MODELLING OF AN ARCHITECTURE FOR LOCAL ENERGY GENERATION AND DISTRIBUTION WITH PEER-TO-PEER ELECTRICITY SHARING IN A SOUTH AFRICAN CONTEXT

By

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DECLARATION

I, EARL AVNER JORDAN, 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.

E.A Jordan Date: **5th July 2019**

DEDICATION

To my saviour Jesus Christ, for blessing me with gifts, talents, a big head and a brain to go with it. To my father, Glen Perry Dandrige Jordan, Daddy I did it!

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Finally, to my rock, my partner and best friend, my wife, Udéne Bronwynn Jordan, for always having my back, for your patience, love, assistance and excitement.

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LIST OF ABBREVIATIONS

AC	Alternating current
ADMM	Alternating direction method of multipliers
ADMM	Alternating direction method of multipliers
BCR	Benefits-to-cost ratio
BEP	Break-even point
BER	Improved bit error ratio
BS	Bill sharing
CCG	Canonical coalition game
CNLP	Constrained non-linear programming
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
ECO-Trade	Energy cost optimization via trade
EMS	Energy management system
ESC	Energy sharing coordinator
ETS	Energy exchange and sharing
EV	Electric vehicle
GHI	Global horizontal irradiance
IRR	Initial rate of return
LLC	Life cycle cost
MG	Multiple microgrids
MILP	Mixed integer linear programming

MMR	Mid-market rate
MMSE	Minimum mean square error
MPC	Model predictive control
MPEC	Mathematical program with equilibrium constraints
MRC	Maximal ratio combining
O&M	Operation & maintenance
OPF	Optimal power flow
P2G	Peer-to-grid
P2P	Peer-to-Peer
PBP	Beyond the payback period
PBT	Power-based distribution tariff
PCC	Point of common coupling
PETCON	P2P Electricity trading system with consortium blockchain
PHEV	Plug-in hybrid electric vehicles
PI	Proportional-integral
PMU	Power management unit
PV	Photo voltaic
RES	Renewable energy sources
SDN	Software defined networking
SDR	Supply and demand ratio
SoC	State of charge
SOCP	Second-order cone programming
SPP	Simple payback period
STC	Standard test condition
SVD	Singular value decomposition
TCP/IP	Transmission
TE	Transaction-based energy
TOU	Time of use
UP	Unified pricing
V2H	Vehicle-to-home

ZAR	South African Rand
ZF	Zero-forcing

ABSTRACT

The increasing share of variable renewable energy sources, strict targets set for the reduction of greenhouse gas emissions and the requirements on the improvement of system security and reliability, are calling for important changes in our energy systems.

In South Africa, distributed renewable energy systems have emerged as effective ways in improving the quality of energy service.

The integration of distributed renewable energy, such as solar photovoltaic systems (PV) and micro-grids, is significantly increasing the coupling and interactions between sources and between supply and end use, at various scales, from multinational, national, and community scale, down to building level.

In a South African context, power produced from the renewable energy that is not consumed by the load, needs to be stored for later use, or discarded, as the power utility, as well as the municipalities do not generally allow the power to be sold, or shared through the national grid.

In the case where various small generation units residing on the same land (estates or a block of townhouses), the power generated from the PV may be shared between the various consumers on the same land.

Consumers on the same land having different load patterns as not everyone uses electricity simultaneously connecting them in a micro-grid may allow the power to flow between the different generation systems and consumers. This will decrease the size of the storage systems, as well as the amount of power dumped and lost when it is not in use. On the other hand, the reliance on the grid power will further decrease. With the increasing installation of distributed generation at the demand side, more and more consumers become prosumers, that may both generate and consume energy. The high penetration of sporadic renewable energy may cause severe problems to power systems. Therefore, in order to facilitate the self-consumption of local generation, the export price at which the prosumers sell electricity to the utility grid is usually designed to be significantly lower than the retail price at which electricity is being purchased.

This is the major motivation for prosumers to share excess electrical energy amongst each other, rather than to feed it back to the utility grid at a significantly reduced cost. The

decreasing tariff rate of the feed-in tariff in most countries, does make this incentive a significantly more attractive approach.

The mathematical modelling of the operation of Peer-to-peer (P2P) energy sharing model between two dissimilar load profiles, will be discussed. These profiles are of typical commercial and residential nature. The P2P system consists of two prosumers: the residential prosumer that has a roof mounted PV system that is fixed at a 30° angle, with energy storage capabilities and commercial prosumer, with a solar tracking system.
A description of the system is discussed in detail, with all the relevant components outlined. In order to evaluate the cost effectiveness of the hybrid system, in terms of money spent, a 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 P2P energy sharing scheme. In addition, two electrical energy storage technologies were evaluated for the proposed system. These technologies include lead acid and lithium ion energy storage configurations. Results from the analysis indicated that, if the system were to use lead acid batteries as a storage medium, the proposed system would break-even in 5.304 years, with an approximate saving of 57%, translating into savings of R 1,972,277.98. The proposed system with Li-ion battery storage, indicated a break-even point of 5.131 years, with an expected saving of 54%, translating into cost savings of approximately R 1,861,939.36 at the end of the evaluated life cycle period.

Based on the results from the study, it was observed that the optimally controlled P2P energy sharing scheme has shown to be economically feasible, in the South African context.

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CHAPTER I: INTRODUCTION

1.1 BACKGROUND

The increasing share of variable renewable energy sources, strict targets set for the reduction of greenhouse gas emissions and the requirements of improvement of system security and reliability, are calling for important changes in our energy systems.

In South Africa, distributed renewable energy systems have emerged as effective ways in improving the quality of energy service [1]. The integration of distributed renewable energy, such as solar photovoltaic systems (PV) and micro-grids, is significantly increasing the coupling and interactions between sources and between supply and end use, at various scales (from multinational, national, and community scale down to building level) [2]. The need for energy storage and flexible demand is further increasing to improve the business case for their deployment. The issues should be addressed, to solve the challenges of intermittent power generation and the mismatching of energy supply and demand, over a time scale.

In the South African context, power produced from the renewable energy, not consumed by the load, should be stored for later use or discarded, as the power utility, as well as the municipalities, do not generally allow the power to be sold or shared through the national grid.

In the case where various smaller generation units on the same land (estates or a block of townhouses), the power generated from the PV may be shared between the different consumers on the same land.

Consumers on the same land and that have various load patterns, as not everyone uses electricity simultaneously, connecting them in a micro-grid may allow for the power to flow between the different generation systems and consumers. This will decrease the size of the storage systems, as well as the amount of power that will be discarded and lost, when it is not used. On the other hand, the reliance on the grid power will further decrease.

With the increasing installation of distributed generation at the demand (consumer's) side, more and more consumers become prosumers, both generating and consuming energy. The high penetration of sporadic renewable energy, may cause severe problems to power systems. Therefore, in order to facilitate the self-consumption of local generation, the export price at which the prosumers sell electricity to the utility grid is usually designed to be significantly lower than the retail price, at which electricity is being purchased [3, 4]. The main motivation for prosumers to share excess electrical energy amongst each other rather than to feed it back to the utility grid at a much reduced cost; the decreasing tariff rate of the feed-in tariff in most countries, makes this incentive a significantly more attractive approach [5].

Inspired by the requirements of such systems, a rapidly growing number of projects have been started by utilities and high-tech start-ups [6]. A number of projects supporting this model, referred to as Peer-to-Peer energy sharing initiative, have been undertaken around the world. There are:

- Piclo (UK) [7]
- Vandebron (Netherland) [8]
- SonnenCommunity (Germany) [9]
- Yeloha and Mosaic (US) [10]

Other projects, such as PeerEnergyCloud and Smart Watts in Germany, focused on the information and communication technologies supporting the energy sharing [5].

The energy sharing models may be grouped into three categories, according to the manner in which prosumers exchange and trade energy with one another:

- Energy sharing, conducted by one centralized authority.
- Energy sharing, achieved by the interaction between an operator (price maker) and a group of prosumers (price-takers).
- Energy sharing, achieved by the interaction of a group of prosumers, i.e. the P2P energy sharing.

With the increase of distributed renewable energy systems, there is a need to investigate new avenues, such as a P2P energy sharing model, particularly for micro-power producers, operating in the South African context.

1.2 PROBLEM STATEMENT

Due to the mismatch between the load demand and energy produced from renewable energy sources (excess or deficit), smaller energy producers experience challenges, such as discarding excess energy, or unused energy or requiring back up power, such as an energy storage system or the grid; this back-up configuration will result in a high cost of the renewable energy system.

Storage systems (such as batteries), to help with power dispatch, constitute the highest cost of a Photovoltaic System.

1.3 RESEARCH AIM AND OBJECTIVES

The main aim is to develop a P2P energy sharing model, allowing the optimal power flow configuration, with the aim of reducing the amount of power wasted (discarded) or stored in batteries, as well as increasing the availability of onsite generated power.

The objectives of this study are:

- To develop a mathematical model that will assist in assessing the potential of energy and cost saving of prosumers in a P2P sharing configuration, by optimally managing the flow of power to and from another consumer in the South African context (on the same area of land).
- To analyse the techno-economic impact of the P2P energy sharing system in the size reduction of the onsite generation as well as a battery storage system.

1.4 RESEARCH METHODOLOGY

The following methodology will be used in this research:

1.4.1 Literature review

A comprehensive study of the literature related to P2P energy sharing models in a South African context, as well as the applicability and viability of this model. A forecast model of the impact P2P energy sharing paradigm will have on the economy and the result it will have on prosumers of energy.

1.4.2 System description

To assess two dissimilar loads that are in a P2P energy sharing model and compare the various electricity demands. Fig.1.1 is a generic layout of two dissimilar loads in a P2P energy sharing model. There is a multitude of load configurations for an energy sharing model. One example of a configuration is that Load 1 may have a PV generation and a battery storage system, where Load 2 may only have a load and PV generation and energy sharing, from Load 1 to Load 2 may take place.

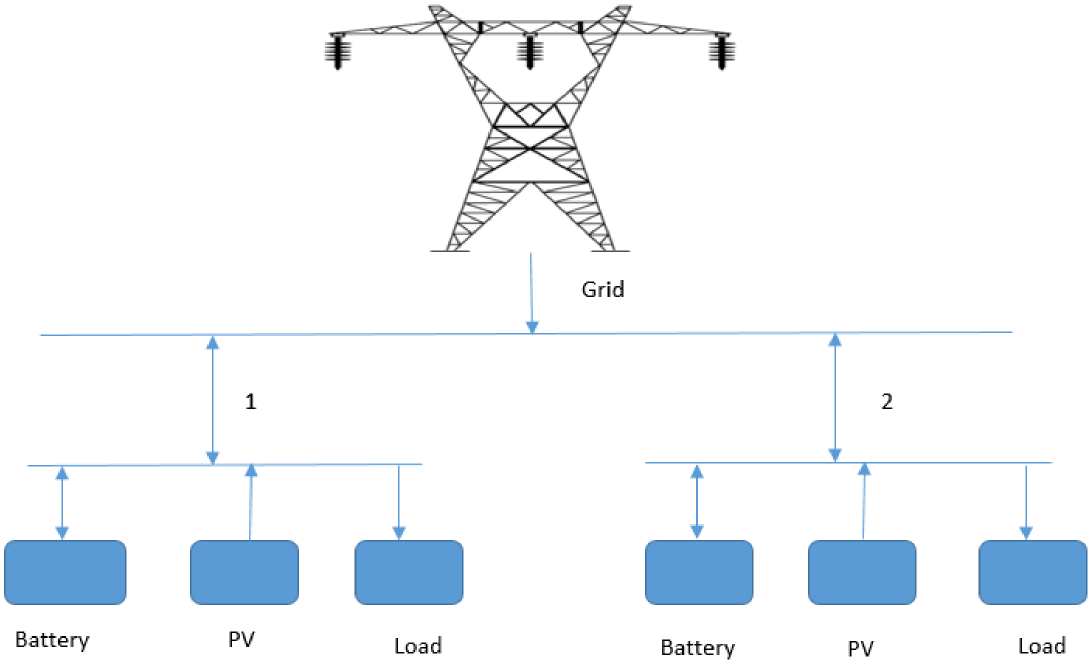

Figure 1.1: Typical layout of a P2P energy sharing model

1.4.3 System modelling

This includes the development of a mathematical model of a P2P sharing model, with photovoltaic and a battery bank, under variable loads, observing the effect that the P2P system will have on prosumers of energy, as well as the monetary effect this model may have in a South African context. The model will comprise of the following:

- The objective function

The control objective to be minimized is the net electricity cost (drawn from the grid), under a given period.

- System Constraints
  - Power balance

At any given time, the load demand (from one prosumer) should be met, however, the combination of the power from the grid, the renewable source, the storage system and the power from the other prosumer.

  - 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 kept within minimum and maximum limits, according to the design specifications, provided by the manufacturer.

  - Exclusive power flow

Power cannot flow in and out of a prosumer’s system at the same time. Also, the battery cannot be charged and discharged simultaneously.

1.5 CASE STUDY

To evaluate the effectiveness of the developed model, a case study will be selected with historical data from the loads and renewable energy resources. Alternative data, such as PV, inverter and battery size, will be obtained from optimal sizing tools, such as HOMER.

From the nature of the optimisation problem, the case study will be simulated utilizing a suitable optimization solver of the matlab optimization toolbox.

As a baseline, so as to study the effectiveness of the developed model, the net energy cost achieved through optimal energy control of the load under the P2P system, will be compared to the energy cost, incurred by the customer, without P2P and operating on a flat tariff.

1.6 PUBLICATIONS DURING THE STUDY

Conference papers:

- Jordan, E. A., K. Kusakana, and L. Bokopane. "Prospective architecture for local energy generation and distribution with Peer-to-Peer electricity sharing in a South African context." In 2018 Open Innovations Conference (OI), pp. 161-164. IEEE, 2018.

Journal papers submitted:

- E.A. Jordan, K. Kusakana, L. Bokopane, P.A. Hohne "Peer-to-Peer energy sharing model in a South African model and economic analysis of lead acid and lithium ion battery storage system".

1.7 DISSERTATION LAYOUT

This dissertation is divided into five Chapters, the main research results are presented in Chapter III and IV.

Chapter I presents the background of the work, underlines the challenges and provides the objectives and methodology.

Chapter II reports a thorough review of advancements in P2P energy sharing schemes and technologies, achieved in other parts of the world, where they have been implemented. This Chapter further outlines the advantages and disadvantages of such systems as well the monetary benefits.

Chapter III illustrates the P2P energy sharing system and all of its components. It further comprises of the mathematical model used to simulate, obtaining the results, as well as the energy cost per day for a baseline system, completely reliant on the electrical grid for power, as well as the proposed system cost per day when electrical energy is shared between two prosumers.

Chapter IV is the evaluation of the economic feasibility of the P2P system and to present the break-even point, as well as the life-cycle cost analysis of the system. In this Chapter, three cases have been analysed. These cases are as follows:

- Baseline system: fully reliant on the grid for power.
- P2P energy sharing system, residential prosumer has a PV panel and lead-acid batteries for a storage system; commercial prosumer that has PV tracking capabilities.
- P2P energy sharing system: residential prosumer has a PV panel and lithium-ion batteries for a storage system; commercial prosumer that has PV tracking capabilities.

Chapter V concludes the work of this dissertation. In this Chapter, an overview, as well as future recommendations for future studies, are discussed.

CHAPTER II: A COMPREHENSIVE REVIEW OF PEER-TO-PEER ENERGY SHARING PARADIGMS AND TECHNOLOGIES

2.1 INTRODUCTION

In this Chapter we will observe the literature on P2P energy sharing and the various works that have been done and experimented with. This Chapter further outlines the grid law of connected renewable energy in South Africa. We will state that municipalities around South Africa have been attempting to urge the population to generate their own electrcity through renewables and sell the surplus energy not used back into the grid. However, this will be sold back into the grid at a signficantly reduced cost that the very same electricity units have been purchased for. The purpose of this Chapter is to illustrate that the rest of the world has, by now, embraced P2P energy sharing in a multitude of companies and startups, that all have their unique method of sharing energy between prosumers.

2.2 LAWS OF GRID CONNECTED RENEWABLE ENERGY IN SOUTH AFRICA

The Electricity Regulation Act, 2006 (Act No. 4 of 2006) ('the Act'), stipulates that no person may operate a generation facility without a license from the Energy Regulator, except for activities listed on Schedule 2, of the Act, namely:

- Any generation plant constructed and operated for demonstration purposes only and not connected to an inter connected power supply.
- Any generation plant constructed and operated for own use.
- Non-grid connected supply of electricity, except for commercial use.
- The small-scale embedded generators that are connected to the grid and operated for commercial purposes must, therefore, be licensed or registered by the Energy Regulator.

- Zero or net consumption customers should too be licensed or registered, due to connection to the grid [11].

Municipalities in the Western Cape province presently have rules and tariffs in place for feeding into the grid when installing a PV system. The remaining municipalities across the province are supported by the Western Cape Government and GreenCape, to design and implement appropriate feed-in tariffs and approve the necessary regulations [12].

2.3 PEER-TO-PEER ENERGY SHARING

In Reference [13], the authors state that, as the installation of distributed generation at the demand side is increasing continuously and an increasing number of energy consumers further develop into prosumers, through stimulating energy sharing and demand response. In some countries, energy consumers have the option to sell surplus energy back to the electrical grid, albeit at a considerably reduced price, compared to purchased electricity. Hence, a new energy sharing model has been designed to convert the consumers into prosumers, allowing them to sell unused energy, which would otherwise have been lost, to the next energy prosumer. This initiative is called a Peer-to-Peer (P2P) energy sharing model. A three stage evaluation methodology is suggested, to assess the financial performance of the P2P energy sharing paradigms. Joint, as well as individual optimization, are established to identify the value contained in the energy sharing region.

The overall energy bill of the prosumer population is estimated through an agent based modelling, with reinforcement learning for each prosumer.

Performance index is defined to quantify the economic performance of P2P energy sharing models. Energy sharing is a relatively new business model at the demand side of power distribution systems and this new model will bring greater benefits to prosumers. In the case of conventional business model, the suppliers purchase electrical energy from the utilities in the wholesale market and, further, sell it to the end users, or the consumers, of the electrical energy. In this ‘older’ model, prosumers will trade with the suppliers separately, by purchasing and selling the energy to and from suppliers, at retail prices. However, as the prosumers sell surplus energy to the grid, it will be at a particularly low rate Figure. 2.1.

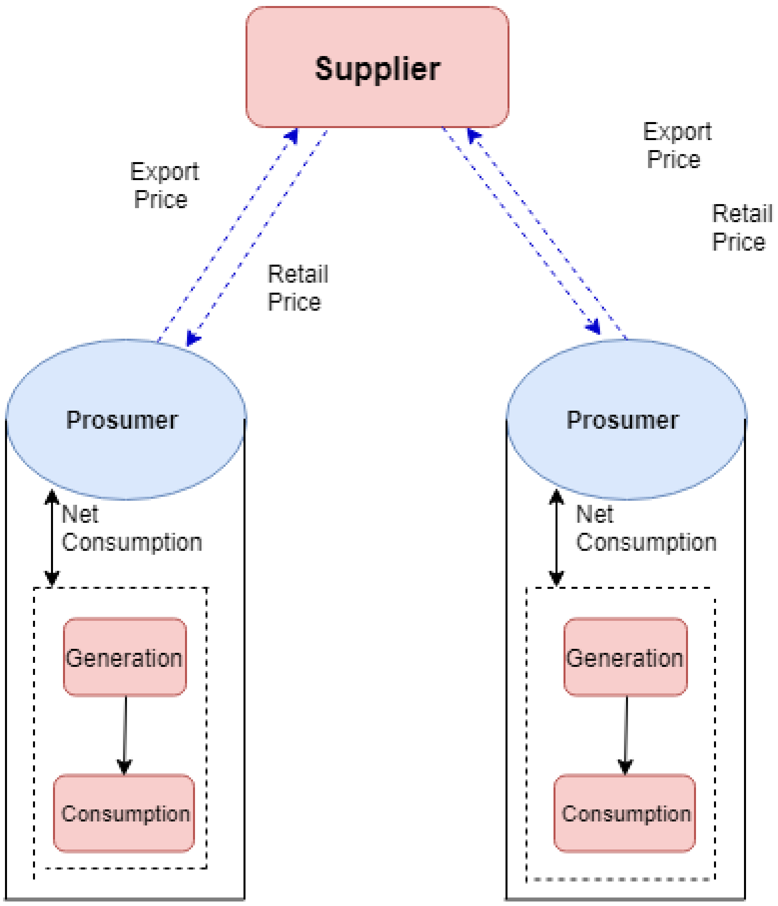

Figure 2.1: Conventional Model

With the current energy sharing model, prosumers exchange and trade energy with each other directly in an energy sharing region, as shown in Figure 2.2. In a South African context, this will solely be possible if all the prosumers are connected in one area of land, for instance, a block of flats or townhouse complex. An energy sharing coordinator manages the internal sharing of energy between prosumers and, will further act as an agent of the prosumers when they trade/sell surplus energy to the grid, however, at a significantly lower rate. P2P energy sharing models specify at which prices prosumers will trade energy with each other and as to how to calculate the energy bill for the prosumers.

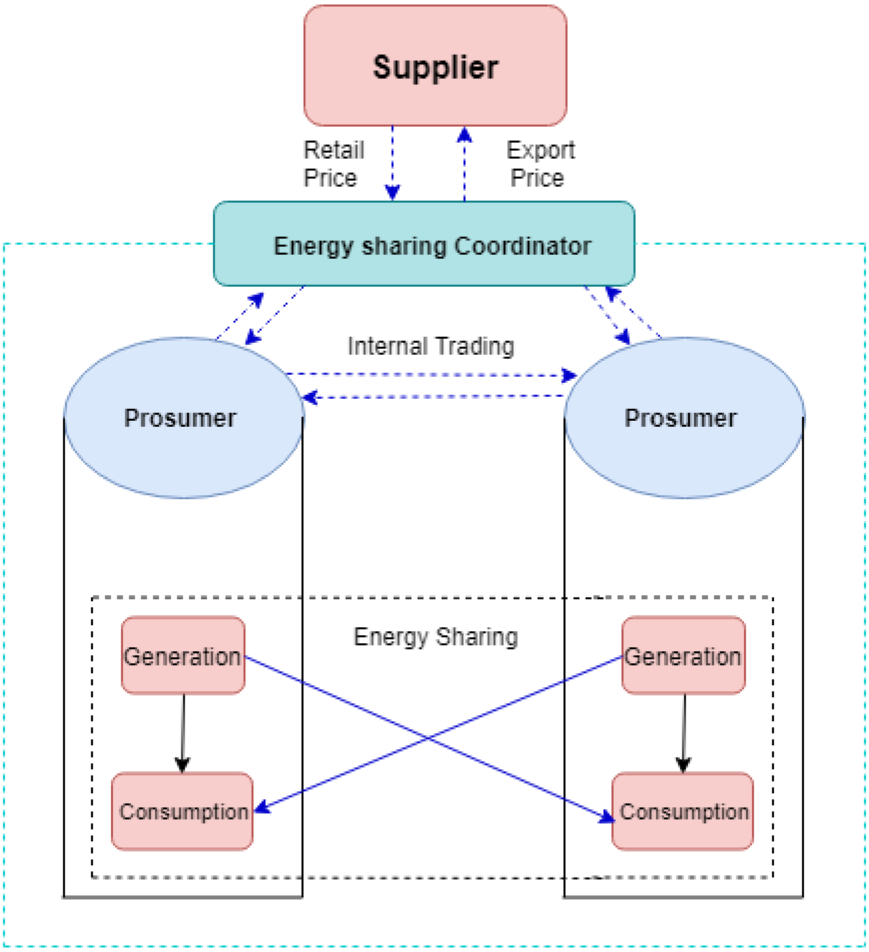

Figure 2.2: P2P energy sharing model

In Reference [14], it is stated that P2P energy trading is a system that allows for people, or prosumers, to generate their own electrical energy from Renewable Energy Sources (RESs), in residents, offices and factories sharing it with one another locally. An architecture model was proposed, to present the design and interoperability aspects of components for P2P energy trading, in a micro-grid. A specific customer-to-customer business model was introduced in a benchmark grid-connected micro-grid, based on the architecture model. The test results have shown that a P2P energy trading model is able to balance the local generation and demand, hence, it has a potential to enable a large penetration of RES's in the power grid.

It was stated in Reference [15] that, P2P energy sharing models have grown significantly around the world, with various projects and trails. A focus study, as well as the outcomes of these projects, has been carried out and a comparison of the similarities and differences of the various projects have been documented. The results have shown that many of the trails' focus on the business models are acting in a similar fashion, compared to the role of the suppliers' in the electricity sector. Further it is of importance to design, or develop necessary communication and control networks, enabling P2P energy trading in or amongst local micro-grids. What follows is a list of current P2P energy sharing models that are currently utilised around the world.

- Piclo is a company based in the UK. This model allows business consumers to purchase electricity from local renewables (household generators). The various electricity generators have complete control and visibility as to who purchases electricity from them. Electricity consumers are further able to select and prioritize from which generators to buy electricity. Piclo matches generation and consumption, according to preferences, as well as locality, providing customers with data visualizations and analytics [16].
- Vandebron is based in the Netherlands. This model allows energy users to purchase electricity directly from independent producers, such as farmers, that have wind turbines in their fields [17].
- PeerEnergyCloud in Germany, has developed cloud-based technologies for a local electronic trading platform, dealing with local excessive production. The company was established in order to investigate state-of-the-art recording and forecasting processes, for device specific electricity consumption, creating a virtual marketplace for electricity trading and to develop value added services, within a Microgrid [18].
- Smart Watts is a German company that developed and tested new approaches for energy optimizing energy supply, using modern information and communication technologies [19].
- Yeloha and Mosaic are US companies, allowing interested consumers, such as apartment owners and those who do not posess solar systems, to pay for a small portion of the solar energy generated by the host's solar system [20, 21].
- SonnenCommunity is a storage manufacturer in Germany. It is a community of SonnenBatery owners, who share self-generated energy with others. As a result, there is no further need for a conventional energy supplier. With a SonnenBatterie and a Photovoltaic system, members can entirely cover their personal energy requirements on days with lack of cloud cover; often actually generating a surplus. This surplus is

not fed into the traditional power grid, but into a virtual energy pool, serving other members in times when they are unable to generate enough energy, due to unfavourable weather. A central software links up and monitors all SonnenCommunity members, whilst balancing energy supply and demand [9]. This idea is particularly similar to Piclo's and Vandebron's, however, SonnenCommunity clearly highlights the importance of a storage system [22].

- Lichtblick Swarm Energy is a unique IT platform in the energy market. On this platform, the procedures of an increasingly complex world of energy to customer-friendly products and services, for residential and business customers, are combined. Customers' local power plants and storages are optimized. Swarm Energy allows for a meaningful interaction of distributed and renewable energy sources [23].
- Transactive Grid is a community energy market. It is a combination of software and hardware that allows members to purchase and sell energy from one another securely and automatically, utilizing smart contracts and the blockchain. The current prototype uses the Ethereum blockchain [24].

Table 2.1: Comparison and key finding on past P2P projects

Authors	Highlights	P2P Configuration	Key Findings
Community First! Village	Energy sharing from donations	Commercial to Residential	A master planned community that provides affordable, permanent housing and a supportive community for the disabled and homeless
Electron	Energy metering and billing platform using blockchain	Energy network, ICT, Commercial	A new platform for gas and electricity metering and billing system, that runs on a blockchain. The platform will be an open source for the benefit of all users.
Lichtblick Swarm Energy	IT platform for energy markets and customers	Energy network, ICT, Commercial, Residential	The processes of an increasingly complex world of energy to customer-friendly products and services for residential and business customers, are combined
PeerEnergyCloud	Cloud-Based P2P energy trading platform, Smart Homes	Energy network, ICT	Cloud-based technologies for a local electronic trading platform. It was established in order to explore advanced recording and forecasting procedures, for device specific electricity consumption
Picolo	P2P energy trading platform from suppliers perspective	Commercial to Residential	Meter data, generator pricing and consumer preferences' information is used to match electricity demand and supply, every half hour.
Smart Watts	Optimizing energy supply via ICT	Energy network, ICT	New approaches for optimizing energy supply through the use of modern information

			and communication technologies
SonnenCommunity	P2P energy trading with storage system	Energy network, Commercial, Residential	SonnenCommunity is developed by SonnenBatterie. It a community of SonnenBatterie owners who share self-produced energy with others in the community
TransActive Gird	P2P energy trading within microgrids using blockchain	Energy network, Commercial, Residential	Energy market with a combination of software and hardware, enabling members to buy and sell energy from each other securely and automatically, using smart contracts and the blockchain
Vandebron	P2P energy trading platform from suppliers perspective	Commercial, Residential	Energy consumer purchases electricity directly from independent producers.
Yaloha, Mosaic	Solar sharing network for lower energy bills	Commercial, Residential	Interested consumers not ppossesing solar systems to pay for a portion of the solar energy generated by the host's solar system and receive a reduction on their utility bill

2.4 WORK DONE UNDER PEER-TO-PEER ENERGY SHARING

Reference [25], states that the shared solar market is poised for growth in the U.S. This is boosted by initiatives that are supported by state and federal agencies, customers, contractors and utilities. Adoption of these energy sharing models will require addressing political and economic barriers, varying between states and program models. Investor-owned utilities will work closely with regulators, defining enabling policies in the coming years, whilst municipal and cooperative utilities will likely continue to pilot these shared programs, benefiting all involved in this shared solar initiative.

The authors in Reference [26], state that an important element are the prosumers in a smart grid. Prosumers not only use energy, but further share surplus energy generated by renewable energy sources, with grid and/or with other consumers, in a community. The prosumer concept is illustrated in Fig.2.3. This phenomenon helps address the environmental, social and economic concerns, related to increasing energy demand. To manage the prosumers in an energy sharing system, smart grid permits consumers to form communities, according to various measures, such as energy consumption behaviour. It is further stated that it is necessary that a prosumer based Energy Management and Sharing system (PEMS), is investigated and reviewed, along with the related challenges. The procedure of energy sharing amongst prosumers, comprises of two key elements, namely: information and communication technologies and optimization techniques.

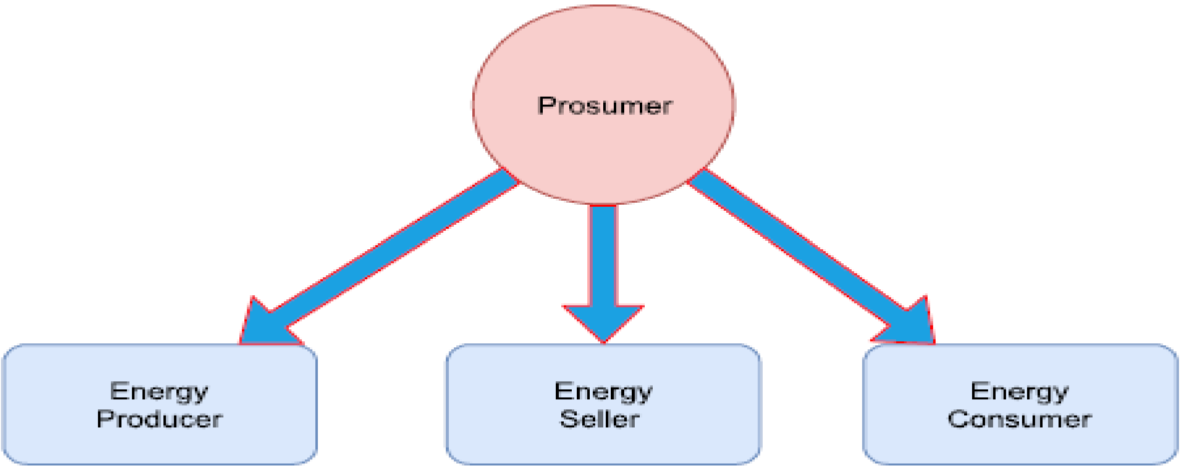

Figure 2.3: Description of prosumer interaction

In Reference [27], the authors state that the sustainability of the Smart Grid (SG) energy sharing process is heavily dependent on the participation of prosumers. This causes the prosumer contribution and management systems table crucial, within the energy sharing approaches. A novel concept is introduced in participating and managing the prosumers in the SG energy sharing process, in the form of autonomous, intelligent goal-driven virtual communities. Hence, the prosumers in that community may collectively increase the amount of power to be auctioned or purchased, offering a higher bargaining power to the community.

An initial step in building an effective prosumer-community, is the identification of those prosumers, of whom would be suitable to form efficient prosumer communities. Identifying parameters that influence the energy sharing behaviours of prosumers.

It is stated in Reference [28], that the objective of "PeerEnergyCloud" is to research and develop cloud-based technologies for just such a trading platform. Techniques were demonstrated for a future energy scenario, necessary as a basis for a civil marketplace for trading renewable energies.

Reference [29], declares that successful sharing should achieve enhanced utilization efficiency of demand-side energy resources (DER's), voluntary participation of prosumers and sharing-enabling aggregator. A mathematical model has been formulated, with equilibrium constraints (MPEC) for DER's evaluation, within a sharing community. The aggregator coordinates DER operations in real-time; it solves this MEPC problem after each billing period. The aggregator evaluates two operating costs for each prosumer:

Actual cost, under coordination of Counter-factual cost if the prosumer independently traded power with the aggregator.

The authors in Reference [30], state that, in order to build real smart cities, heterogeneous data from various sources should be correctly collected, integrated and shared. An actual district scale example of an urban sharing ecosystem based on coopetition, is presented. This digital ecosystem enables data sharing that may be holistically applied to different sectors relevant to the urban context, for example, energy and transportation, in order to create innovative solutions for energy monitoring, citizen engagement, evaluation and monitoring, at district and city level.

Reference [31] states that renewable energy harvested from the environment, is an attractive option, however, the intermittent nature of this renewable energy results in a mismatch when these sources are generated and when homes or consumers are in demand of it. An alternative approach is currently being devised, where nearby homes explicitly share energy with one another balancing the local energy being harvested and demanded in micro-grids. A novel approach is developed in energy sharing, determining which homes should share energy and at which times. This is carried out to maximize system-wide efficiency losses. Evaluation of this approach is a real time simulation, using actual traces of solar energy harvesting and home consumption data. The system shows that: 1) energy loss is reduced on the AC line by 60%, without requiring of large batteries; 2) performance is improved with large batteries; 3) robust to changes in the micro-grid topology.

2.5 MAJOR WORKS CARRIED OUT ON PEER-TO-PEER ENERGY SHARING FROM 2015 – 2019

The authors in Reference [32], have specified that the feasibility of applying P2P energy trading to decrease costs for energy consumers and to increase income for DER producers in a community microgrid, was investigated. Three representative market paradigms were recommended, i.e, bill sharing, mid-market rate and an auction-based pricing strategy. Each of these specified detailed business models, local energy exchange prices, as well as quantified individual customer energy costs.

In Reference [33], the authors propose that an optimization problem aiming at minimizing the overall energy cost and the P2P energy sharing losses, in a distribution system, consisting of multiple microgrids (MGs) and openly incorporates the practical constraints (e.g., power balance and battery's operational constraints). The proposed optimization problem is challenging to solve directly due to the non-convex constraints. Nevertheless, motivated by the very recent result in radial distribution networks, the projected non-convex optimization problem may be eased to a second-order cone programming (SOCP) problem, without incurring any loss of optimality. The proposed problem was applied to a radial distribution network testbed and obtained the corresponding optimal energy management strategy, exploiting the diversified energy consumption profiles, dynamically coordinating multiple MGs and reducing the total energy bill of all MG's. Moreover, an interesting observation from the simulation results, is that the cooperation scheme in the P2P sharing network, is significantly affected by the MG's relative locations, in the distribution network.

The authors in Reference [34], describe a new concept of P2P energy sharing producing a marketplace for electricity. This marketplace is for individuals who are able to afford power generating sources, such as solar panels, selling electricity to individuals who are unable to afford generating sources, or who might have access to electricity but require more electricity at certain times. These ad-hoc microgrids, created by the sharing of resources, provide affordable electricity and are enabled by a Power Management Unit (PMU).

In Reference [35], the authors strive to provide a theoretical study for energy production and distribution. The evolution of energy systems technologies and their impact on the global socio-economic structure has been analysed and discussed in detail. Further critically analysed, was the evolution of the energy production infrastructure and a review of the renewable and decentralized energy production technologies, while focusing on the concept of microgrids. It was proposed that an alternative model, inspired by the commons-oriented practices, currently observed in the production of information, that utilizes microgrids in order to create a peer-to-peer energy grid and then discuss the conditions necessary for the "energy commons" to emerge.

Reference [36], states that an architecture paradigm was proposed, presenting the design and interoperability aspects of components, for P2P energy trading in a microgrid. A specific Customer-to-Customer business model was introduced in a standard grid-connected microgrid, based on the architecture model. The core element of a bidding system, called Elecbay, was further proposed and simulated, using game theory. The test outcomes show that P2P energy trading is able to balance local generation and demand, therefore, having a potential to enable a large penetration of RES's in the power grid.

Reference [37], presents an innovative P2Penergy trading system between two sets of electric vehicles, which significantly reduces the impact of the charging process on the power system, during business hours. This trading system is further economically beneficial for all users involved in the trading process. An activity-based model is utilized in predicting to predict the daily agenda and trips of a synthetic population for Flanders (Belgium). These drivers are primarily classified into three sets; after discarding the set of drivers short of energy, without taking chances, due to their tight schedule, we focus on the two remaining relevant sets: those who complete their daily trips, with an excess of energy in their batteries and, those who need to (and can) charge their vehicle during some daily stops, within their scheduled trips. The last pair of drivers have the opportunity to individually optimize their energy cost in the time-space dimensions, taking into account the grid electricity price and their mobility constraints. Thereafter, collecting all the available offer/demand information amongst vehicles parked in the same area, simultaneously, an aggregator determines an optimal P2P price per area and per time slot, allowing customers with an excess of energy in their batteries to share the benefits with the other users who require a charge for their vehicles, during their daily trips. Results show that, whilst applying the proposed trading system, the energy cost paid by these drivers at a specific time slot and in a specific area, may be reduced up to 71%.

In Reference [38], the authors have stated that prosumers are agents that both consume and produce energy. With the growth in small and medium-sized agents, using solar photovoltaic panels, smart meters, vehicle-to-grid electric automobiles, home batteries and other ‘smart’ devices, prosuming offers the opportunity for consumers and vehicle owners to re-evaluate their energy practices. As the number of prosumers increases, the electric utility sector of today is likely to undergo significant changes in the approaching decades, offering possibilities for greening of the system, however, further bringing many unknowns and risks that require identification and management. To develop strategies for the future, policymakers and planners require information of how prosumers could be integrated effectively and efficiently into competitive electricity markets. Here, we identify and discuss three promising potential prosumer markets, related to prosumer grid integration, P2P models and prosumer community groups. We further caution against optimism, by laying out a series of caveats and complexities.

The authors in Reference [39], have formulated numerous original energy exchange optimization complications, minimizing the global energy loss during the exchange in various situations, then developing an efficient and privacy-preserving scheme, to solve the energy exchange optimization challenges, without private information disclosure. They have further extended the privacy-preserving scheme, to a collusion-resistant scheme in which the microgrids are unable to learn any additional information, through conspiring with one another. The performance of the proposed approaches is experimentally validated on real microgrid data.

Reference [40], made reference to the feed-in tariff, encouraging local consumption of photovoltaic (PV) energy. The energy sharing among neighboring PV prosumers in the microgrid could be more cost-effective than the independent operation of prosumers. For microgrids of P2P PV prosumers, an energy-sharing model with price-based demand response, is suggested. Firstly, a dynamic internal pricing model is formulated for the operation of energy-sharing zone, which is defined based on the supply and demand ratio (SDR) of shared PV energy. Furthermore, since the energy consumption flexibility of prosumers, an equivalent cost model is designed in terms of economic cost and the users' willingness. As the internal prices are coupled with SDR in the microgrid, the algorithm and implementation technique, for solving the model, is designed on a distributed iterative way. Finally, through a practical case study, the effectiveness of the method is verified in terms of saving PV prosumers' costs and improving the sharing of the PV energy

In Reference [41], the results express that, although many of the trails focus on the business models acting similarly to a supplier's role in the electricity sector, it is further necessary to design the essential communication and control networks, that could enable P2P energy trading in, or among, local microgrids.

The authors in Reference [42], proposed a three-stage evaluation methodology, to assess the economic performance of P2P energy sharing models. Firstly, joint and individual optimization are established, identifying the value contained in the energy sharing region. The overall energy bill of the prosumer population is estimated through an agent-based modelling, with reinforcement learning for each prosumer. Finally, a performance index is defined, to quantify the economic performance of P2P energy sharing models. Simulation results verify the effectiveness of the proposed evaluation methodology and compare three existing P2P energy sharing models, in a variety of electricity pricing environments.

In Reference [43], the authors proposed a new framework for the time-slotted P2P energy sharing and coordination in Energy Internet, aiming to accomplish flexible and efficient distributed energy management and control. Users in this framework are equipped with distributed generators (DG's), distributed energy storage systems (DES's) and smart meters; the P2P energy sharing fashion is supported, where users can buy or sell electricity to and from a utility company and neighbouring users. The energy sharing and coordination problem is formulated as a convex optimization problem, with the objective to minimize the economic cost of users. A distributed algorithm is proposed, in combination with alternating direction method of multipliers (ADMM). On the basis of a real-world dataset of renewable energy and real-time electricity price, both analytical and numerical results show the effectiveness of the proposed framework and algorithm, in terms of, not only fast convergence in a time slot, but further economic saving prominently for an extended application.

In Reference [44], the authors stated that the simulation framework is composed of three types of agents and three corresponding models. Two techniques, i.e. step length control and learning process involvement and a last-defence mechanism were proposed to facilitate the convergence of simulation and contend with the divergence. The evaluation indexes include three economic indexes, i.e.: value tapping, participation willingness and equality and three technical indexes, i.e.: energy balance, power smoothness and self-sufficiency. They are normalised and further synthesized to reflect the overall performance. The planned methods were applied, simulating and evaluating three existing P2P energy sharing mechanisms, i.e.: the supply and demand ratio (SDR), mid-market rate (MMR) and bill sharing (BS), for residential customers in current and future scenarios of Great Britain. Simulation results showed that, both of the step length control and learning process involvement techniques improve the performance of P2P energy sharing mechanisms, with moderate ramping/learning rates. The results further showed that P2P energy sharing has the potential of bringing both economic and technical benefits for Great Britain. In terms of the overall performance, the SDR mechanism out-performs all other mechanisms and the MMR mechanism has acceptable performance, with moderate PV penetration levels. The BS mechanism performs at a similar level as the conventional paradigm. The conclusion on the mechanism performance is not sensitive to season factors, day types and retail price schemes.

In Reference [44], it is presented that an all-inclusive review of Transaction-based energy (TE), involving P2P energy trading and further covering the concept, enabling technologies, frameworks, active research efforts and the prospects of TE. The formulation of a regular approach for TE management modelling is challenging, given the diversity of circumstances of prosumers, in terms of capacity, profiles and objectives. This has resulted in divergent opinions in the literature. This study identified that the majority of the techniques in the literature exclusively formulate energy trade problems as a game, an optimization problem or a variational inequality problem. It was further observed that, none of the existing works have considered a unified messaging framework. This is a potential area for further investigation.

In Reference [46], the authors states that the P2P energy exchange and sharing (ETS) network derives from the conventional smart-grid systems. The smart-grids operate smart meters, that may be equipped with both wireless and powerline communication standards. In this study, we extend this communication strategy to a hybrid wireless-powerline communication scheme, operating in cooperation and involves transmitting the same information over these two channel infrastructures, combining the received signals, using maximal ratio combining (MRC) at the receiver. To maximize the received signal strengths, with improved bit error ratio (BER) at the receiver side, the characteristic channels formed into a matrix and used singular value decomposition (SVD), to process the signals. Compared to either zero-forcing (ZF), or minimum mean square error (MMSE) detection scheme, the proposed SVD processing achieves 5dB and 7dB more effective than ZF and MMSE, respectively, at 10-5 BER performance, when operated with 10-2 impulsive noise probability.

The authors in Reference [47], propose a model that achieves demand response, by providing incentives to discharging plug-in hybrid electric vehicles (PHEV), balancing local electricity demand, for their own self-interests. Nonetheless, since transaction security and privacy protection issues present serious challenges, we explore a promising consortium blockchain technology, improving transaction security, without reliance on a trusted third party. A localized P2P Electricity Trading system, with consortium blockchain (PETCON) method is proposed, to illustrate detailed operations of localized P2P electricity trading.

In Reference [48], the authors design an agent-based control framework, ensuring the coordinated power management within the microgrids, through effective utilization of electric vehicles (EV). The required agent communication framework is adhered to the graph theory, where the control agents interact with each other, using local, as well as neighbouring information and their distributed coordination successfully steers the proportional sharing of real and reactive powers among the inverter-interfaced EV’s to maintain the stability of microgrids. The well-known Ziegler-Nichols method is utilised, to tune the proportional-integral (PI) controller of the inner current control loop within each individual control agent, to perform necessary shared control tasks. A microgrid, with solar photovoltaic (PV) and vehicle-to-home (V2H) systems, is chosen to illustrate the results and observed that the proposed scheme improves the system performance in a smarter way, through information exchange. Furthermore, the proposed framework is further validated by a comparison, with an existing traditional approach and it is found that the proposed scheme provides excellent, robust and faster performance.

The authors in Reference [49], provide a view to P2P approach for smart grid operation, adopted in P2P-SmarTest project. It provides an overview of solutions, proposed for distributed P2P energy trading, P2P grid control and wireless communication, enabling the proposed P2P operation.

In Reference [50], describes the design, build and demonstration of a scaled down (100 W) P2P microgrid system, providing a low-cost, modular, safe, portable testing environment, for new smart energy management system (EMS) algorithms. The paradigm, nonetheless, has realistic behaviour, in terms of control interfaces, measurements and dynamics and, therefore, provides a valuable insight into EMS implementation that cannot be obtained through simulations alone. Three microgrid emulators were built and they communicate with each other via transmission control protocol/internet protocol (TCP/IP), enabling development and demonstrations of distributed forecasting, control and optimisation algorithms.

The authors in Reference [51], propose an evaluation model to analyse the impact of microgrid topologies on self-sufficiency, for a given size of batteries and photovoltaic (PV) panels (resources). Three topologies are evaluated for a community of 19 houses: centralized resources (ideal case), stand-alone resources and a multi-microgrid topology, with autonomous exchange. Depending on the ratio of PV and battery size, the topology with stand-alone resources has a clear disadvantage, in terms of self-sufficiency, compared to the centralized, ideal topology. To counteract this, a hybrid topology was proposed: households are interconnected, exchanging energy between one another based on an autonomous energy exchange algorithm developed. It is illustrated that, for a well-chosen ratio of batteries and PV, the interconnected system may improve the stand-alone design, by up to 10%, without requiring any additional resources. This topology may approach performance, similar to that of a centralized microgrid, although the design is more flexible and resilient to failures or accidents. The evaluation model computes the self-sufficiency ratio (SSR) for the three topologies, for 0–20 kWh batteries and 1–14 kWp PV sizes. Furthermore, seasonal differences in SSR, per topology, are analysed for an actual community, with actual resources. They further calculated the savings in PV and battery, due to the interconnected topology. Finally, the third topology's feasibility is demonstrated on a full-scale platform in Okinawa, on which the autonomous energy exchange software was tested for over a year in a community of 19 houses.

In Reference [52], it is stated that P2P energy trading, characterizes direct energy trading between peers, where energy from small-scale DER's in dwellings, offices, factories and the like, is traded amongst local energy prosumers and consumers. A graded system architecture model was proposed, identifying and categorizing the key elements and technologies, involved in P2P energy trading. A P2P energy trading platform was designed and was simulated using game theory. Test results in a LV grid-connected Microgrid show that P2P energy trading is able to improve the local balance of energy generation and consumption. Furthermore, the increased diversity of generation and load profiles of peers, is able to further facilitate the balance.

The authors in Reference [53], demonstrate how decentralization may be achieved, using P2P frameworks as underlying control structures and implemented a pure P2P eliminating single points of failure. For this, a direct current (dc) open energy system, compromised of the interconnection of standalone DC nanogrids, is utilized as an underlying microgrid. The power flowing between nanogrids, are controlled by a decentralized exchange strategy: each household may request or respond to energy deals with its neighbours without requiring system-wide knowledge, or control. Using DC, combined with a layered, modular software allows loose coupling, which increases flexibility and dependability. The system has been applied and tested on a full-scale platform in Okinawa, including 19 inhabited houses. Actual data analysis, as well as simulations, demonstrate improvements in self-sufficiency, compared to other types of systems. Resilience against utility blackouts, is proven in practice.

In Reference [54], it is stated that virtual power plants and P2P energy trading, offers various sources of value to prosumers and the power network and have been proposed as different potential structures, for future prosumer electricity markets. In this perspective, it is argued that it may be combined, to capture the benefits of both. Hence, it is proposed that, the concept of the federated power plant, a virtual power plant formed through P2P transactions, between self-organizing prosumers. This addresses social, institutional and economic issues, faced by top-down strategies, for coordinating virtual power plants, whilst unlocking additional value for P2P energy trading.

The authors in Reference [55], proposed a two-stage aggregated control, realizing P2P energy sharing, in community Microgrids, where solely the measurement at the point of common coupling (PCC) and one-way communication, are required. This method allows for individual prosumers to control their DER's, via a third party entity, a so called energy sharing coordinator (ESC). Within the first stage, a constrained non-linear programming (CNLP) optimization, with a rolling horizon, was used to minimize the energy costs of the community. Within the second stage, a rule based control was carried out, updating the control set-points, according to the real-time measurement. The benefits of P2P energy sharing were assessed from the communities, as well as the individual customers' viewpoint. The proposed method was applied to residential community Microgrids, with photovoltaic (PV) battery systems. It was revealed that P2P energy sharing is able to reduce the energy cost of the community by 30%, compared to that of the the conventional peer-to-grid (P2G) energy trading. The modified supply demand ratio-based pricing mechanism, ensures that every individual customer is better off and may be utilized as a benchmark for any P2P energy sharing model. For consumers, the electricity bill is reduced by -12.4% and for prosumers, the annual income is increased by £57, per premises.

In Reference [56], introduces real-time and forward markets, consisting of energy contracts, offered between generators with fuel-based sources, suppliers acting as intermediaries and consumers with inflexible loads and time-coupled flexible load. For each type of agent, utility-maximising preferences, for real-time contracts and forward contracts, are derived. It is shown that these preferences satisfy full substitutability conditions essential for establishing the existence of a stable outcome; an agreed network of contracts specifying energy trades and prices, which agents do not wish to equally deviate from. Important characteristics of energy trading are incorporated, including upstream–downstream energy balance and forward market uncertainty. Full substitutability ensures that a distributed price-adjustment process may be used, which solely requires local agent decisions and agent-to-agent communication, between trading partners.

In Reference [57], the authors provide a summary of the use of game theoretic methods, for P2P energy trading, as a feasible and effective means of energy management. As such, it is further discussed that, various games and auction theoretic approaches, by following a methodical classification, providing information on the importance of game theory for smart energy research. It further focuses on the P2P energy trading, describing its key features and providing an overview of an existing P2P testbed. Furthermore, it focuses on the detail of some specific game and auction theoretic models, recently used in P2P energy trading and discusses a few important findings of these schemes.

The authors in Reference [58], evaluate the Brooklyn Microgrid project, as a case study, of such a market, according to the required components. It is shown that, the Brooklyn Microgrid fully satisfies three and partially fulfils an additional three of the seven components. Furthermore, the case study demonstrates that, blockchains are an eligible technology to operate decentralized microgrid energy markets. However, current regulation does not allow the running of local P2P energy markets in most countries, hence, the seventh component is not able to be satisfied as of yet.

In Reference [59], the authors examined a P2P energy sharing method, allowing the surplus of DER's to be shared between prosumers, in a neighbourhood. An aggregated control of many small-scale batteries was adopted, considering the energy requirement of the entire community. This method significantly reduces the amount of electricity fed back into the grid, allowing for individual prosumers to obtain economic benefits. Results showed that, with a moderate proportion (e.g. 40%) of customers, having individual photovoltaic (PV) systems, P2P energy sharing is able to reduce the energy cost of the community by 30%, compared to P2G trading.

Reference [60], proposes an original game-theoretic model for P2P energy trading, among the prosumers, in a community. The buyers may adjust the energy consumption behaviour, based on the price and quantity of the energy offered by the sellers. Two separate competitions exist during the trading process: (i) price competition amongst the sellers and (ii) seller selection competition amongst the buyers. The price competition amongst the sellers is modelled as a non-cooperative game. The evolutionary game theory is used to model the dynamics of the buyers, for selecting sellers. Furthermore, an M-leader and N-follower Stackelberg game approach, is used in modelling the interaction between buyers and sellers. Two iterative algorithms are proposed for the implementation of the games, such that an equilibrium state exists, in each of the games. The proposed method is applied to a small community microgrid, with photovoltaic (PV) and energy storage systems. Simulation results illustrate the convergence of the algorithms and the effectiveness of the proposed model, handling the P2P energy trading. The results further show that P2P energy trading provides substantial financial and technical benefits to the community and is emerging as an alternative for cost-intensive energy storage systems.

In Reference [61] the authors proposed work attempts to address this problem, by developing an optimal P2P energy sharing, amongst the individual households, in a DC microgrid. A nonlinear optimization problem is formulated, aiming to minimize the power transmission loss and overall energy cost, in a distribution network, consisting of a number of households incorporating practical constraints (e.g., power balance and battery's operational constraints). Three different aspects of operation viz., battery usage, power from the grid and P2P sharing, have been considered in order to facilitate maximum utilization of local distributed energy resources, thereby, saving the energy costs for all households.

Reference [62], explores the probability of social collaboration between prosumers within an energy network, in establishing their sustainable participation in P2P energy trading. In particular, a canonical coalition game (CCG), is utilized to propose a P2P energy trading scheme, in which a set of participating prosumers form a coalition group to trade their energy, if there is any, with one another. By exploring the concept of the core of the designed CCG framework, the mid-market rate is utilized as a pricing mechanism of the proposed P2P trading, confirming the stability of the coalition, as well as to guarantee the benefit to the prosumers, to form the social coalition. Furthermore, it introduces the motivational psychology models, relevant to the proposed P2P scheme and it is shown that the outcomes of the proposed P2P energy trading scheme satisfy the discussed models. Consequently, it is proven that the proposed scheme is consumer-centric and has the potential to corroborate sustainable prosumer participation, in P2P energy trading. Finally, a few numerical examples are provided, demonstrating the beneficial properties of the proposed scheme.

In Reference [63], a P2P energy trading mechanism is presented, using non-cooperative bidding among microgrids. Multidimensional readiness, including time pressure and counter behaviour, to mimick the personalized behaviours of microgrids, was taken into account, in the design of the bidding strategy. Under a parallel trading framework, based on a blockchain, the proposed multidimensional willingness bidding strategy, transcripts to be able to construct rational decisions, with adequate flexibility in the bidding process. The simulation results of a realistic case of microgrids, from the Guizhou Province, China, authenticate that the proposed P2P energy trading mechanism is capable of raising the microgrids' profits and renewable energy source utilization.

The authors in Reference [64], proposed two market designs, centred on the role of electricity storage. Therefore, focusing on the following questions: (1) What is the value of prosumer batteries in P2P trade? (2) What market features do battery system configurations need?, and (3) What electricity market design opens the economic potential of end-user batteries? These questions were addressed; an optimisation model was implemented to represent the P2P interactions, in the presence of storage for a small community in London, United Kingdom. The contribution of batteries located at the customer level, versus a central battery shared by the community, was investigated. Results illustrate that the combined features of trade and flexibility from storage, produce savings of up to 31% for the end-users. More than half of the savings derives from cooperation and trading in the community, while the rest is due to the battery's flexibility in balancing supply-demand operations.

Reference [65], proposes two user-centric pricing strategies, for facilitating P2P energy trading, in residential microgrids: a Unified Pricing (UP) strategy and Identified Pricing (IP) strategy. The proposed strategies aim to maximize the profit of small-scale distributed energy resources owners, while taking into account the user's life convenience and solar photovoltaic uncertainty. UP strategy includes a centralized market pool, determining the market clearing price, at a regular time interval; IP strategy recognizes each energy transaction with variations on different time, based on the consumers' bid. The auction algorithm is utilized in solving the energy allocation, achieving the foremost social welfare, in the community microgrid. Numerical studies, based on fifteen simulated residential users, are conducted validating the reasonability and effectiveness of the proposed methods.

In Reference [66], the authors studied the energy management problem of multiple MG's, interconnected by both the direct current (DC) energy exchange network and the alternating current (AC) traditional distribution networks. The identified problem; each microgrid (MG) is equipped with renewable energy generators, as well as distributed storage devices. In order to handle the non-convex power flow constraints, we exploit the recent results of the exact optimal power flow (OPF) relaxation method, which may equivalently transform the original non-convex problem, into a second-order cone programming problem and efficiently determine the ideal solution successfully. The objective for this problem, is to minimize the overall energy cost in a distribution network, consisting of multiple MGs, with the practical operating constraints (e.g., power balance and the battery's operational constraints), explicitly incorporated. Considering the privacy and scalability, a distributed algorithm is proposed with convergence assurance, based on the alternating direction method of multipliers (ADMM). The method is further implemented, based on the model predictive control (MPC) approach, in order to manage the forecasting errors of the renewable energy generation. Simulations are carried out for various MG exchange topologies, on three radial distribution network testbeds. Numerical results establish that certain topologies are more favourable than others and the cooperation strategy for the energy exchange is significantly affected by the MG's locations, within the distribution network.

In Reference [67], the economic influences of revising the tariff structure from energy-based tariffs (EBT), to power-based distribution tariff (PBT), on customers participating in P2P community microgrids, with PV installations, were evaluated. We consider four seperate Finnish customer types and compare the benefits obtained by thirty-six customers of each type, after their EBT was replaced by PBT. We further apply PBT to the power supplied by prosumers, to their peers. Approximately the total of customers, expectedly benefited from electricity exchange, particularly for the typical PV system size of 5 kWp. When the PV system sizes were increased, the benefits decreased and became negative at PV system size ≥ 17.5 kWp. In particular, the savings in the EBT and PBT cases were similar, the tariff change from EBT to PBT did not significantly affect the customers' benefits from electricity exchange.

The authors in Reference [68], present a review of the key research topics revolving around P2P energy trading (P2P DET). Particularly, it presented a wide-ranging survey of existing demand response optimization models, power routing devices and power routing algorithms. It further identified some key challenges faced in realizing P2P DET. Furthermore, state of the art enabling technologies, such as Energy Internet, Blockchain and Software Defined Networking (SDN), providing provide insights into future research directions, has been discussed.

In Reference [69], the authors propose a two-stage energy sharing framework, for a new prosumer microgrid, with renewable energy generation, multiple storage units and load shifting. The first stage, a robust bi-level energy sharing model, is formulated, to deliver a robust energy sharing schedule for prosumers and retailers, overcoming the impact of the uncertainties of market prices and renewable energy. Through proper linearization techniques, the bi-level optimization problem is transformed into a single-level, mixed integer linear programming (MILP) problem, which is practically solvable. The second stage, an online optimization model, is formulated for each prosumer, continually optimizing its energy schedule at each hour, according to the latest system state and the proposed penalty mechanism is embedded for prosumers, adjusting their previous energy sharing schedules.

In Reference [70], a technique to curtail the peaks of the domestic power demand and share the surplus energy with neighbours in need, are proposed. The method utilizes PV's, electric vehicled and battery storage at the domestic point and manages these based on a few predefined algorithms. The proposed method is tested in a Australian power distribution network and has proved to minimize the domestic peak load demand of the owner and their neighbours substantially, hence, it is expected to reduce the energy costs.

In Reference [71], the authors proposed attempts to address this problem, by developing an optimal P2P energy sharing, amongst the individual households in a DC microgrid. A nonlinear optimization problem is formulated, aiming to minimize the power transmission loss and overall energy cost, in a distribution network, consisting of a number of households incorporating practical constraints (e.g. power balance and battery's operational constraints). Three distinct aspects of operation, viz. battery usage, power from grid and P2P sharing, are considered, in order to facilitate maximum utilization of local distributed energy resources, thereby saving in energy costs for all households.

The authors in Reference [72], evaluate the bearing of P2P energy trading, amongst the smart homes, within a microgrid. Current tendencies illustrate that the households are gradually adopting renewables (e.g., photovoltaics) and energy storage (e.g., electric vehicles), in their premises. This research addresses the energy cost optimization problem in the smart homes, connected together for energy sharing. Firstly, it is proposed that a near-optimal algorithm, named Energy Cost Optimization via Trade (ECO-Trade), coordinating P2P energy trading amongst the smart homes, with a Demand Side Management (DSM) system. The results show that, for actual datasets, 99% of the solutions generated by the ECO-Trade algorithm, are optimal solutions. Secondly, P2P energy trading in the microgrid potentially results in an unfair cost distribution amongst the participating households. It is further addressed that this inequitable cost distribution problem, by enforcing Pareto optimality, ensures that no households will be worse off, improving the cost of the others. Finally, it is evaluated that the impact of renewables and storage penetration rate in the microgrid. The results show that cost savings do not always increase linearly with an increase in the renewables and storage penetration rate. Rather they decrease gradually after a saturation point.

In References [73] and [74], the authors made contributions with an overview of these new P2P markets, starting with the motivation, challenges and market designs moving to the potential future developments in this field, providing recommendations whilst considering a test-case.

2.6 SUMMARY

As observed in the literature above, the current legislation and laws concerning the existing grid, as well as grid connected renewable sources, does not allow for energy to be shared amongst direct neighbours. Although the four quadrant smart meter exists in homes across Southern Africa, in the current market and sharing of electricity or power, is not possible for dwellings or homes not connected on the same earth; the current legislation states that "one earth, one meter" approach. Some municipalities in South Africa, for example a company called GreenCape in Cape Town, have adopted a new system; as the consumer generates their own electricity they have the option to sell it back to the National grid, however, this will be at a significantly reduced rate, compared to the original cost. P2P energy sharing may solely be possible for a block of flats, or in a complex of townhouses, where there are many meters in one erf. Further observed in the literature, is that there are many iterations on P2P energy sharing across the world, working and saving the prosumer money, or, brought their electricity costs down, in a significant manner, within a P2P paradigm. P2P may be a feasible approach in South Africa, with the natural climate for optimal renewable generation, as well as storage concepts. P2P may further be a resolution for our ever-changing economic climate, as well as the dire situation that our national electricity generator is currently in. This situation does call for newer and innovative technologies of generating and distributing electricity.

CHAPTER III: A MODEL OF AN OPTIMAL PEER-TO-PEER ENERGY SHARING BETWEEN PROSUMERS IN A SOUTH AFRICAN CONTEXT

3.1 INTRODUCTION

In this Chapter, the mathematical modelling of the operation of a P2P energy sharing model, between two dissimilar load profiles, will be discussed. The P2P system consists of two prosumers, the residential prosumer, with a roof mounted PV system that is fixed at a 30° angle with energy storage capabilities and the commercial prosumer, with a solar tracking system.

In Section 3.2, a description of the system is discussed in detail, with all the relevant components outlined. In section 3.3, the mathematical model developed is discussed. The case study of two prosumers, with dissimilar loads and the effect the P2P energy sharing model will have on the sharing of energy in Section 3.4. The effects of costs will be discussed in the economic analysis in Section 3.5.

The model is developed and presented, with the aim to minimize the reliance on the grid as the only source of power for both prosumers, taking into account the time-of-use (TOU) tariff. In Section 3.5.5, a daily economics analysis is further illustrated and discussed.

3.2 SYSTEM DESCRIPTION

In this paradigm, the case of two prosumers operating on the same premises are observed, with various load demand patterns. Both of the prosumers are generating electricity, using solar PV systems, however, only one of the prosumers has the capability of storing energy.

The various power flows between the two selected residential and commercial prosumers, are shown in Fig.3.1. From this Figure, it may be seen that the load-demand from the residential prosumer, is primarily met by the power from its own photovoltaic system. If there is surplus power than which the residential prosumer requires, the excess is either used to recharge the battery, or to supply the load demand of the commercial prosumer.

In another instance, where the PV power from the residential prosumer is not sufficient to supply its own load demand, power from the commercial prosumer 2 if the commercial load has excess, may be used as a first backup option; the battery is used as a second backup option and the power from the grid may be used as a third backup option.

The battery from the residential prosumer may be recharged from residential prosumer's PV power; from the commercial prosumer's PV power or from the grid, as the last option.

The same operating scenario observed for the residential prosumer, may be observed for the commercial prosumer. The main difference is that; the commercial prosumer does not have a battery storage system.

The various power flows from Fig. 1 may be defined as follows:

- P_1: Power from the residential prosumer's PV, used to supply its load demand.
- P_2: Power from the residential prosumer's battery, used to supply its load demand.
- P_3: Power from the residential prosumer's PV, used to recharge the battery.
- P_4: Power from the grid, used to supply the residential prosumer's load demand.
- P_5: Power from the residential prosumer's PV, used to supply the commercial prosumer's demand.
- P_6: Power from the residential prosumer's battery, used to supply the commercial prosumer's demand.
- P_7: Power from the commercial prosumer's PV, used to supply its own load demand.
- P_8: Power from the commercial prosumer's PV, used to supply the residential prosumer's demand.
- P_9: Power from the residential prosumer's PV, used to recharge the residential prosumer's battery.
- P_{10}: Power from the grid, used to supply the commercial prosumer's load demand.
- P_{11}: Power from the grid, used to recharge the residential prosumer's battery.

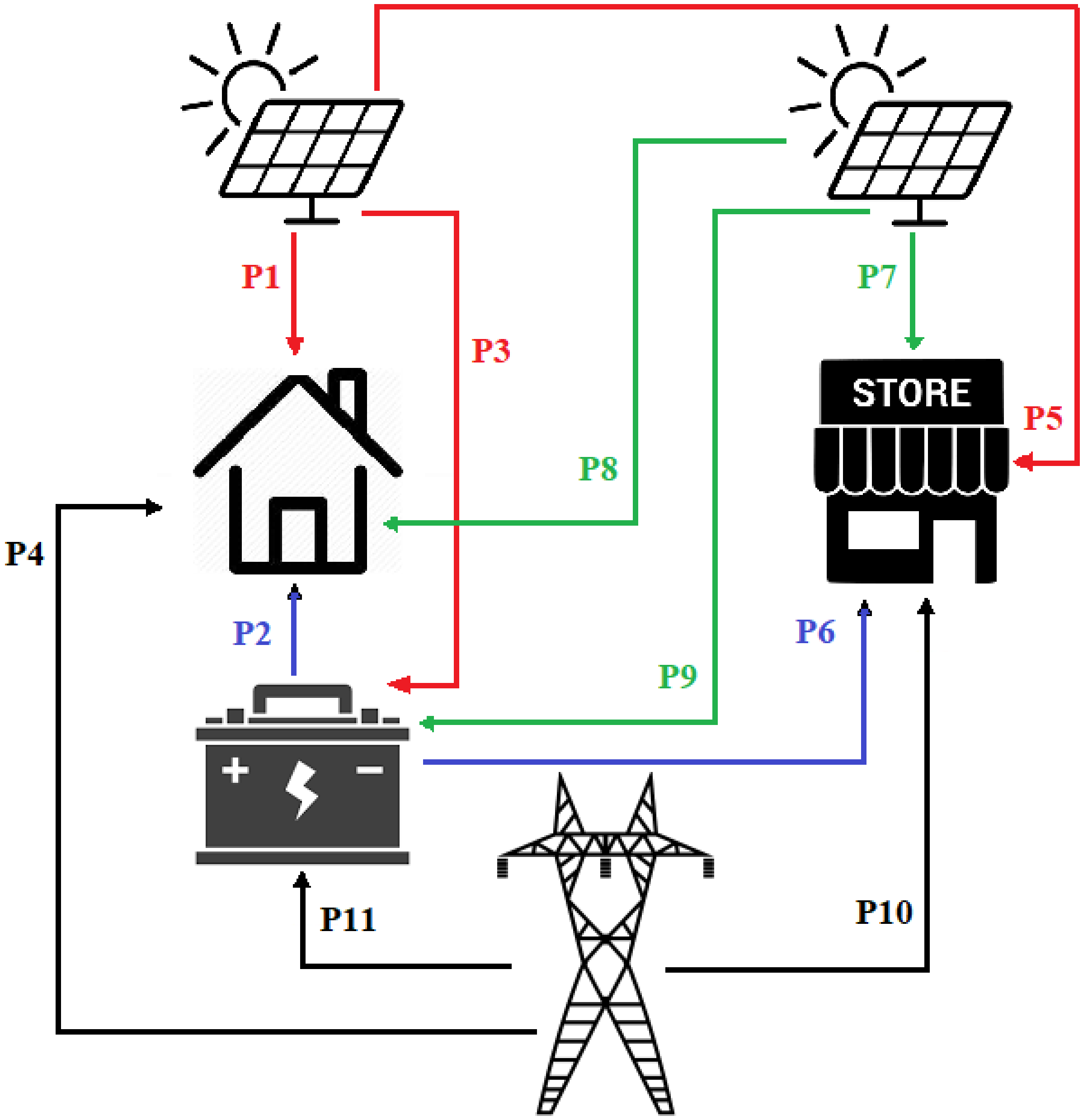

Figure 3.1: P2P energy sharing between prosumers

3.2.1 PV Peak capacity

The magnitude of a solar PV system is primarily dictated by the budget, energy saving target and available mounting space. In this case, the maximum penetration is taken as the size selection principle. A PV system, with a capacity not exceeding 5 kWp, is to be installed for single-phase residential buildings. With this, the minimum and maximum limits on power exchanged with the grid are set, respectively, as P_{EXP}^{min} = 0 kW and P_{EXP}^{max}= 5 kW. For the commercial building a 5kWp, dual axis solar tracking system is proposed. This will provide the maximum solar radiation throughout a standard working day, as well as standard working hours. A 5kVA Victron Multiplus-II inverter, for the commercial as well as the residential building, is proposed [75]. A PV array, with peak power of 5 kWp, is to be installed for the residential building, according to the Victron inverter manufacturer. For the commercial side, a 3kWp solar tracking system will be installed, according to the inverter specifications, and the potential for future expansion. The power flow limits on the MPPT (Maximum Power Point Tracking) boost converter, are set to P_{MP}^{min} = 0 kW and P_{MP}^{max} = 5 kW, for the residential building and P_{MP}^{min} = 0 kW and P_{MP}^{max}= 5kW, for the commercial building. By choosing Peimar Monocrystalline 310 W PV panel, the total number of panels to be installed is obtained to be sixteen for the residential building and ten for the commercial property. The residential prosumer has a larger installed capacity, in terms of the number of PV panels due to the difference in cost of installing a PV tracking system, compared to a PV system without tracking capabilities.

3.2.2 Battery bank sizing

Based on best practice, the battery bank in PV systems is sized in such a way that the charging current is between 10% and 20% of the total battery capacity. The maximum charging current of the Victron SmartSolar MPPT charge controller is 100A; a maximum battery capacity of 200 A h may be used. In this study, a total battery capacity, Cn, of 200 A h is considered. 12–200 (12 V 200 Ah) Synerji sealed Acid Gel Battery, from Heroldt's Group [76], is proposed. For a nominal charging voltage of 48 V and required battery capacity of 200 A h, five batteries are connected in series. Hence, the battery capacity may be expressed in kWh, as $200 \times 48 = 9.6$ kWh. The battery power flow limits are calculated, based on the maximum level of charging and discharging currents, respectively, 25 A and 80 A and the charge controller nominal voltage (48 V). Hence, the battery maximum charging and discharging power flow limits are obtained to be $P_{B}^{max} = 48V \ \times 25A = 1.2kW$ and $P_{B}^{min} = -48V \ \times 80A = -3.84kW$. The round trip battery efficiency, η_B, is assumed to be 94%.

3.2.4 PV Power output

The PV power output is predicted, based on the on the following model:

$$P_{PV} = P_{PV,STC} N_{PVs} N_{PVp} \frac{I_t}{1000}[1 - \alpha(T_C - 25)] \quad (3.1)$$

With:

$$T_C = T_a + \frac{I_t}{800}(NOCT - 20) \quad (3.2)$$

Where P_{PV} is the PV power output, is the PV output, $P_{PV,STC}$ at the maximum power point and standard test condition (STC), N_{PVs} and N_{PVp} are, respectively, the number of PV panels in series and parallel. It is the solar irradiance on a tilted surface, α is the temperature coefficient of power, T_C is the cell temperature, T_a is the ambient air temperature, and NOCT is the nominal operating cell temperature. It is calculated, based on the following equation [77]:

$$I_t = I_d \cos\theta_\beta + I_{dif}\left(\frac{1+\cos\beta}{2}\right) + \rho I_g \left(\frac{1-\cos\beta}{2}\right) \quad (3.3)$$

Here, I_{dif} is the diffuse horizontal irradiance (DHI), I_d is the direct normal irradiance (DNI), I_g is the global horizontal irradiance (GHI), β is the tilted angle, θ_β is the incidence angle of solar radiation on a tilted surface and ρ is the reflectance of the surrounding area. The different values of all input parameters, used to predict the PV power output are given as follows: $P_{PV,STC} = 0.31\ kWp$, $N_{PVs} = 8$, $N_{PVp} = 2$, $\alpha = 0.0045°C$, $NOCT = 46°C$, $\rho = 0.2$, $\beta = 30°$. This is for the stationary PV system, for the solar PV tracking system for the commercial building: $P_{PV,STC} = 0.31\ kWp$, $N_{PVs} = 5$, $N_{PVp} = 2$, $\alpha = 0.0045°C$, $NOCT = 46°C$.

3.3 MATHEMATICAL MODEL DEVELOPMENT

3.3.1 Objective function

The main objective of the developed optimal energy management model, is to minimize the daily operating cost function, while enhancing the internal sharing of energy between prosumers, for a considered simulation horizon. In this specific case, the cost of power from the grid to supply the load-demands, or to recharge the battery, is considered to be main component, carrying some operation costs for the considered optimization horizon. This is mathematically expressed as follows:

$$f1 = min \sum_{j=1}^{N} \left[\rho_j \left(P_{4(j)} + P_{11(j)} \right) + \Psi_j (P_{10}) \right] \Delta t \tag{3.4}$$

Where: f_1 is the cost function to be minimised, it results from the different power flows from the grid;

ρ_j: is the cost of energy for single phase residential building from the grid, which is defined by the Time of Use tariff (ToU);

Ψ_j: is the cost of energy for single phase commercial building from the grid, which is defined by the ToU;

j : is the considered j^{th} optimization sampling interval;

N : is the total number of sampling intervals;

Δt: the considered simulation sampling time.

Additionally, the different internal power flows between the prosumers are considered to be free. Therefore, each prosumer should maximise the usage of its own power generated, while minimizing the amount of power shared with the other prosumer. This is expressed as:

$$f2 = min \sum_{j=1}^{N} [(P_{5(j)} + P_{8(j)})] \Delta t + max \sum_{j=1}^{N} [(P_{1(j)} + P_{3(j)} + P_{7(j)})] \Delta t \tag{3.5}$$

The different load power balances that are to be observed in the studied system, are expressed as follows:

$$P_{L1(j)} = P_{1(j)} + P_{2(j)} + P_{4(j)} + P_{8(j)} \tag{3.6}$$

$$P_{L2(j)} = P_{5(j)} + P_{6(j)} + P_{7(j)} + P_{10(j)} \tag{3.7}$$

Equation (3.6) states that for each sampling time "j", the prosumer 1's load demand should be met, by a combination of the different variables P_1, P_2, P_4 or P_8.

Equation (3.7) states that for each sampling time "j", the prosumer 2's load demand must be met, by a combination of the different variables P_5, P_6, P_7 or P_{10}.

3.3.2 Generator output power

At any sampling time (j), for both prosumers, the sum of instantaneous PV power for supplying both load-demands, or for charging the battery, should be less, or equal to the maximum PV power generated by each prosumer, for the considered specific time interval. For each prosumer, this condition is mathematically expressed as:

$$P_{1(j)} + P_{3(j)} + P_{5(j)} \leq P_{PV1(j)}^{max}; \tag{3.8}$$

$$P_{7(j)} + P_{8(j)} + P_{9(j)} \leq P_{PV2(j)}^{max}. \tag{3.9}$$

Furthermore, for each sampling interval (j), the sum of powers from the battery to supply the load of both prosumers should be less than the rated power that is allowed to be drawn from the battery. This can be mathematically expressed as:

$$P_{2(j)} + P_{6(j)} \leq P_{Bat}^{Rated} \tag{3.10}$$

3.3.3 Battery state of charge

At any given sampling interval (j), the battery state of charge (SoC), may be expressed as follows:

$$SoC_{(j)} = SoC_{(0)} + \frac{\Delta t}{C_n} \times \left[\eta_{Ch} \times \sum_{j=1}^{N}\left(P_{3(j)} + P_{9(j)} + P_{11(j)}\right) - \frac{\sum_{j=1}^{N} P_{2(j)} + P_{6(j)}}{\eta_{Disch}}\right] \quad (3.11)$$

Where: $SoC_{(0)}$is the initial state of charge at the beginning of every sampling time;

Cn is the nominal capacity of the battery storage system;

η_{Ch} and η_{Disch} are the battery charging and discharging efficiencies respectively.

3.3.4 Variable boundaries

For safety purposes, the power flow from the separate generators, as well as from the storage, should be operated within their minimum and maximum limitations, according to the design specifications from the manufacturer. For all the control variables linked to the prosumers, these constraints may be expressed as:

$$0 \leq P_{i(j)} \leq P_{i(j)}^{max} \quad (3.12)$$

Where: *i* represents the different control variables;

$P_{i(j)}^{\max}$ is the maximum power that is produced by the PV generators and which depends on the resources. However, the maximum power may be written as $P_{i(j)}^{Rated}$ in the case of control variables linked to the battery. As the state of charge is the only considered state variable in the system, the boundaries linked to this variable may be written as:

$$SoC_0 \leq SoC_{(j)} \leq SoC^{max} \quad (3.13)$$

3.3.5 Exclusive power flows

It is a well-known fact that power cannot flow in and out of the battery simultaneously; the product between the battery's input and output powers should be zero, as expressed in the equation below:

$$\left(P_{2(j)} + P_{6(j)}\right) \times \left(P_{3(j)} + P_{9(j)} + P_{11(j)}\right) = 0 \quad (3.14)$$

3.3.6 Fixed-final state condition

In order to repeatedly implement the optimal control of the P2P energy model between prosumers, the SoC at the end of the control horizon should be equal to the SoC at the beginning of the control horizon. This may be mathematically expressed as:

$$\sum_{j=1}^{N}\left(P_{2(j)} + P_{6(j)} - P_{3(j)} - P_{9(j)} - P_{11(j)}\right) = 0 \qquad (3.15)$$

3.3.6 Solver selection

Given the non-linear nature of Equation (3.15), the whole model developed may be treated as a nonlinear programming problem. Therefore, the problem, with the developed objective function, as well as operation constraints, may be solved, using any solver able to deal with non-linear problem. In this case, "*fmincon*" (find minimum of constrained nonlinear multivariable function) optimization solver of the matlab optimization toolbox, has been selected, with the algorithm "interior-point" [78].

3.4 CASE STUDY DESCRIPTION

3.4.1 System sizing

The size of the generator on both prosumers' sides is dictated by the available investment of funds, implementing the project which is closely related to the energy saving target. With this, the size (rating) of the system's various components are given in Table 3.1. Additional details on the PV and battery sizing methodology may be found in References [79 and 80].

Table 3.1: Simulation parameters

Item	**Figure**
Sampling time (*⊿t*)	10 min
PV_1 rated power	3.5 kWp
PV_2 rated power	5 kWp
Battery nominal capacity	13 kWh
ρ_k residential	183.60c/kWh
ρ_0 residential	129.50c/kWh
ρ_s residential	142.50c/kWh
ρ_k commercial	239.85c/kWh
ρ_0 commercial	124.21c/kWh
ρ_s commercial	133.84c/kWh
SoC_0	82%
SoC^{max}	100%
$SoC^{\min}$	50%
η_{Ch}	94%
η_{Disc}	94%

3.4.2 Power from the utility grid

The considered cost of energy the grid, is defined by the ToU. For the selected season, the ToU structure has three periods, namely, peak, standard, and off-peak pricing [81]. Where: ρ_k, ρ_0, ρ_s are the costs of energy in the peak, off-peak and standard pricing period respectively.

$$\rho(t) = \begin{cases} \rho_k; t\epsilon T_k, T_k = [7,10) \cup [18,20) \\ \rho_0; t\epsilon T_0; T_0 = [0,6) \cup [22,24) \\ \rho_s; t\epsilon T_s; T_s = [6,7) \cup [10,18) \cup [20,22) \end{cases} \quad (3.16)$$

3.4.3 Load profiles and resources

In the recommended case study, two dissimilar load demands are selected for each of the prosumers. Prosumer 1 has a load profile of a residential type, whilst prosumer 2 has a load profile of a commercial type. The two profiles are represented in Fig.3.2. More info on the solar resources used are found in Reference [82].

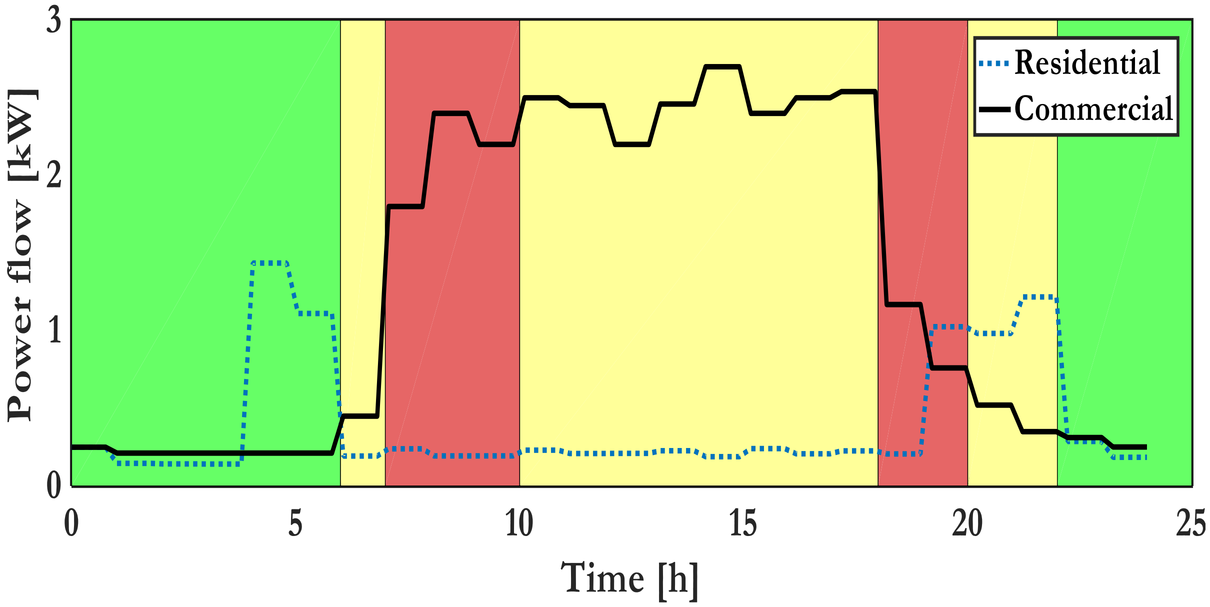

Figure 3.2: Residential and commercial prosumers' load profiles

3.5 SIMULATION RESULTS AND DISCUSSION

The optimal control problem in this work has been solved as an open loop over a control horizon of 24, hours by means of the sampling time given in Table 1. This means that the optimal solution over the proposed control horizon is obtained once and, thereafter, applied to plan the future operation/outputs of the controlled system. In other words, the control actions are applied ahead of time to the process, due to the off-line nature of the open-loop optimal control strategy.

In this Section, the simulation is performed on the proposed P2P energy sharing model, applied to the case study of the selected prosumers in Bloemfontein (South Africa). The results are compared to the case where the electrical grid is used as a baseline, supplying the electrical demands of the selected residential and commercial loads. The simulation is performed for the worst case condition, a day in the winter season, where the solar resource is low, while the load-demands and the grid electricity costs are high. Data for diffuse horizontal, diffuse normal, global horizontal irradiance and air ambient temperature of a typical winter day in June and a summer day in January, are plotted in Figs. 3.3 and 3.4. The data was collected from the weather station located at the University of the Free-State (latitude: -29.11074, longitude: 26.18503 and elevation: 1491 m), in Bloemfontein [83, 84].

Referring to Fig. 3.3 and Fig. 3.4, it should be noted that most summer days in Bloemfontein are overcast. This may be attributed to the fact that Bloemfontein obtains its rain in the summer months, unlike most winter days, when clear skies are apparent. However, the 2nd of January was a perfect day, with no cloud cover. Furthermore, it may clearly be observed that the solar irradiance representing the two seasons vary in magnitude, with the summer irradiance having a larger magnitude than the winter irradiance.

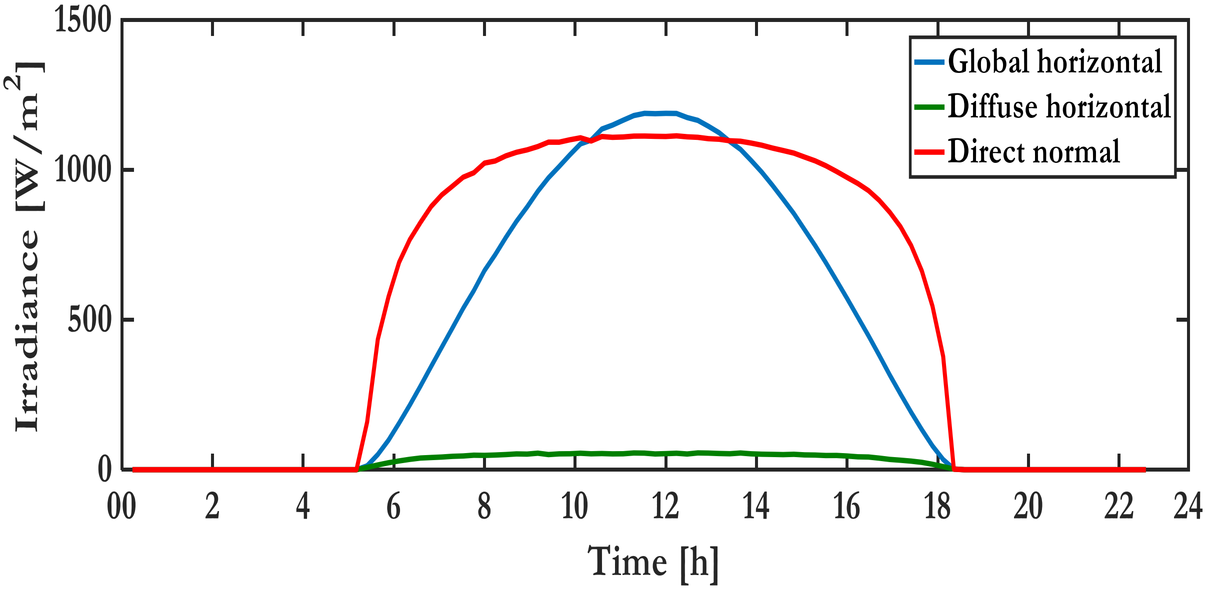

Figure 3.3: Summer solar irradiance

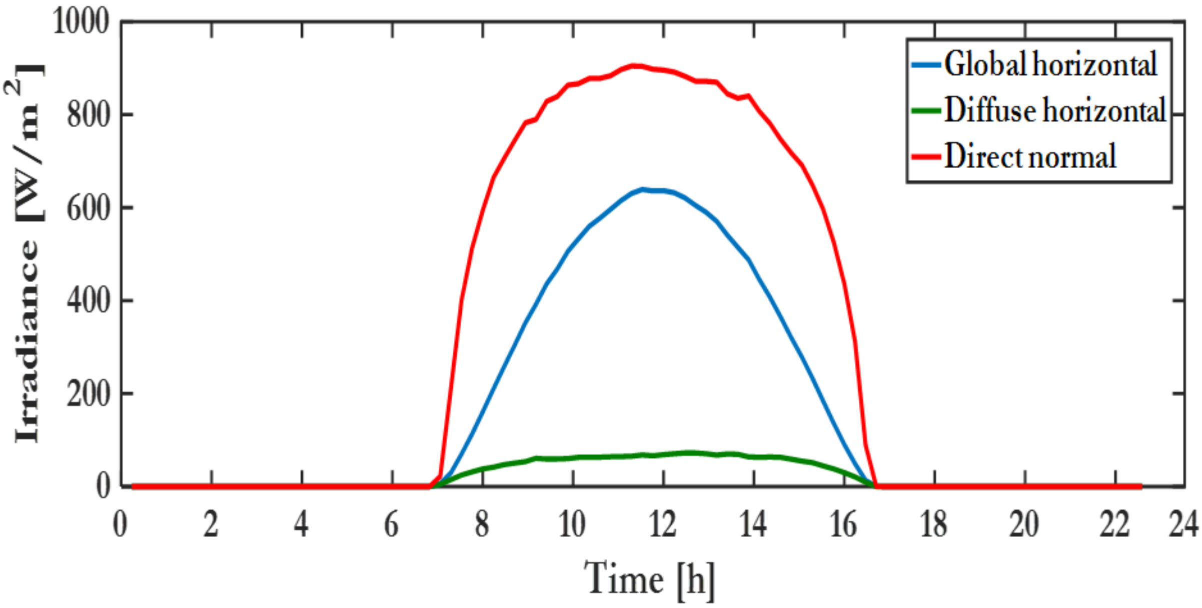

Figure 3.4: Winter solar irradiance

3.5.1 Baseline: loads exclusively supplied from the grid

Figs.3.5 and 3.6, present the simulation results in the case where the grid is used exclusively to supply the demand for the considered residential and commercial loads, respectively. In this case, there are no prosumers present, as the PV system for both commercial, residential buildings, as well as storage systems, on the consumer's side, are not considered. It may be noted that the grid power profile is following a pattern of both demands for the various pricing periods. The baseline system is a true reflection of the effect that the grid will have on both commercial and residential loads. As well as the power required throughout the day, for both load demands.

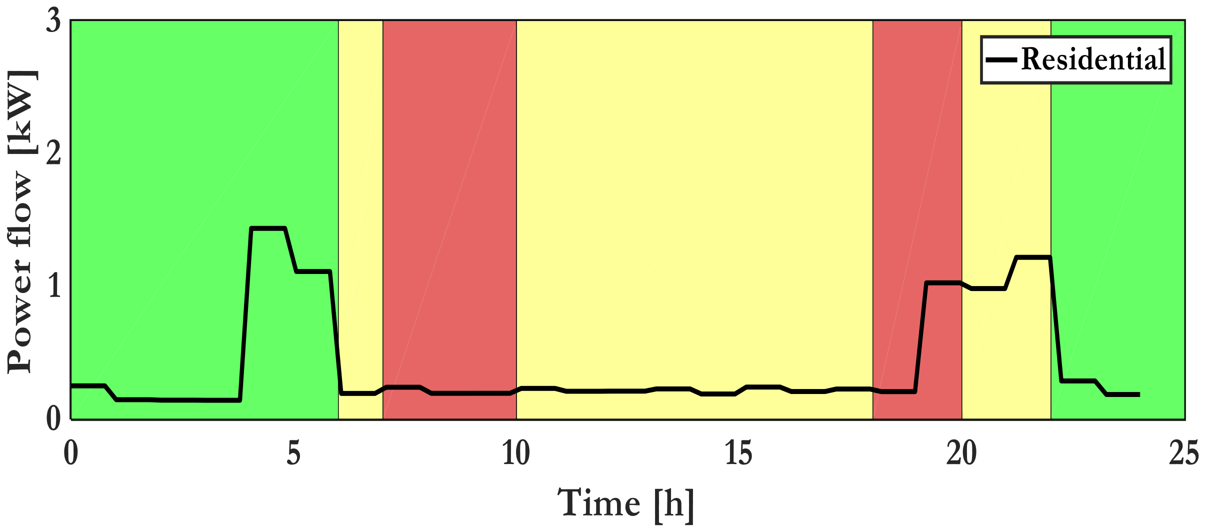

Figure 3.5: Baseline for residential demand exclusively supplied by the grid

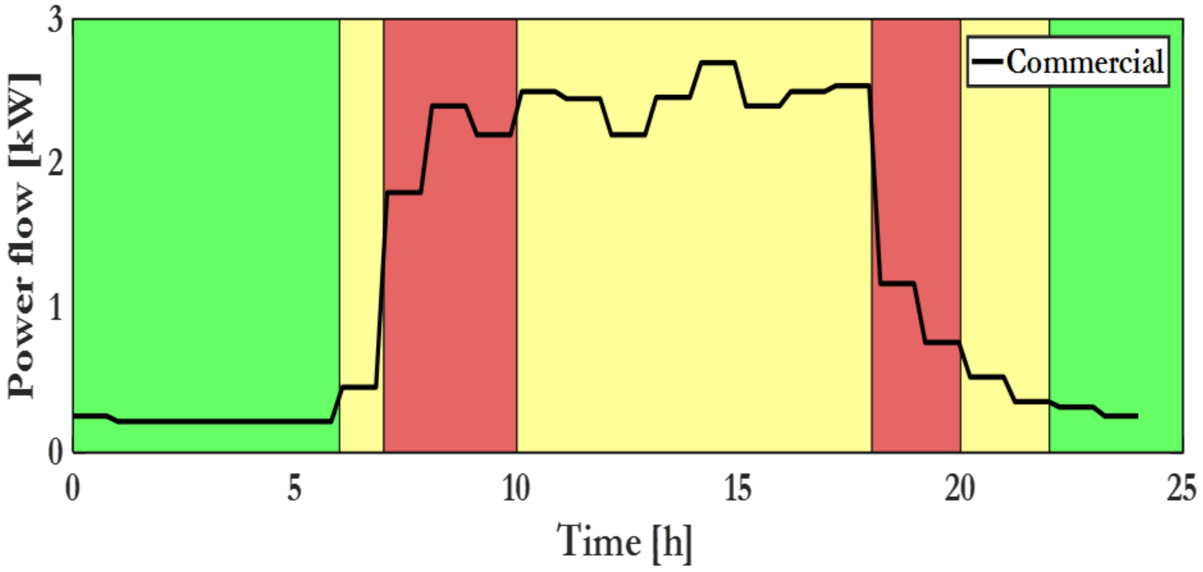

Figure 3.6: Baseline for commercial demand exclusively supplied by the grid

3.5.2 Grid-connected residential prosumer with PV generation and storage system

In this Section, the power flows related are for the separate prosumers. These are investigated, based on the renewable power generation, power storage, imported power from the grid, as well as from the power shared between prosumers' point of views. The main objective is to minimize the power from the grid to the residential prosumer, as well as to minimize the power from grid to the commercial prosumer.

A representation of the optimal PV systems fixed on the roof of the residential prosumers at an angle of 30°. This angle is chosen so that the solar panels may have maximum penetration. This may be clearly observed in Fig.3.7; the PV system starts generating power at the earliest hours of the day and steadily increases throughout the day. This happens until the system reaches its peak. This is normally between the hours of 12H00-14H00. This is when the PV system will generate at its peak which in this case is 3.5 kW. The PV will generate whether or not the power is being used. Hence, most of the 'unused' generated power will be shared with the commercial prosumer and the battery, for storage of power, that could be used at a later stage by the residential prosumer, when the demand for power is at its peak. This peak demand is usually at the end of the day between 16H00-20H00. This is coincidentally the peak time for TOU. Meaning the electricity is at its highest for both prosumers.

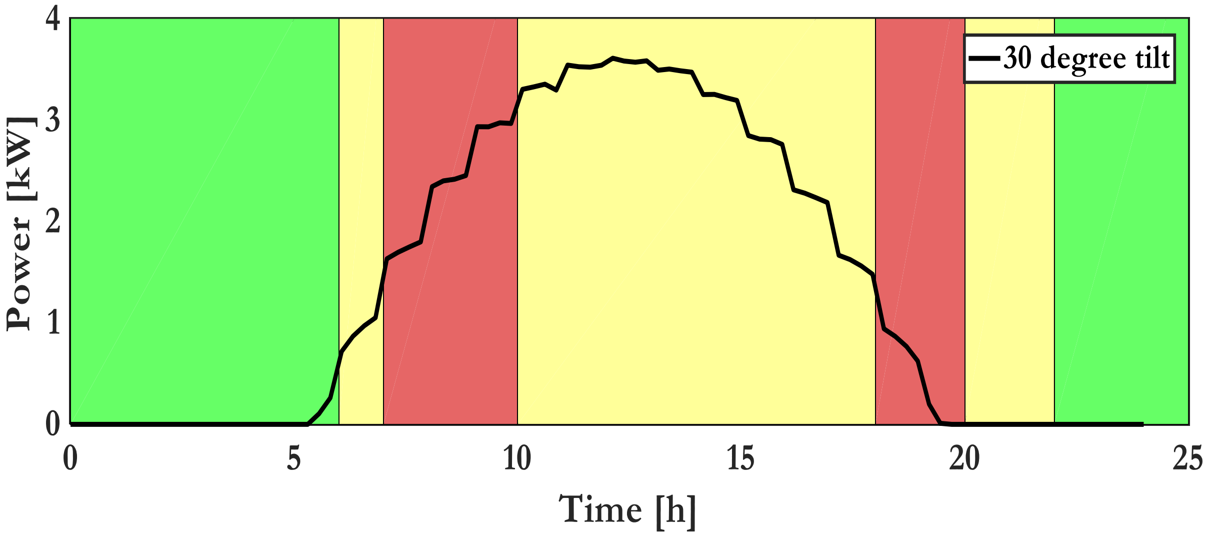

Figure 3.7: Representation of solar power generated by a fixed PV system with an angle of 30°

From Figures 3.8-3.11, the optimal power flows for the residential prosumer are illustrated during the first off-peak and standard pricing periods lapsing from 00h00 to 07h00, there is no PV generation. Hence, the load is mainly supplied by the battery, Fig.3.8 (through P_1), as well as from the grid. The supply from the grid is particularly low during this period, Fig.11 (through P_4), as the price of electricity is low. During this period, there is no power shared from this prosumer's PV system to the commercial prosumer's load demand. This is because between this time the residential load will be in high demand, as the population prepares for the day.

The first peak pricing period coincides with the starting of power generation from the PV, due to the availability of solar resources. Therefore, from 07h00, up until the end of the second standard pricing period, occurring at 18h00, as well as overlapping into the peak period, the load demand of the residential prosumer is mainly supplied by Fig.3.8 (P_1), from its own PV system.

It may further be seen that, from 07h00 to 18h00, the output power from the battery, Fig.3.9 (P_2), is zero. Therefore, the battery is not being used to supply the load. This may be attributed to the fact that there is little or no demand for power from the residential prosumer.

However, there is power flowing from the commercial prosumer to supply the load of the residential prosumer as shown by the power flow, Fig.3.10 (P_8), this power flow is very small.

The involvement from the grid, Fig.3.11 (P_4), towards contributing to the residential prosumer's demand satisfaction is minimal. The reliance on the grid is almost negated by the energy sharing scheme. It solely picks up minimally, as the population come back to their residents. Starting from the second peak pricing period up to the last off-peak pricing period (18h00-24h00), there is no power produced from the residential prosumer's PV system. Therefore, the power flows from the PV to the residential prosumer's demand (P_1), as well as from the commercial prosumer (P_8). There is a significant contribution from the battery bank (P_2), while the contribution from the grid (P_4), is small. This is due to the process of energy sharing, between the commercial PV (P_8) sharing energy to the residential prosumer, as well as charging the battery when not in use, as the demand on the residential prosumer is not high.

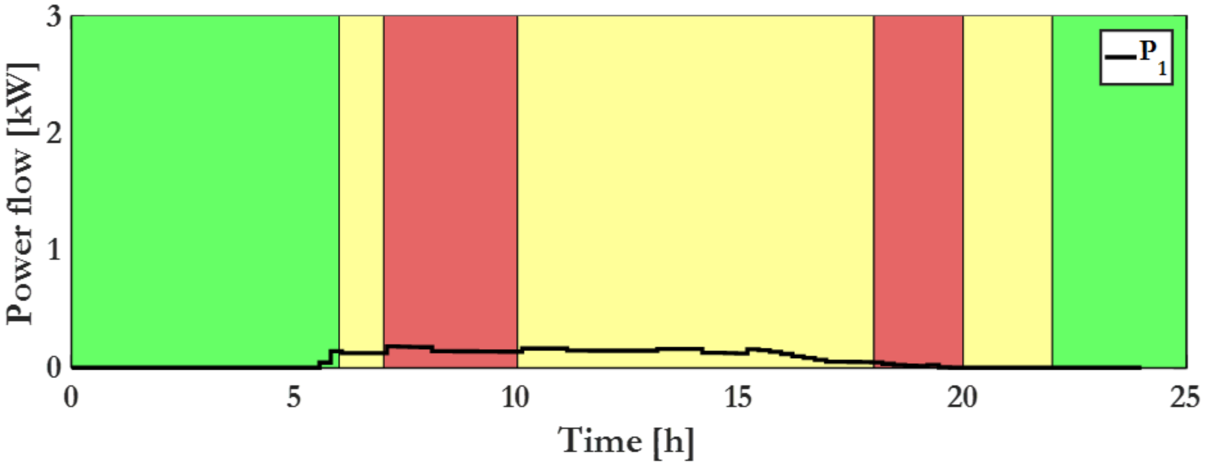

Figure 3.8: Power flow from residential PV to house

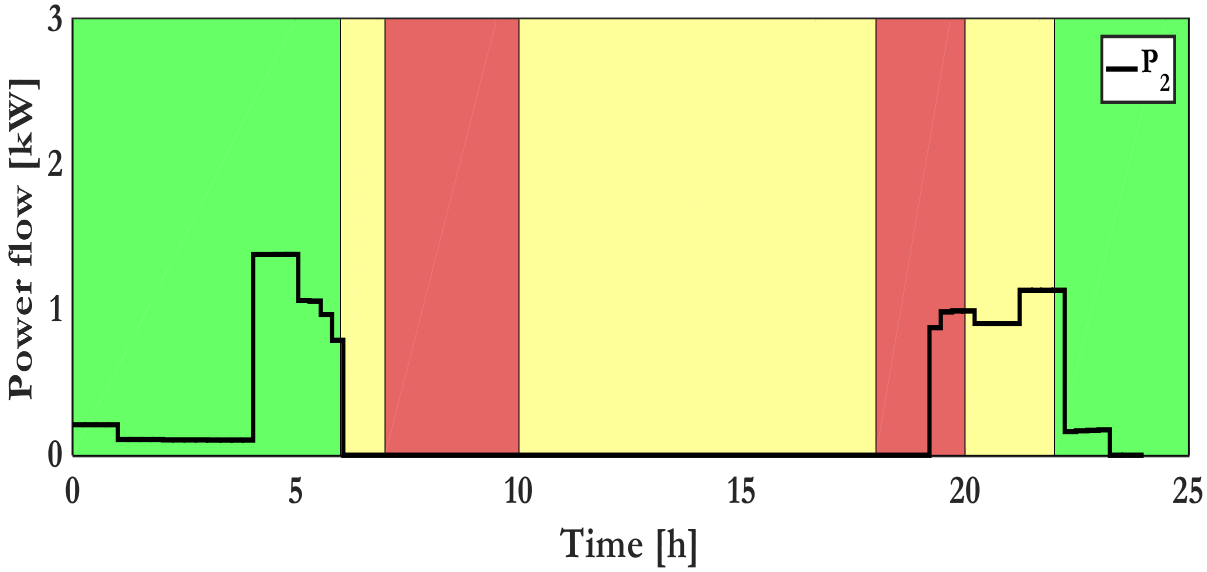

Figure 3.9: Power flow from battery to residential prosumer

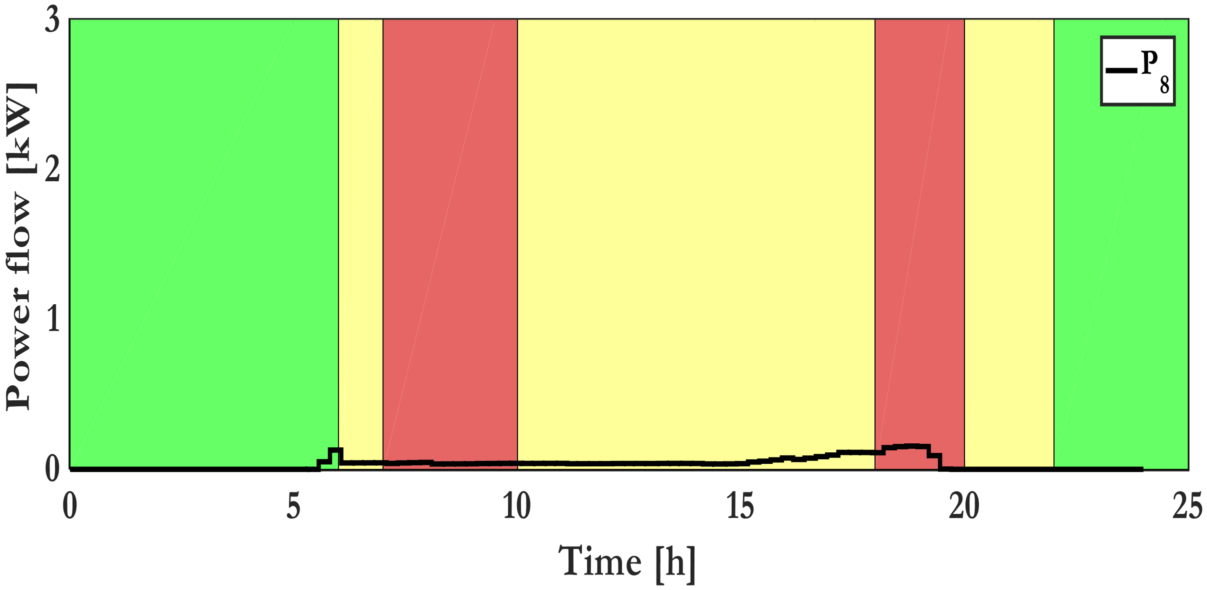

Figure 3.10: Power flow from PV tracking system to residential prosumer

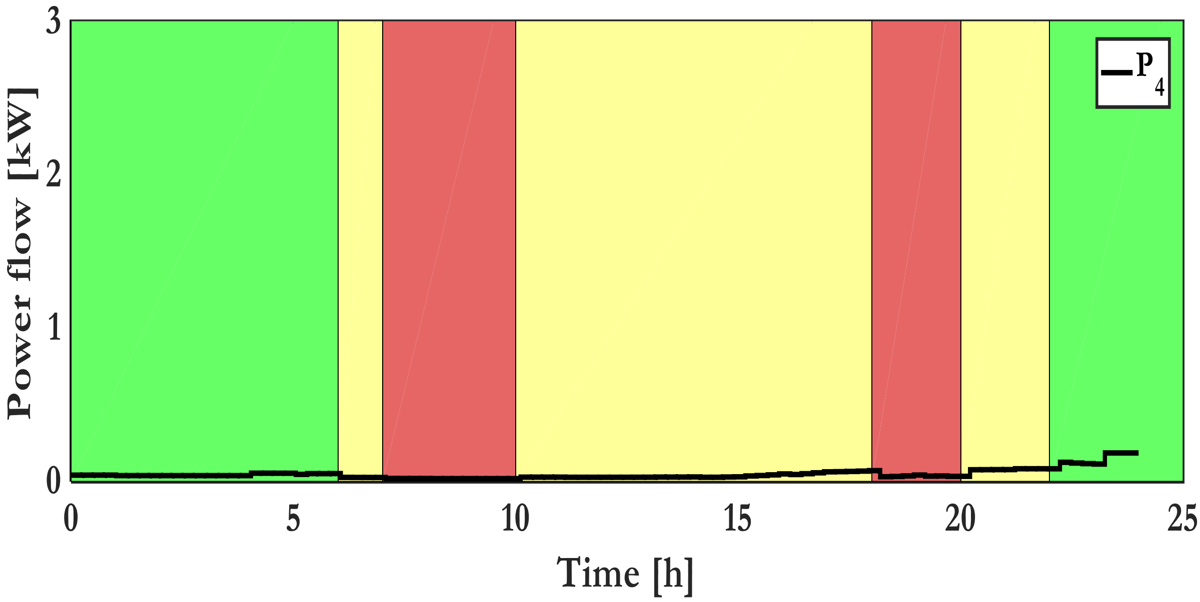

Figure 3.11: Power flow from grid to residential prosumer

3.5.3 Grid-connected commercial prosumer with PV generation

Except for the fact that their load patterns are different, the main difference between the two, is that the commercial prosumer does not have a battery storage system. It may further be observed that the size of the commercial prosumer's PV generation is smaller than that of the residential prosumer. Further it is equipped with solar tracking capabilities, making the generation much greater, due to the fact that it is constantly tracking the sun from the very first solar rays in the morning, to last light in the evening. Figures 3.12-3.16 illustrate the operation of a solar tracking system. From 5H00, there is power generation and it gradually increases, as the tracking system is constantly seeking for maximum penetration from the sun on the PV panels. Unlike a fixed PV system, that is found on the residential prosumers' roof. Peak generation is reached at 9H30. The dips in the graph are due to cloud cover, or they may be attributed to shadows falling on the panels. The tracking system will immediately adjust its position to further obtain maximum solar penetration. It may further be seen in Fig.3.12, that in this system the generation solely decreases at 19H00, when there is no optimum solar penetration. However, the tracking capabilities of the commercial PV system constantly adjusts its position, to keep on generating. Generation ceases to happen just before 20H00.

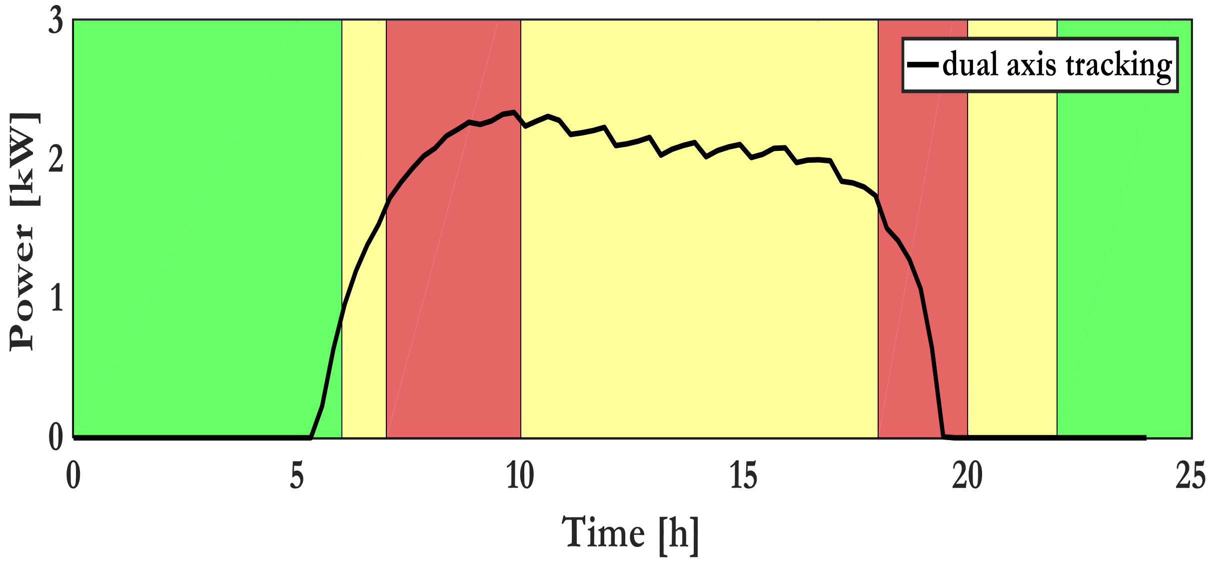

Figure 3.12: Representation of solar power generated by the commercial solar tracking PV system

From Fig.314, it may be noted that, from 00h00 to 07h00, due to the lack of solar resources, the load at about 0.05 kW is mainly supplied by the battery (through P_6). This may be attributed to the fact that the essential equipment is constantly on and should never be switched off. This may be equipment like fridges and computer servers, supplemented by the grid, Fig.3.16 (through P_{10} approximately 0.01 kW); a small quantity of power that is being supplied. The commercial prosumer is solely receiving power from the residential battery system.

From 07h00 to 08h00, the cost of electricity from the grid is high. Therefore, the commercial prosumer's demand is mainly supplied by the PV system of the residential prosumer, through Fig.3.13 (P_5) and by its own production, through Fig.3.15 (P_7). This operation strategy is implemented during the second standard pricing period, from 08h00 until 18h00, where the load demand of the commercial prosumer is mainly supplied by (P_7), from its own PV tracking system, as well as (P_5) from the residential prosumer. The commercial prosumer is mainly supplied by its own PV tracking system. (P_5) is solely supplementing the load if there is a sudden rise in demand. The small contribution from the grid, (P_{10}), to the commercial prosumer, is further observed, as the load demand is high. In this pricing period, the battery contribution, (P_6), to the commercial prosumer, is zero. Therefore, the battery is not being used to supply the load of the commercial prosumer.

From 18h00 to 24h00, it may be observed that (P_7) continuously supplies the commercial prosumer, due to the PV tracking system being exceedingly effective. It may further be observed that Fig.3.16 (P_{10}), as well as (P_6), supply the commercial property. This may be credited to the lack of solar resources. However, due to the fact that the load demand is decreasing, (P_{10}) is contributing a small amount of power to the commercial prosumer.

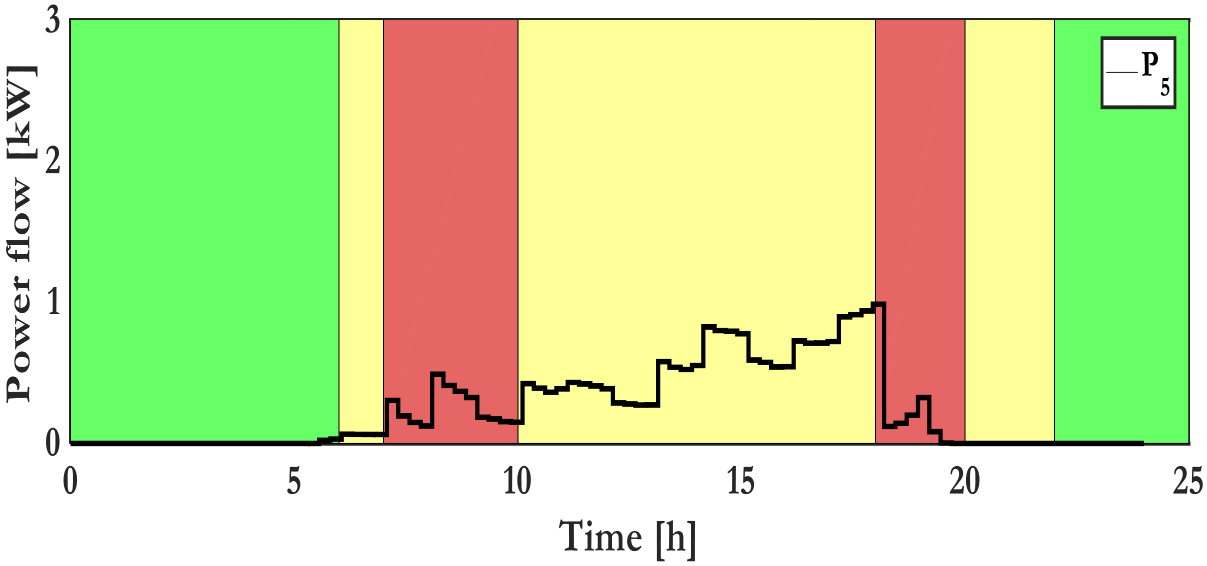

Figure 3.13: Power flow from residential PV to commercial prosumer

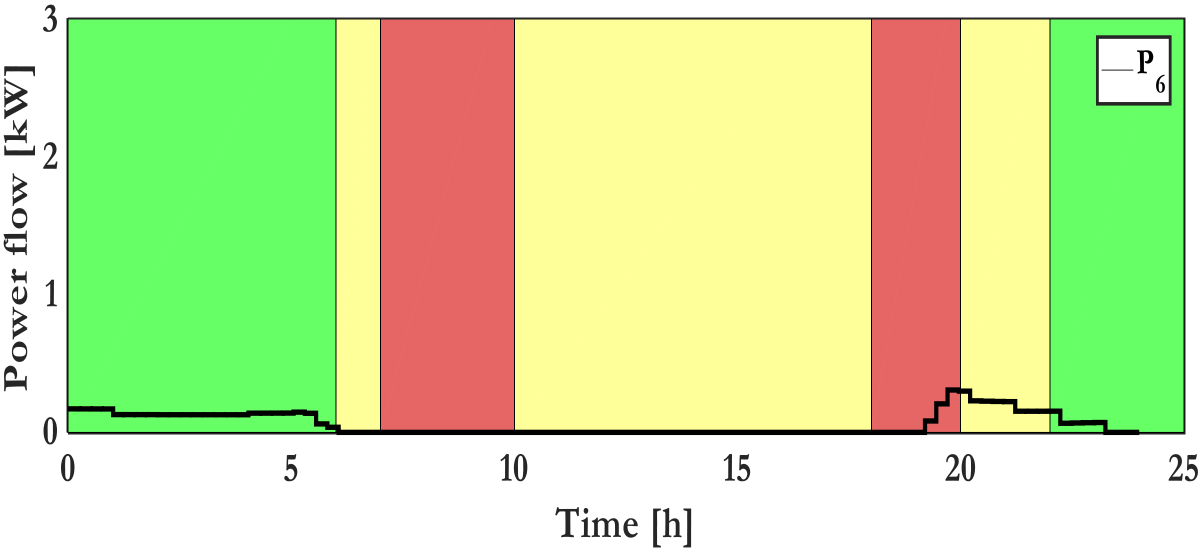

Figure 3.14: Power flow from battery to commercial prosumer

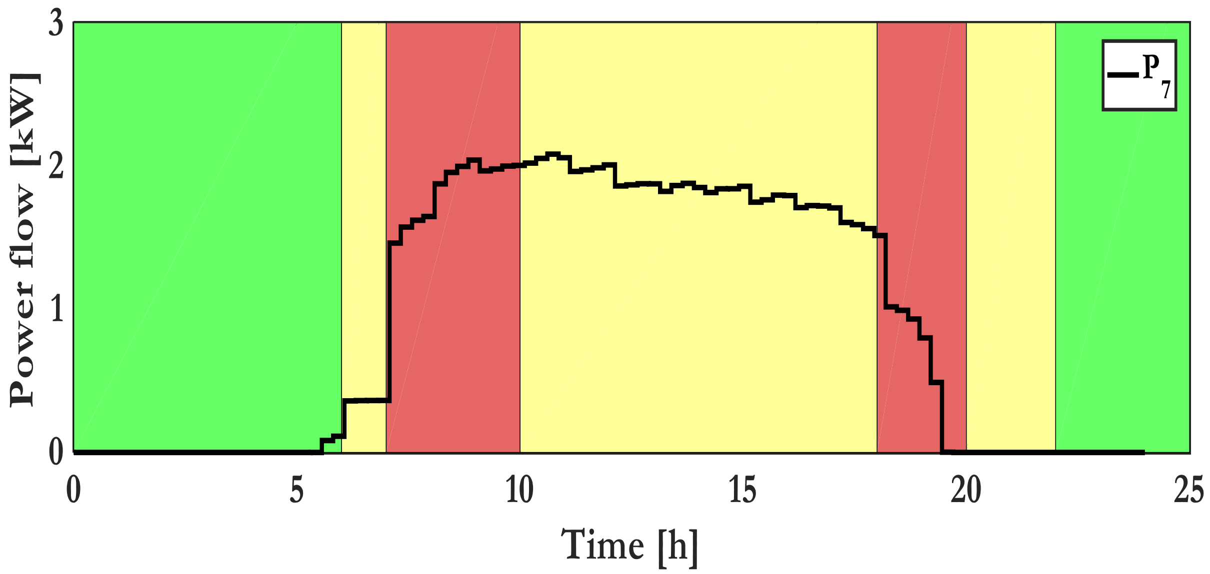

Figure 3.15: Power flow from solar tracking PV system to commercial prosumer

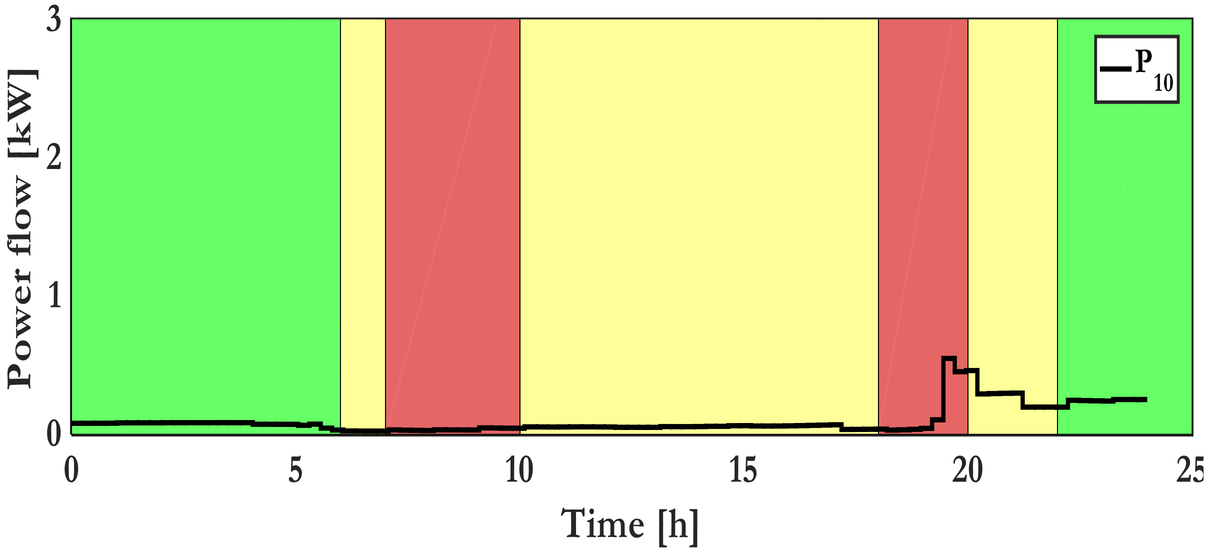

Figure 3.16: Power flow from grid to commercial prosumer

3.5.4 Battery storage system

Figures 3.17-3.20, illustrate the different sources of power, utilized in recharging the battery. These are from the residential prosumer's share of the PV production, Fig3.17 (P_3), the commercial prosumer's share of PV production Fig3.18 (P_9), as well as from the grid Fig.3.19 (P_{11}). These power flows depend on the resources, prosumers' load demands, Time of Use (ToU) as well as the battery state of charge, Fig.3.20 (SoC).

From Fig.3.17, it may further be seen that, for the two first pricing periods, there is a small amount of power flow linked to (P_3), (P_9) and (P_{11}), while the SoC is decreasing. This implies that the battery is being used to supply the two prosumers, as shown by (P_2) in Fig. 3.9 and (P_6) in Fig.3.14.

From 07h00, the battery (SoC) is at its minimum the result of being used by both prosumers. Therefore, it is being recharged by (P_3), (P_9) and (P_{11}), to reach a maximum, catering for the second peak pricing period.

From 18h00 to 24h00, when the demand is at its highest for both prosumers, a huge amount of power is being utilized from the battery, supplying the two prosumers, as shown by (P_2) and (P_6) respectively. The majority of the power used from the battery, is being used by the residential consumer. Only a small amount of power is used by the commercial prosumer, as the demand is decreasing. This may further be seen in (P_2) and (P_6), respectively. (P_{11}) is giving the most power to charge the battery in the off-peak pricing period. This the stage at which electricity is most affordable.

The operation of the battery is carried out in a way so as to respect the final SoC condition expressed in Fig.3.20. This is to have the battery at the same stage SoC just above 80% SoC, for the beginning and final stage (P_{12}). This is further carried out while staying in the boundary constraints of the battery, which is at 100% and 50% depth of discharge.

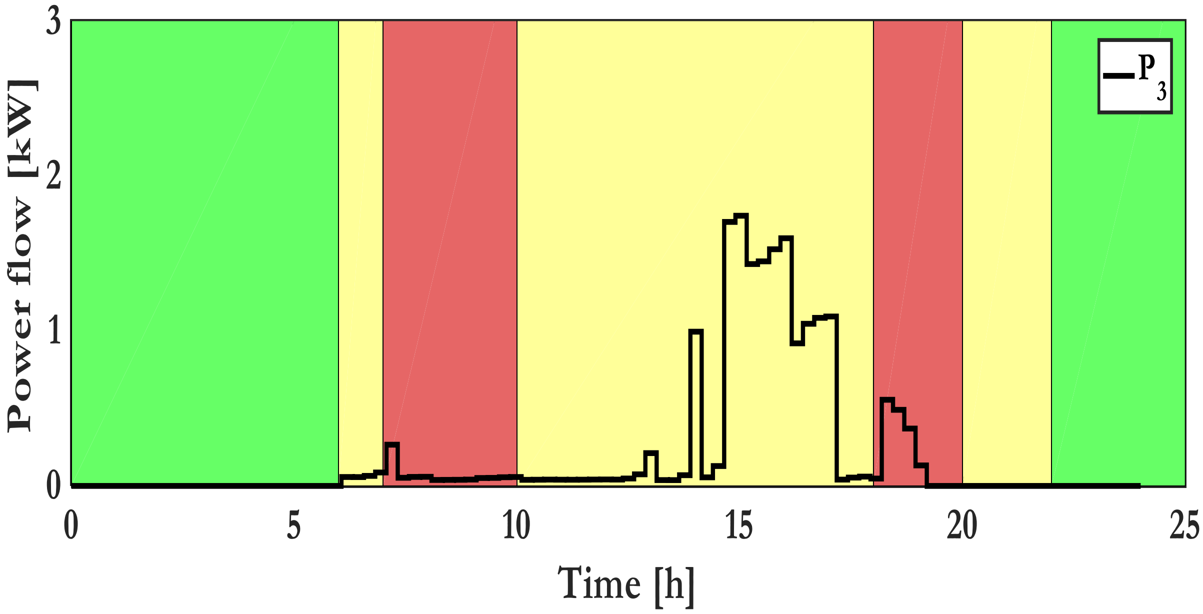

Figure 3.17: Power flow from residential PV system to battery

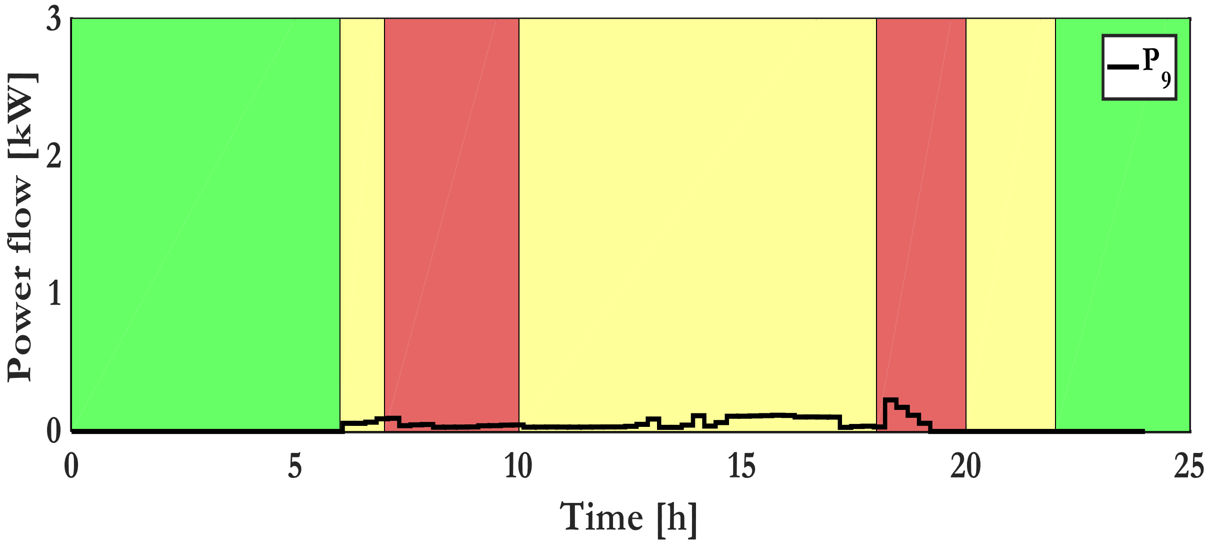

Figure 3.18: Power flow from PV tracking system to battery

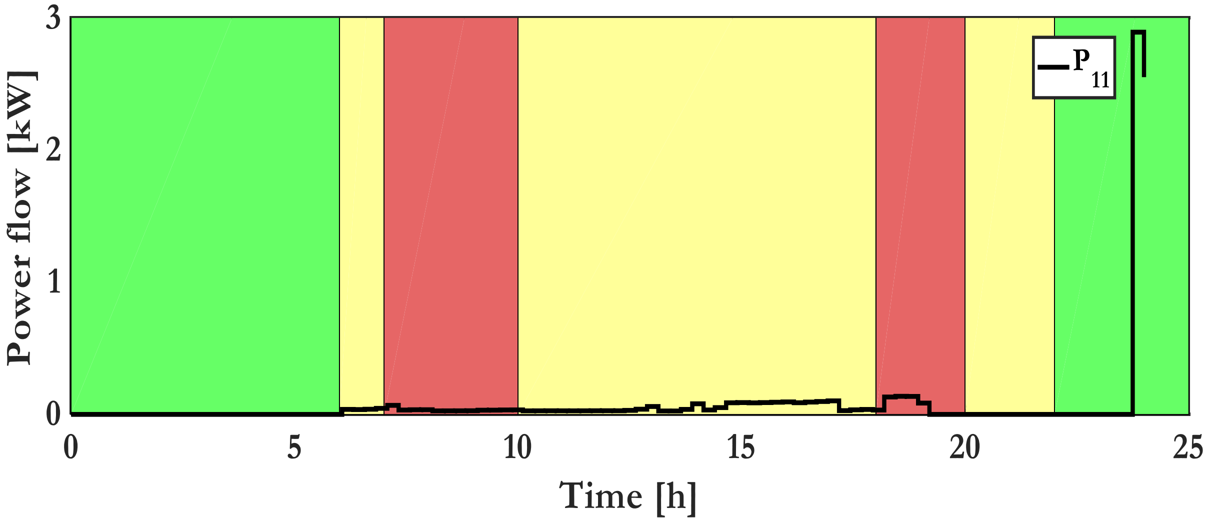

Figure 3.19: Power flow grid to battery

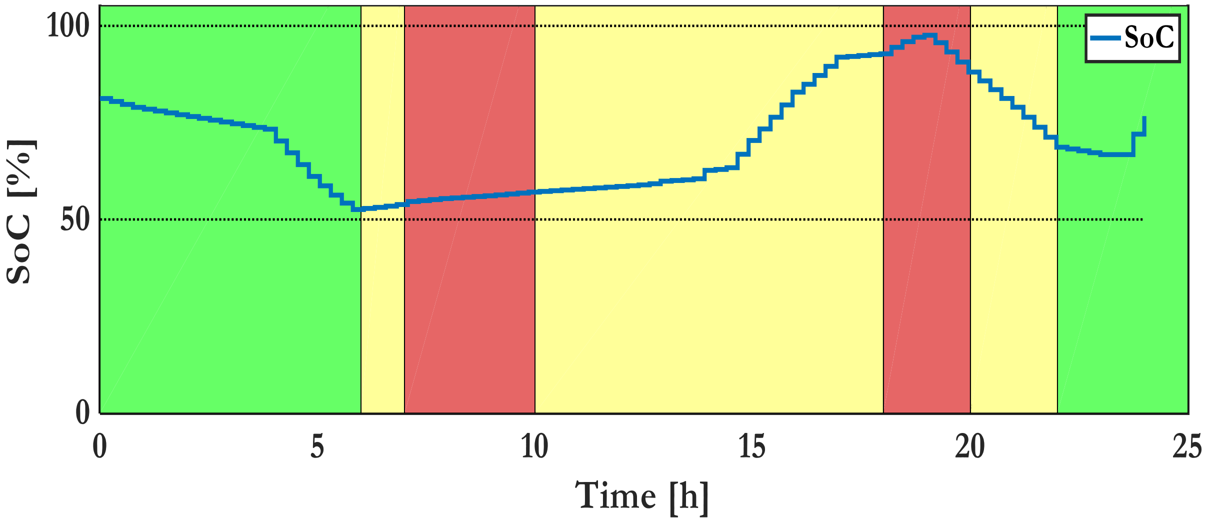

Figure 3.20: State of charge for battery

3.5.5 Daily economic analysis

Table 3.2 provides a summary on the cost saving that may be realized by using the proposed prosumers in an optimum P2P energy sharing paradigm, instead of supplying the load demands exclusively by the grid. In Table 3.2 it may be seen that an overall daily saving of R 62.85 for summer and a saving of R41.43 for winter. This is proof of how efficient the P2P energy sharing scheme may be, if implemented correctly. An in depth investigation of the economic analysis is conducted and discussed in Chapter IV.

Table 3.2: Daily cost comparison summer (ZAR)

Supply option	**Daily operation cost (ZAR)**
Load exclusively supplied by the grid	71.15
P2P energy sharing	8.30
Savings	62.85
Percentage savings	88.33%

Table 3.3: Daily cost comparison winter (ZAR)

Supply option	**Yearly operation cost (ZAR)**
Load exclusively supplied by the grid	108.08
P2P energy sharing	66.65
Savings	41.43
Percentage savings	38.33%

3.6 SUMMARY

In this Chapter the mathematical model for simulating the case for P2P energy sharing model is discussed in detail. An fmincon solver in matlab was used, simulating cases for energy sharing in winter (high demand) as well as summer (low demand) periods, between the baseline, where the electrical grid is the sole supply for power for both the residential and commercial buildings and the proposed P2P system, where the consumers of electricity are no longer just consumers. However, they produce their own energy and have the capability to share it with another consumer with the same system. The various power flows were set out in Fig.3.1 and the effects the P2P sharing system have on them. All the power flows had a significant impact on the system when power being shared between the two prosumers. The P2P system was designed in such a way that, the batteries are charged when the price of electricity is particularly low and when there is surplus power from the two systems. A small economic analysis illustrated the effect that the P2P system has on the daily energy cost. For the summer baseline case a daily energy cost of R71.15 was obtained and R8.30 for the proposed system, with a significant saving of R62.85. For winter, the baseline cost is R108.08 and for the proposed system R66.65, that equates to a substantial saving of R41.43. The different power flows for the case that has the lithium ion battery as storage system, is illustrated in Appendix A.

CHAPTER IV: ECONOMIC ANALYSIS

4.1 INTRODUCTION

In order to evaluate the cost effectiveness of the hybrid system, in terms of money spent, several economic performance indicators exist. These indicators may include the simple payback period (SPP), life cycle cost (LLC), benefits-to-cost ratio (BCR) and initial rate of return (IRR). The SPP is the simplest to understand, due to its simplified cost calculation. However, limitations exist in the sense that it does not take into account future inflation that may affect the total cost over the lifetime of a project. An added drawback of the SPP, is that it does not account cash flows beyond the payback period (PBP), as the project lifetime is not taken into consideration. This reduces the accuracy of the economic analysis and leaves investors with an approximate cost or profit prediction. With this in mind, methods, such as the BCR, LCC and IRR, offer a more precise cost analysis, when compared to SSP, due to the fact that inflation and project lifetime are taken into account [82]. Therefore, for increased accuracy, a total lifecycle cost evaluation is done, followed by a break-even point (BEP) analysis, in terms of the baseline and proposed hybrid system. The lifecycle costs will further be compared, calculating the savings over a specific project lifetime. The project lifetime for this case study was chosen to be 20 years.

4.2 INITIAL INSTALATION COST OF THE PROPOSED PEER-TO-PEER ENERGY SHARING SYSTEM

For the proposed system detailed in Chapter III, two separate cases for an in-depth economic analysis were considered. In the first case, the PV system will have 26 solar panels, 16 Peimar Monocrystalline 310W PV modules for the residential prosumer and 10 Peimar Monocrystalline 310W PV modules for the commercial prosumer. Two Victron Smart Solar MPPT charge converters, for both prosumers, as well as Victron Multi Plus inverters. The solar energy storage system will be located on the residential prosumer's free-standing building, for this five Synerji Sealed Acid Gell Battery 200Ah will be optimal for demand for the residential prosumer. The reason that the battery bank is situated at the residential prosumer, is because of the fact that the residential prosumers is at the time that the demand for the commercial prosumer is decreasing and the residential prosumers' demand is increasing simultaneously. The cost of both systems are detailed in Table 4.1, with the total cost amounting to R169 482.65. For the second case, the systems are precisely the same, as with the first case, the solely change is that, instead of Lead Acid batteries, one SolarMD Advanced Li-ion Battery 7.4kWh was chosen. The reason for this change is that a cost analysis will be carried out on how the change in battery technology will have an effect on cost through the entire life cycle for the 20-year period of the system. Table 4.2, is a detailed outline of the proposed system, with the Lithium-ion Battery, which drives up the cost to amount to R 201 451.15.

Table 4.1: Bill of quantity for lead acid storage system

Component Description	**Quantity**	**Net Price (ZAR)**
Peimar Monocrystalline 310W PV module	26	46735.2
Synerji Sealed Acid Gell Battery 200Ah	5	26911.5
Victron Smart Solar MPPT	2	28766.1
Victron Multi Plus inverter	2	64400
Solar Cable 100m	1	1425.71
Male Connector	26	606.97
Female Connector	26	637.17
Total (ZAR) initial investment cost		169482.65

Table 4.2: Bill of quantity for lithium-ion storage system

Component Description	**Quantity**	**Net Price (ZAR)**
Peimar Monocrystalline 310W Pv module	26	46735.2
SolarMD Advanced Li-ion Battery 7.4kWh	1	58880
Victron Smart Solar MPPT	2	28766.1
Victron MultiPlus inverter	2	64400
Sola Cable 100m	1	1425.71
Male Connector	26	606.97

Femal Connector	26	637.17
Total (ZAR) initial investment cost		201451.15

4.3 CUMULATIVE COST COMPARISON

Calculating the cumulative costs incurred over a specific project lifetime, in this case 20-years, some factors should be taken into consideration. Described in Section 5.2, the initial cost of implementation cannot be seen as cumulative, due to the fact that the cost implementation is a once off amount, incurred only at the inception of the project. With this in mind, the annual costs incurred, which include replacement costs and operation & maintenance (O & M) costs, after each year since the starting point of the project, may directly be added to the initial implementation cost, in order to obtain the total cumulative cost over the project's lifetime.

The salvage costs for these cases were not included, as the entire system may still be utilised with appropriate maintenance.

4.3.1 Cumulative energy cost

In order to calculate the daily cumulative energy cost, the primary objective function may be adapted from Chapter III, so that Eq. (4.1) may be used in this instance:

$$C_{daily} = t_s . P_g \sum_{k=1}^{N} (C_{TOUk}) \tag{4.1}$$

Where: t_s: is the sampling time;

P_g: is the power supplied from the grid;

C_{TOUk}: is the time-based cost of electricity at each kth interval defined in Chapter III, Section 4.2.2, Table 4.2 in ZAR/kWh;

S_{e_k} : is the switching status of the electric resistive element.

With this, the daily cumulative daily cost values (ZAR), were obtained and illustrated in Sections 4.3.1.1. - 4.3.1.2. and compared in Section 4.3.1.3, for the summer and winter cases, respectively. In section 4.3.1.4, 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 Eskom.

4.3.1.1 Winter cumulative energy cost comparison

The cumulative cost for the winter period, is shown in Fig. 4.1. The cumulative costs are calculated throughout the day. The ToU tariff is further taken into account, in the calculation of the cumulative energy cost per day. The high demand period should have a higher price tariff time interval is further considered for this calculation. The cumulative energy cost for the baseline, that is represented by the red line in the graph. The case where the storage system is represented by the green line and for the blue line, the lithium-ion battery is the storage option. There is a significant difference in price in the three cases. The net energy cost for the baseline case at the end of the day, equals to the amount of R 108.08 (ZAR), and for lithium-ion, the net energy cost per day is R 65.12 (ZAR). The lowest cost of R49.46 (ZAR), is observed in the case where the lead-acid battery is the storage option. It may further be observed that there are sharp increases in the cumulative energy cost for the three cases, at 06H00, as well as 16H00. This is because of the fact that these time periods are when electricity most expensive, as it is in the peak time, set out by Eskom as well as the local municipality.

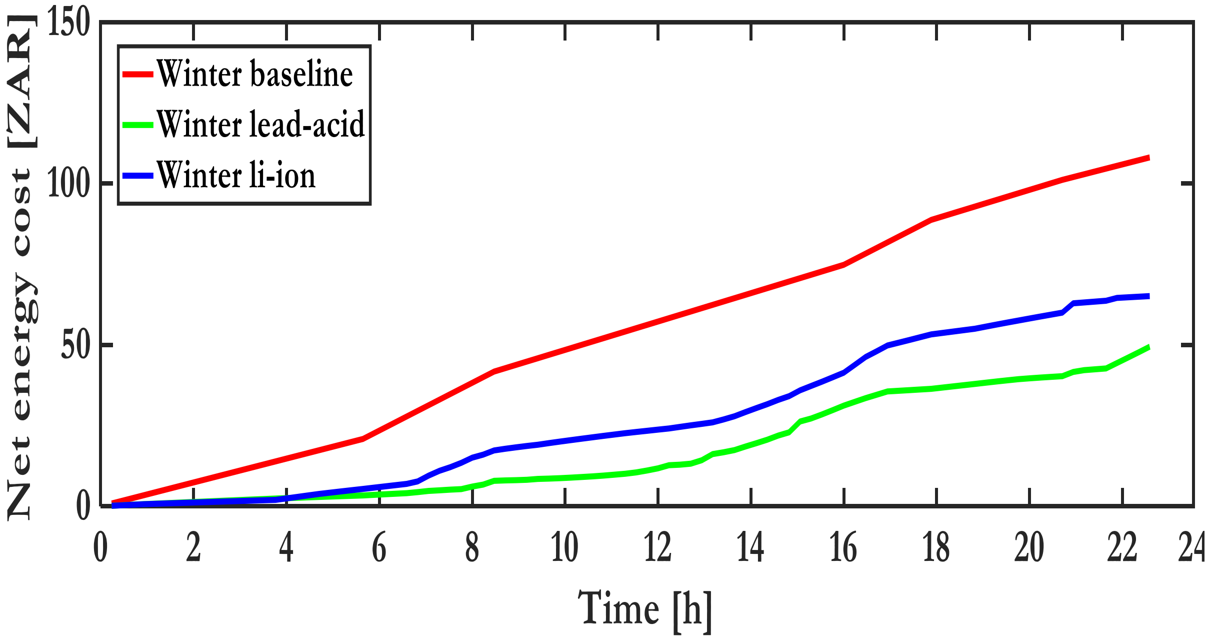

Figure 4.1: Winter cumulative energy cost

4.3.1.2 Summer cumulative energy cost comparison

The cumulative cost for the summer period, is shown in Fig. 4.2. The cost calculation is carried out precisely the same as it is done for the winter (high demand) period. The solely difference, is the ToU tariff, hence the low demand tariff utilised in this period. The baseline for summer will be represented by the red line and the lead-acid case will be illustrated by the green line. Lastly the blue line represents the case in which the storage option is in the form of lithium-ion battery. The cumulative energy cost per day, without any PV panels for a summer day, will be R 71.14 (ZAR). The cost comparison for both lithium-ion and lead-acid cases are R8.07 and R7.81, respectively. The baseline case follows the equivalent pattern as the winter case, the solely difference is the net cost, at the end of the day. For the cases in which PV panels are introduced, the graphs follow a steady but not steep increase in price. It is seen in the graphs that there is a slight difference in price, between the lead-acid and the lithium-ion cases.

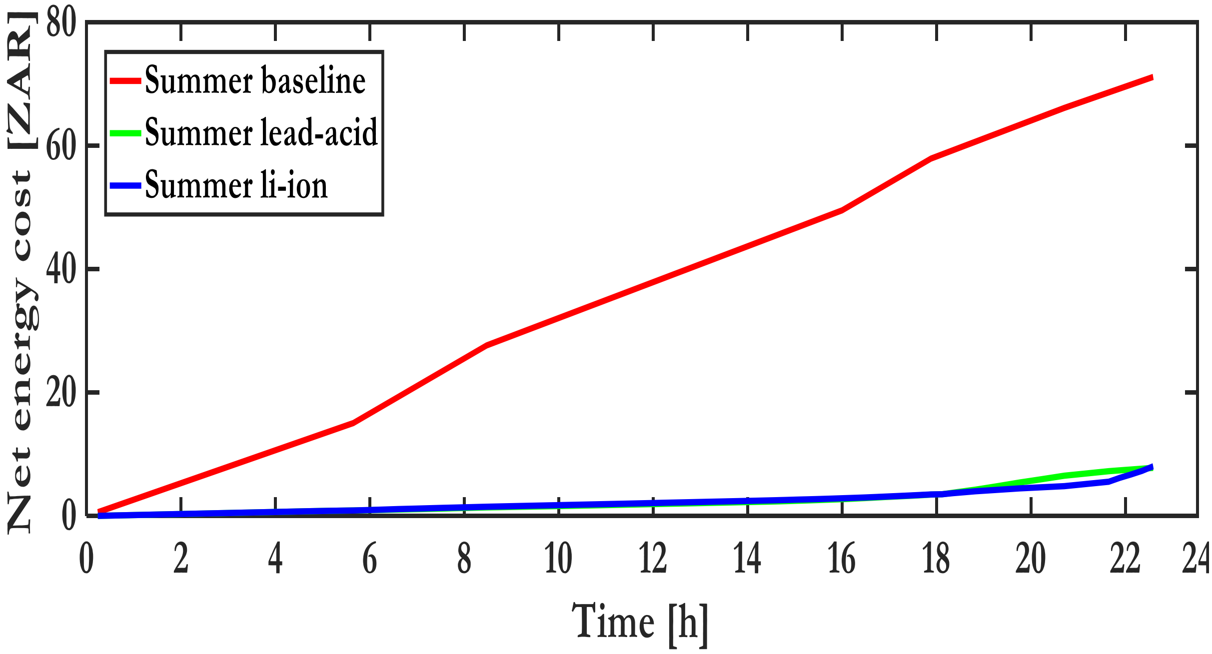

Figure 4.2: Summer cumulative energy cost

4.3.1.3 Energy costs and saving

The cumulative costs for the three cases are shown in Tables 4.3 and 4.4, as well as 4.5. The cases are as follows: Baseline, Lead-acid battery storage and, lastly, Lithium-ion storage. The tables will, in the three cases, show the daily, monthly, as well as yearly energy costs. In both cases, where PV panels and storage are introduced, a massive saving in electricity cost per day, as well as per year, is observed. These savings underline the importance of the P2P energy sharing system, when it is implemented appropriately and either with a lead-acid battery bank, as well as a lithium-ion battery storage system. A yearly saving of 72%, for the case in which lead-acid is the proposed storage system and a saving of 73% for the lithium-ion storage option. In terms of money saved year on year, taking into account that the electricity price will increase by 15%, the option for P2P energy sharing is an attractive one. Further in terms of longevity of the system, it will also be an attractive option.

Table 4.3: Cumulative energy cost: Baseline

Energy Cost	**Month**	**Number of days**	**Monthly Energy Cost**
71.14803	January	31	2205.59
71.14803	February	28	2091.75
71.14803	March	31	2426.15
71.14803	April	30	2454.61
71.14803	May	31	2734.93
108.0832	June	30	4215.24
108.0832	July	31	4355.75
108.0832	August	31	4154.72
71.14803	September	30	2454.61
71.14803	October	31	2426.15
71.14803	November	30	2241.16
71.14803	December	31	2205.59
Annual Baseline Energy Cost			33966.25

Table 4.4: Cumulative energy cost: Lead-acid

Energy Cost	**Month**	**Number of days**	**Monthly Energy Cost**
8.2965	January	31	257.19
8.0932	February	28	237.94
7.9825	March	31	272.20
8.3324	April	30	287.47
4.736	May	31	182.05
54.8862	June	30	2140.56
66.6561	July	31	2686.24
57.1496	August	31	2196.83
8.4178	September	30	290.41
8.2592	October	31	281.64
8.05669	November	30	253.79
7.92917	December	31	245.80
Annual Proposed System Energy Cost			9332.13

Table 4.5: Cumulative energy cost: Lithium-ion

Energy Cost	**Month**	**Number of days**	**Monthly Energy Cost**
8.067887	Jan	31	250.10
7.609033	Feb	28	223.71
7.89279	Mar	31	269.14
8.017329	Apr	30	276.60
7.373697	May	31	283.44
53.57025	Jun	30	2089.24
65.12154	Jul	31	2624.40
54.98622	Aug	31	2113.67
8.112144	Sep	30	279.87
8.001003	Oct	31	272.83
7.887719	Nov	30	248.46

7.762701	Dec	31	240.64
Annual Proposed System Energy Cost			9172.11

4.4 LIFE CYCLE COST ANALYSIS

In order to reduce the margin of error, a project lifetime of 20 years was chosen for the P2P energy sharing system. The 20-year lifetime was chosen based on the replacement of several factors that require replacement. At five year intervals, the lead-acid batteries should be replaced and lithium-ion batteries require replacing every ten years, as well as the inverter and charge controller that require replacement after fifteen years. However, several reports have shown the lifetime reaching over 30 years for the PV panels, unless they are damaged and require replacing. Hence, the average number of years between guaranteed and actual reported lifespan, was selected.

The salvage costs were excluded for both cases as the residential, as well as the commercial PV systems, may be upgraded, to include more prosumers in future.

The replacement cost is calculated, using Eq. (4.1). With the average inflation rate, the future costs of components are predicted, by assuming that the average inflation rate will be equal to the interest rate [85, 86].

$$C_{rep} = \sum_{k=1}^{N} C_{cap}.k(1 + nr) \qquad (4.2)$$

Where:

C_{cap}: is the initial capital cost for each component (given in Table 5.3),

N_{rep}: is the number of component replacements of the 20-year lifetime,

n: is the lifespan for a specific component (years),

r: is the average inflation rate shown as 5.49%.

4.4.1 Baseline lifecycle cost analysis

For the baseline, no replacement costs are calculated because of the complexity of the system. The municipalities generally carry out the maintenance and replacement for the electrical grid.

Total lifecycle replacement cost ($C_{rep-BTC}$), is equal to the replacement costs of the P2P sharing project, as represented in Eq. 4.2.

$$C_{rep-BTC} = C_{rep} \tag{4.2}$$

Eq. 4.2 is used to calculate the total replacement cost ($C_{rep-ESTWH}$) over the project lifespan.

The cumulative electricity costs incurred over a 20-year lifespan for the baseline system, is shown in Appendix B. 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 15% annually taken into account, shown in Eq. 5.4.

$$C_{EC} = \sum_{k=1}^{20} C_{initial-EC}.k(1+a) \tag{4.3}$$

Where:

$C_{initial-EC}$: is the cumulative cost of energy at the end of year one (ZAR),

k: represents the year in which the cumulative cost should be calculated (years),

a : is the annual increase of 15%.

The operation and maintenance costs at the end of each year (i) of the optimal P2P system may be taken as 1% of the initial implementation cost, so that Eq. (4.4) will be:

$$C_{OM} = \sum_{k=1}^{20} C_{initial-OM}.k(1+r) \tag{4.4}$$

The initial cost of implementation ($C_{initial}$), salvage cost ($C_{salvage}$) is 20% of the initial implementation cost ($C_{initial}$) of the P2P PV system, can be calculated using Eq. 4.5. However, for this case, the salvage cost calculation is not used.

$$C_{salvage} = 0.2.C_{initial} \tag{4.5}$$

The addition of Eqs. (4.2-4.5) and the subtraction of the salvage cost ($C_{salvage}$), will be equal to the total lifecycle cost for the P2P system in Eq. (4.6):

$$LCC_{P2P} = C_{initial} + C_{rep-BTC} + C_{EC} + C_{OM} - C_{salvage} \tag{4.6}$$

The total lifecycle cost value LCC_{P2P} (ZAR), using Eq. (4.6), is shown in Table 5.5. over a 20-year project lifetime

4.4.2 P2P PV system with lead-acid battery bank

Table 4.6: Total replacement cost for PV system and lead-acid battery bank

Parameters	**Lead-acid Value**	**Lithium-ion Value**
P2P energy sharing system lifetime, n(years)	20	20
Synerji Sealed Acid Gel Battery (years)	5	10
$N_{rep-bat}$	5	1
$C_{rep-bat}$ (ZAR)	134557.5	58880
Victron Smart Solar MPPT (years)	15	15
$N_{rep-MPPT}$	1	1
$C_{rep-MPPT}$ (ZAR)	27046.05	27046.05
Victron Multi Plus inverter (years)	15	15
$N_{rep-inv}$	1	1
$C_{rep-inv}$ (ZAR)	67942	67942
	229545.55	153868.05

In the case of the P2P energy sharing system, several more components exist with different life expectancies, so that the total replacement costs (C_{rep}), calculated using Eq. 4.1, over the 20-year project lifespan for all the hybrid system's components, shown in Table 4.5 are added, in order to receive the total lifecycle replacement costs (C_{rep-TC}), denoted in Eq. (4.7):

$$C_{rep-TC} = C_{rep-SC} + C_{rep} + C_{rep-CONT} + C_{rep-ARV} + C_{rep-CP} + C_{rep-TMV} \tag{4.7}$$

The same method for cumulative electricity costs, with an annual 15% increment, was calculated for the hybrid system, using Eq. (4.3), as well as for the salvage cost (which is not included) and the cumulative operation and maintenance costs for the P2P system, in Eq. (4.4) and (4.5), respectively. Eq. (4.8) shows the calculation of the life-cycle cost for the P2P energy sharing system.

$$LCC_{P2P} = C_{initial} + C_{rep-TC} + C_{OM} + C_{EC} - C_{salvage} \tag{4.8}$$

Table 4.7: Total lifecycle cost for the P2P energy sharing system

Cumulative cost	**Value (ZAR) lead-acid**	**Value (ZAR) Lithium-ion**
$C_{initial}$	169482.65	201451.15
C_{rep}	322750.95	389974.2
C_{OM}	59095.7494	70242.6276
C_{EC}	132812.751	132812.751
$C_{salvage}$	0	0
LCC_{P2P}	684142.1	794480.729

The total lifecycle cost valueLCC_{P2P} (ZAR), using Eq. (4.8), with the data shown in Table 4.6, is calculated. Over a 20-year project lifetime, a total amount of approximately R684 142.1 will be spent, in the case where lead-acid batteries are used as a storage option and for lithium-ion case the total amount spent will be R794480.729, with an optimal P2P energy sharing system applied.

4.4.3 Break-even point (BEP)

The break-even point is determined when the total implementation and operating costs of two systems incurred, are equal. In this case, the baseline, where the sole source of electrical power is the national electrical grid, is compared to the proposed P2P energy sharing system, with the optimal energy management scheme, in terms of the total cumulative annual energy cost in the project lifetime of 20 years.

The cumulative cost curves, which contains the initial investment cost and the total annual costs incurred over this period for the baseline and optimal P2P system is plotted on the same axis for both cases, respectively. The intersect point of these two curves shows the point in time (years) at which the two systems break even.

Table 4.1 and 4.2 outline the initial total cost of implementation of the P2P system for lead-acid storage, as well as the lithium-ion storage is R169482.65 and R201451.15, respectively. These values are therefore starting points of the two curves in Figs. 4.3 and 4.4. After the first year has passed, the total annual cost of energy is added to the initial investment cost, which is the total present cost of energy, shown in Tables 4.1and 4.2. This equates to the total cumulative cost for the first year after implementation. For the second year after application, a 15% increase in the price of electricity is taken into account, to calculate the annual energy costs. This amount is, furthermore added to the previous total cumulative cost of the first year. The same method is followed for years 3 to 10 in Fig. 4.3. In this curve, the replacement costs and lifetimes of all the components are taken into account, for increased accuracy of cumulative cost representation. From Fig. 4.3, as well as Fig.4.4, a clear observation may be made that the break-even point occurs early in the project lifetime, for both cases. For lead-acid, the break-even point occurs in 5.34 years after initial implementation of the P2P system. The cost at that point will amount to R296600.00. Lithium-ion in Fig.4.4, the break-even point will occur within 5.131 years and R293800.00. In both cases, there is a clear indication between the proposed system and the baseline system that can be observed.

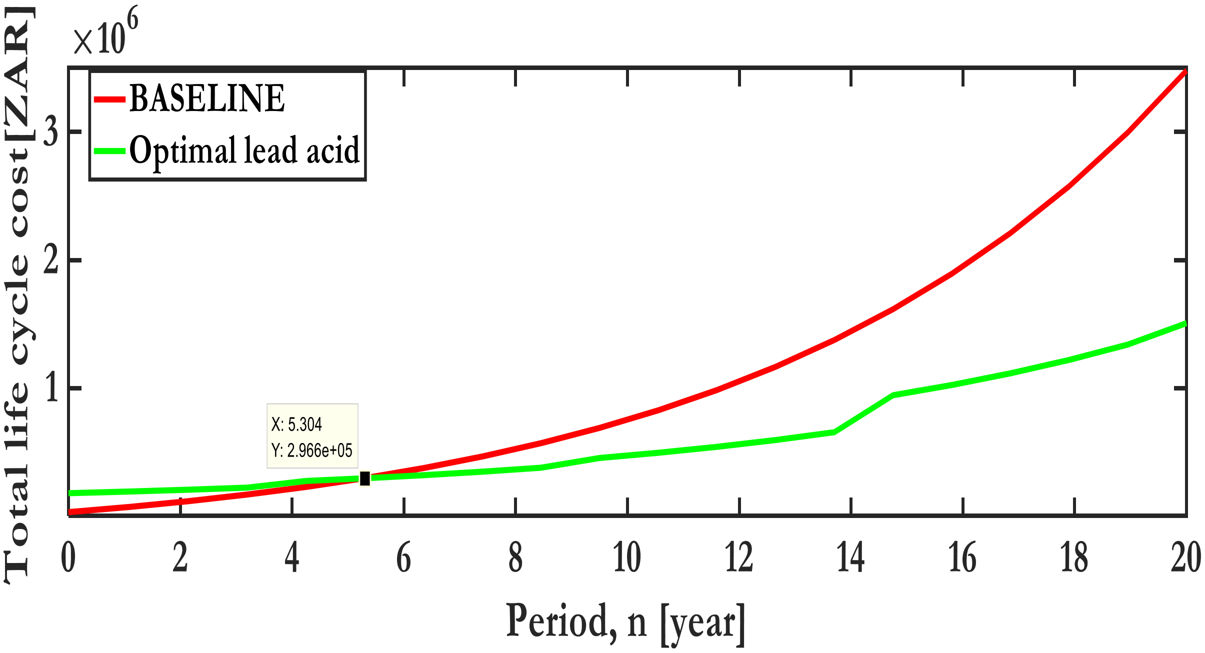

Figure 4.3: Break-even point illustration for lithium-ion storage system

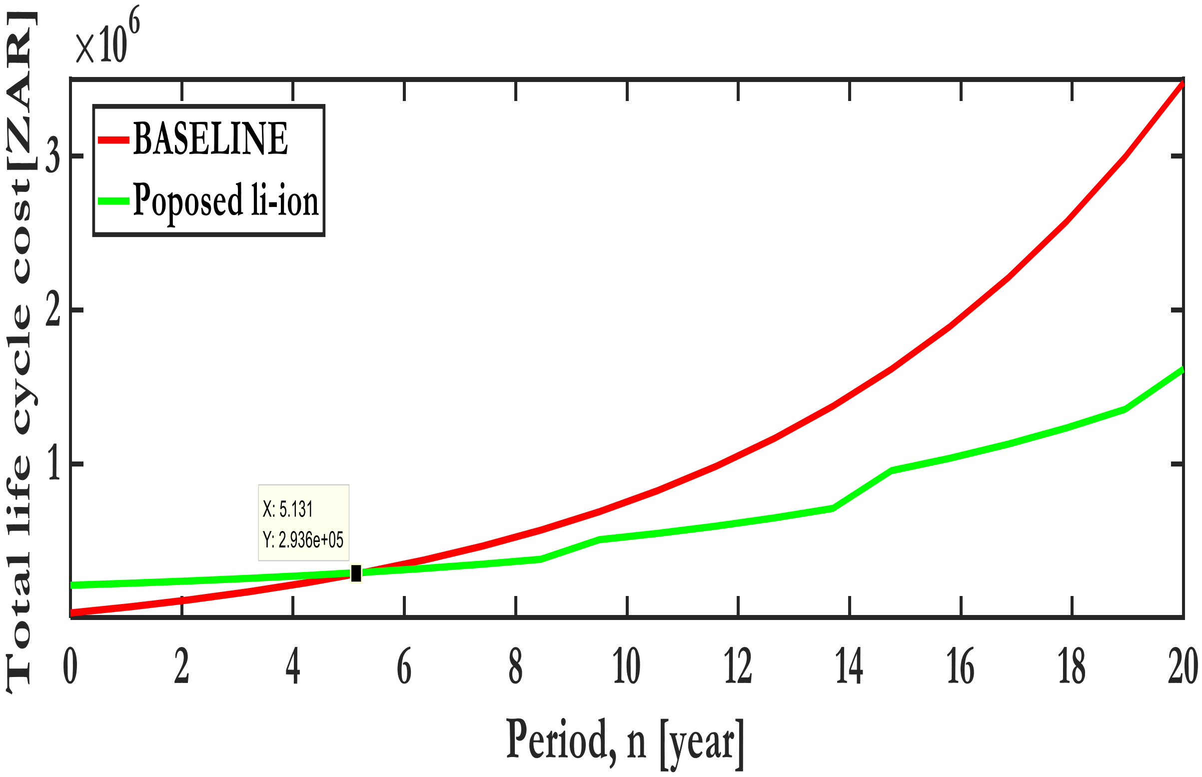

Figure 4.4: Break-even point illustration for lead-acid storage system

4.4.4 Lifecycle cost comparison

The lifecycle costs for the traditional electrical grid to supply power, only as well as the two P2P energy sharing schemes, are compared in Tables 4.7 and 4.8. The break-even point analysis shows the time it will take for cumulative cost equalization. The difference in LCC is calculated in order to note the savings in cost, at the end of the project lifetime.

Table 4.8: Life cycle cost comparison lead-acid storage system

LCC	**Value (ZAR)**
$LCC_{baseline}$ (ZAR)	3,479,624.22
LCC_{P2P} (ZAR)	1,507,346.24
Total savings over 20 years (ZAR)	1,972,277.98

Table 4.9: Life cycle cost comparison lithium-ion storage system

LCC	**Value (ZAR)**
$LCC_{baseline}$ (ZAR)	3,479,624.22
LCC_{P2P} (ZAR)	1,617,684.86
Total savings over 20 years (ZAR)	1,861,939.36

From Table 4.7, as well as Table 4.8, a conclusion may be made that in the long run (over the 20-year project lifetime of the system), an approximate savings of R1,972,277.98 and R1,861,939.36, respectively, may be made if either of the P2P energy sharing system were implemented. This renders savings of 57% and 54%, for the two cases, that were investigated. The detailed lifecycle cost breakdown is shown in Appendix B, illustrating the cumulative costs after each year.

4.4 SUMMARY

The cost effectiveness of the P2P energy sharing system has been analysed and evaluated. Two cases were evaluated, namely: Lead-acid and Lithium-ion storage systems. The differences in cumulative energy consumption and costs were noted, so that the annual energy usage and cost savings comparisons could be made.

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. The evaluation showed that after 5.131 years (li-ion) and 5.34 years (lead-acid), the cumulative costs were lower for the proposed system, as opposed to the baseline. It was detected that, after the break-even point, 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 LCC comparison of the proposed system, with respect to the baseline presented a R1,972,277.98 (lead-acid) and R1,861,939.36(li-ion) savings in cost over the project lifetime. In order to put this into perspective, savings of 57% and 54% in cost, was calculated. This percentage signifies a significant saving once the break-even point has been reached. This further means, that once the break-even point has been reached, solely the savings may be noticed for the entire lifecycle of the project. A 15 % increase in electricity costs may further can also be seen as a conservative assumption, due to the fact that past increments in cost were much higher in comparison.

Chapter V: Conclusion

5.1 FINAL CONCLUSIONS

This Chapter serves as a conclusion of the research that has been carried out on an optimally designed P2P energy sharing system. As seen in Chapter II, the P2P energy sharing system has worked throughout the world, where it has been implemented. The P2P system consists of two prosumers. The first being a single-phase residential building, the other being a single phase commercial building. According to the grid code in South Africa, all excess energy from prosumers, if not used, should be dumped or stored for later use. It is in this context that the P2P energy sharing scheme between prosumers, has its value, as no energy will be lost.

The aim of the developed model, is to assess the energy cost saving, that may be realized by prosumers, if energy not used by one consumer may be shared in a P2P scheme. A model has been developed to minimize the reliance from the grid, whilst optimizing the power-flow between the generation loads as well as storage of prosumers. Using two prosumers in the South African electricity pricing, as well as with the grid operation restriction; the simulation results have revealed that, using the developed model to optimally manage the power flows in the P2P energy sharing scheme may substantially reduce the prosumers' operation cost, by maximizing the local renewable energy production and storage management, whilst minimizing the reliance on the grid. In this Chapter, solely the Time of Use tariff linked to the electricity consumed from the grid was considered to have the main cost component to be minimized. The ToU tariff has two pricing options which was included in the simulated results; one for low demand period (summer) and the other for the high demand period (winter). In both instances, a significant saving of the cost for energy per day, was seen. Based on the fact that the energy shared between the prosumers was considered to be free, the controller managed the two prosumers as a single unit, giving equal importance to all the shared internal power flows.

In Chapter IV, the economic feasibility and the lifecycle cost have been evaluated. Operation and maintenance cost have been calculated as 1% of the initial investment cost. Inflation rate for the future replacement costs of 5.5% and an annual increase of 15% for

the electricity price. Two cases were proposed in this case: P2P system with Lead -acid battery, as the preferred mode of storage and the other Lithium-ion battery, for storage. The initial cost of investment was R169482.65, for the lead-acid and R201451.15, for li-ion battery storage. The economic analysis was carried out for a period of 20 years. The break-even point for the lead-acid case was reached in 5.304 years and an overall cost savings for the twenty-year period amounts to R 1,972,277.98. For the li-ion battery storage system, the break-even point was reached in 5.131 years and an overall savings of R1,861,939.36.
In order to put this in perspective, saving of 57% and 54% in costs was calculated. This percentage signifies a substantial saving after the break-even point has been reached. This further means that once the break-even point has been reached, only savings will be noticed for the entire lifecycle of the project. From the data collected and the simulation of the optimal operation control of the P2P energy sharing schemes, using various energy storage configurations, it has been noted that the system was economically feasible in the South African context in terms of energy cost savings. Therefore, these systems may be recommended for commercial and residential buildings sharing, the same earth.

5.2 SUGGESTIONS FOR FUTURE RESEARCH

A change in the South African grid code should be made, allowing prosumers that are not on the same "earth" to be in a P2P sharing scheme. This will allow anyone who wants to save on energy cost in the future and has the capital available to them to invest in a P2P energy sharing system.
A further constraint should be added to the model, with the aim of coordinating the internal energy sharing between the prosumers, while allocating a cost component to all these transactions. This could be carried out at a significantly lower rate, compared to the grid prices. This may assist each prosumer in maximizing its own production, while minimizing the amount of energy procured from the other prosumer, as well as the reliance on the electrical grid alone for power.

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APPENDICES

APPENDIX A: EXCLUSIVE POWER FLOWS FOR LITHIUM-ION BATTERY

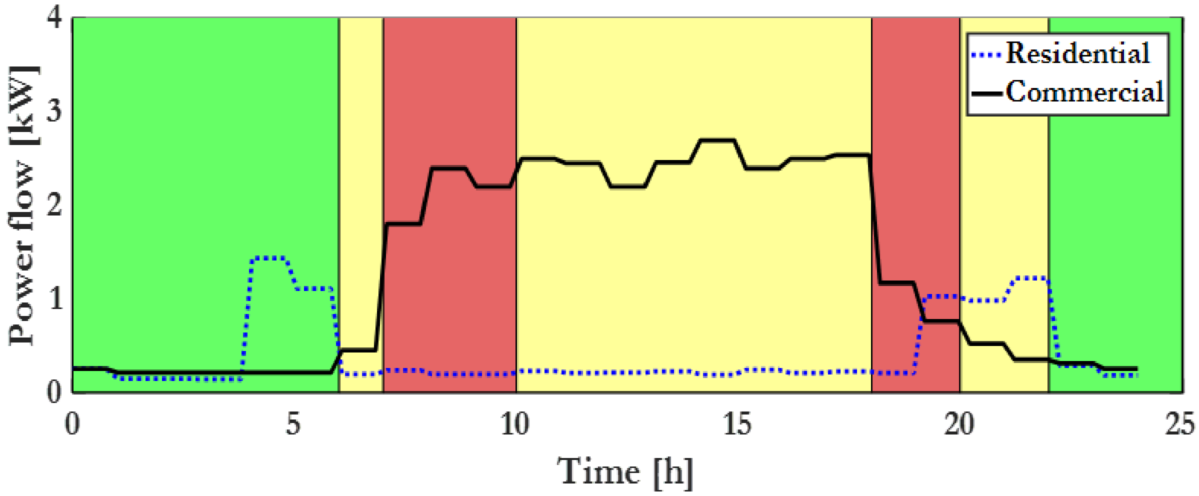

Figure A I: Residential and commercial prosumers' load profiles

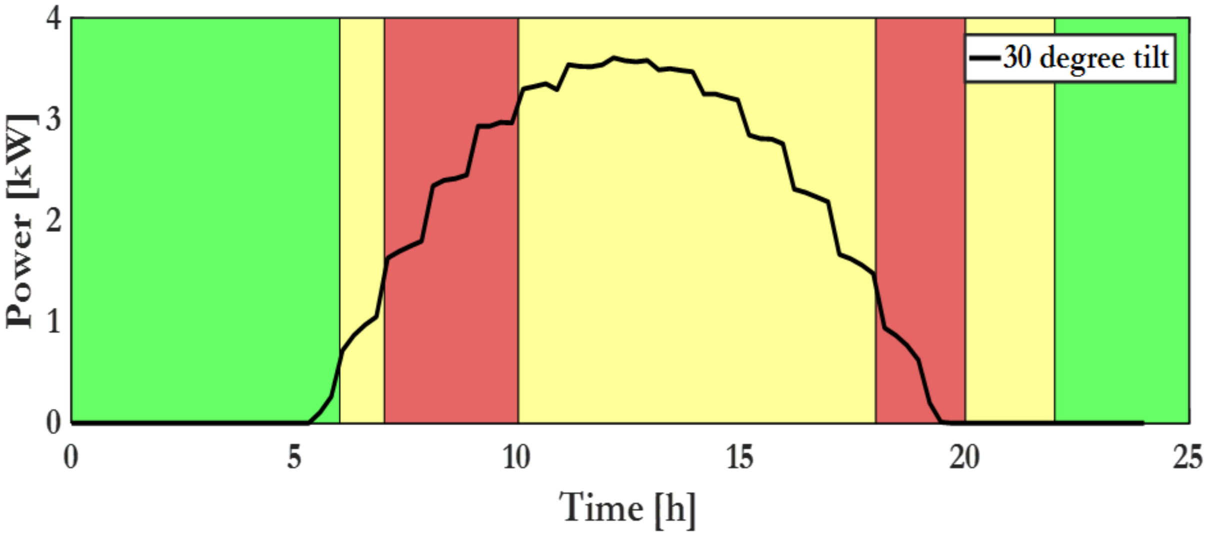

Figure A II: Representation of solar power generated by a fixed PV system with an angle of 30°

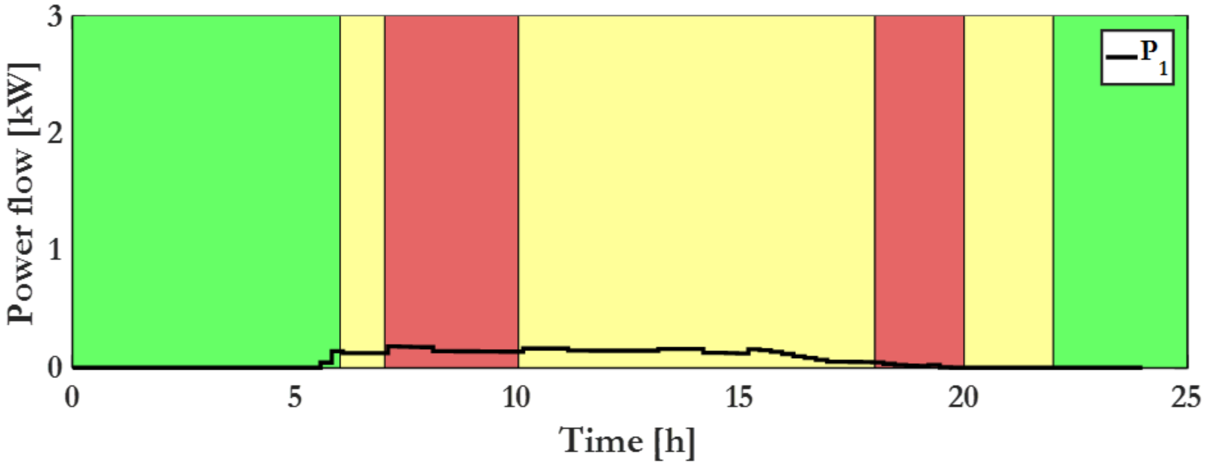

Figure A III: Power flow from residential PV to house

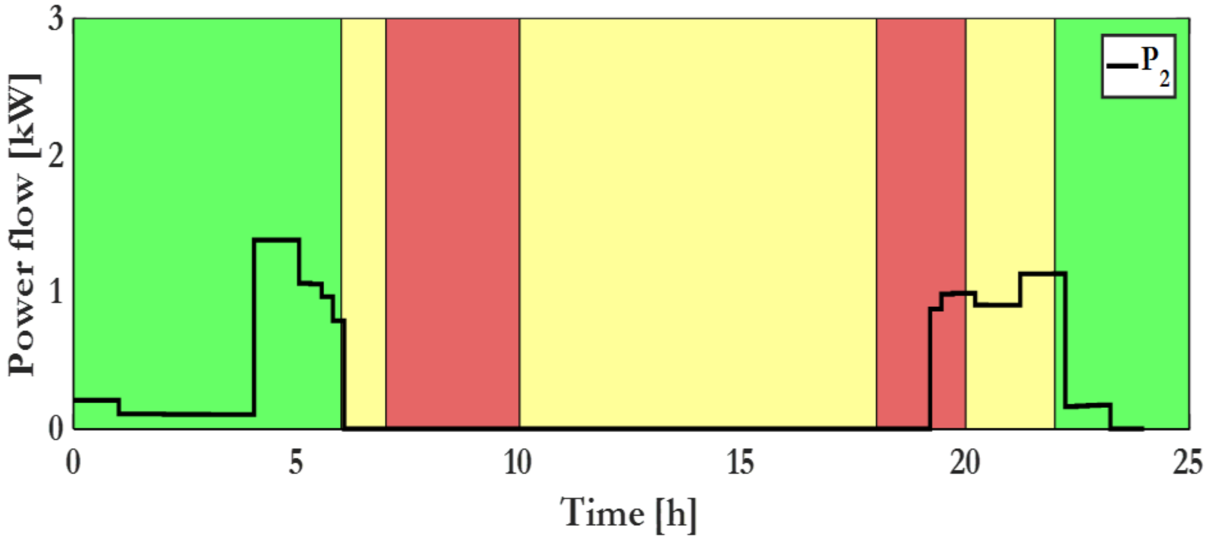

Figure A IV: Power flow from battery to residential prosumer

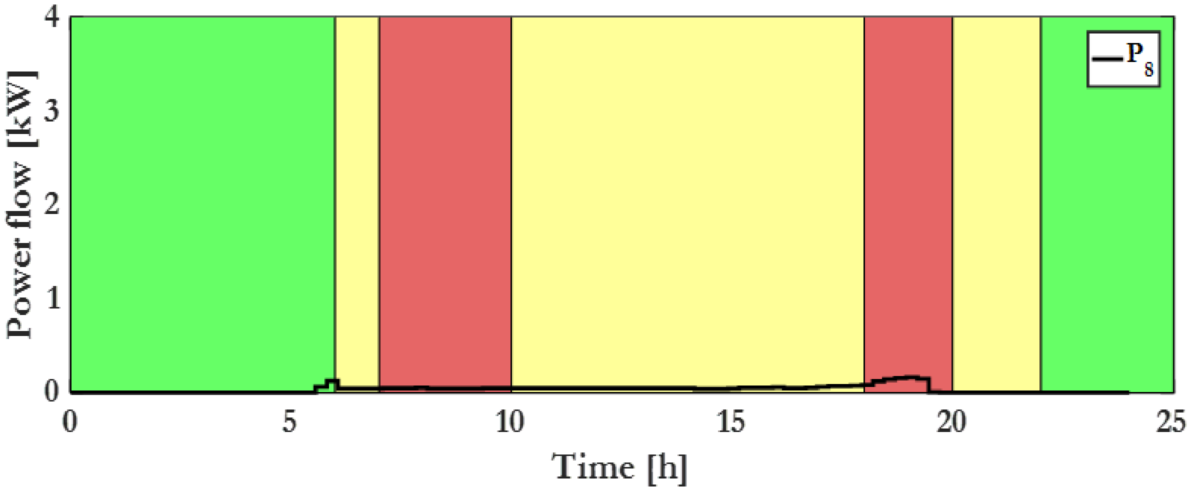

Figure A V: Power flow from PV tracking system to residential prosumer

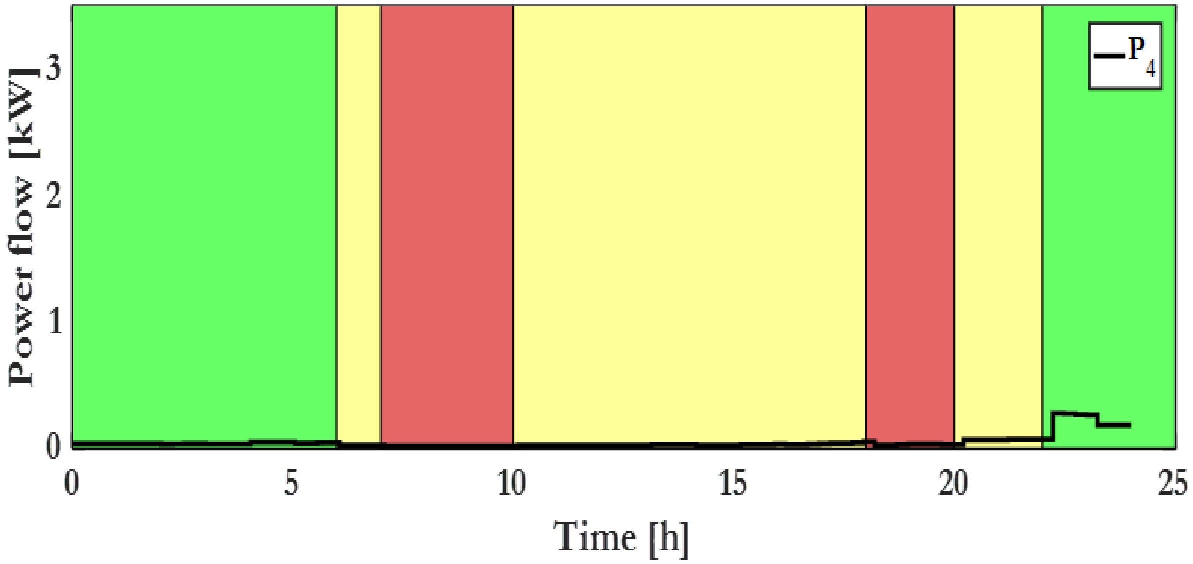

Figure A VI: Power flow from grid to residential prosumer

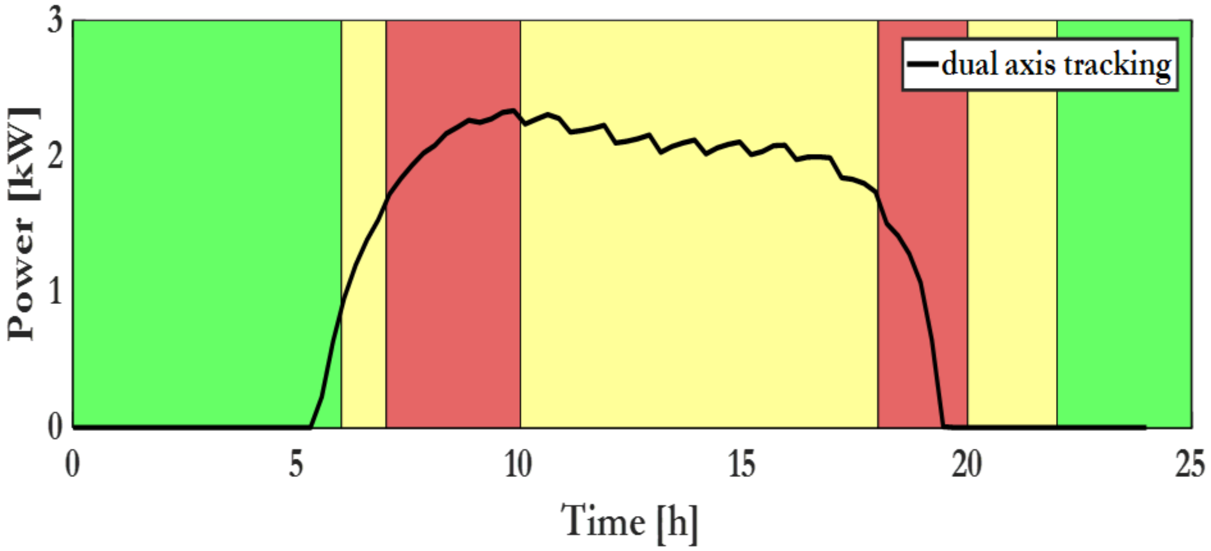

Figure A VII: Representation of solar power generated by the commercial solar tracking PV system

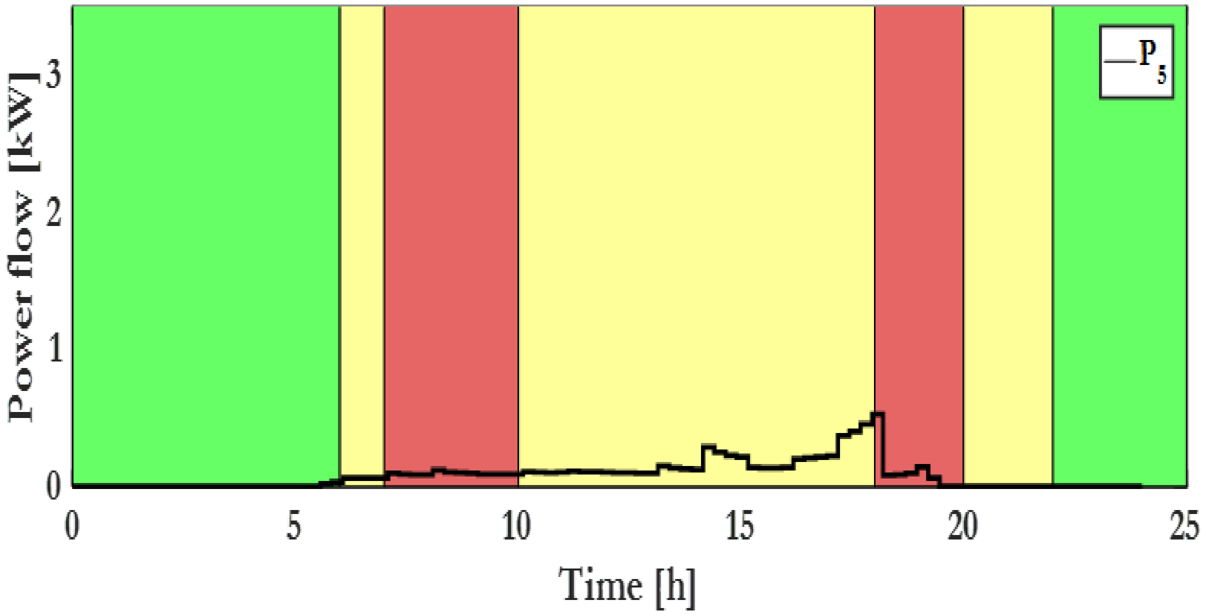

Figure A VIII: Power flow from residential PV to commercial prosumer

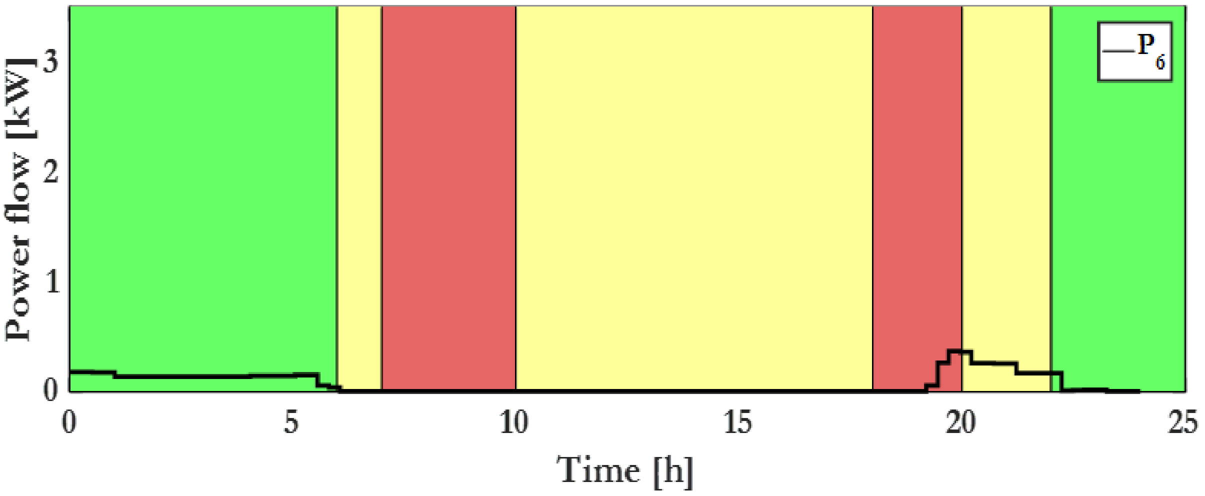

Figure A IX: Power flow from battery to commercial prosumer

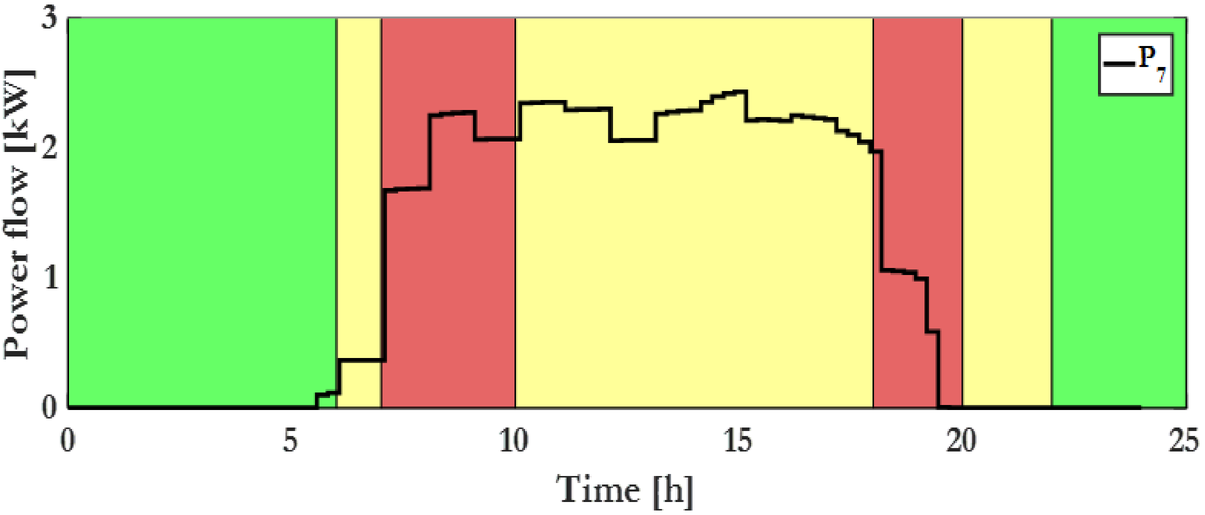

Figure A X: Power flow from solar tracking PV system to commercial prosumer

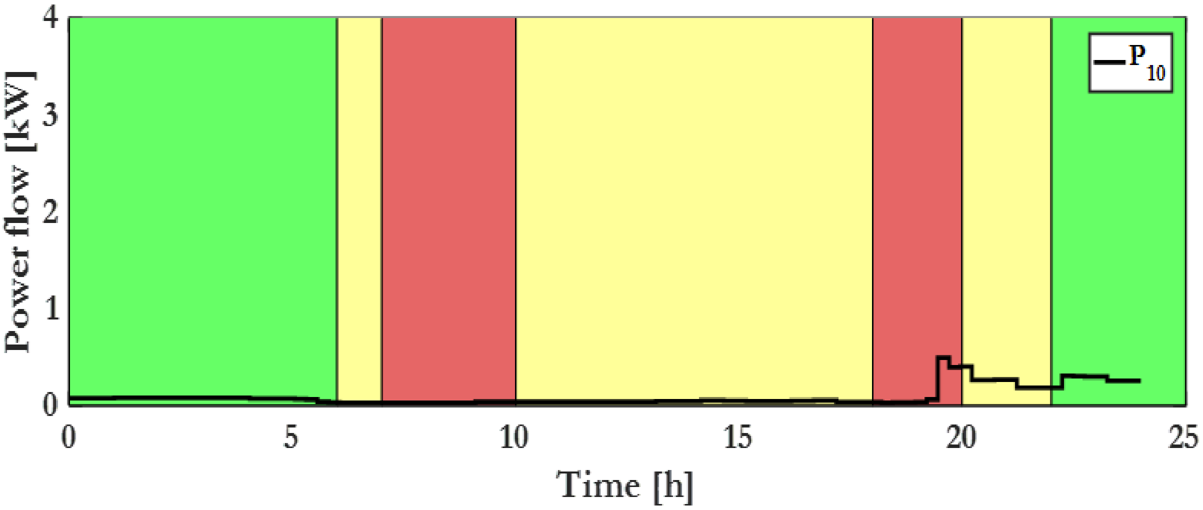

Figure A XI: Power flow from grid to commercial prosumer

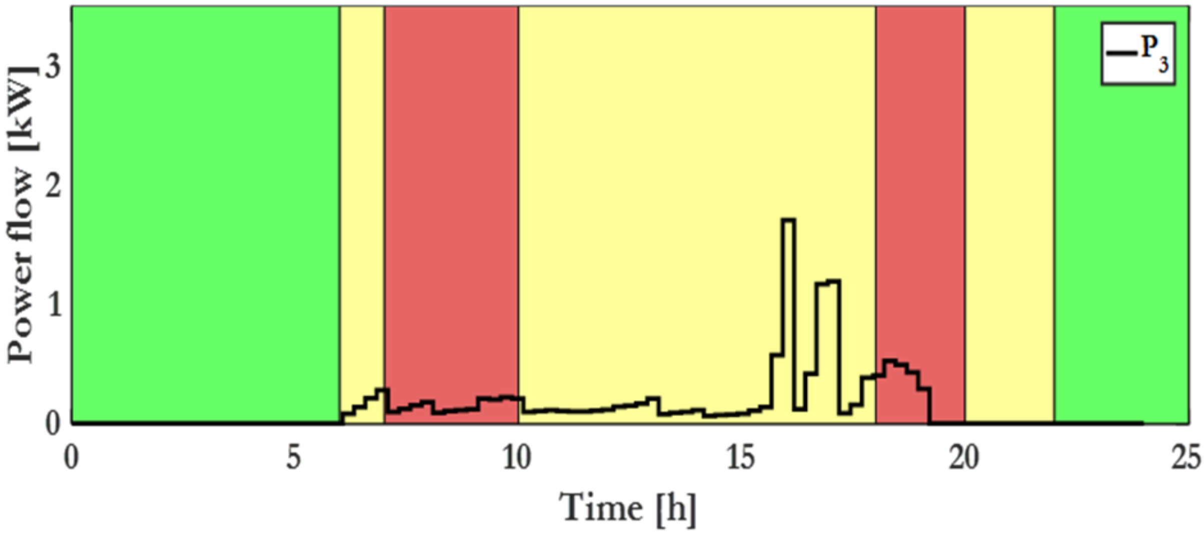

Figure A XIII: Power flow from residential PV system to battery

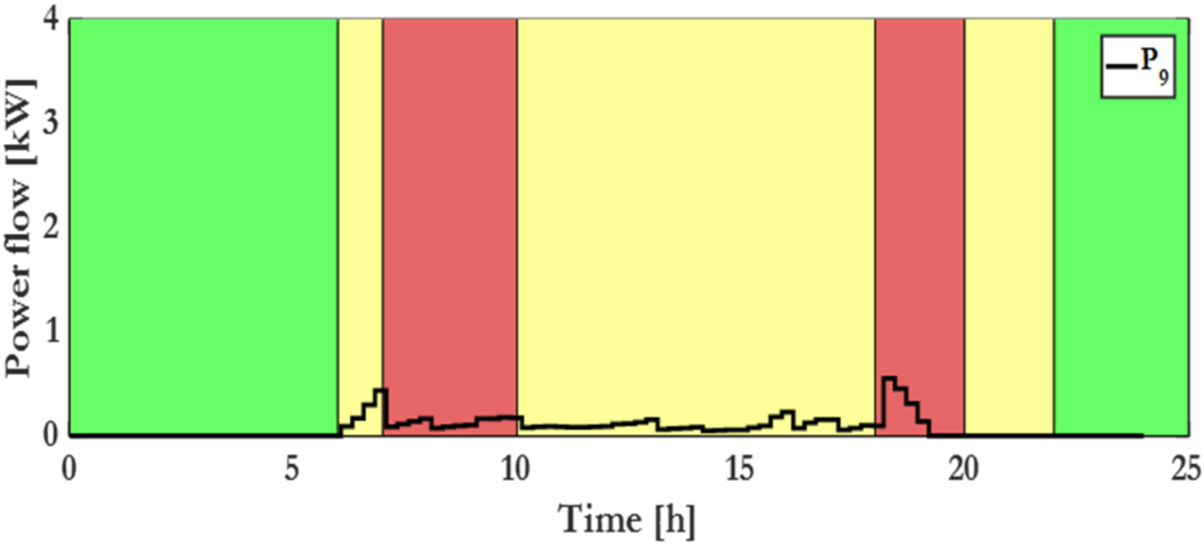

Figure A XIV: Power flow from PV tracking system to battery

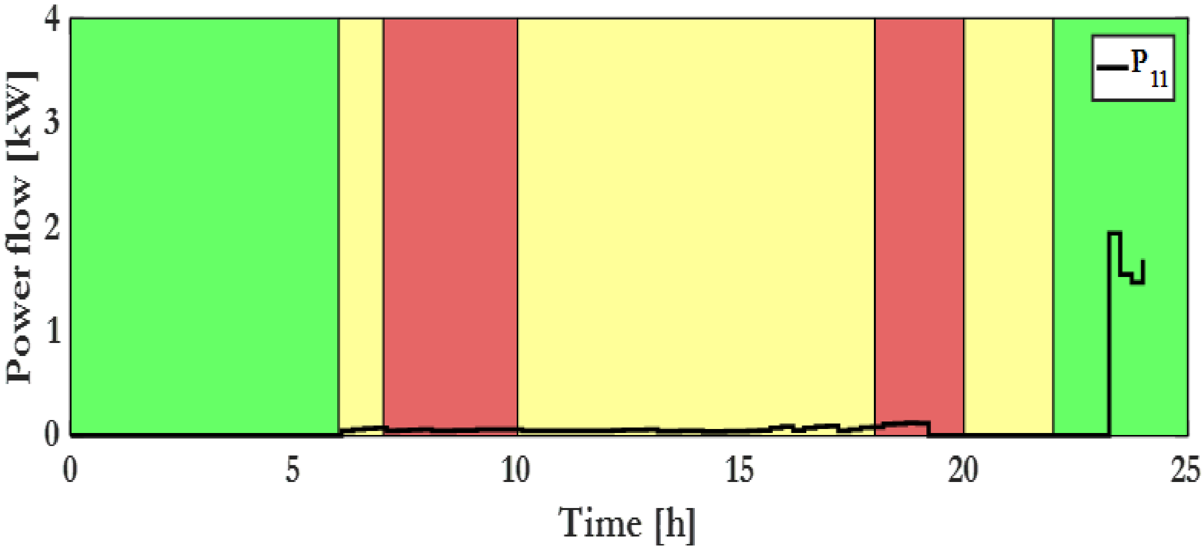

Figure A XV: Power flow grid to battery

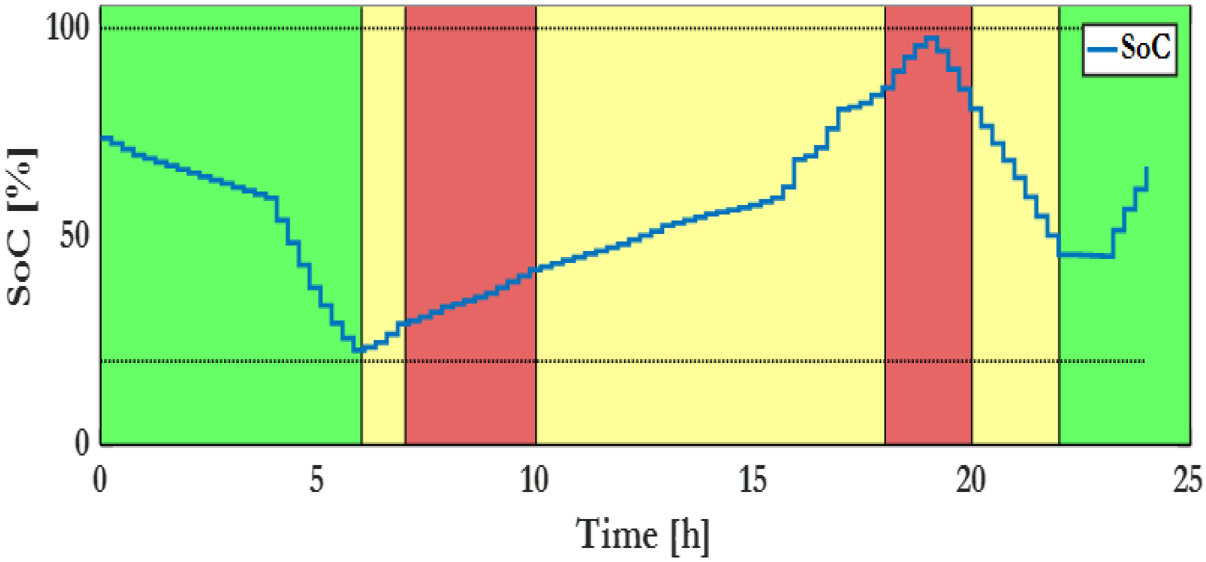

Figure A XVI: State of charge for battery

APPENDIX B: ANNUAL ENERGY AND CUMULATIVE COSTS (LCC)

B1: Annual energy and cumulative costs for lead-acid battery storage

Year	Baseline energy cost after each year (ZAR)	Lead-Acid energy cost after each year (ZAR)	O&M energy cost after each year (ZAR)	Baseline Annual cumulative cost (ZAR)	Lead-acid Annual cumulative cost (ZAR)
0	0.00	0.00	0.00	0.00	169482.65
1	33966.25	9332.13	1694.83	33966.25	180509.61
2	39061.19	10731.95	1788.04	73027.44	193029.60
3	44920.36	12341.74	1886.38	117947.80	207257.73
4	51658.42	14193.00	1990.14	169606.22	223440.87
5	59407.18	16321.95	2099.59	229013.40	275501.79
6	68318.26	18770.25	2215.07	297331.66	296487.11
7	78566.00	21585.79	2336.90	375897.66	320409.79
8	90350.90	24823.65	2465.43	466248.55	347698.87
9	103903.53	28547.20	2601.03	570152.08	378847.10
10	119489.06	32829.28	2744.08	689641.15	454787.72
11	137412.42	37753.67	2895.01	827053.57	495436.40
12	158024.28	43416.72	3054.23	985077.85	541907.36
13	181727.93	49929.23	3222.22	1166805.78	595058.81
14	208987.12	57418.62	3399.44	1375792.89	655876.86
15	240335.18	66031.41	3586.41	1616128.08	944636.30
16	276385.46	75936.12	3783.66	1892513.54	1024356.13
17	317843.28	87326.54	3991.76	2210356.81	1115674.44
18	365519.77	100425.52	4211.31	2575876.59	1220311.26
19	420347.74	115489.35	4442.93	2996224.32	1340243.54
20	483399.90	132812.75	4687.29	3479624.22	1507346.24

B2: Annual energy and cumulative costs for lithium-ion battery storage

Year	Baseline energy cost after each year (ZAR)	Li-ion energy cost after each year (ZAR)	O&M energy cost after each year (ZAR)	Baseline Annual cumulative cost (ZAR)	Lead-acid Annual cumulative cost (ZAR)
0	0.00	0.00	0.00	0.00	201451.15
1	33966.25	9332.13	2014.51	33966.25	212797.79
2	39061.19	10731.95	2125.31	73027.44	225655.05
3	44920.36	12341.74	2242.20	117947.80	240239.00
4	51658.42	14193.00	2365.52	169606.22	256797.52
5	59407.18	16321.95	2495.63	229013.40	275615.10
6	68318.26	18770.25	2632.89	297331.66	297018.24
7	78566.00	21585.79	2777.69	375897.66	321381.72
8	90350.90	24823.65	2930.47	466248.55	349135.84
9	103903.53	28547.20	3091.64	570152.08	380774.68
10	119489.06	32829.28	3261.68	689641.15	508129.65
11	137412.42	37753.67	3441.08	827053.57	549324.40
12	158024.28	43416.72	3630.34	985077.85	596371.46
13	181727.93	49929.23	3830.00	1166805.78	650130.69
14	208987.12	57418.62	4040.65	1375792.89	711589.97
15	240335.18	66031.41	4262.89	1616128.08	956946.47
16	276385.46	75936.12	4497.35	1892513.54	1037379.94
17	317843.28	87326.54	4744.70	2210356.81	1129451.18
18	365519.77	100425.52	5005.66	2575876.59	1234882.36
19	420347.74	115489.35	5280.97	2996224.32	1355652.69
20	483399.90	132812.75	5571.43	3479624.22	1617684.86