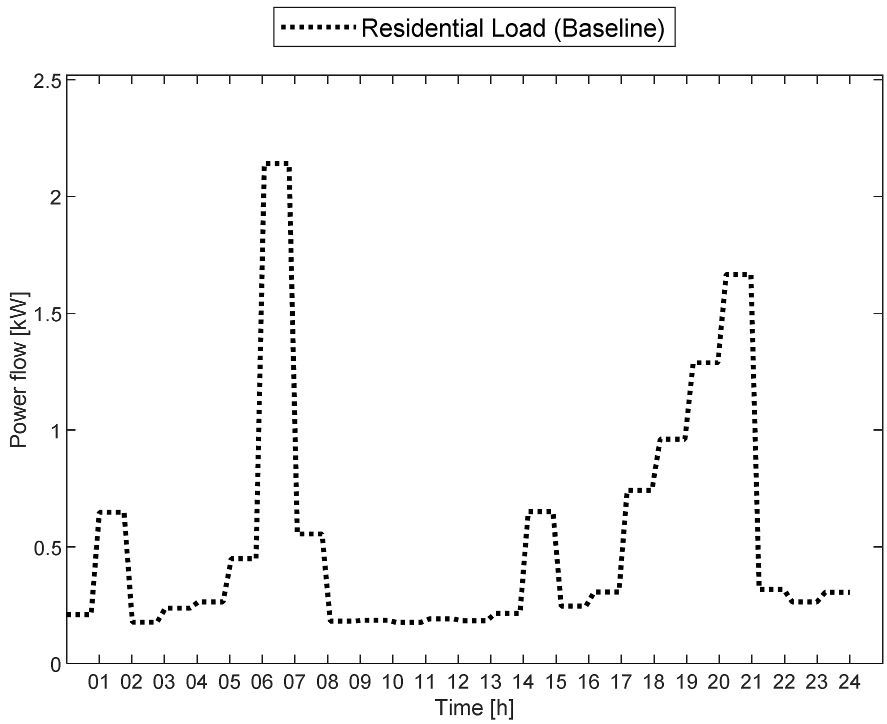

Figure 4.2: Baseline consumption during low demand season

Figure. 4.3, displays the behaviour of the consumers load demand during high demand season (winter period), when completely dependant on the utility as a source of power. When analysing Figure. 4.3 and 4.4, a comparison is identified. The consumer uses the majority of the electricity during peak pricing periods.

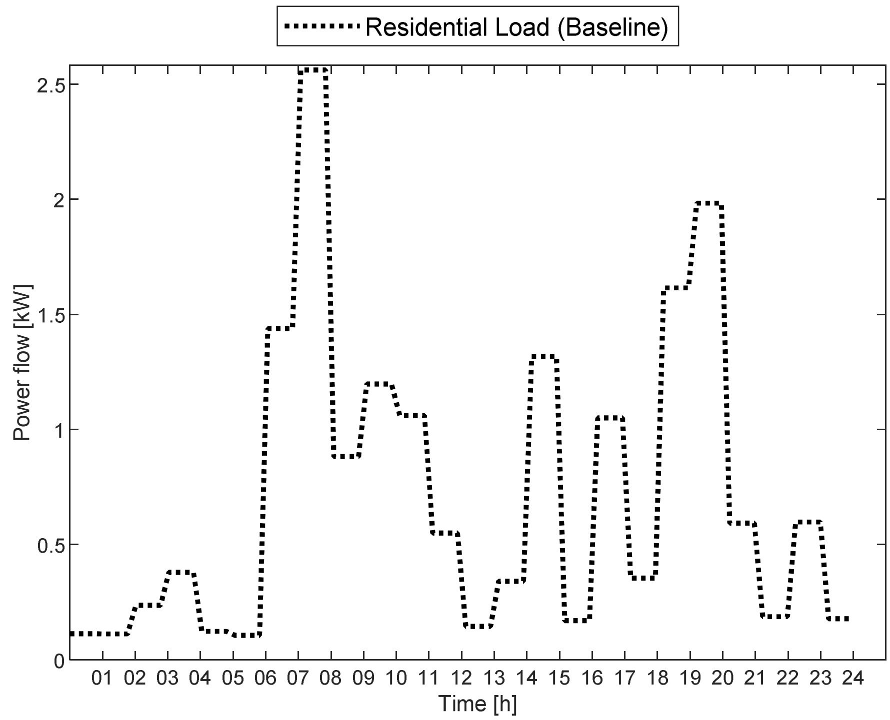

Figure 4.3: Baseline consumption during high demand season

4.3.2 Optimal control of the proposed grid-interactive PV with battery storage system

The optimal control results for the residential load during high demand season are discussed in Section 4.3.1.1 and the results for the low demand season are discussed in Section 4.3.1.2.

Therefore, to accurately determine the cost benefits, the baseline cost will be determined for both the high and low demand seasons.

The parameter of the PV with battery system for meeting the residential load demand, are as given in Table 4.1.

Table 4.1: Simulation parameters for the grid-tie systems

Parameters	Values
Sampling time (Δt)	30 min
PV rated power	2.1 kWp
Battery nominal capacity	3.78 kWh
SoC_0	85%
SoC^{MAX}	100%
SoC_{MIN}	20%
η_{Ch}	85%
η_{Dis}	95%

4.3.2.1 Low Demand Season

The following section presents the results for the data recorded on 12 January 2017 and are displayed in Figures. 4.4 – 4.16. Figures 4.4, 4.5, show that the non-linear constraints, discussed in Section 4.2.1.2 (b), are implemented in the model. Figure. 4.4 shows that the model obeys the constraint in Eq 4.2 not permitting power to be imported and exported simutaneously. The same is seen in Figure. 4.5, which does not permit the battery to charge and discharge simutaneously, shown in Eq 4.3.

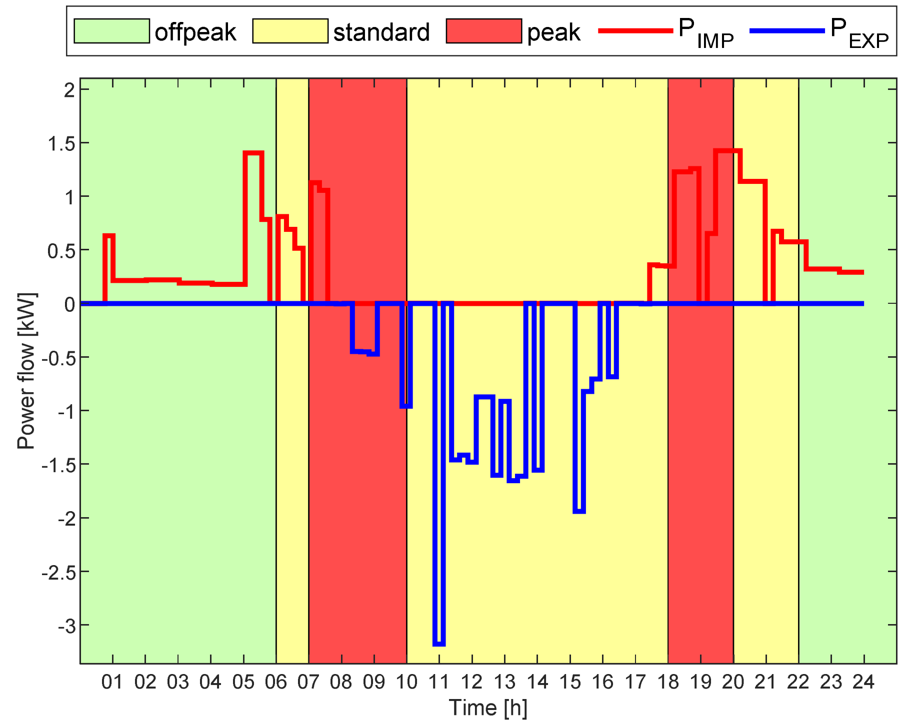

Figure 4.4: Overall power imported and exported (summer)

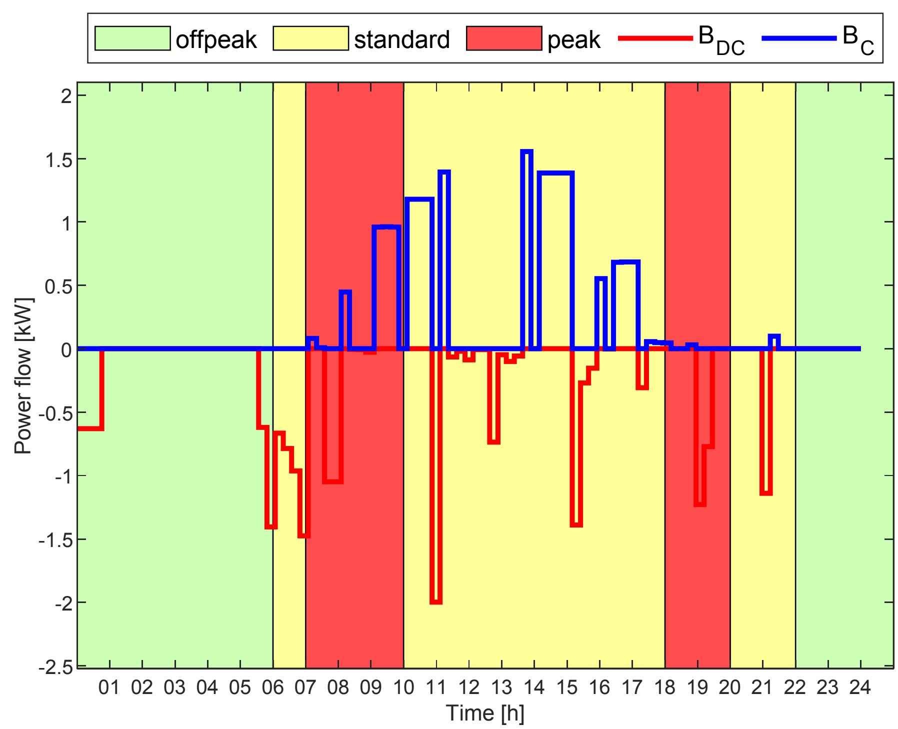

Figure 4.5: Overall Battery charging and discharging (summer)

The system behaviours with the specific optimal operation decision, for each sampling time j, are discussed according to the different pricing intervals, as defined in Table 3.3, namely peak, standard and off-peak periods.

a) Systems behaviour during the first off-peak pricing interval from 00h00 to 06h00 (Green).

- From 00h00 to 01h00

From Figure. 4.6, the residential load reaches a peak of 0.63kW, between 00h00 and 01h00. Figure. 4.7 shows that the model uses the battery to meet the load during between 00h00 and 01h00. Due to the power from the battery, Figure. 4.8 shows that the battery state of charge dropped from 80% at 00h00, to 72.5% at 01h00. Figure. 4.9 shows that the grid is not being used.

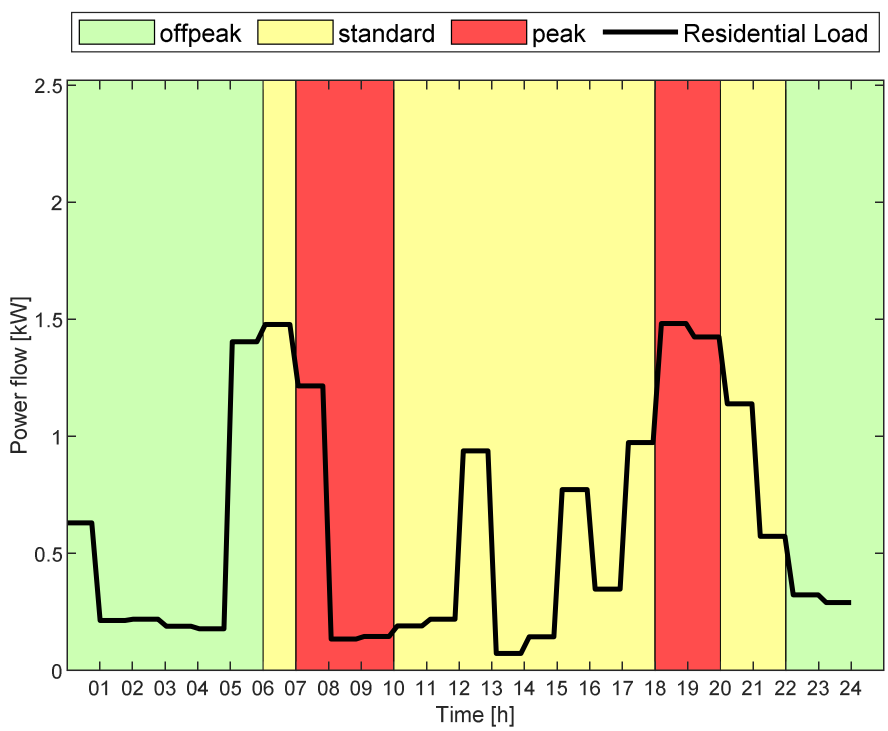

Figure 4.6: Residential load under TOU tariff

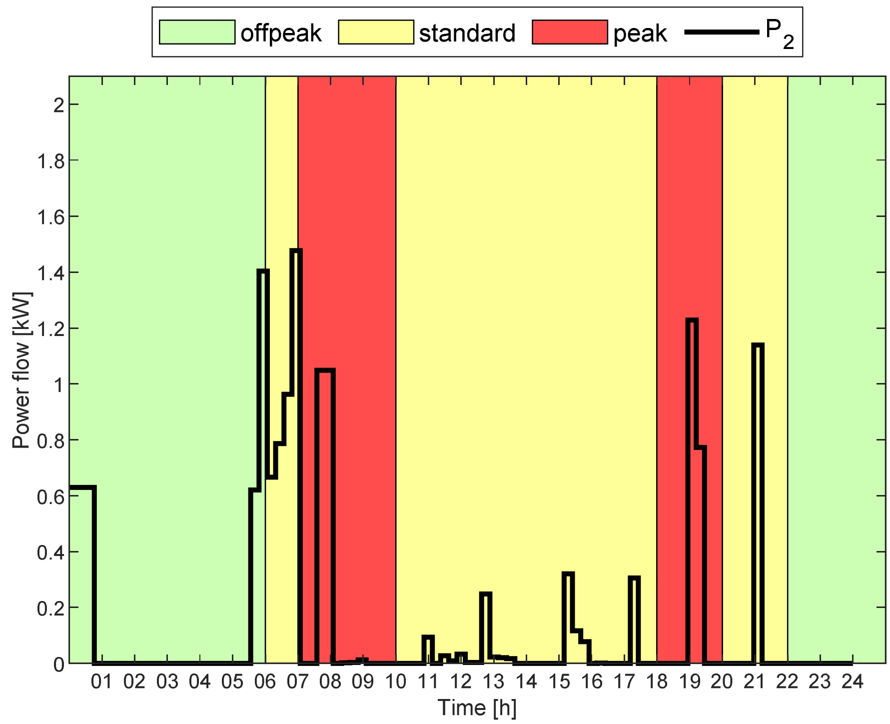

Figure 4.7: Power flow from battery to load

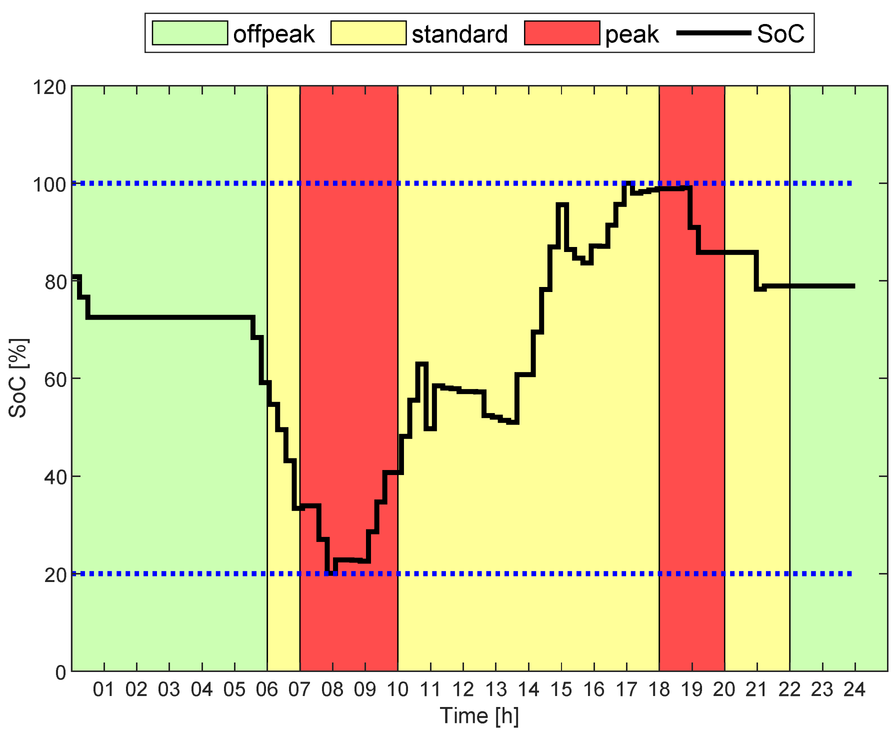

Figure 4.8: Battery state of charge

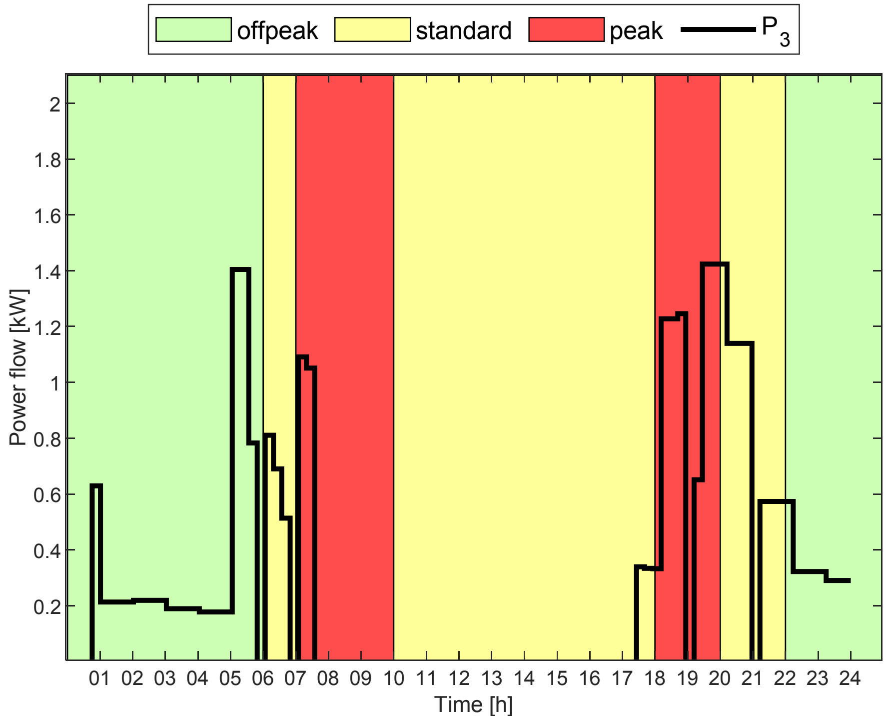

Figure 4.9: Power flow from the grid to the load

- From 01h00 to 05h00

From Figure. 4.6, the load remains constant and does not exceed a maximum of 0.2 kW. During this period, all the load demand is met by the grid, seen in Figure. 4.9, representing the power flow from the grid to the load.

b) Systems behaviour during the standard pricing interval from 06h00 to 07h00 (Yellow)

- From 06h00 to 07h00

During this period, the load demand reaches a maximum of 1.4kW, seen in Figure. 4.6. The model uses both power from the grid and power from the battery storage, to supply the load. Figure. 4.7 shows that the model uses the power from the battery as a first option to supply the load. Figure. 4.8 shows that the battery state of charge reduces at a high rate, reaching a minimum of 33%. Due to the high discharge rate of the battery bank. the model imports power from the grid, shown in Figure. 4.9, in order to prevent the battery bank from discharging completely.

c) System behaviour during the first peak pricing interval from 07h00 to 10h00 (Red)

- From 07h00 to 07h30

From 07h00 to 07h30, the load reaches a maximum of 1.2 kW, shown in Figure. 4.6. As the sun rises between 06h00 and 07h00 in the summer, Figure. 4.10 shows the solar PV has begun to generate power, reaching a rate of 0.172kW. Figure. 4.11 shows that 0.1661 kW of power is used to supply the load, while the remaining power is used to charge the battery bank, shown in Figure. 4.12. Figure. 4.13 shows that 0.082 kW further imported from the grid, to charge the battery bank. Figure. 4.9 shows that the grid is used to supply the remaining load.

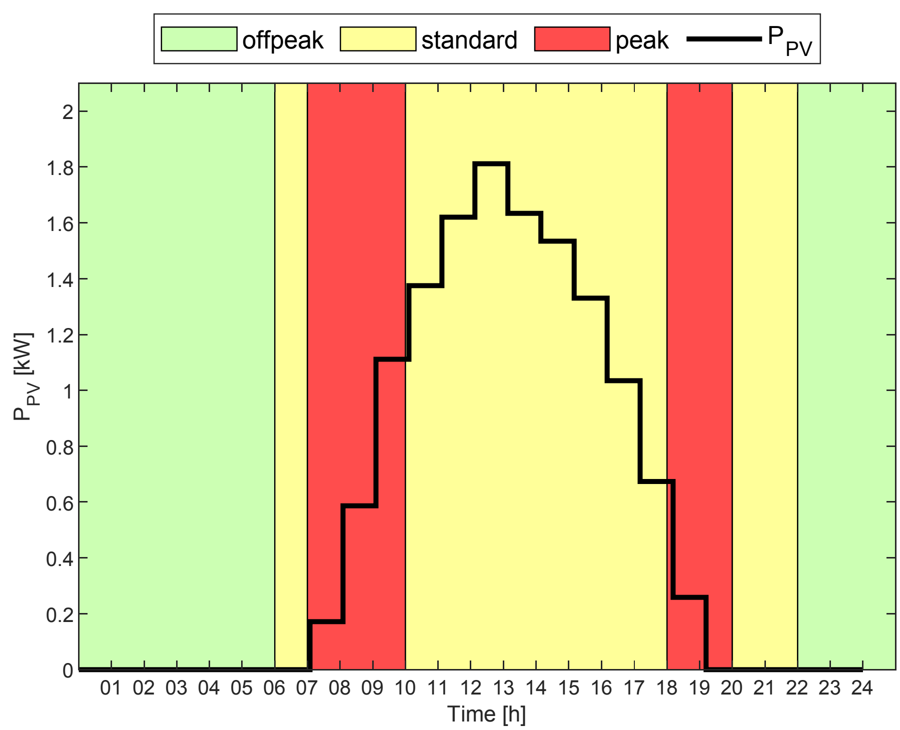

Figure 4.10: PV power flow

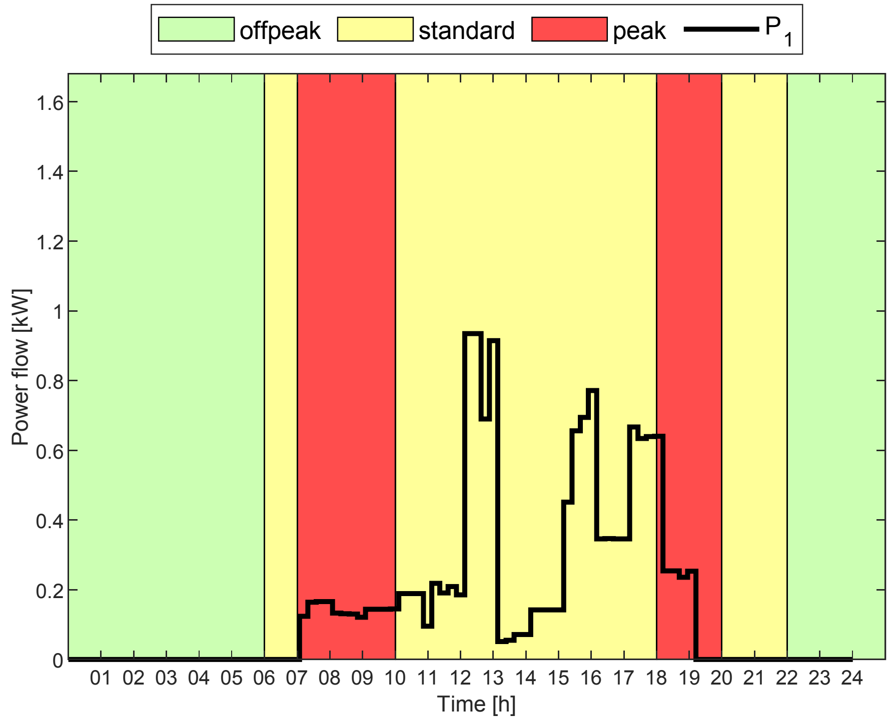

Figure 4.11: Power flow from PV to load

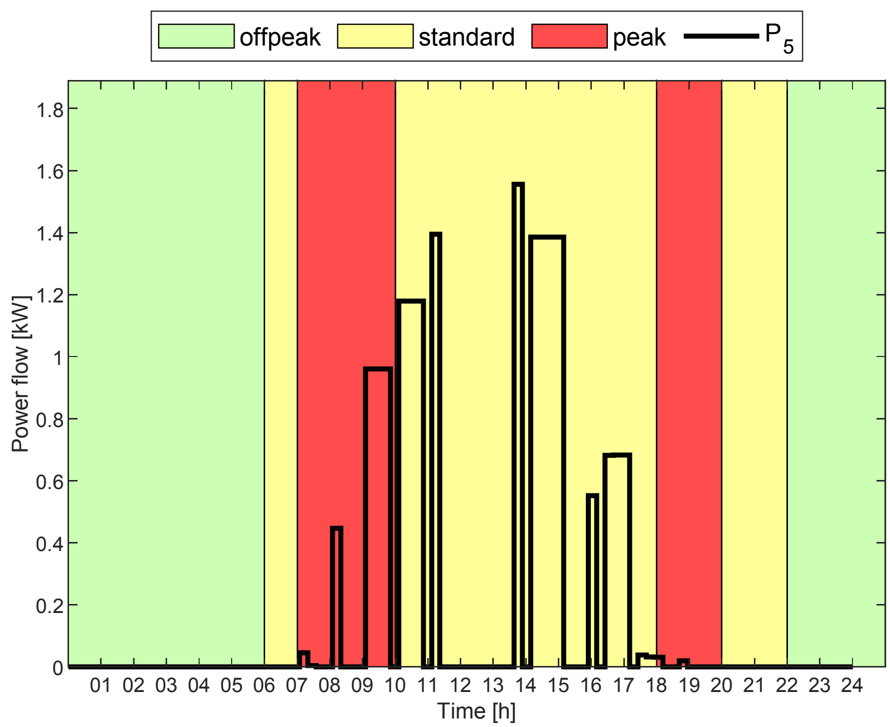

Figure 4.12: Power flow from the PV to the battery bank

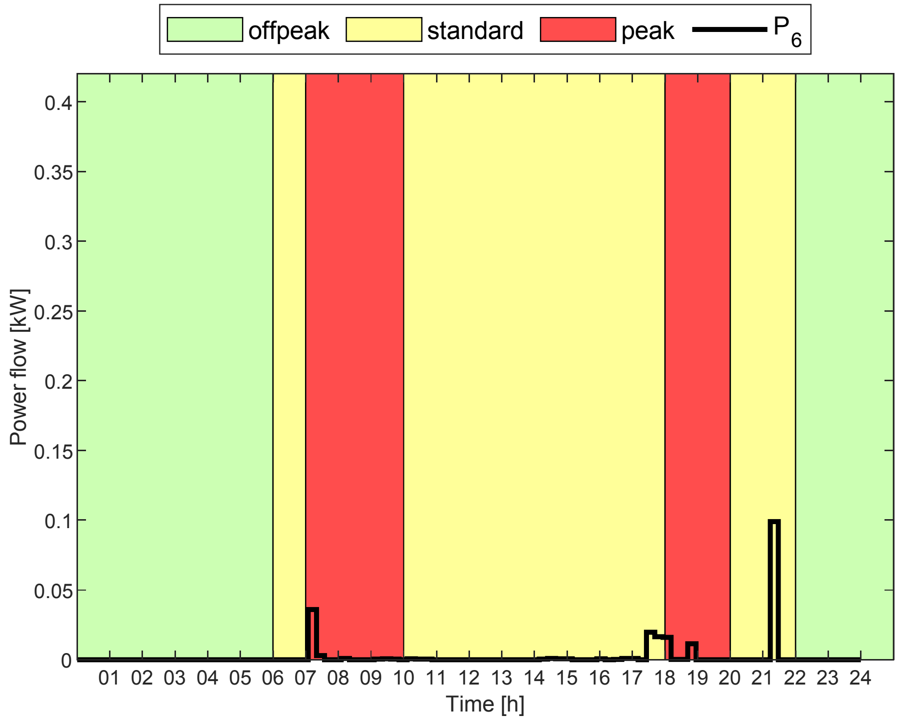

Figure 4.13: Power flow from grid to battery

- From 07h30 to 08h00

The load demand and the PV power remain constant from the previous interval. Figure. 4.4 shows that no power is being imported from the grid at this time. With no power being imported, the model uses the available PV power to supply the load. From Figure. 4.10, the PV solely produces 0.172 kw and is not sufficient to meet the entire load demand. The model uses power from the battery bank to supply the unmet load demand, shown in Figure. 4.7. As the load is supplied from the battery bank, Figure. 4.8 shows that the battery bank reaches its minimum discharging of 20% at this time.

- From 08h00 to 09h00

As the consumers leave for work, the load reduces and remains constant at 0.13 kW, shown in Figure. 4.6. At this point the PV power starts increasing and reaches a maximum of 0.586 kW, shown in Figure. 4.10. The amount of PV power generated exceeds the load demand, making it possible to sell power to the grid, as shown in Figure. 4.4. The model uses the power from the PV to supply the load first, before using the power elsewhere. Figure. 4.12, shows that the model allows the PV to charge the battery bank from 08h00 to 08h30 with 0.44kW. After 08h30, the model does not permit the battery to be recharged, instead the PV power is sold into the grid, as shown in Figure. 4.14.

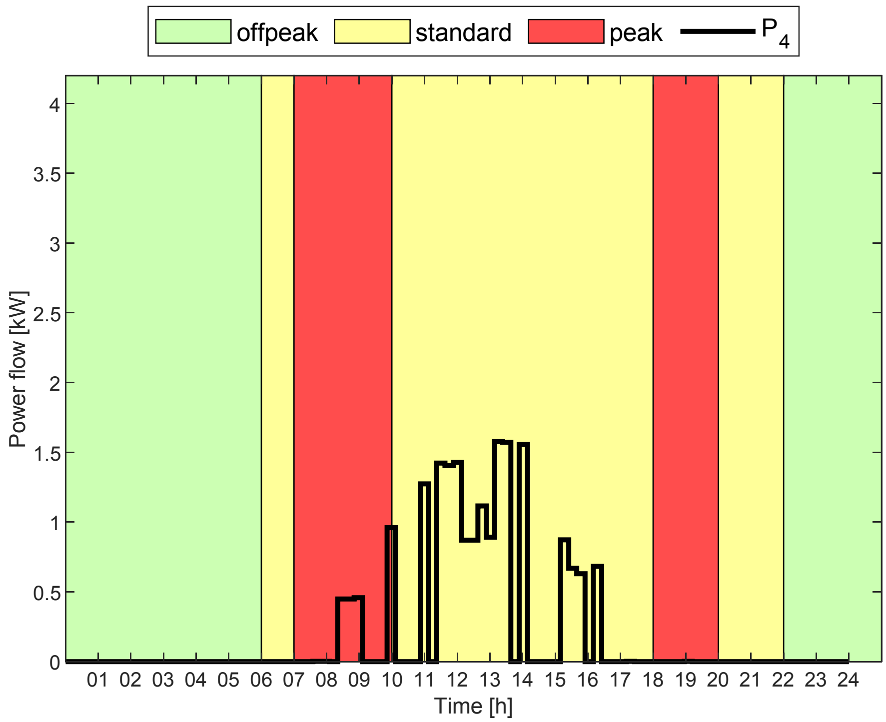

Figure 4.14: Power flow from the PV to the grid

- From 09h00 to 10h00

As the sun continues to rise, more power is generated by the PV reaching 1.11 kW. At this point, Figure. 4.12 shows that most of the PV generated is used to charge the battery bank, with minimal power used to supply the load, shown in Figure. 4.11. As all the PV power is used, the model does not export or import power, shown in Figure. 4.4.

d) System behaviour during the second standard pricing interval from 10h00 to 18h00 (Yellow).

- From 10h00 to 11h00

Figure. 4.10, shows that the PV generated approximately 1.375 kW exceeding the amount of power required to meet the load demand. Figure. 4.12 shows that the majority of the power from the PV is used to charge the battery bank, with 1.179 kW flowing to the battery bank and 0.1897 kW to the load. At 10h50, the model stops charging the battery bank and exports energy to the grid, shown in Figure. 4.14. At this point the model starts using the battery bank to supply 0.093 kW to the load and exports 1.9 kW, shown in Figure. 4.15.

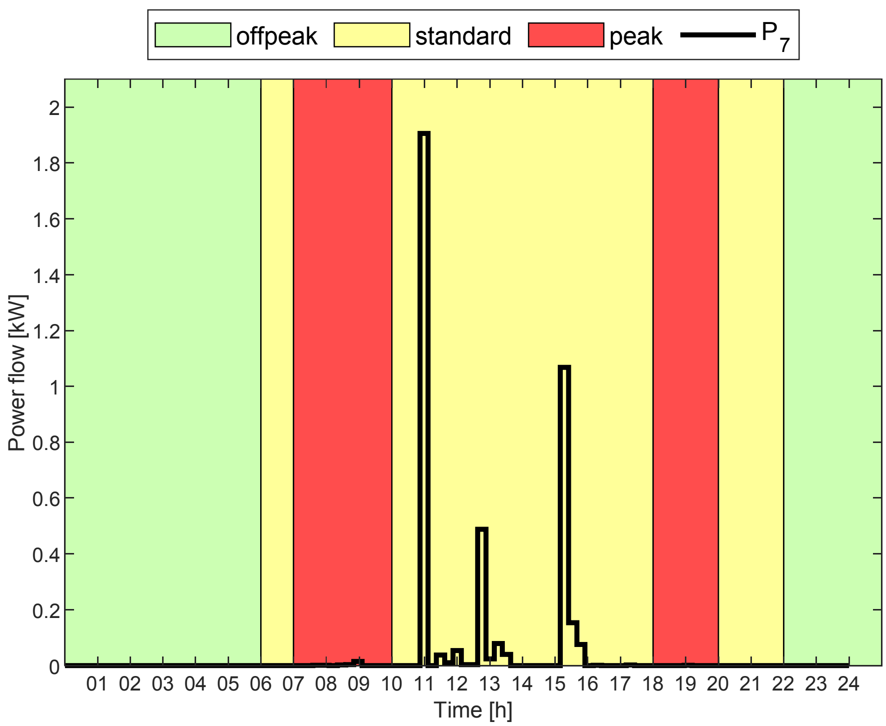

Figure 4.15: Power flow from the battery bank to the grid

- From 11h00 to 12h00

At the start of 11h00, power is continuously sold from the PV and the battery bank to the grid, shown in Figure. 4.4. The load demand is supplied through power from the PV (Figure. 4.11) and the battery bank is shown in Figure. 4.7.

- From 12h00 to 13h00

Figure. 4.6 shows that the load demand increases up to 0.938 kW during this time interval. Figure. 4.11 shows that the PV is used to supply the load, as the PV generates a maximum of 1.8 kW, shown in Figure. 4.10. Figure. 4. 14 shows that the remaining power from the PV is sold back to the grid. Around 12h30, the battery state of charge starts reducing, shown in Figure. 4.8, as the model starts using the battery bank to supply a part of the load, shown in Figure. 4.7 and sells power to the grid, shown in Figure. 4.15.

- From 13h00 to 14h00

During this time interval, the load demand reduces to 0.072 kW and is supplied by the battery bank Figure. 4.7 and the power from the PV, Figure. 4.11. The remaining power from the PV is sold back to the grid, shown in Figure. 4.14. From Figure. 4.15, shows that the model sells power from the battery bank to the grid.

- From 14h00 to 15h00

Figure. 4.10 shows that the PV generates 1.5 kW, which is used to supply the load in Figure. 4.11. The remaining PV power is used to charge the battery bank, shown in Figure. 4.12 and allows the battery bank to reach a charging capacity of 93%.

- From 15h00 to 16h00

Figure. 4.6 shows that the load demand increases, reaching 0.77 kW. Figure. 4.10 shows that the PV generates 1.3 kW, which is used to supply the load in Figure. 4.11 and then, the excess power is sold into the grid, as shown in Figure. 4.14., as the battery bank state of charge is at 93%, the model further sells power from the battery bank back to the grid in Figure. 4.15, reducing the battery state of charge to 83%.

- From 16h00 to 17h00

Figure. 4.6 shows that the load demand remains at approximately 0.34 kW. Figure. 4.10 shows that the PV continues to generate a maximum power of 1.03 kW. The model continues to significantly rely on the PV power to supply the load, as shown in Figure. 4.11. For the first 20 min, the model sells the excess PV power back to the grid, as shown in Figure. 4.14, where it then starts using the power to charge the battery bank, as shown in Figure. 4.12.

- From 17h00 to 18h00

Figure. 4.6 shows that the load demand starts increasing, reaching 0.937 kW. As the amount of PV power generated reduces, the model no longer sells power back to the grid, shown in Figure. 4.14, however, rather uses the power to supply the load. At 17h30, the model starts importing power from the grid and uses it to charge the battery bank in Figure. 4.13 and supply the load in Figure. 4.9.

e) System behaviour during the second peak pricing interval from 18h00 to 20h00 (Red)

- From 18h00 to 19h00

As the consumer starts preparing dinner, the load demand increases rapidly to 1.48 kW, shown in Figure. 4.6, to meet the load the model imports 1.2 kW from the grid shown in Figure. 4.9. The remaining load is met through the PV power, shown in Figure. 4.11.

- From 19h00 to 20h00

As the load demand remains at 1.4 kW, the model uses the battery bank to supply the load for the first 30 min, shown in Figure. 4.7. Where the model starts importing power from the grid to supply the load, shown in Figure. 4.9.

f) System behaviour during the third standard pricing interval from 20h00 to 22h00 (Yellow)

- From 20h00 to 22h00

During this time interval, the model uses the grid to supply the load shown in Figure. 4.9. Figure. 4.8 shows that the battery state of charge remains constant, as no power is used from the battery bank. The model solely uses the battery to supply the load at 21h00, reducing the battery state of charge to 78%. The reason the model uses power from the battery bank, was to obey the fixed final state, discussed in Section 4.2.1.2.

g) System behaviour during the second off pricing interval from 22h00 to 24h00 (Green)

- From 22h00 to 24h00

During this time interval the load demand remains below 0.3 kW and is supplied from the grid, shown in Figure. 4.9. Figure. 4.16 presents the net energy consumption for the day. From the figure, the consumer reduced the amount of power imported from 14.69 kWh to 7.39 kWh.

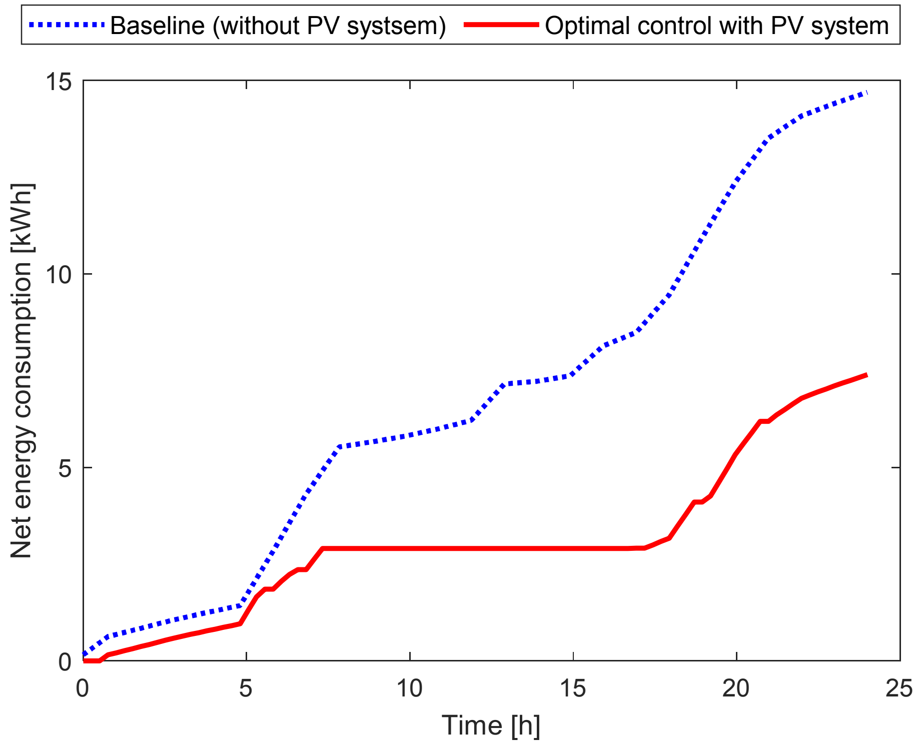

Figure 4.16: Net energy consumption (summer)

4.3.2.2 High Demand Season

The following section presents the results for the data recorded on 1 June 2017 and are displayed in Figures. 4.17 – 4.28. Figures. 4.17, and 4.18, show that the non-linear constraints discussed in Section 4.2.1.2 (b), are implemented. Figure. 4.17 shows that the model obeys the constraint in Eq 4.2, not permitting power to be imported and exported simutaneously. The same is seen in Figure. 4.18 which does not permit the battery to charge and discharge simutaneously shown in Eq 4.3.

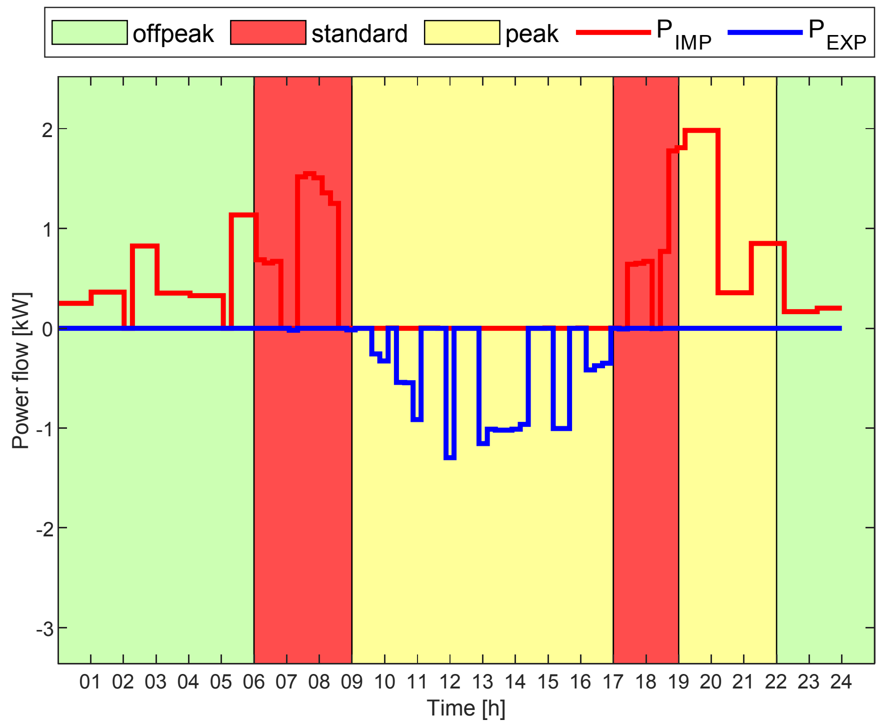

Figure 4.17: Overall power imported and exported (summer)

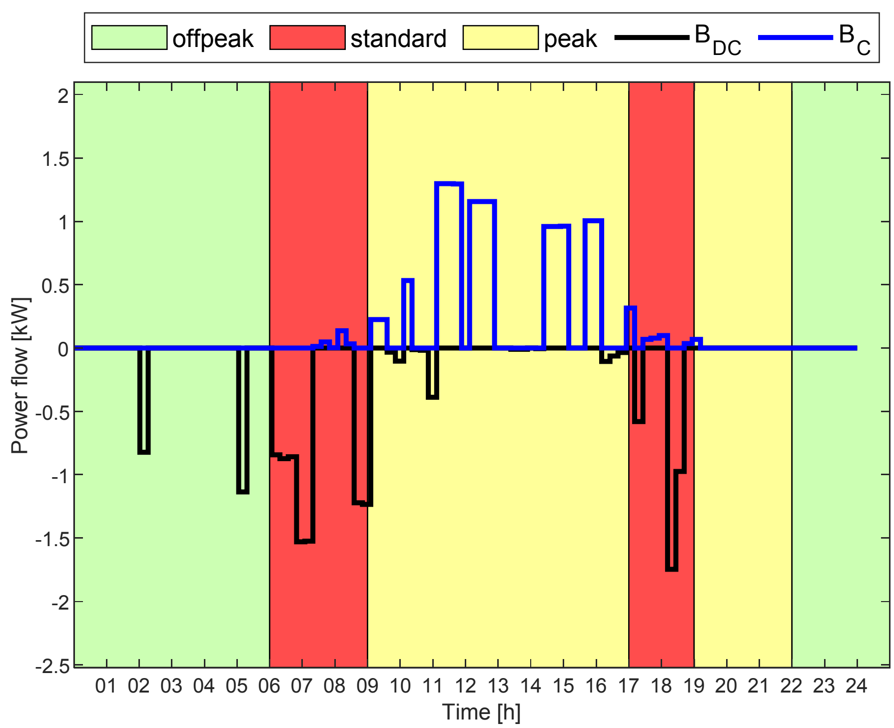

Figure 4.18: Overall battery charging and discharging (winter)

The system behaviours, with the specific optimal operation decision for each sampling time j, are discussed according to the different pricing intervals, as defined in Table 3.3, namely peak, standard and off-peak periods.

a) System behaviour during the first off pricing interval from 00h00 to 06h00 (Green)

- From 00h00 to 02h00

From Figure. 4.19, the residential load reaches a peak of 0.36 kW between 00h00 and 02h00. Figure. 4.20 shows that the model imports all power from the grid to supply the load.

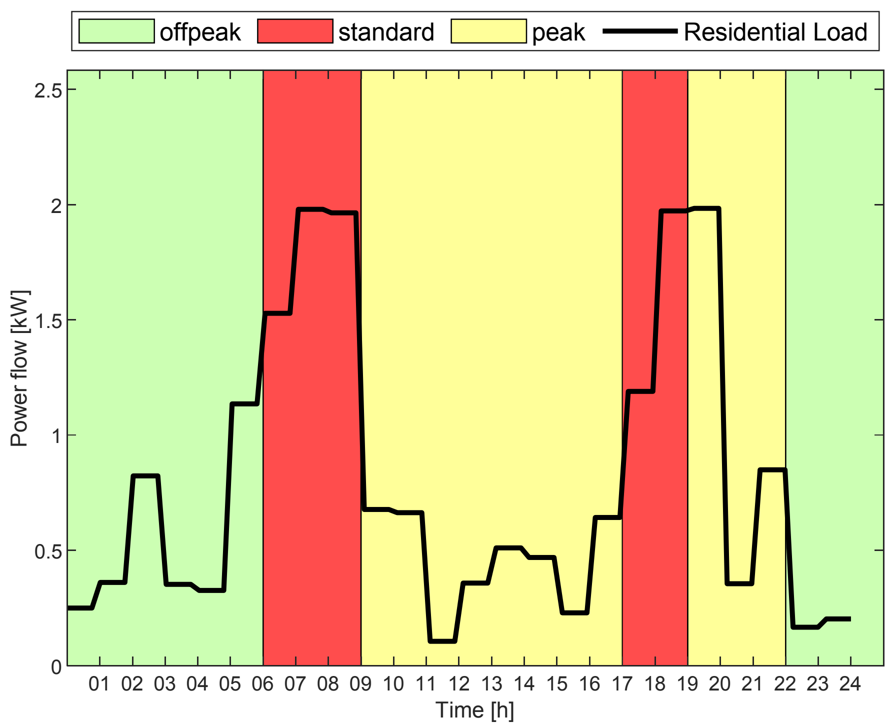

Figure 4.19: Residential load under TOU tariff

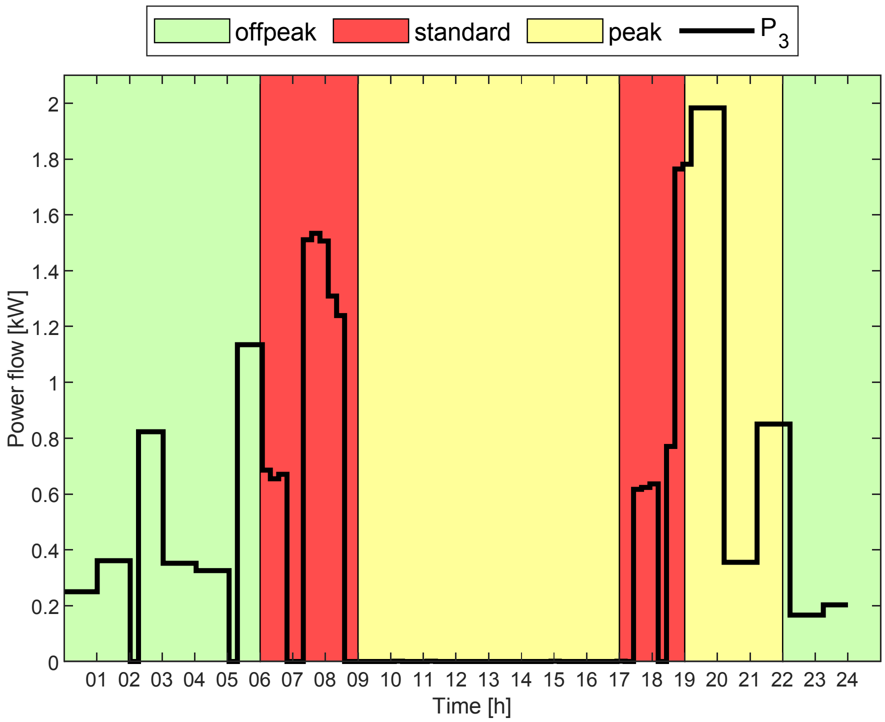

Figure 4.20: Power flow from the grid to the load

- From 02h00 to 03h00

At 02h00, the load demand increases to 0.8 kW, shown in Figure. 4.19 and is supplied from the battery bank, shown in Figure. 4.21. The power used to supply the load caused the battery state of charge to drop to 79%, shown in Figure. 4.22. The model solely uses power from the battery bank for about 20 min, where it starts using the grid to supply the load, shown in Figure. 4.20.

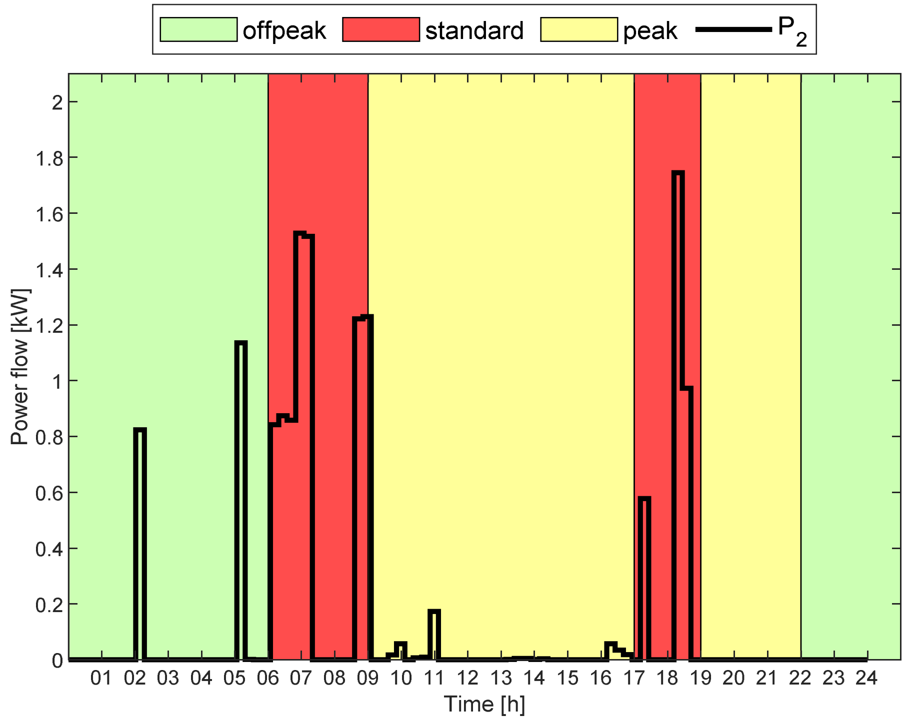

Figure 4.21: Power flow from the battery bank to the load

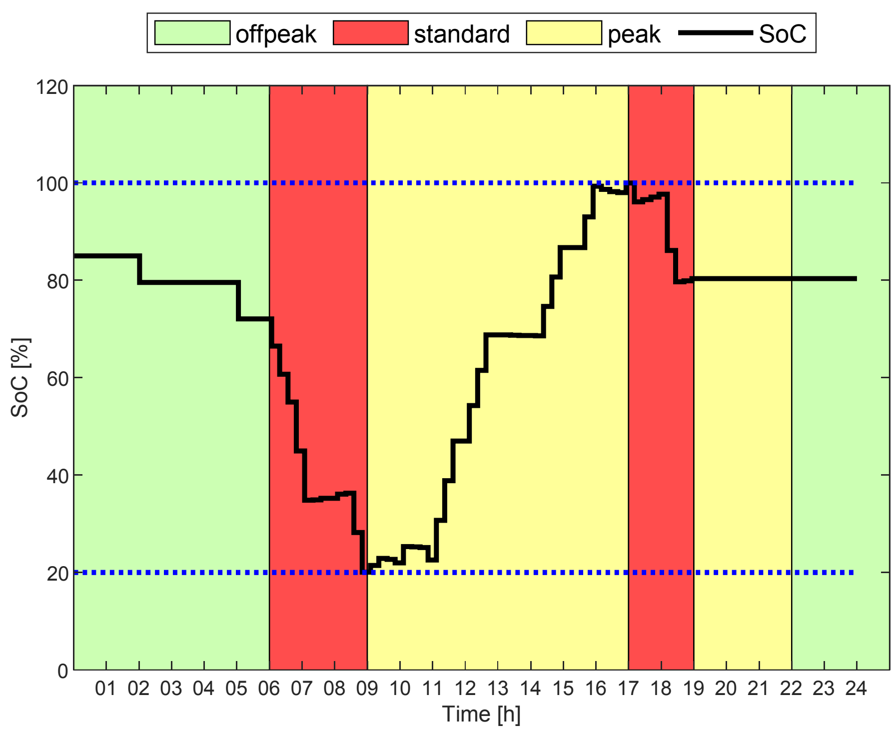

Figure 4.22: Battery state of charge

- From 03h00 to 05h00

During this time interval, the load demand remains below 0.35 kW and the model imports power from the grid to supply the load, shown in Figure. 4.20.

- From 05h00 to 06h00

At 05h00, the load demand increases to 0.32 kW, shown in Figure. 4.19 and is supplied from the battery bank, shown in Figure. 4.21. The power used to supply the load caused the battery state of charge to drop to 72%, shown in Figure. 4.22. The model solely uses power from the battery bank for about 20 min, where it then starts using the grid to supply the load shown in Figure. 4.20.

b) Systems behaviour during the first peak pricing interval from 06h00 to 09h00 (Red)

- From 06h00 to 07h00

At the start of the first peak pricing interval, the load demand reached a peak of 1.53 kW. To supply the load, the battery uses the battery bank as a first option, shown in Figure. 4.21. At this time, the battery discharges at a higher rate, reaching a minimum of 34%, shown in Figure. 4.22. In order to reduce the batteries discharging rate, the model imports the remainder of the power from the grid, shown in Figure. 4.20.

- From 07h00 to 08h00

As the consumer prepares for work, the load increases again reaching 1.9 kW. As the sun starts to rise around 07h00, the PV starts generating around 0.48 kW of power, shown in Figure. 4.23. The model immediately starts using the PV power to supply the load, shown in Figure. 4.24 and charge the battery bank in Figure. 4.25. Figure. 4.20 shows that the load not met by the PV is suppied by the grid.

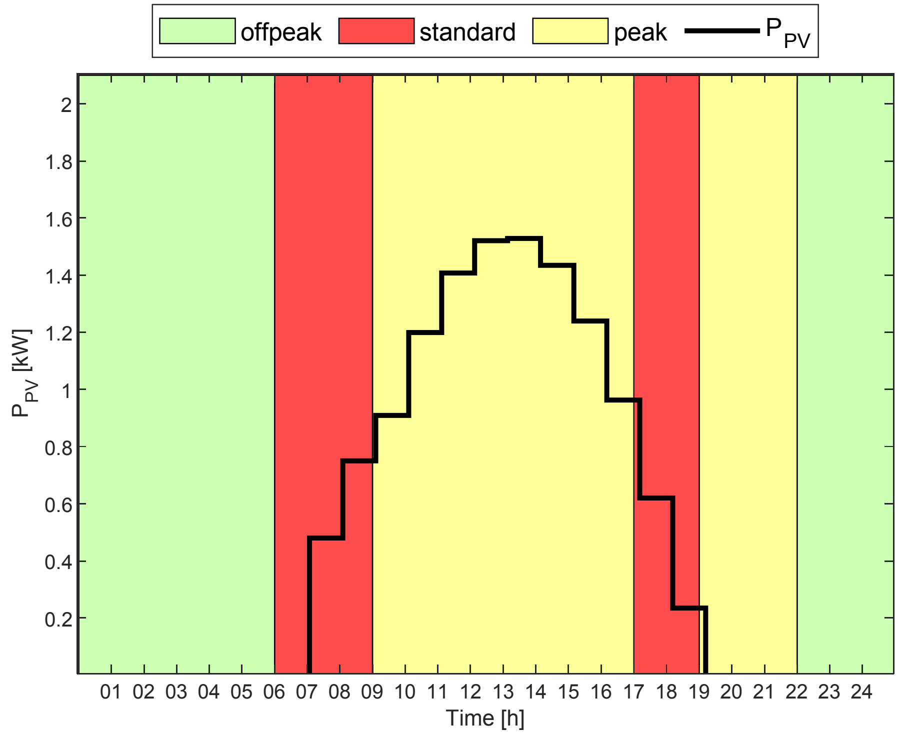

Figure 4.23: PV power generated

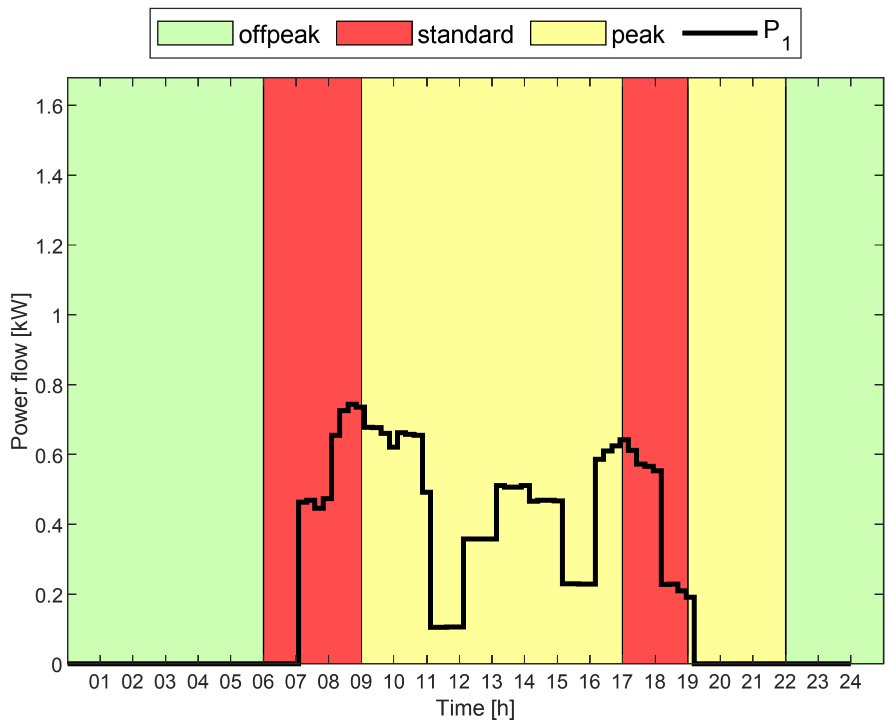

Figure 4.24: Power flow from the PV to the load

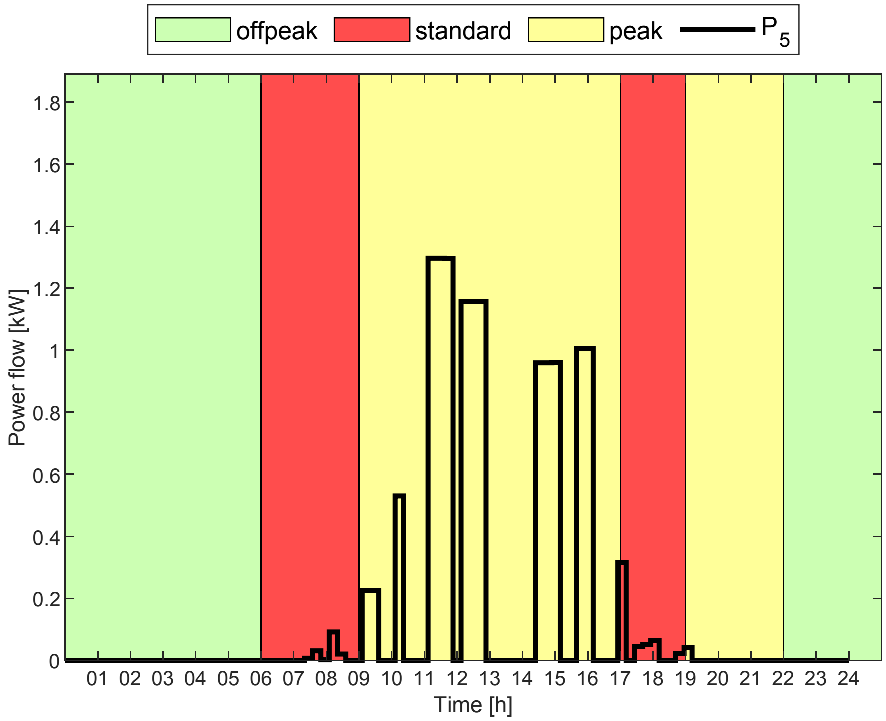

Figure 4.25: Power flow from the PV to the battery bank

- From 08h00 to 09h00

Figure. 4.20 shows that the load demand remains constant at 1.9 kW. As the PV power generated increases to 0.75 kW, the model uses 0.665 kW to supply the load shown in Figure. 4.24. During this time, the battery bank is charged as shown in Figure. 4.18 and may further be seen in the battery state of charge as it slightly increases. The model uses power from the PV shown in Figure. 4.25 and power from the grid, shown in Figure. 4.26, to charge the battery bank. As the battery bank reaches 37% state of charge the model stops importing power from the grid and uses the battery bank to supply the load Figure. 4.21.

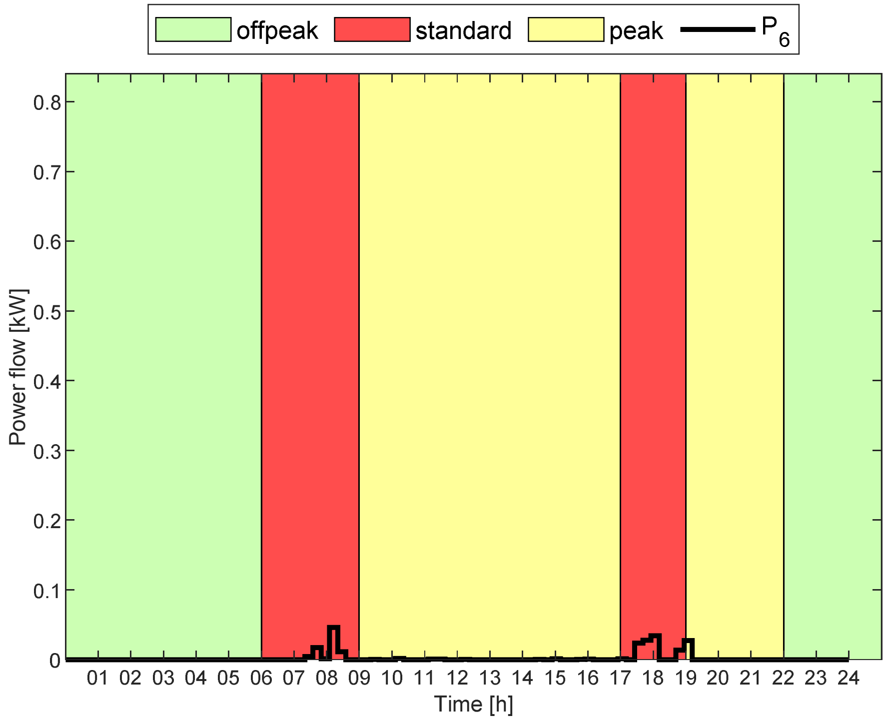

Figure 4.26: Power flow from the grid to the battery bank

c) Systems behaviour during the first standard pricing interval from 09h00 to 17h00 (Yellow)

- From 09h00 to 17h00

During this period, the residential load never exceeds 0.67 kW, shown in Fig. 4.19. As the solar radiance increases, the amount of power generated from the PV further increases, reaching a peak of 1.4 kW. As the power generated by the PV exceeds the load demand, the model does not import power during this period, shown in Figure. 4.17. What is noted during this period is that the battery bank is continually charged from the excess power from the PV, after the load demand is met. As the sun rises the amount of power generated from the PV further increases and may be seen in Figure. 4.27, which is the power exported from the PV after the load demand is met.

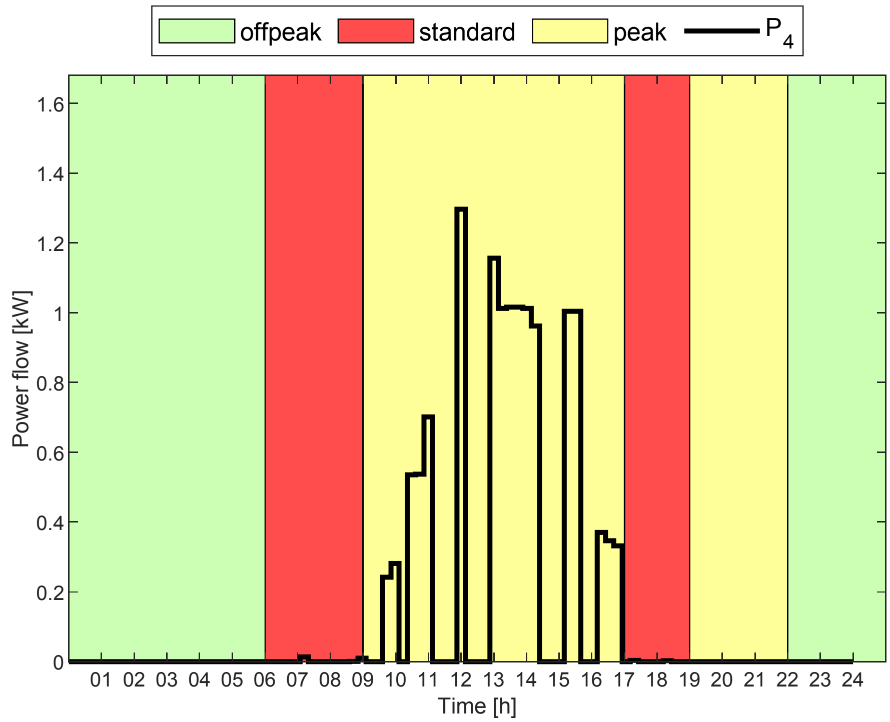

Figure 4.27: Power flow from the PV to the grid

d) Systems behaviour during the second peak pricing interval from 17h00 to 19h00 (Red)

- From 17h00 to 18h00

As the consumers start to prepare dinner, the load demand increases rapidly, reaching a peak of 1.2 kW. For the first 30 min, the load is met by the remaining PV power shown in Figure. 4.24 and the battery bank shown in Figure. 4.21. As the PV starts reducing, the model starts importing power from the grid to meet the load demand shown in Figure. 4.20. Figure. 4.18 shows that 0.098 kW of power is used to charge the battery bank. Figure. 4.26 shows that 0.034 kW is derived from the grid and 0.064 kW from the PV shown in Figure. 4.25.

- From 18h00 to 19h00

Figure. 4.21 shows that 1.7 kW is used to supply the load from the battery bank for 30 min, reducing the state of charge to 79%. Where the model starts using the grid to supply the load, shown in Figure. 4.26.

e) Systems behaviour during the second standard pricing interval from 19h00 to 22h00 (Yellow)

- From 19h00 to 22h00

During this period, all the power is imported from the grid to meet the load demand, shown in Figure. 4.26. Figure. 4.22 shows that the battery state of charge remains constant as no power from the battery is used.

f) Systems behaviour during the second off pricing interval from 22h00 to 24h00 (Green)

- From 22h00 to 24h00

During this period, the load demand is supplied through the grid, as shown in Figure. 4.26. Figure. 4.28, presents the net energy consumption for the day. From the figure, the consumer reduced the amount of power imported from 19.1 kWh to 10.2 kWh.

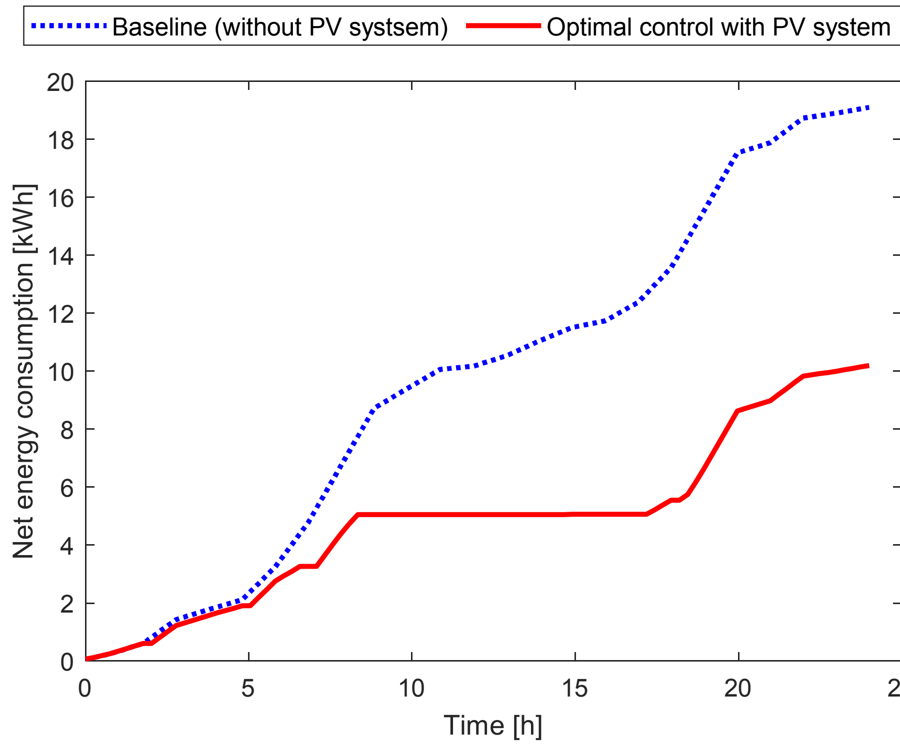

Figure 4.28: Net energy consumption (winter)

4.4. SUMMARY

An optimal energy model of a 2 kW residential grid-interactive solar PV with battery storage system under the feed-in tariff (FIT), was modelled in this chapter. A residential household within the City of Cape Town municipality, is considered. With the limitaions seen in Chapter 3, regarding the HOMER software, a model was developed in Chapter 4 using MATLAB. The model developed in MATLAB showed the different power flows from each component, which could not be illistrated in HOMER.

The algorithm assisted in minimizing the total cost of energy from the grid, while maximizing the amount of energy sold within the system operation constraints.

Therefore, the model has decreased the reliance from the consumer on the grid during peak periods, making consumption from the grid as a last option.

For the studied residential load, the consumption from the utility grid has decreased from 14.69 kWh/day from the grid to 7.39 kWh/day during summer periods. This comes as a result of the high solar irradiance and low energy demand during summer periods, the model primarily charged the batteries from the PV.

During the high demand season (winter periods) the model was more reliant on the grid to charge the batteries. The model's result during this period indicated that the consumer normally imported 19.05 kWh/day and the simulated results show that the consumer presently imports 10.2 kWh/day.

When comparing the results from the summer period and the winter period it is clear that the algorithm avoids buying electricty when it is costly, however, preferable sells the electricity back to the grid during these periods under the residential FIT tariff generating revenue.

CHAPTER 5: ECONOMIC ANALYSIS

5.1. INTRODUCTION

Various economic indicators are used to evaluate the economic performance and cost effectiveness of a project. These indicators include, but are not limited to the life cycle cost (LCC) method, levelized cost of energy (LCOE) method, net present value (NPV) or NB (net present worth) method, benefit/cost (or savings-to-investment) ratio (SIR) method, internal rate-of-return (IRR) method, overall rate of- return (ORR) method and discounted payback (DPB) method [3]. All of these methods measured in ZAR. The simple payback period (SPP), is one of the most commonly used cost analysis methodologies [102]. SPP is further referred to as the Payback Period (PBP) analysis, which is used to determine the years it will take to recover the initial investment through project returns [103].

The advantage of the SPP is its simplicity and it is easily understood by workers and management. It provides a rough measure of the worth of a project. A few of the disadvantages of the SPP is that the value of time and money is not considered along with the costs or benefits of the investment following the payback period. These limitations mean that the SPP tends to favour shorter-lived projects [104], a bias that is often economically unjustified. However, using the SPP in conjunction with methods such as IRR, BCR and LCC, take into account both the time value of money and the project lifetime respectively, by discounting all future worth cash flows to a present worth (PW) cash flow.

Therefore, for increased accuracy, a total life cycle cost evaluation is done followed by a break-even point (BEP) analysis, in terms of the baseline and proposed hybrid system. The life cycle costs will be compared to calculate the savings over a specific project lifetime. The project lifetime for this case study was chosen to be 20 years.

5.2. NET PRESENT COST OF THE PROPOSED PV SYSTEM

The NPC is the cumulative discounted cost of the system, including initial cost, financing, tax impacts, incentives and operation and maintenance (O&M), equal to the sum of the cost in each year multiplied by the discount factor in that year. The initial investment cost of the proposed system is shown in Table 5.1; the manufacturers' products all comply with South African Bureau of Standards (SABS) criteria. It is important to ensure that your installation complies with the relevant legal, technical and safety standards. Apart from your personal safety, insurance companies require that the installation is compliant with recognized standards.

For this installation, all the installation requirements comply to the South African National standard (SANS). To standardize the requirements for photovoltaic components and systems for residential purpose, the SANS 959 was developed.
The prices in Table 5.1 obtained from [97] are average component prices for the year 2017.

Table 5. 1: Bill of quantity (proposed system)

Component Description	Quantity	Net price (ZAR)
PV Panel	5	R 14 182.56
Battery	4	R15 364.44
Inverter	1	R 11 495
Charge controller	1	R5000
Installation cost		R 60000
Total initial investment cost		R 106 042

From Table. 5.1, the following equation was used to determine the total initial investment cost.

$$TC = C_{PV} + C_{INV} + C_{INST} + C_{BATT} + C_{CC} \tag{5.1}$$

Where:

- TC is the Total cost of the PV system;
- C_{PV} is the Cost of PV modules or solar cells;
- C_{INV} is the Cost of inverter;
- C_{INST} is the Cost of installation which included mounting structures, wiring, protective elements, electrical, mechanical and labour cost;
- C_{BATT} is the Cost of the battery bank;
- C_{CC} is the Cost of the charge controller installed.

5.3. CUMULATIVE COST CALCULATIONS

The initial costs of the renovation (costs of the envelope renovation and systems) and of the replacement of the systems at the end of their lifetime (20 years for the PVs and 15 for the other systems) are high. Therefore, it is important to analyse, for each renovation scenario, the evolution of the lifetime cumulative costs.

For correct cumulative cost calculations over a specific project's life time, a few factors are taken into consideration. As tabulated in Table 5.1 above, the initial implementation cost is not considered as cumulative, since it is a once off payment i.e. solely at the beginning of the project implementation. The same applies to the salvage cost at the end of the project's lifetime. This cost may be deducted from the total life cycle cost. This is considered as a cost benefit than a loss. Therefore, the total annual cost incurred which is calculated from replacement cost (RC) and O&M after each year since the beginning of the project. This amount is added to the initial implementation cost, to obtain the total cumulative cost over a lifetime of a project

5.3.1 Cumulative energy cost

To calculate the daily cumulative energy cost, with the primary objective function, so that Eq. (5.2) may be used in this instance:

$$C_{daily-EC} = t_s . \sum_{r=1}^{N} (P_{Grid} . C_{TOU_r}) \quad (5.2)$$

Where:

- t_s is the sampling time;
- P_{Grid} is the power allowed from the grid;
- C_{TOUr} is the time-based cost of electricity at each rth interval.

From this, the daily cumulative cost values in Rands (ZAR) were obtained and illustrated in Section 5.3.1.1. and 5.3.1.2. and compared in Section 5.3.1.3. for both seasons respectively. In Section 5.3.1.4., the annual cumulative costs were calculated using the total daily energy cost values, obtained in terms of the low and high demand seasons, defined by the utility company.

5.3.1.1 Winter cumulative energy cost comparison

The cumulative cost of the winter period is shown in Figure. 5.1. As shown from the figure, it may be observed from the curves that, every time grid electricity is used, the grid cost in the specific TOU tariff period increases the total daily cost.

The cumulative curves in Figure. 5.1 shows that from the beginning of the control horizon, the baseline already increases at a higher rate than the controlled strategy. Based on the time-of-use periods, it may be seen that during the first peak period (06h:00-09h:00), the baseline graph, as well as the optimally controlled system increases significantly, however, the baseline graph increases at a significantly higher rate. Around 09h:00, the optimally controlled system begins to decrease at a constant rate, yet the baseline continues to increase. The same result as earlier may be seen during the second peak period (17h:00-19h:00), where the optimally controlled graph increases significantly. When comparing the operational cost curves the end of the control horizon, it may be deduced that the baseline's total net energy cost is approximately 2.4 times higher than the optimally controlled system.

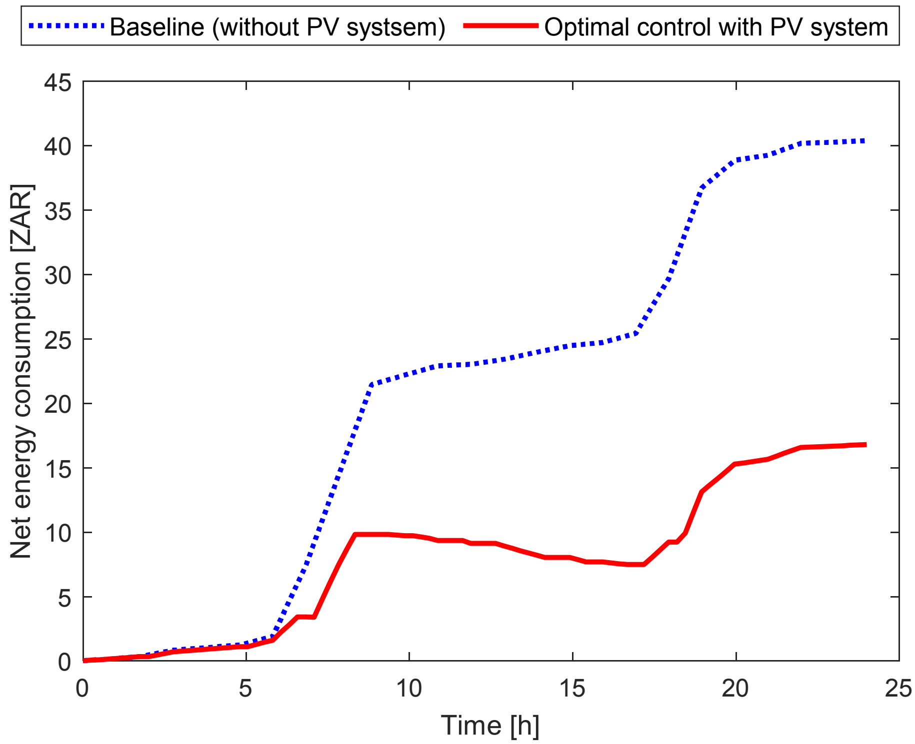

Figure 5.1: Winter cumulative energy cost

5.3.1.2 Summer cumulative energy cost comparison

The cumulative cost of the summer period is shown in Figure. 5.2., alternative to the winter cumulative cost curve, in Figure. 5.1, the electricity usage during summer is significantly less, as compared to winter. Figure. 5.1 clearly shows that the optimally controlled system barely increases past the single margin. From the beginning of the control horizon the baseline system increases at a rapid pace, with extreme increases during the peak TOU periods. The difference in cumulative energy cost at the end of the control horizon represents the daily energy cost savings for the day. The baseline energy cost, compared to the optimal controlled system, shows that the baseline's cost of energy is 10.8 times higher than that of optimally controlled system. This is significantly higher, as compared to the winter case and, with this, it proves that the optimal system is more effective during the summer season.

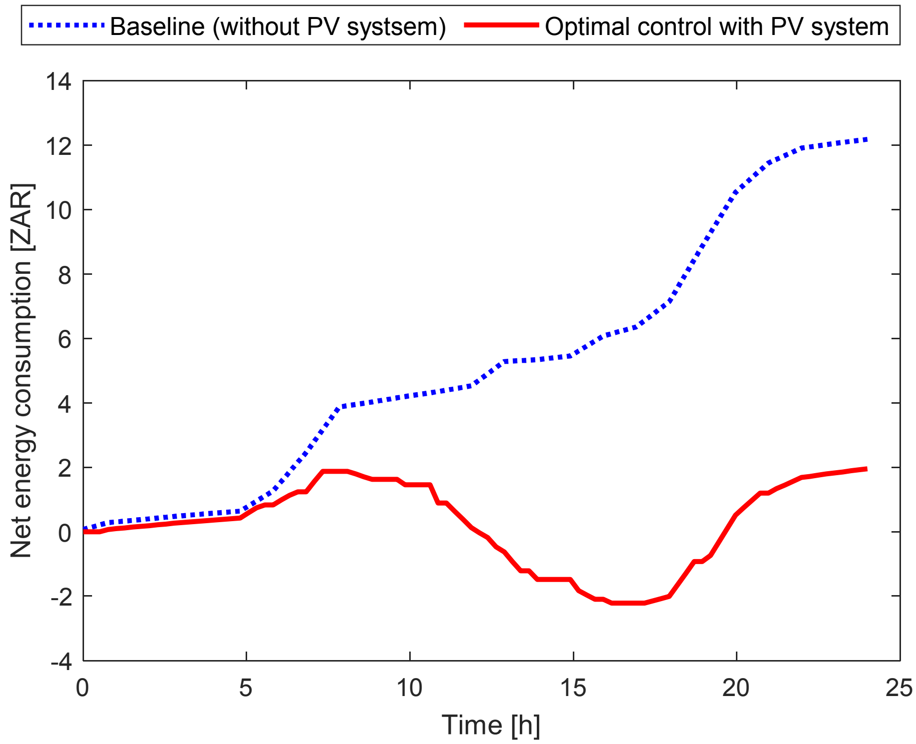

Figure 5.2: Summer cumulative energy cost

5.3.1.3 Daily energy consumption and saving

The cumulative costs and energy consumed after each simulation of the baseline and optimal control strategies, are shown and compared in Table 5.2. With grid electricity being used during standard and off-peak only for optimal control strategy, a saving of 84.7% in cost may be observed for summer season, while in winter a total savings as low as 58.4% in electricity cost is observed. The results of this comparison highlight the importance of avoiding the use of electricity during high demand periods, more specially, during winter where the electricity prices are high.

Table 5.2: Daily energy consumption and savings

Strategy / Season	Baseline (Grid alone) Cost (ZAR)	Optimal control (PV-Batt system) Cost (ZAR)	Daily Savings (ZAR) Cost	Daily Savings (%) Cost
Winter	40.39	16.8	23.59	58.4
Summer	12.81	1.955	10.855	84.7

5.3.1.4 Annual energy consumption and saving

The annual cost saving is determined by analysing the recorded data. From the analysis, the most energy intensive day was selected and simulated in MATLAB. The results from the simulated data is tabulated in Table 5.3, for the baseline and Table 5.4 represents the optimized system. By using the generated cost (results from MATLAB), the average monthly cost may be determined by multiplying the cost of the day by the number of days per month.

a) Annual Baseline cost consumption

The annual baseline cost is represented in Table 5.2. The data from this table clearly indicates the difference in the electricity bill between the high tariff period (winter) and the low-tariff period (summer). With the consumer reaching a peak cost of 1213.96 ZAR in the month of July 2017, while keeping the costs below 620 ZAR, during summer periods. With the consumer consuming even more electricity during the high tariff period, the annual expected electricity bill from Table 5.2, will be 7692.71 ZAR.

Table 5.3: Baseline daily energy cost for each month

Baseline Daily Energy Cost for each Month (ZAR)			
Energy Cost	Month	Number of Days	Monthly Energy Cost
12.81	Jan	31	397.11
12.61	Feb	28	353.08
15.4	Mar	31	477.4
16.371	Apr	30	491.13
19.71	May	31	611.01
40.39	Jun	30	1211.7
39.16	Jul	31	1213.96
33.93	Aug	31	1051.83
16.34	Sep	30	490.2
15.66	Oct	31	485.46
15.21	Nov	30	456.3
14.63	Dec	31	453.53
Baseline Annual Cost			7692.71

b) Annual cost for optimized system

The optimized system cost is represented in Table 5.3. By analysing the results from Table 5.2, a similar trend is noticed, as compared to the baseline cost. The major difference may be seen in the total monthly energy cost. Where the baseline system reached a peak of 1213.96 ZAR, the optimized system barely reaches a cost of 620 ZAR during the high tariff period. The available solar has a tremendous effect on the electricity cost for the consumer, resulting in a few months where the consumer gains a profit, rather than spending money.

From Table 5.3, with the optimized system, the consumer total cost of electricity for 2017 was 2501.95 ZAR.

Table 5.4: Proposed system daily energy cost for each month

Proposed System Daily Energy Cost for each Month (ZAR)			
Energy Cost	Month	Number of Days	Monthly Energy Cost
1.955	Jan	31	60.605
2.33	Feb	28	65.24
4.6	Mar	31	142.6
5.84	Apr	30	175.2
5.7	May	31	176.7
16.8	Jun	30	5.4
19.72	Jul	31	611.32
14.68	Aug	31	455.08
1.34	Sep	30	40.2
2.6	Oct	31	80.6
3.04	Nov	30	91.2
3.2	Dec	31	99.2
Proposed System Annual Cost			2501.945

5.4. LIFE CYCLE COST ANALYSIS

The life cycle cost (LCC) for a project is its total cost of purchase and operation over its entire service life [24]. To calculate the lifecycle cost, a summary of the entirety of the content in the project that affects the investment decision must be included, such as the cost of maintenance, repair, replacement, energy and any other monetary costs. The time value of money measured in either present value (ZAR) should be considered over the relevant period for all amounts.

The project lifetime of 20 years, was selected for the system. The 20-year lifetime was selected, based on the guaranteed collector lifetime being 10 years. However, several reports have shown that the lifetime reaches over 30 years[105, 106]. Hence, the average number of years between guaranteed and actual reported lifespan was chosen. The salvage costs were taken as 20% of the initial cost of implementation, for both the baseline and the proposed system. This accounts for replacement upgrades, to more efficient systems in the future.

The replacement cost is calculated using Eq. (5.3). With the average inflation rate, shown in Figure. 5.3, the future costs of components may be predicted, by assuming that the average inflation rate will be equal to the interest rate [107].

$$C_{rep} = \sum_{k=1}^{N_{rep}} C_{cap} \times k(1 + n \times r) \quad (5.3)$$

Where:

- C_{cap} is the initial capital cost for each component;
- N_{rep} is the number of component replacements of the 30-year lifetime;
- n is the lifespan for a specific component (years);
- r is the average inflation rate shown as 4.5% in Figure. 5.3.

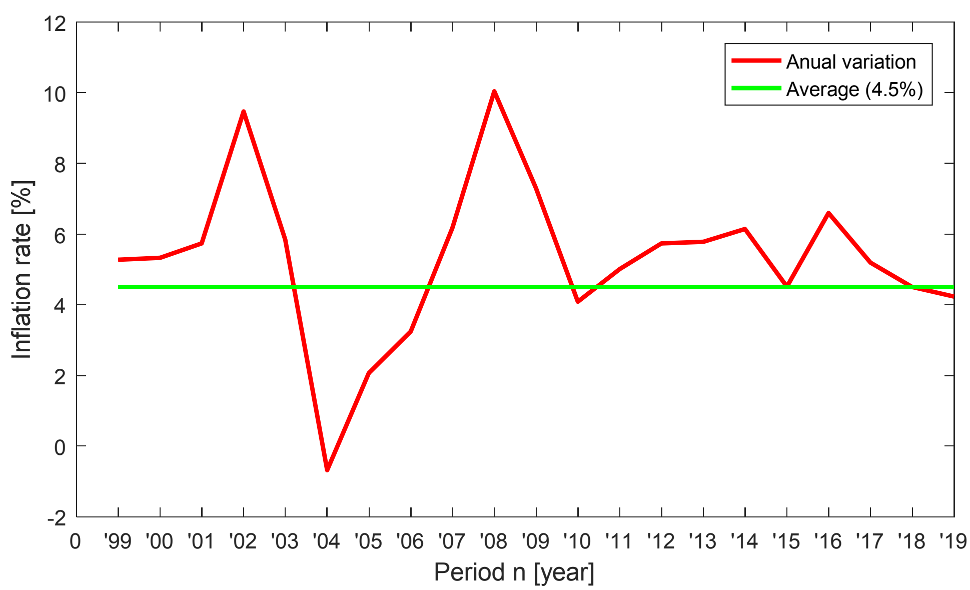

Figure 5.3: Inflation rate of South Africa from 1999 to 2019 [92].

5.4.1 Baseline life cycle cost analysis

The total replacement costs (C_{rep}), over the 20year lifespan for the baseline, are not calculated as the baseline system possesses the grid solely as a component that cannot be replaced. Therefore, the total lifecycle replacement costs are equal to Zero. The cumulative cost of energy for the first year was taken from Table 5.3. The cost at the end of year 20 equates to the total cumulative electricity cost (C_{EC}), with an increase of 10% annually taken into consideration, as shown in Eq. 5.4.

$$C_{EC} = \sum_{k=1}^{20} C_{initial-EC} . k\,(1+a) \tag{5.4}$$

Where:

- $C_{initial\text{-}EC}$ is the cumulative cost of energy at the end of year one (ZAR);
- k represents the year at which the cumulative cost should be calculated (years);
- a is the annual increase of 10%.

The operation and maintenance costs at the end of each year is calculated using Eq. 5.5, however, in this case is assumed to be zero, since the grid requires no maintenance by the end user.

$$C_{OM} = \sum_{k=1}^{20} C_{initial-OM} . k(1+r) \tag{5.5}$$

A salvage cost ($C_{salvage}$) is assumed to be 20% of the initial implementation cost ($C_{initial}$) of the baseline system, as shown in Eq.5.5. However, the no salvage cost will be calculated, since the grid connection to the end user is managed by the utility company. Therefore, the total life cycle cost for the baseline, is calculated using Eq.5.7.

$$C_{salvage} = 0.2 \times C_{initial} \tag{5.6}$$

$$LCC_{Grid} = C_{initial} + C_{rep} + C_{EC} + C_{OM} - C_{salvage} \tag{5.7}$$

The total life cycle cost value LCC $_{Grid}$ (ZAR), using Eq. (5.7), is shown in Table 5.5. Over a 20year project lifetime, a total amount of approximately R 103 647.57 will be spent, in the case of the Grid supplied electricity.

Table 5.5: Total life cycle cost of the grid

Cumulative Cost	Value (ZAR)
$C_{initial}$	0
$C_{rep-BTC}$	0
C_{OM}	0
C_{EC}	103 647.57
$C_{salvage}$	0
LCC Grid	103 647.57

5.4.2 Optimally controlled system's life cycle cost analysis

Table 5.6: Total replacement cost for the proposed system

Parameters	Value
Optimally controlled system lifetime (years)	20
PV panels lifetime (years)	20
N $_{Rep-PV}$ (-)	1
C $_{Rep-PV}$ (ZAR)	14182
Charge controller (CC) lifetime (years)	15
N $_{Rep-CC}$ (-)	1
C $_{Rep-CC}$(ZAR)	10000
Inverter (years)	20
N $_{Rep-INV}$ (-)	1
C $_{Rep-INV}$ (ZAR)	11 495
C $_{Rep-TC}$ (ZAR)	84 024

In the case of the Proposed system, more components exist with various life expectancies. Therefore, the total replacement costs (C_{rep}) may be calculated, using Eq. 5.4, over the 20year project lifespan for all the proposed system's components, shown in Table 5.5. These are added to get the total lifecycle replacement costs ($C_{rep\text{-}TC}$), denoted in Eq. (5.8).

$$C_{rep-TC} = C_{rep-PV} + C_{rep-CC} + C_{rep-INV} \quad (5.8)$$

Following the same method for cumulative electricity cost, with an annual 10% increment, was calculated for the Proposed system using Eq. (5.4), as well as for the salvage cost and the cumulative operation and maintenance costs for the pro in Eq. (5.6) and (5.5), respectively.

Eq. (5.9) shows the calculation of the life cycle cost for the Proposed system.

$$LCC_{Proposed} = C_{initial} + C_{rep-TC} + C_{OM} + C_{EC} - C_{salvage} \quad (5.9)$$

Table 5.7: Total life cycle cost for the proposed system

Cumulative Cost	Value (ZAR)
$C_{initial}$	106 042
C_{rep-TC}	84 024
C_{OM}	2 932.75
C_{EC}	103 647.57
$C_{salvage}$	21 208.4
LCC proposed	317 854.72

The total life cycle cost value (ZAR), was calculated using Eq. (5.8) The detailed data is presented in Table 5.7. Over a 20-year project lifetime, a total amount of approximately R317 854.72 will be spent in the case where the proposed system is implemented.

5.4.3 Break-even point (BEP)

Where the PV-generated electricity equals the cost of electricity purchased from the grid, is defined as the break-even point. The break-even point is further described as the point of zero profit, as typically when the system passes this point, the consumer starts seeing a return profit on the initial investment. In this case, the baseline electricity cost is compared to the proposed system electricity cost over a period of 20 years. The cumulative cost curves, which includes the initial investment cost and the total annual costs incurred over this period for the baseline and optimal system, is plotted on the same axis for clear comparison. The point where these two curves intersect, shows the point in time (years) at which the two systems break even.

The initial total cost of implementation of the optimal system and the Grid connected is merely R106 042 and R0 respectively. The values are therefore considered as the starting points of the two curves in Figure. 5.4. After the first year has passed, the sum of total annual cost of energy and the initial investment cost is the total present cost of energy, shown in Table 5.2. This equates to the total cumulative cost for the first year after implementation. After the first year of implementation, a 10% increase in the price of electricity is considered to calculate the annual energy costs. This amount is again added to the previous total cumulative cost of the first year. The same method is followed for the remaining years, until year 10, as shown in Figure. 5.4. In this curve, the replacement costs and lifetimes of all the components are considered for increased accuracy of cumulative cost representation. From Figure. 5.4, a clear observation may be made that the break-even point occurs in 11.5 years, after the project has started. The costs incurred are equal to R 218 604.51 and the differences in total money spent at the end of the project lifetime further presents an important economic performance indicator.

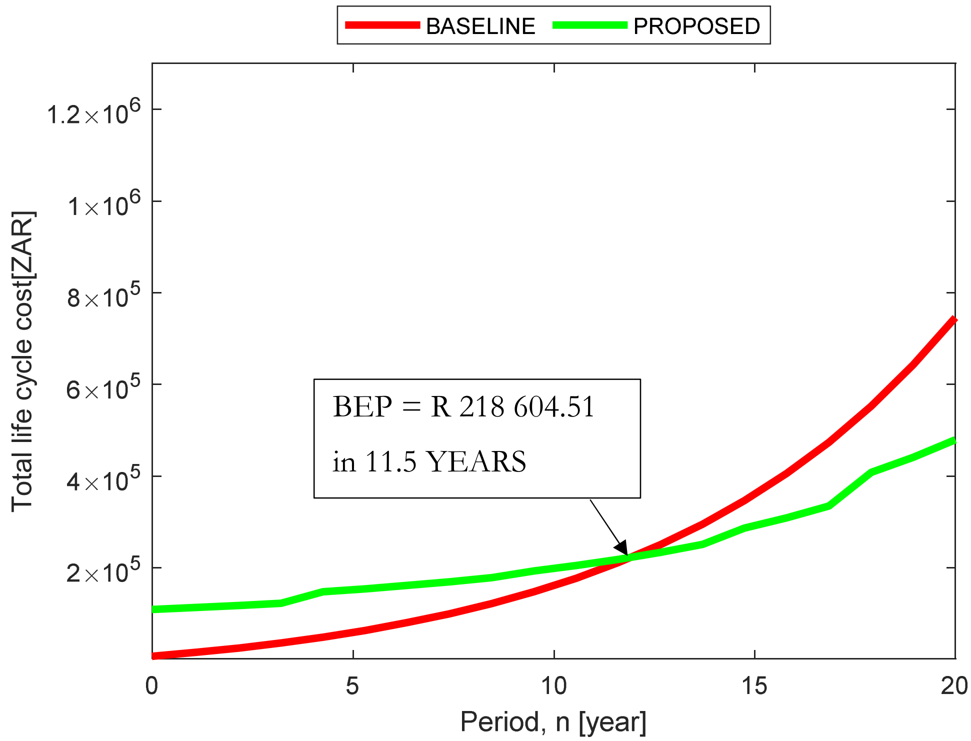

Figure 5.4: Break-even point

5.4.4 Life cycle cost analysis

The economic method of project evaluation is referred to as the life-cycle cost analysis (LCCA). LCCA analysis is observed as being a direct contrast to the Payback method of economic analysis. Payback method is mostly used to determine how rapidly the initial investment may be recovered. The Life cycle cost method is the building block for LCCA and is used to reflect the time-value of money by incorporating the overall running cost of the system over a given period (usually the rated lifespan of the system)[24].

The life cycle costs for the Grid solely operated system and the system with optimal energy management scheme is compared in Table 5.7. With the predicted operating results for 20 years, the variation in the baseline cost and the proposed system cost may be evaluated to determine the LCC. The LCC is calculated, in order to note the savings in cost at the end of the project lifetime. From the table below, tit may be concluded that at the end of the project's lifetime, an approximate saving of R270 022.83 may be made, if the proposed optimal system is implemented. This translates into a saving of 35.7%.

Table 5. 8: Life cycle cost comparison

LCC	Value (ZAR)
LCC Grid (ZAR)	746 079.20
LCC Proposed (ZAR)	479 056.37
Total savings over 20 years (ZAR)	270 022.83

5.5. SUMMARY

The purpose of this chapter was to asses and evaluate the effectiveness of the proposed system, in terms of investment. A break-even point analysis was carried out, in order to calculate as to when the proposed system would have an equivalent cumulative cost, compared to the baseline system. We define the break-even point of the system, as the point at which the net present cost (NPC) of the PV system equals the net present benefit (NPB), realized to its owner. In simple terms, it is the point where the cost of PV-generated electricity equals the cost of electricity purchased from the grid.

The evaluation showed that after 11.5 years, the cumulative costs were lower for the proposed system, as opposed to the baseline. The results further indicated that, when the break-even point is passed, the difference in cumulative costs significantly increased with the baseline cost, following an exponential trend. The break-even point analysis was followed by a thorough lifecycle cost evaluation, so that the savings over a project lifetime of 20 years could be calculated. The results of the LCC, when comparing the baseline against the proposed system, indicated that the proposed system could reduce the total cost up to 35% at the end of the project lifetime. The results plainly mean that the consumer (owner) of the proposed system, should receive an acceptable return from the installation. The results explained are directly related/influenced by the location, pricing tariff and the components used.

CHAPTER 6: CONCLUSION

6.1. FINAL CONCLUSION

This chapter serves as a conclusion of the research that has been carried out on an optimally designed grid-interactive PV with battery storage system, under the residential feed-in tariff. The cost of electricity rising significantly over the past decades is a direct consequence of Eskom's new building programs and the cost of essential plant maintenance. This has caused the price of electricity to increase rapidly over the last couple of years. The South African electricity utility company (Eskom), permits the seasonal variation of TOU tariffs during high demand season (winter), the tariff rates are higher compared to low demand season.

The aim of the developed model, is to maximize the energy cost saving, that may be realized by consumers operating under the TOU and FIT tariff schemes. The model developed will minimize the reliance that the consumer has on the grid, whilst optimizing power flow from the battery bank and the PV.

As seen in chapter 2, the grid interactive PV, with battery storage has been implemented throughout the world. In South Africa, however significantly less attention has been provided to this system, due to strict regulations in the past. However, recent development has shown that Municipalities are coming to the realization that there is a need to be proactive in developing appropriate procedures and standards for SSEG integration, to avoid unregulated proliferation of installations. With the significant change in municipal regulations, there is opportunity for residential consumers to make use of grid-interactive PV with battery storage system technology. An optimal energy management model has been developed, with the objective of minimizing the grid consumption cost, while maximizing the use of renewable energy resources to meet the load demand.

In chapter 3, HOMER software was used, since it is the most generally used optimization tool. The optimal results revealed that the load demand was adequately met at no shortage and incurred the levelized cost of energy of ZAR 5/kWh. The results further revealed that the reliance on the grid went from 100% to 51%, with the PV producing 49% of the required energy. The results revealed that the total energy consumption for the year was 8.274 kWh, where 73% was consumed by the load and 27% exported back to the grid. To determine as to when power was exported back to the grid, the power flow through the inverter was analysed. The power flowing through the inverter may either be derived from the PV, or the battery bank. In order to determine whether the system is optimally controlled, each component should be analysed individually and this cannot be carried out in HOMER.

Hence, this limitation denoted that there is currently a need to design an optimal PV with a battery-based system allowing the consumer to analyze the power flowing in each component, permitting the consumer to make optimal changes. An optimal energy management model should be developed.

In chapter 4, the operating principle of the grid-interactive PV with battery storage is described. All the simulating parameters, the time-based pricing, variable input and load data, for the mathematical model, was presented and discussed. The objective function was to maximize the electricity exported to the grid, while minimizing the electricity imported. To evaluate the effectiveness of the model, a baseline was established, which presented the load profile of the residential consumer supplied from the grid, which was compared to the optimally controlled model.

The baseline and the optimal controlled system were simulated, and the results obtained were presented. The simulated results illustrated that the consumer had the potential to save energy, depending on the solar radiance.

In Chapter 5, the effectiveness of the proposed system, in terms of investment was evaluated. A break-even point analysis was carried out in order to calculate as to when the proposed system would have an equivalent cumulative cost, compared to the baseline system. We define the breakeven point of system as the point at which the net present cost (NPC) of the PV system equals the net present benefit (NPB) realized to its owner. In simple terms, it is the point where the cost of PV-generated electricity equals the cost of electricity purchased from the grid.

The evaluation showed that, after 11.5 years the cumulative costs were lower for the proposed system, as opposed to the baseline. The results further indicated that, when the break-even point is passed, the difference in cumulative costs significantly increased with the baseline cost, following an exponential trend. The break-even point analysis was followed by a thorough life cycle cost evaluation, so that the savings over a project lifetime of 20 years could be calculated. The results of the LCC, when comparing the baseline against the proposed system, indicated that the proposed system could reduce the total cost up to 35% at the end of the project lifetime. The results basically mean that the consumer (owner) of the proposed system, will get a good return from the installation.

To conclude, it is important to highlight that the model was simulated with real data recorded from a household in Cape Town and that the aim of the model was to optimally manage the power flows, in order to reduce the amount of power imported from the grid. The initial cost of the project, along with the payback period, is directly related to the components used and the resources available. The results demonstrate that the model could be used anywhere, as long as all the parameters are changed according to the desired system.

6.2. SUGGESTIONS FOR FUTURE RESEARCH

From the study, areas of future research works have been identified, as explained below:

- This study focused on the case in the Western Cape. The research could be adapted to fit various geographical locations with different input parameters, which may in turn, change the configuration of the PV system Incentive for renewable energy. This may be carried out by changing the input data.
- Further work should be carried out in developing an optimal scheduling model for the proposed grid-interactive PV with battery storage system, when applying the load shifting mechanism.
- Further work should be carried out on developing an optimal scheduling model for the proposed grid-interactive PV with battery storage system, when applying it to the peer-to-peer electricity sharing system.
- The current model is open loop; further work on a closed loop system, such as Model Predictive Control (MPC), may be carried out.
- Furthermore, it would be of interest to investigate how the model would perform when applied to the commercial and industrial sector.

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