OPTIMAL MANAGEMENT OF A SMALL GRID CONNECTED PV WITH GROUNDWATER PUMP HYDRO ENERGY STORAGE FOR FARMING IN ARID AREAS

By

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DECLARATION

I, KHANYISA SHIRINDA, student number , hereby declare that this research project which has been submitted to the Central University of Technology, Free State for the degree for the degree: Master of Engineering in Electrical Engineering, is my own independent work; 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 and has not been submitted before by any person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

Student Signature:

Date: 23 October 2019

DEDICATION

To my Almighty GOD, for the wisdom and opportunity. To myself, for maintaining the courage without losing focus and lastly to my first love, Grace Mushandu N'wa Mbodi.

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ABSTRACT

Running a farm that solely depends on grid electricity, is not easy-going, considering the current state of electrical energy in our country (South Africa). Therefore, onsite electricity generation is achieved by using off-grid approaches, such as wind, diesel generator, conventional small hydro system and solar. However, due to high cost of diesel fuel, unavailability of continuous energy from the sun and wind, these energy generation methods may require extra energy storage systems in order to be considered as a reliable solution for onsite electricity generation for farming environment. Further combination and incorporation with various affordable energy generating sources, is a necessity in improving the grid's economical management. This study used solar PV, incorporated with an underground pumped hydro storage (UPHS) system, whilst a borehole is used as a lower reservoir.

An off-grid UPHS is a promising technology that may be used in any farming environment that has sufficient underground water. This technology is currently under development and lacks implementation.

The purpose of this study was to investigate the possibilities of controlling and optimising the daily operation of the proposed grid-connected renewable energy system, by maximising the usage of the renewable resources, whilst minimising the use of grid electricity to supply the load demand of a farm, without any load supply shortage. The design and sizing of the proposed system was performed, using a Hybrid Optimization Model for Electric Renewable (HOMER). The model formulation, effectiveness and economic analysis was performed and simulated, using linear programming with MATLAB software. Therefore, the simulation results reveal that using the developed model to optimally manage power generated by PV and the PHS, the cost of the electricity for farm operation may be reduced. Nonetheless, the study also raises awareness to the use of renewable energy in conjunction with grid electricity under TOU tariff rates. As well as water conservation and food production to boost our current economic status.

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NOMENCLATURE

A_{PV}	Total area of a PV panel [m^2]
α	Annual increase of 10%
C_0	Initial investment cost [US$]
C_{BAT}	Battery capacity [Ah]
C_{cap}	Initial capital cost for each component [ZAR]
CF_t	Net cash flow of the investment in year [ZAR]
$C_{initial\text{-}EC}$	Cumulative cost of energy at the end of year one [ZAR]
C_j	The TOU electricity tariff [ZAR]
C_p	Power coefficient of a turbine
C_T	Total annualised costs of a system [US$]
C_{TOU}	Time-based cost of electricity at each k^{th} interval
D	Number of autonomous days
E	Induced voltage in a stator [Volts]
E_L	Required daily load [Wh]
E_{PV}	Output energy of a solar PV [Wh]
E_{pot}	Nominal potential energy in the upper reservoir [kWh]
F	Electrical frequency [Hz]
G	gravitational acceleration [9.8 m/s^2]
H	Turbine height [h]
H	Difference in height [h]
I_h	Hourly irradiance [kWh/m^2]
I	Discount rate
J	Considered sampling interval
K	Year at which the cumulative cost should be calculated [years]

M	Water mass [kg]
N	Lifespan of the system [years]
N	Lifespan for a specific component [years]
p_f	Packing factor
P_{Grid}	Power allowed from the grid [w]
R	Average inflation rate
T	Time [s]
v	Capacity of the reservoir [m^3]
V_s	System voltage on the DC side [V]
η_{BAT}	Battery efficiency
η_{CONV}	Converter efficiency
η_{MP}	Pumping efficiency
η_{TG}	Turbine generator unit efficiency
η_{PV}	PV module efficiency
η_{PC}	Power conditioning efficiency
Δt	Change in Sampling time [s]
Q_{TG}	Turbine flow rate [m^3/s]
Q_{MP}	Pump flow rate [m^3/s]
ϱ	Water density [1000 kg]
US$	US Dollar [$]

ABBREVIATIONS

AC	Alternating Current
BCR	Benefits to Cost Ratio
BEP	Breakeven Point
CF	Cash Flow
COE	Cost of Energy
CRF	Capital Recovery Factor
DC	Direct Current
DG	Diesel Generator
DCF	Discounted Cash
DME	Department of Minerals and Energy
DOD	Depth of Discharge
DoE	Department of Energy
DSM	Demand Side Management
GHGs	Concentration of Greenhouse Gases
HOMER	Hybrid Optimization Model for Electric Renewable
IRP	Integrated Resource Plan
IRR	Internal Rate of Return
MHR	Micro-Hydrokinetic River
MWPS	Mechanical Wind Pumping Systems
MPPT	Maximum Power Point Tracking
NASA	National Aeronautics and Space Administration
NPC	Net Present Cost
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
LCC	Life Cycle Cost
O&M	Operation and Maintenance
PMSG	Permanent Magnet Synchronous Generator
PAT	Pump-As-Turbine

PHT	Pumped Hydro Turbine
PHS	Pumped Hydro storage
PHES	Pumped Hydro Energy Storage
PV	Photovoltaic
RC	Replacement Cost
RE	Renewable Energy
REIPPPP	Renewable Energy Independent Power Producer Procurement Programme
SPP	Simple Payback Period
SWP	Solar Water Pumps
TOU	Time of Use
USA	United State of America
UK	United Kingdom
UPHES	Underground Pumped Hydro Energy Storage
WMA	Water Management Area
WECS	Wind Energy Converting Systems

CHAPTER 1: INTRODUCTION

1.1. BACKGROUND

Electricity has an immense contribution in promoting the economic and social development of remote located societies. South Africa's human population growth is directly proportional to its electricity demand. Hence, the electricity demand is increasing with a decrease in South Africa's most dependant energy production resources (fossil fuels) [1]. South Africa's economy is highly reliant on the agricultural sector, which currently consumes more than 62% of the country's runoff rain water [2]. Supplying water through municipal water piping to this sector mainly constituted of remote farms, is a reliable option, however; it comes with several techno-economic challenges, due to factors such as distance and the nature of the terrain [3]. Therefore, pumping groundwater has been the preferred option for farmers compared to surface water, since it can be pumped near the point of use and it is available when needed [4].

As for electricity supply, adequate and reliable electricity supply is an absolute necessity in the farming sector. According to Storm, M E; Gouws, R; Grobler, L J [5], the agricultural sector contributed 6.5% to annual South African electricity sales, with pumping irrigation water being the largest electricity demand allocation. Electrical power is required in controlling the environment and sustaining the life of livestock, poultry and plants and to, allow appropriate harvesting, storing and food conservation and maximizing financial gain and security of the farm capital investments. Therefore, the proximity of electrical network, as well as the farm of electricity source used to supply a given farm is further considered as the main component of the financial returns of the farming activities.

To decrease the operation cost linked to electrical equipment, Demand Side Management (DSM), such as load shifting on pumping and irrigation activities to avoid operating during the utility peak pricing periods [6]. However, this may disrupt the appropriate scheduling of the different activities which may require to be performed at specific times.

Diesel generator (DG) is one of the most popular power generators. It is known as an affordable option as compared to grid extension for remote electrification [7]. It comes with advantages, such as considerably low initial capital costs and to be constantly available on site, at any time of the day as required. However, DG is becoming an unsustainable option to remote areas, due to long distances travelled in terms of fuel transportation, greenhouse gases and rapid diesel price increase. As a result, this promotes the use in renewable energy (RE) sources as being economical.

Renewable technologies, such as wind, solar, biomass, geothermal and hydro may offer clean sources of energy. They may provide an economic means of electricity to small isolated farming areas, situated a long distance from utility grid lines. From various renewable energy technologies, hydropower generation appears to be holding prime position, in terms of its contribution to the world's electricity generation [8-11]. Hydropower comes in different scales i.e. large and small scales. A large scale comes with drawbacks, such as costly construction of dams and disturbance of aquatic ecosystem. Hence, small-scale hydropower generation is much preferred for electricity supply to isolated/remote areas, near adequate water resources [8]. Therefore, renewable energy resources used in conjunction with groundwater storage and pumping infrastructures, may be redesigned to generate onsite electricity that may be used to minimize the total amount and cost of electricity drawn from the grid. Nevertheless, this research will be focusing on pumping water from underground, using solar power to regenerate electricity through a hydro turbine and using the depth of the open well as the working head of the hydro power.

1.2. PROBLEM STATEMENT

- Many farms in South Africa have both challenges of electricity and water supply, which makes the operation cost significantly high, which in turn reduces the return on investment of the overall farming activities. Frequent electricity blackouts and load shifting has been a common problem, to both farmers and wholesalers, who are benefiting from the farms.
- Available software packages/tools for modelling renewable energy systems (HOMER), do not accommodate storage tank or reservoir components. Hence, it is a hustle to study/analyse the performance of the proposed PV-UPHS system i.e. redesigning of a few parts of the proposed system to match the software.

1.3. AIM AND OBJECTIVES OF THE STUDY

The main aim of this research is to develop a model that will allow the optimal utilisation of solar photovoltaic with pumped hydro storage through open wells (borehole), for minimization of electricity cost for farming activities in a dynamic electricity pricing environment.

The objectives of this research are:

- To review literature based on the South African case, context or opportunity, different methods of ground water pumping, electricity generation using ground water and renewable energy, types of storages used to store water from underground, types of generators used for conversation of energy stored in water reservoirs, as well as relevant works on solar and its tracking device.
- To collect data related to Bloemfontein's sun radiation, TOU tariff, the local farm load, as well as the PV's output power for all seasons.
- Size the proposed PV-UPHS system.
- Model and simulate the proposed system in MATLAB.
- Do economic analysis of the proposed system, to reveal its economic viability.

1.4. RESEARCH METHODOLOGY

To achieve the above-mentioned objectives, the following scope of work is carried out for this research:

1.4.1. Literature study

The study was conducted in Bloemfontein, to investigate application of power generation from renewable energy, combined with groundwater storage in the smallholder farming systems. Literature related to the topics bellow was reviewed:

- Description of different methods for ground water pumping
- Review of electricity generation using ground water and renewable energy resources.
- South African case, context or opportunity.
- Type of storage used to store water pumped from boreholes

- Type of generators used for conversation of energy stored in water reservoir into electricity.
- Site ground water assessment.
- Relevant works on solar and its tracking device

1.4.2. Data collection

A small farm was identified, where the following data was collected and drawn from the measurement and monitoring.

- Two types of electrical loads are generally found on farms; these are the primary (critical) and secondary (non-critical) loads. The primary loads are those of high priority that should constantly be supplied, shifted or reduced, while the secondary loads can be managed without causing substantial discomfort to the farm. The primary load on the considered farm consists of the bulk milk cooler, milking machine, fan, water pump, freezer, electric fence and light, while the secondary load consists of equipment, such as a stove and electric water heater. The total corresponding load profile was therefore computed.
- The electricity cost of supplying the load demand exclusively from the grid was further simulated for the same study period.
- The solar resource on site was assessed and analysed.
- PV's energy production based on Bloemfontein's sun radiation

1.4.3. System optimal sizing

The optimal sizing of the corresponding solar, upper storage and hydro turbine that was used to supply the load was conducted, using specialised software HOMER (Hybrid Optimization Model for Electric Renewables). This software was developed by the National Renewable Energy Laboratory (NREL) of the United State of America (USA) [26]. It has been used to determine the optimal cost-effective grid connected option (among pumped hydro, DG and wind), fulfilling the basic electrical load requirement at the study site.

1.4.4. System Modelling and Simulation

The simulation and modelling have been conducted using MATLAB. This section includes the development of a mathematical model of a PV-UPHS system model, with photovoltaic and pumped hydro storage. The model will comprise of the following:

- The objective function

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

- System Constraints

- Power balance

At any given time, the farm load demand should be met, however, the combination of the power from the grid, the renewable source and the storage system.

- Dynamics of the PHS water level.

During charging and discharging, the state of water level in the upper storage tank should be maintained between its minimum and maximum values. Further, the tank cannot be filled up and discharged simultaneously.

- Variable limits

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.

- Fixed final state condition

The final state of the water level in the reservoir, should be equal to the water level at the start of generation.

1.5. HYPOTHESIS

- In areas without flowing water, but with an adequate solar resource within South Africa, a non-grid interactive UPHES system generates electricity more efficiently and affordable than using the grid alone for the same load demand.
- The system will minimize the cost of electricity from the grid.
- The system will maximise the use of renewable energy, while minimising the number of people connecting to the grid.

1.6. DELIMITATION OF THE STUDY

The study has been conducted with the following limitations:

- This study focuses solely on turbines related to micro and pico-scale pumped hydro systems (5kW-100kW), since it is suitable for electrification at a domestic, small commercial loads, Small community or remote industrial area level. Large-scale pumped hydro systems such as the ocean, large dams, civil reservoirs etc., are not considered in the study.
- Mathematical modelling of batteries, power electronic and mechanical control circuits, will not be part of this study.
- No new turbine design was considered in this study, since hydro turbines are presently available in venomous forms and sizes.

1.7. CONTRIBUTION TO KNOWLEDGE

- Relevant literature on PV-UPHS system, related to recent technologies and developments, status as well as the application into a farming environment is presented by the author on a South African context. This has filled the open gaps and provided more opportunities to researchers to identify further missing parts of the research in the future.
- The development of a model that optimally controls the operation of the PV-UPHS based system, to minimize the costs of the grid electricity to operate the farm and to maximize the use of renewable energy, satisfying the load. The model considers various electricity pricing plans for different weekdays, as well as the variability of the load demand, to satisfy different daily farm operations. The objective is to meet the daily farm load demand, while limiting the use of the grid when the energy cost is higher and maximizing the use at its lowest price.
- For awareness to the community and local famers, based on the potential benefits of using underground pumped hydro storage system for maximising the use of renewable energy, to reduce the amount of monthly electricity bill. This will bring a huge social impact, due to reduction in the number of people relying on grid electricity. Therefore, less chances of load shedding will be expected.

1.8. RESEARCH OUTPUT

Conference papers:

- Shirinda Khanyisa, Kanzumba Kusakana and Sandile Philip Koko. "A Survey of Groundwater Pumping Technologies for Electricity Generation Through Hydropower." In *2018 Open Innovations Conference (OI)*, pp. 96-101. IEEE, 2018.
- Shirinda, K., K. Kusakana and S. P. Koko. "Techno-economic analysis of a standalone solar PV with groundwater pumped-hydro-storage system." In *2019 International Conference on the Domestic Use of Energy (DUE)*, pp. 90-95. IEEE, 2019.

Journal paper:

- Shirinda, K., K. Kusakana and S. P. Koko."Optimal energy management and economic life cycle analysis of a small grid-connected PV with groundwater-pumped-hydro energy storage system" *submitted.*

1.9. OUTLINE OF THE DISSERTATION

Chapter 1 introduces the dissertation, which outlines the background, problem statement, objectives, methodology, hypothesis, delimitation of the study, as well as the research outputs.

Chapter 2 provides an overview of how hydropower is being used and the potential of it in South Africa. The focus of the chapter is based on the application of the proposed system in our local farms, as well as the review of the system technologies and the type of generators and storage, used for hydro electricity generation. Site solar and ground water assessment further forms part of this Chapter.

Chapter 3 reveals the design and optimal sizing of the proposed system, its techno analysis, as well as revealing the economic benefits that come with the chosen renewable resource. The techno-analysis was performed using HOMER software.

Chapter 4 covers the formation of the mathematical model of the proposed system, as well as the discussion of the simulation results. The performance of the proposed system is compared to the base system (sole grid supply) revealing its benefit. MATLAB has been used to develop this model.

Chapter 5 presents the economic analysis of the proposed system. The financial implications of the system are analysed, based on its life expectancy. The process of analysis is carried out using MATLAB.

Chapter 6 presents the conclusions and suggestions for future areas of research, to be carried out to better the application of the proposed technology.

CHAPTER 2: LITERATURE REVIEW

2.1. INTRODUCTION

Water is a universal requirement of every living organism. It is one of the leading elements of economic development through the agricultural sector (farming). However, many South African farms have both challenges of water and electricity supply. Africa runs its energy harness on both renewable and non-renewable energy sources. This Chapter presents a brief review of the status and potential of hydropower generation in South Africa. It reviews the status of pumped hydro energy systems, as applied in semi-arid and arid areas, globally. It further focuses on the alternative methods for pumping ground water, relevant works on solar water pumping and recent development studies focusing on hydro energy storage.

2.2. Description of different methods of ground water pumping

There are various options available for water pumping purposes. This may include PV pumps, mechanical wind driven and electrical pumps, a solar-wind hybrid pumping system and dual-fuel engine pumps, using producer gas or biogas [12]. These options minimize dependence of fossil fuel-based electricity. The following alternative sources of energy to the utility grid are commonly used, to extract groundwater through a borehole for irrigation purposes and other farming activities.

2.2.1. Diesel pumps

These pumps are significantly effective and operate to extract water on demand. However, they display all the disadvantages of systems powered with diesel generators, such as noise pollution, environment pollution and high operation and maintenance costs, associated with the ever-increasing price of fuel. Furthermore, the transport action and storage of fuel are major challenges [13].

2.2.2. Solar pumps

Photovoltaic (PV) are a product of series connected solar cells. The commonly used cells for commercial use are made from purified silicon (Si). The Silicon cell is essentially a p-n junction that utilizes the energy from the sunlight to generate electron flow from the p-type Si (via an external resistance) to the n-type Si. A typical solar module is comprised of 36 cells connected in series, to produce an operating voltage of 12V. The PV may then be used to supply the specific pumping machine, i.e. solar pump.

When choosing a site for the PV panels, it important to confirm that the area has a high level of sunshine and no prolonged process of clouds or mist [14]. The main benefit is access to inexpensive electric power in remote areas that are not connected to the national electricity supply network. The advantage of using solar energy is that solar power is renewable, clean and has no direct emissions. Solar panels may be used almost anywhere in South Africa and are suitable for low energy use, such as lights and television. The disadvantage is, without energy storage, there won't be power supply to the load at night or when conditions are not favorable, i.e. the sun is not constantly available and the equipment for storage is costly.

Solar pumping system consists of a solar photovoltaic array and a controller, to provide energy to an electric pump that lifts the water from the water source to the surface. However, this system requires energy storage, as water is constantly required, even without sunshine [15]. Water plays a significant role in the development of any specific country. The quality of life in any country greatly depends upon the quantity and quality of available water resources in that country. It is estimated that an average of five litres of fresh water is required per person per day for daily survival [16] and although a large amount of high-quality water is present in the world, it is often not available at locations where it may be readily used. This raises the requirement to pump high-quality water from its source, to the locations where it is in demand. For this purpose, water pumps have been in use for decades.

Recently, environmental and sustainable development has shifted the focus to the use of renewable energy driven water pumping. Today, the use of PV conversion of solar energy to power the water pumps is an emerging technology and yet, comes with great challenges. This technology may be used for large scales and it is found to be a great alternative to diesel and electricity powered conventional water pumps. Moreover, the importance of solar PV energy to power the pumps increases, due to non-availability and high distribution cost of grid power. Besides this, operation and maintenance costs of diesel pumps are generally 2-4 times more than PV pumps. Solar water pumps (SWP) have a greater advantage during summer seasons, as the availability of solar radiation and water requirements are altogether too high. SWP are available in the range of 1.5-7.5 KW or higher. They are suitable for pumping water from 5m (shallow), to higher water table (100 m or more).

2.2.3. Wind pumps

The principle involved in electricity generation is significantly the same as what has been used throughout the centuries. The sole difference is the introduction of an electricity generator. The movement of air is used to propel blades. Thereafter, these blades turn with the wind direction and along with it, an axle attached at the center of the blades. The axle carries the energy to a gearbox. From there it travels to the generator, where the electricity is generated. The advantage of Wind energy is its availability. It is renewable, clean and does not produce harmful gases. The coastal regions of South Africa are ideal for the use of this technology. The disadvantage being that the wind is not constantly available for driving the windmill blades, wind generators create noise and are costly to build.

Wind pumps may be Mechanical Wind Pumping Systems (MWPS), where the blade turning kinetic energy of the windmill is used directly to pump water and Wind Energy Converting Systems (WECS), where the wind turbine is used to generate electricity and then further used to power an electric water pump [17]. Several authors have previously discussed the use of alternative water pumping energy sources in sparsely distributed, rural environments, with significantly unreliable or lack of access to the grid. However, the writer on Reference [18] has concluded that, in certain cases, when connection to the grid is easily implementable, the use of wind and solar pumps are viable and cost-effective options, compared to diesel pumping [19].

2.2.4. Solar–wind water pumping system

Renewable energy integrated into electric power systems, such as hydropower, solar and wind power, has been the primary choice for many countries [20]. However, both wind and PV are random when it comes to power generation. Therefore, they are preferred to be generating electricity in one system for reliability [21]. Hybrid water pumping systems may consist of several combinations, including wind with PV, wind, PV and another renewable energy source, wind with diesel, or PV with diesel. Each combination may have battery storage and/or inverters, with or without a backup generator or utility powerline. Hybrids offer greater reliability than either wind or PV technology alone, as each power source (wind or solar) is independent of the other. For example, in winter, when solar energy is low, significant wind energy is usually available to compensate for the loss from a PV power source. Another advantage of a hybrid system over an individual wind or PV system, is the use of the technology's reliability for integrated applications.

In most cases, wind comes as a supplement to the stand-alone solar system. However, this may be decided based on the availability of the solar and wind resources. As wind and PV technologies advance, the use of hybrid systems, as stand-alone systems, is growing as a preferable and less expensive, than individual wind or PV systems. Hybrid systems do not require to be designed for worst-case scenarios, as the power does not come from a single source. Hybrid systems permit the use of smaller component sizes and this lowers the cost of the system. Although hybrid systems are improving in reliability and are reducing the overall size of the power system, their initial costs are still high. Maintenance of hybrid systems further requires a highly skilled professional. Therefore, hybrid systems are particularly suitable for economically strong communities, with well-equipped, skilled manpower for maintaining the systems.

2.3. Review of electricity generation using ground water and renewable energy resources.

The attainable assets of a sustainable power source in South Africa are: sun based, wind, biomass, geothermal, hydropower, waste to energy and the tidal (wave) energy. Their potential varies from province to province. Apart from KwaZulu-Natal and the

Mpumalanga provinces, which have the most outstanding potential for biomass, the other seven regions have the most elevated potential for sun-oriented energy. Wind has the second most elevated potential in the three Cape Provinces. Biomass has the second most elevated potential in the Limpopo region and hydro has the second most elevated potential in the Free State [22].

South Africa's greenhouse emission is the highest in Africa. Central generated power cannot reach remote areas, due to lack of distribution infrastructure. SA may have been found with more of various sustainable power sources, but it has significant potential in both solar and wind power generation [23]. Renewable energy power plants utilize either the thermal energy originating from renewable sources, i.e. geothermal, solar-thermal, and biomass-power plants, or directly generate electricity from renewable sources, i.e. hydroelectric, photovoltaic and wind-power plants. As the former pathways involve a steam turbine or boiler, water use is in a similar range as steam-based fossil-fuel plants. On the other hand, at hydroelectric power plants, a large volume of water is evaporated from the surface of artificial reservoirs, although wind and photovoltaic-power plants hardly require water during their operation [24].

Water for power is of specific significance, as thermoelectric control plants are among the highest consumers of water. In the United States, the topographical review evaluated that in 2005, the thermoelectric power plants oversaw approximately 52% of surface freshwater withdrawals and 43% of aggregate water withdrawals [25]. Dry cooling power plants consume 7% of water for cooling while 70% of water is expended in closed loop (wet) cooling and restoring the rest to nature. 43% of the producing limit is related with open loop cooling while 42% is used for (wet) closed loop cooling [26]. To place it into the point of view of thermoelectric withdrawals, where 200 billion gallons a day or 670 gallons for each U.S. habitant. The Author in Reference [27] defined withdrawal as water that is derived from a source and may be returned to the source and water that is derived from the source and may never be returned to the source, is categorized as consumption. Different sectors have dissimilar water withdrawal and consumption rates. The technologies used in the various sectors further affect the withdrawal and consumption rates.

In various events, licenses for proposed plants have been denied, as a result of securing water accessibility concerns and possible antagonistic impacts on aquatic life in different areas internationally. Likewise, during dry seasons events have taken place where generation plants have been closed, since if operating, they would not be agreeable with water use regulation. Henceforth, water use for power generation influences territorial nature and security of supply of both water and electricity [27]. From the above information, water withdrawal for electricity generation is not common in South Africa, as a mid-arid country. South Africa is in a state where it is currently using water under the category of consumption. This may further be the reason as to why it is suffering in both needs.

South Africa, as a nation, should adjust to water deficiencies in the close to medium future, as examined in the early on segment. An intrinsic absence of freshwater assets, combined with expanding populaces and changing precipitation designs, will undoubtedly produce a requirement for effective and inventive changes in water utilization. Although the horticultural division is the predominant consumer of freshwater resources, the industrial and power generation sector, likewise, have significant water utilization impressions.

Many technologies have been developed to extract hydrokinetic energy, such as float or buoy system and oscillating Colum devices. Within these technologies, hydro kinetic turbines are the most popular. They are designed to extract the kinetic energy of the flowing water instead of potential energy of falling water. As a result, no water head is required to convert the kinetic energy to electrical energy. The physical operation principle of a hydro turbine is closely like that of wind turbines. However, unlike a wind energy resource, it is predictable and may generate 800 times greater than wind turbine, as the water is 800 times denser than that of the wind [28].

2.4. South African case: context or opportunity

South Africa has substantial hydropower potential for both small and large-scale hydropower generation, as presented by the department of mineral and energy of South Africa. It is currently experiencing broad changes in the power generation sector, in view of the presentation of key sustainable power source activities. The sustainable power source activity embraced by the South African government, has seen the support of various free power producers, enthused over the vast accessibility of natural resources. The non-specific impetus to utilize sustainable power age plans originates from the accessibility of assets and the absence of carbon discharges. However, there is an expanding number of studies internationally; examining the outside expenses of sustainable power age plans. Despite the accentuation on renewable energy, non-sustainable technologies still play a noteworthy part in the electricity generation, as featured in impact assessment studies.

South Africa is in a stage of building and incorporating renewable technologies to the national grid and within the following few years' affective evaluations of renewable generation mechanism will be required. To gauge the effects over numerous generation mechanisms, it is plainly fundamental to evaluate the effects from current power generation technologies.

Coal is currently the most widely used primary fuel nationwide, covering approximately 36% of the world's electricity production. This situation is likely to remain until at least 2020. Coal has traditionally dominated the energy supply sector in South Africa, from as early as 1880, when coal from the Vereeniging area was supplied to the Kimberley diamond fields. Currently, approximately 77% of the country's primary energy requirements are covered by coal [23], followed by nuclear energy (5%) and various other sources, including renewable energies, such as hydro power [29]. This was estimated to unlikely change significantly in the next decade, due to the relative lack of suitable alternatives to coal as an energy source [30]. However, most recently, renewable energy in South Africa has become synonymous with large-scale, grid-connected projects, as constructed under the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP), as the department of energy and the national energy regulator of South Africa has developed policies and projects for the procurement and implementation of renewable energy, supplementing its fossil fuel based production for a greater sustainability and diversification in energy sourcing .

Renewable energy may, however, further be deployed on a smaller, stand-alone scale, where it can directly benefit households, farmers, communities and businesses [22]. The energy sector in South Africa is a critical part of worldwide energy administrations, as a result of the nation's development and advances in sustainable power source. South Africa's commitment to ozone depleting substance (GHG) outflows, is positioned as direct and the per capital emission rate is higher than the worldwide average. Energy requests within the nation is relied upon, to rise consistently and double by 2025 [22]. In 2010 it was estimated by IRP that SA will require an increase in generation capacity of over 46 GW, of which 23.6 GW is desired from renewables (including Hydro). This represents 26% from renewable energy sources, including Hydro, towards the total system capacity of 89,532 MW, planned for 2030.

In 2017 the total power generation capacity installed was estimated to be 52.811 GW, where fossil fuels covered more than 80% of the total share. However, since the government made a commitment towards renewable energy, the total contribution of solar, wind and hydropower energy sources are increasing. Despite the growth, South Africa is, as of yet, unable still not able to meet its total demand, without involving energy measures such as demand side management, time of use tariffs or optimal management of available energy storage. For commercial and industrial consumers, the situation is most evident, due to the increase in electricity cost during peak pricing periods, which may be up to four times the price of electricity during off peak pricing periods. This is further translated by an increase in retail prices of farm products.

The sun is the resource with the greatest potential in South Africa. There are two main technologies for producing electricity from solar radiation: concentrating solar power (CSP), also known as solar thermal energy and solar photovoltaics (PV). CSP technology uses mirrors to concentrate the thermal energy of the sun and heat a transfer fluid. Thereafter, the heat energy is used to produce steam with which electricity is generated in conventional turbines. Photovoltaic panels usually use silicon to convert the solar radiation directly into electricity [31]. Another sustainable power source in South Africa with high potential is wind energy [32]. As a result of the high breeze speed on the shore of the nation, Cape Town has executed numerous wind farms, effective in generating noteworthy measures of power for residents; the total wind power generation is estimated to be 6,700 GW and is found to be competitive with the solar potential [23].

Sustainable power source frameworks in the long haul are practically comparable or fetched, somewhat not precisely non-inexhaustible sources. Biomass is, at present, another large sustainable power source supporter in South Africa, with 9-14% of the total energy mix [33]. Sustainable power source frameworks are costly to execute before all else, however, they produce high monetary returns in the long-run [34]. Currently, the overall penetration of hydropower electricity is a mere 5% of the present 45,500 MW installed [35]. Hydropower projects are not common in South Africa, as a majority of our water sources are seasonal in nature. It is regarded to be, indirectly, a further form of solar energy, where vapour cycle is giving rise to rain for filling rivers and dams, which are used for hydroelectricity generation.

Since the past 30 years, with a lack of records of significant hydropower development [36], except for the total of 7 MW independent hydropower plants in Bethlehem, in the Free State province, 4 MW plant in Merino, with a head of approximately 14 m and a single Kaplan turbine. The 3 MW is located at the wall of the Sol Plaatjie dam, with a generating head of approximately 11m at a maximum flow rate of 30 m^3/s [37].

2.5. Types of storage used to store water pumped from boreholes.

2.5.1. Upper tank

Storing water in the upper tank, or upper reservoir, is a method that is mainly used by small farms or domestic water sparing. Usually, water would be pumped from underground via a borehole, or rain water collected from the house roof via gutters to the tank for later use. However, the method is known as pumped hydro energy storage (PHES) in case of power generation purposes. This method stores energy in the form of potential energy, carried by water when pumped from the lower reservoir or underground to the upper tank or reservoir. In this type of storage, low cost electric power, such as solar or wind energy may be used to run the pump to raise the water [38].

The technique is currently the most efficient and cost effective to store electrical energy [39-41]. However, it comes with very high capital costs and the geographical situation may be a critical factor, i.e. the design of every PHES is highly dependent on the topographical and geographical characteristics of the area or chosen site. The PHES may be rated in different sizes and capacity i.e. they can be classified from large, small, micro and Pico. Its capacity may vary from a few kW to more than 10 MW [42]. Table 1 shows the different categories and their relevant capacities.

Table 2.1

Classification of hydropower generation [35]

Hydro power generator	Capacity	Feeding
Large	More than 100MW	National power Grid
Small	Up to 25 MW	National power grid
Mini	Bellow 1 MW	Micro power grid
Micro	Between 6 and 100 kW	Small community or remote industrial area
Pico	Up to 5 kW	Domestic and small commercial loads

Many countries, including South Africa, have realised the feasibility of this technology and are planning for the addition of PHES to the power system, particularly to promote the use of renewable energy sources. In 2010, there were at least 300 installations, with a total capacity of 127 GW worldwide. The first pumped hydro storage plant was commissioned in 1980-1985 [43]. Several studies have been conducted on utilisation of pumped storage, increasing the annual share of power supply and to better the energy supply of rural areas. PHES come with various advantages, such as generating electricity at a lower cost, as compared to gas and diesel power plants; it promotes the conservation of water. This form of storage system is not limited by river flow and seasonal variations inflow. However, they are accompanied by disadvantages, such as suffering from the economical requirement, due to the high capital cost and the fact that they require dual conversion of energy. Since South Africa is a semi-arid country, it has few sites suitable for pumped storage schemes [44].

Padrón et al [45], presented an analysis of a pumped storage system, increasing the penetration level of renewable energy in isolated power systems. In this paper, the PHES method of storage is used to store energy. Wind was used as a primary energy producer, pumping the water from the source to the two existing reservoirs, on the island of Gran Canaria.

Manolakos et al [46], proposed a standalone photovoltaic power system, for remote villages, using pumped water energy storage. The paper implements a standalone PV plant; in which they replace a battery storage system with a micro hydraulic storage system. The same concept of pumping water from the lower tank to the upper tank, is used for electricity generation, mainly during the night where PV is used to directly feed the load, during the day.

2.5.2. Small dam

Furthermore, dams are used for water storage, to generate electrical energy. This technique may at times use both potential and kinetic energy, carried by water, depending on the topographical and geological state of the environment, or site chosen for construction. Small dams may at times be classified as conventional reservoir dams, as a result of their size. They are used to store water, reducing river flow seasonality, to guarantee the supply of water and optimise the hydropower downstream. They are further used for food control and other various water uses, such as agriculture, human consumption and leisure. A few aspects are considered when designing and building a dam. Often, it depends on the topography of the land. However, it does not affect the storage volume of the design. Some topographical formations are more suitable for dams than others, e.g. steep valley topographies allow a large volume with a low land requirement and, on the other hand, shallow topographies are not appropriate, due to the small level variation. This results in lower water and energy storage capacity per land use. It is further accompanied by high flood area variation and high evaporative losses.

2.6. Types of generators used for conversation of energy stored in a water reservoir into electricity.

A hydraulic power generation plant uses water to produce electricity. However, the process starts by pumping and storing water in some form of storage (e.g. pumped hydro energy storage, battery bank, small and large dams). The last stage of this process is generation, i.e. converting the potential or kinetic energy carried by water into electrical energy. This may be done in various ways, however, in this case, two will be discussed.

2.6.1. Pump as turbine

A pump as turbine (PAT) is a pump that can be reversed and used as a turbine, i.e. it can be operated both as a pump and as a turbine respectively, with system. During pumping mode, the reversible pump requires electrical power to run and pump water from the lower up to the upper storage, for energy storage. During peak hours of the electricity usage, or when the electrical power generation is necessary, the pump may be operated in reverse (generating mode). The electrical power is generated by releasing water, stored through the reverse pump back to the lower storage tank. This type of pump comes with a series of disadvantages, such as significant vibration and operation discontinuation unannounced [47]. The vibrations are said to be caused by abnormal fluid flow inside the turbine and the mechanical aspects of the rotor [48]. However, the vibration's origin has not as of yet been fully investigated.

The performance of a PAT is poor, when compared to the reaction micro-turbine, however, they come with low investment and maintenance costs. To add, they further require lower flow rate for operation, as compared to the normal one.

Rossi and Massimiliano [49], presented analytical prediction models to evaluate the PAT's performance. Different physical magnitudes, such as flow rate, rotation speed and impeller diameters, were taken into consideration.

Francesco and Francesco [50], have performed experimental characterisation of two PAT's for hydropower generation. In this work, two centrifugal pumps were investigated. One was a horizontal single stage pump and the other, a vertical multi-stage pump. Experiments were compared with the theoretical model, available in the literature, to assess the reliability in predicting PAT.

2.6.2. Pico hydro generation

A Pico hydro turbine, is a turbine that produces a small scale hydro power, with a maximum of 5 kW. For a Pico hydro generator, environmental impacts are negligible, since a lack of large dams are involved. In developing countries, where finances are of primary concern, the micro and Pico hydropower has proven to be practical and potentially low-cost option for generating electricity in remote areas, small villages and mountainous areas. Pico hydro may, at times, be mistaken for micro, as it generates electricity at household level. On the other hand, micro generates at village level [51]. It is the smallest standalone power generator and mostly installed to supply significantly smaller loads. The same principle of pumping water from the lower to upper tank, is used for generating electrical power.

Anilkumar et al. [52], presented a residential electricity cost minimization model, through open-well Pico turbine pumped storage system, was proposed. The proposed system may be implemented in a sub-Saharan setup, where open wells are readily available. A pumped storage method is used and the stored energy is retrieved using a pumped hydro turbine (PHT), which feeds the load during peak hours.

Haidar and Mohd [53], have presented the use of Pico hydro generation, in domestic and commercial loads. The system was designed and simulated using MATLAB. The Pico Hydro Generator uses a Pelton turbine, of which high pressure of falling water from the main tank to the faculties, was used.

2.7. Site ground water assessment

South Africa, as a nation, should adjust to water deficiencies, in the close future, as examined earlier. An intrinsic absence of freshwater assets, combined with expanding populaces and changing precipitation designs, will undoubtedly procure a requirement for effective and inventive changes in water utilization. Although the horticultural division is the predominant consumer of freshwater resources, the industrial and power generation sector, likewise, have significant water utilization impressions.

The proposed system has a socio-economic benefit: It allows abandoned reservoirs to be kept in use and prevents them from being filled with highly polluted water, which should frequently be released to the surface, or be treated at a significant cost. Thus, the proposed system is an open system, where the continuous ingress of water is balanced by corresponding discharges. In this way, the abandoned farms, due to unavailability of fresh water or operating electricity, will be reduced. In fact, they are converted into assets generating energy and providing clean water. Furthermore, instead of dams occupying large parts of pristine and scenic mountain areas, this system would be entirely dependent on underground water, which may be available near the required area. The proposed site/area has great potential, in terms of its average borehole yield.

As seen from the Figure 2.1, Bloemfontein falls within the upper Orange River water management area (WMA), of the Free State, situated within the Karoo basin. The yield of the upper Orange River WMA, is the largest of all water management areas in the country, with significant potential for further water resource development. Currently, there are thirty-two boreholes within Bloemfontein, with yield test results ranging between 0.3-1.7 L/s sustainable yields. The tests were performed by the department of water affairs, in the Free State. The sustainable yields determined, are closely what will be expected of the Karoo formations in South Africa, i.e. between 0.5 and 1.5 L/s [54].

Figure 2.1. South Africa's water basins [55]

2.8. Relevant works on solar and its tracking device

Standalone solar systems are very affordable & uncomplicated to operate. However, they are considered unreliable, due to the inconvenience of their random energy generation nature. These systems are strongly dependant on the climatic conditions. As a result, the generated power may necessarily require a backup device, or external energy storage, to supply the load to its peak demand or save excess energy produced by more favourable days [56] [57]. However, renewable energy generation technologies associated with solar are gaining attention, due to the uncomplicated set-up and decreasing sales prices, followed by its advantages, such as energy from the sun. The fact that it does not require too much attention during operation and, lastly, for its significantly low maintenance cost [58-61]. Nevertheless, it further consists of disadvantages, such as high initial costs and the fact that the energy production depends on a variable resource (the sun), which fluctuates within the fourteen hours of sunshine in a day. Therefore, as a result, it does not match the load power during unfavourable conditions and seasons with less radiation [62]. Currently, there is no device or technology available to increase the output of a solar array, apart from a solar tracker. Most of the solar applied systems lack a solar tracker system, mainly as a result of its high cost. Even though it comes with these disadvantages, it is accompanied by advantages, such as increasing the output power given by the PV.

2.8.1. Solar tracker VS Static panel

A solar tracker is a system that guides the solar panels to a convenient angle, relative to the sun. These systems are designed to trace the sun's direction at a specific time of the day. They maintain the panel at 90 degrees to the sun, for more sun rays to strike the panel and to reduce light reflection. Therefore, it improves energy absorption for conversion into electrical power. This works as an advantage over a static solar panel. However, they are accompanied by several disadvantages that may be of significance, i.e. they may have shorter warranties, require regular maintenance and reduction of reliability. Further they require actuators, to control the movement of the panel. These extra costs may add more to the expenses of the project. On the other hand, static solar panels have a longer warranty and require low, or no maintenance. Solar tracking systems are categorized, based on the degree of movement and the freedom of direction.

2.8.2. Single axis

A single axis solar tracker uses a one direction technique, tracking the sun by means of one pivot port for rotation. The author in Reference [63], has developed a tracking system with higher efficiency, as compared to the static panel, based on the output power. This work discusses the benefits of a single axis tracker, using a steeper motor and light sensor. This method benefits the collection efficiency, by means of following the direction of the sun rays and maintaining them at right angle with reference to the panel. The single axis system has three main divisions: tilted, horizontal and vertical single axis. Furthermore, at least 30% of the output power may be gained by the system, with reference to a horizontal array. The system's main disadvantage is that it cannot track annual movement of the sun, solely a daily movement [64]. When the weather conditions are unfavourable, its tracking efficiency decreases, due to the single axis rotation.

2.8.3. Dual axis

Dual tracking systems have two degrees of sun tracking freedom. Where the axis that is usually attached to the ground is called primary axis and the one referenced to the primary axis is called the secondary axis. This system may improve the output power of a panel by 40%, according to several studies [65-67]. S. Abdallah and S. Nijmeh, [68] shows an increase of 40% in the output energy, by adjusting the panel's position four times in a day, by an hourly rate. In reference [69], a dual tracking system was designed and constructed. The system influences the output power, by means of monitoring intensity and wave length of the sunlight. The results of this work conclude that the efficiency drastically increases, as compared to the fixed panel.

2.8.4. Tracker driving mechanism

2.8.4.1. Active tracker

An active tracker may be driven in many ways, including sensors, microcontrollers and auxiliary bifacial solar cells. The author, in Reference [70], presented a dual solar tracker, using a microcontroller. In this work, a PIC16F72 microcontroller is used to activate the motors to achieve dual way rotation. The results in this work concluded that the micro controlled solar tracker was 37% more efficient than the static solar panel. In Reference [71], an explanation of the design, construction and effect of a hybrid automatic solar tracking system, using two different materials of solar cells, is outlined. In this work, emophorous and crystalline solar panels are analysed in a solar tracking system at static, single axis, dual axis and hybrid axis solar tracker. The results of this work show that, the dual axis system is 17.8% above single axis and at least 52% above the static tracking system, based on the output power.

2.8.4.2. Passive tracker

Passive tracker uses a boiling point of compressed fluid; it is driven from one side to the other by the solar heat. This is a non-procession orientation and may be unsuitable for a few types of CSP. However, it works sufficiently with other common PV panels. In Reference [72], a direct shape memory alloy for sun tracking purposes is designed and developed. The results promise the development of a sun tracking method, using SMA that uses the sun with no requirement for any additional power source.

2.9. Conclusion

A review of relevant pumped hydro energy systems (PHES), as applied to arid and semi-arid areas of South Africa. Technologies involved in the generation parts of PHES, as well as the available storage types that are associated with the technology, were discussed in this Chapter. With South Africa being considered to process potential for both small and large-scale hydropower, it is concluded that authors and researchers have carried out work on pumped hydro energy systems. However, there is no evidence or studies manifesting on the technical and economic benefits of the system. Since South Africa is being found in a water crisis recently, it is assumed to have been contributing to the non-implementation of such systems is our country, more specifically within the farming sector.

CHAPTER 3: SYSTEM SIZING USING HOMER

3.1. INTRODUCTION

In South Africa, adequate and reliable electricity supply is an absolute necessity in the farming sector. The sector is a significant energy consumer, with irrigation being the single largest electricity-demanding farming activity [73]. This production is suffering, due to the lack of access to grid electricity. However, to improve the production, an electrical supply method should be affordable and reliable. Hence, a sustainable electrification solution for remote farmers is achieved, through renewable energy systems. In this study, a farm situated in an area with adequate sun radiation and ground water, has been selected. Economic analysis is of the requirements when selecting an off-grid energy source from the existing and available sources. Therefore, the primary aim of this Chapter is revealing the economic benefits that come with the selected off-grid energy source. The techno-analysis was performed using HOMER software.

3.2. Economic Methods

To achieve a successful comparative cost analysis, financial measures, such as a net present value (NPV), internal rate of return (IRR) [74] and payback periods, are usually used. With HOMER software, net present cost (NPC) [75], is used to analyse the life cycle cost of the system, predicting the cost effectiveness. Both technical and financial information of the system components of the system are required, to calculate the cost of installation and operation of the system over its lifespan. Therefore, the optimization results are listed starting with the least net present cost (NPC)

3.2.1. Net present value VS Net present cost

The net present value, is the current value of the cash flow at the required payback rate of the project, as compared to the initial investment. It uses streams of cash flow, to predict the value of money. Producing the optimal project choice, one should select a project with the highest positive NPV, meaning that the project may be running at a loss. HOMER represents a negative NPV, by means of a positive NPC (US$). However, the

NPC does not solely involve the investment, but is also inclusive of costs, such as installation costs, operation and maintenance costs, over its expected lifespan. HOMER calculates the NPV and NPC, by making use of Eq. (3.1) below [76]:

$$NPV = \frac{CF_1}{(1+r)} + \frac{CF_2}{(1+r)^2} + \ldots. \frac{CF_N}{(1+r)^N} - C_0 = \sum_{t=1}^{N} \frac{CF_t}{(1+i)^t} - C_0 \qquad (3.1)$$

Where:

C_0 = initial investment cost (US$);

CF_t = net cash flow of the investment in year (US$);

i = discount rate;

N = lifespan of the system (years).

If an NPV is negative, it generally suggests that an investment will result in a loss, instead of a net profit. HOMER shows a negative NPV by utilising a positive NPC (US$). NPC is essential, as it includes not only investment, but further costs, such as total cost of installing, operating and maintaining the system, over its lifespan. The project offering the lowest NPC, is the optimal cost-effective option. HOMER calculates the NPC, by making use of Eq. (3.2) below [77]:

$$NPC = \frac{C_T}{CRF} \qquad (3.2)$$

where:

C_T = total annualised costs of the system (US$);

CRF = capital recovery factor.

CRF is the ratio of the constant annual payments, to the present value of receiving this constant annuity, over a specified time. By using a specified interest rate, CRF may be determined as follows [78]:

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \qquad (3.3)$$

3.3. Site Load Forecast

The agricultural sector contributes at least 6.5% to the annual South African electricity sales, with pumping irrigation water being the largest electricity demand allocation [5]. Electrical power is required in controlling the environment and sustaining the conditions of livestock, poultry, plants and for allowing appropriate harvesting, storing and food conservation; maximizing financial gain and security of the farm capital investments. To ensure satisfactory operation and quality production, electricity is predominantly used for lighting, refrigeration, irrigation, bulk milk processor and motor-pump applications. Nevertheless, a water pump is further included in the load forecast, since irrigation is a process that takes place daily within a typical farm. Additional appliances, such as water heating tanks, bulk milk coolers, milking machines, fans, freezers and electric heaters compile the load demand. A typical farm operates at least twelve hours in a day, i.e. between 06h00 and 18h00. Figure 3.1 shows the average electricity consumption of different sections of a typical dairy farm.

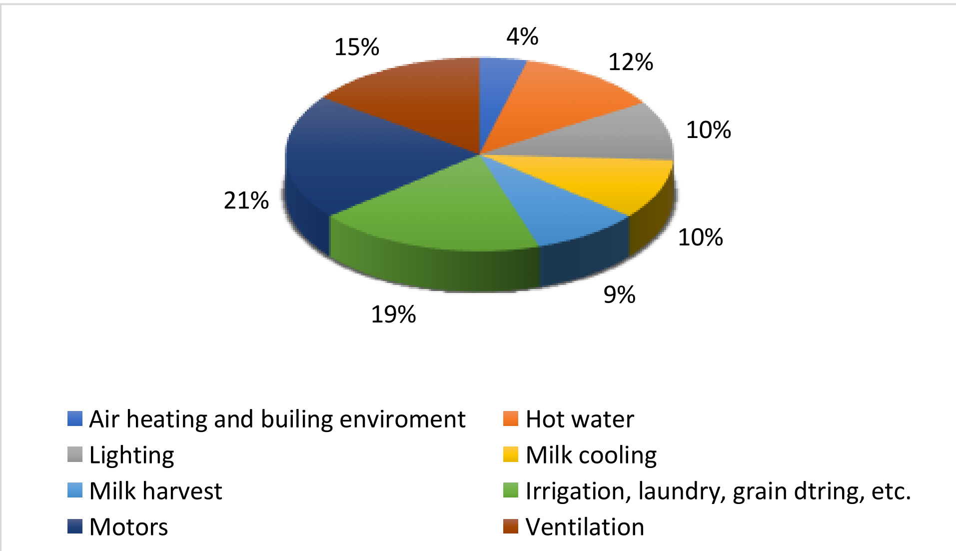

Figure 3.1. Sectional electricity consumption of a typical dairy farm

Throughout the day, the load demand is significantly high. This is where a majority of the daily operations take place. From 10h00 to 18h00, the fan/air conditioner may be on due to the high ambient temperature. After 18h00 up until 5h00 the majority of workers are off-duty, the load decreases, since there are minimal machinery operations apart from irrigation, electric fencing, lighting, refrigeration and water storage recharge. Starting from 05h00 up until 07h00 the pumping motor is usually switched on since the storage tank was in use during period of irrigation overnight.

In this study, the estimated load profile is based on the supply of a typical farm-load. With renewable energy systems, energy efficiency plays a crucial role in minimizing the investment costs. The estimated load profile, as shown in Figure 3.2, is based on the appliances mentioned above. In this work, a representative commercial daily load profile is obtained, by adding the respective demand profiles of the various equipment available, on a typical small sized farm. It is assumed that the load demand is constant throughout the year, since the proposed system was not designed to specifically supply the available appliances on site. Excluding an electric heater, all of the appliances mentioned above are usable in all the seasons of the year. Hence, the simulations are carried throughout the year, i.e. from January through to December.

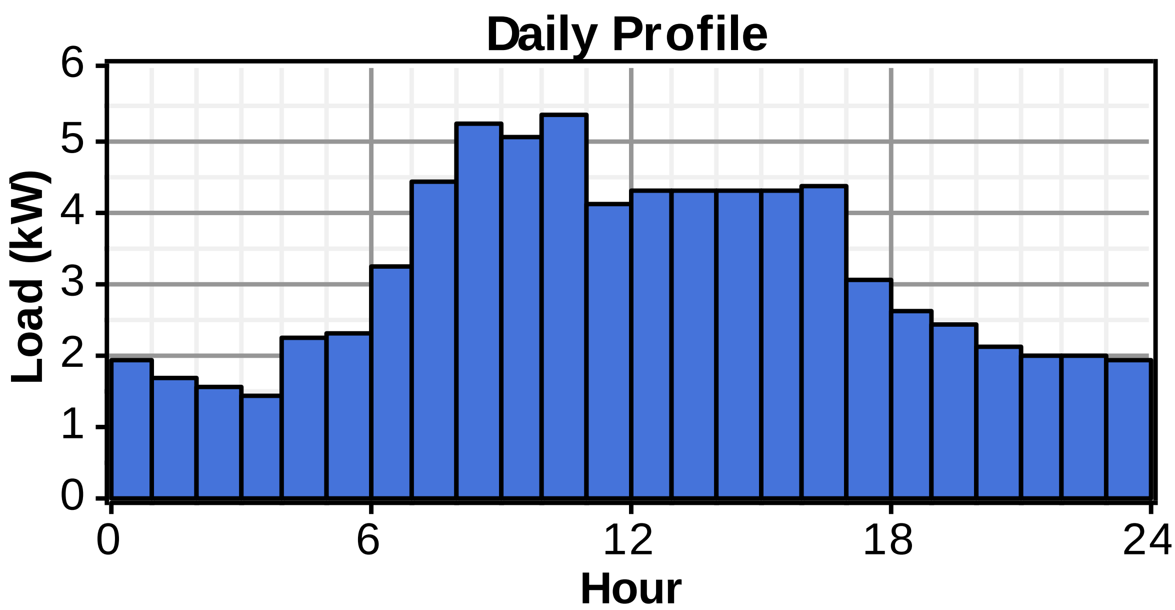

Figure 3.2. Load profile for a typical dairy farm

Practically, it is impossible for the load to follow the same pattern daily, since each day comes with its own operation. Hence, HOMER uses random variability, to estimate the realistic load demand from the given load profile. This caters for fluctuations, which may occur each day within the load profile. In this study, the daily variation of 10% and hourly variation of 10% were used for accurate simulation. To satisfy these variations, HOMER generated a new annual load.

The profile shown in Figure 3.3 below, consists of the peak load demand of 7.7 kW, with a scaled annual average energy of 76 kWh/day.

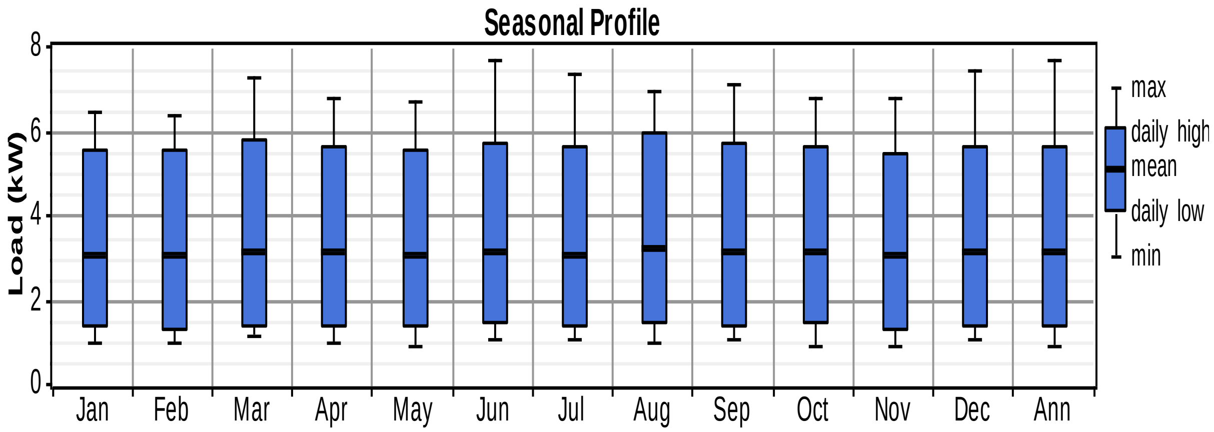

Figure 3.3. Seasonal electrical load profile (with 10% daily and hourly variation factors)

3.4. Solar and Water Resources Assessment

South Africa is greatly equipped with solar resources. The annual 24-hour global solar radiation average is around 220w/m² compared to 150 w/m² in a few sections in the United States of America (USA) and to about 100 w/m² for Europe and the United Kingdom (UK) alike [78]. The majority of areas in South Africa average more than 2500 hours of sunshine per year and average solar-radiation levels range between 4.5 and 6.5 kWh/m² in one day alone.

The potential energy of solar and groundwater resources was assessed at the study site. The solar resource used, was obtained from the NASA surface meteorology and solar energy website. Annual summary of the solar radiation is as shown in Table 3.2 below [79]. The average solar radiation level of the selected site is 5.66 kWh/m2 /day. Figure 2 shows the solar resource profile over an annual period. The maximum radiation levels take place during the months of November, December and January. The solar radiation is available throughout the year. Hence, this reveals that a large amount of photovoltaic (PV) power may be obtained in this study area. The sustainable borehole yields of the selected site, ranges between 0.3 and 1.7 L/s, which is close to the expected (0.5-1,5 L/s) of Karoo formations in South Africa [54]. This reveals that borehole water in this area, may be sufficient for power generation, with great sustainability.

Table 3.1

Solar resource data

Month	Clearness index	Daily radiation average in kWh/m²/d
January	0.740	7.450
February	0.635	6.590
March	0.541	5.680
April	0.466	4.750
May	0.423	4.080
June	0.389	3.620
July	0.417	3.930
August	0.485	4.810
September	0.557	5.750
October	0.626	6.490
November	0.709	7.160
December	0.774	7.670
Average	0.566	5.661

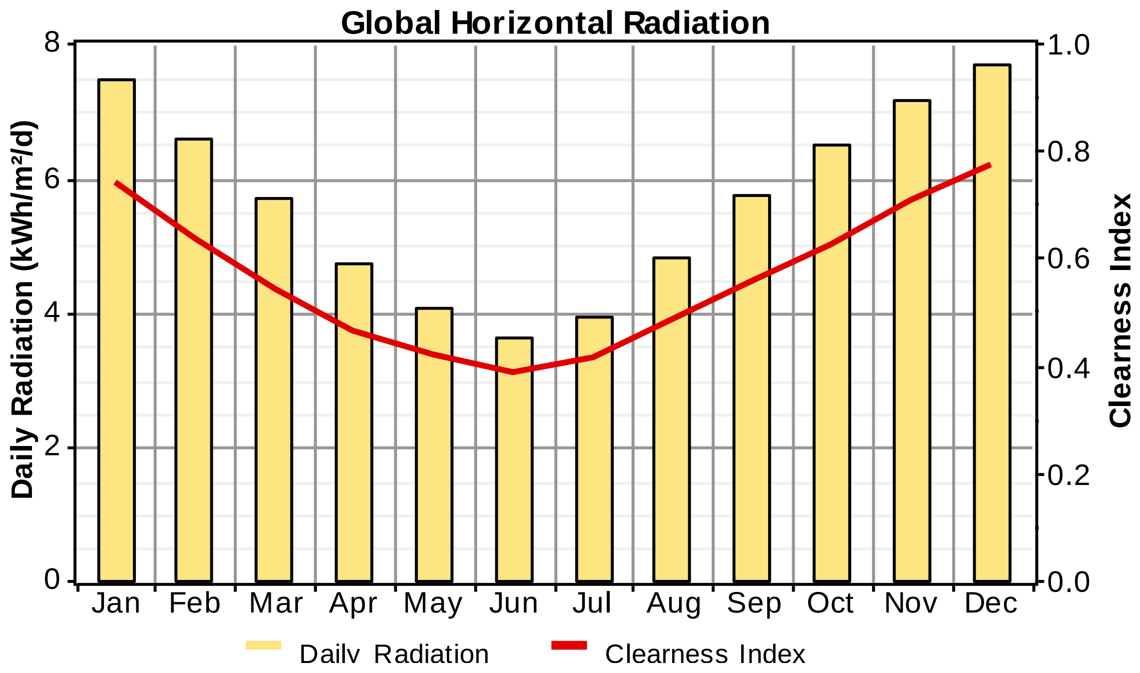

Figure 3.4. Global horizontal radiation profile

3.5. System Sizing and Costs

The selection of the system components is based on meeting a peak demand of 7.71 kW. System components costs consist of capital, replacement and operation and maintenance (O&M) costs. The purchasing costs of various technologies may decrease over time at different rates. For a simplified comparison of this study, a worst-case scenario was considered by assuming that the replacement costs are equal to the capital costs, after the lifespan of each component. The lifespan of the project is assumed to be 30 years.

The O&M costs are assumed to be evenly distributed over the entire project lifespan. Further costs such as labour, installation and structures are not included in the simulations. All of the selected system components are based on the peak demand of 7.7kW. The system designed may be suitable to use for both grid-connected and standalone systems. For a standalone system, electrical energy should be stored for later use, when the load demand is lower than the generated capacity. In this case, a pumped hydro storage system is designed, using a battery storage method, since HOMER is not equipped with the pumped hydro storage module in its library [80].

3.5.1. Pumped Hydro Storage

This storage system stores energy in the form of gravitational potential energy, it uses at least two reservoirs at different heights. Since HOMER lacks pumped hydro storage as an option in its component's library, a battery is used instead, since a storage tank/ reservoir operates similarly, in terms of charging and discharging.

To represent the upper reservoir, a Trojan T-105 battery was selected and modified, to represent the minimum reference volume of the water storage tank. The voltage and the nominal capacity of the Trojan T-105 battery were set to 230 V and 4.35 Ah respectively, allowing each battery to store up to a maximum of 1 kWh.

For a hydro-storage power, discharging at a volumetric discharge rate of *Q*, is similar to the electrical-storage power that discharges at a rate of certain current *I*. This relationship is as shown by Eq. (3.4) and (3.5), respectively [81].

$$P = V.I \tag{3.4}$$

$$P = g \times \eta_{TG} \times Q_{TG} \times h \tag{3.5}$$

Where:

V is the voltage supplied by the storage system (V)

I is the current consumed from the storage system (A)

g is the gravitational acceleration (9.81 m/s^2);

η_{TG} is the efficiency of the turbine-generator unit;

Q_{TG} is turbine flow rate (m^3/s);

h is the useful falling water head (m).

Hence, by associating Eq. (3.4) and Eq. (3.5), it is found that for the same power storage, a maximum discharge current of 8.69 A is equivalent to the 0.0194 m^3/sec volumetric discharge rate, at a head height and round-trip efficiency of 15m and 70%, respectively.

The costs of the pumped hydro storage (PHS) have been entered into the battery model, with a lifespan taken to be thirty years. The PHS system's installation cost/kWh varies between $213 and $313 [6]. Using South African currency, this ranges between ZAR2899 and ZAR4260, since 1US$ was equivalent to ZAR13.6, during the study. Hence, in this study, the installation cost of ZAR3500/kWh was used during simulations. The O&M costs were assumed to be 6% of the initial capital cost (ZAR210).

The capacity of the designed storage using a Trojan T-105 battery (C_{BAT}), was calculated as follows [82]:

$$C_{BAT(Ah)} = \frac{E_L \times d}{V_s \times \eta_{BAT} \times \eta_{CONV} \times DOD} \tag{3.6}$$

Where:

E_L = required daily load (Wh);

d = number of autonomous days;

V_s = system voltage on the DC side (V);

η_{BAT} = battery efficiency;

η_{CONV} = converter efficiency;

DOD = depth of discharge (%).

Table 3.2

Technical parameter of Trojan T-105 battery

Parameter	**Value**
Nominal voltage	230V
Nominal capacity	4.35 Ah
Maximum discharge current	8.69 A
Round trip efficiency	70%
Maximum state of charge	30 %
Life time throughput	845 h

3.5.1.1. Pumping system

Before the energy is stored, water should be pumped from the lower reservoir, to the upper reservoir. Therefore, the power used to pump water from the lower reservoir to the upper reservoir is, given by Eq. (3.7) [83]:

$$p_{MP} = \frac{\rho_W \times g \times h \times Q_{MP}}{\eta_{MP} \times t} \tag{3.7}$$

Where:

ρ_W is the water density (1000 kg/m^3);

Q_{MP} is the pumping flow rate (m^3/s)

η_{MP} is the efficiency of the pumping system

t is the time (s).

3.5.1.2. Upper reservoir

For a pumped hydro storage system, the energy stored depends on the volume of the pumped water and the difference in height of the water storage tanks. Hence, the potential energy (kWh) stored in the reservoir is given by Eq. (3.8) [83]:

$$E_R = \rho \times V \times g \times h \tag{3.8}$$

Where:

V is the volumetric size of the reservoir (m^3)

3.5.1.3. Hydropower generator

The electrical power generated from the hydropower system, P_{TG} is determined using Eq. (3.9) [83]:

$$P_{TG} = \rho_W \times g \times h \times Q \times \eta_{TG} \tag{3.9}$$

3.5.2. PV system

A PV panel is characterized by a series of cells connected. The efficiency of the solar panel is based on its ability to convert the absorbed light/heat energy into electrical energy. Therefore, the panel's efficiency, together with its output current, is directly proportional to the sun's radiation level.

The photovoltaic comes with a twenty years' performance warranty, however, their output decreases as time goes by. The capital of the 250-kW polycrystalline PV panel is US$0.1483/unit. There are four units of PV panels used in the design, to build 1-kW PV panel. For this analysis, an annual O&M cost of 1% of the capital cost. The replacement cost of PV is assumed to be 100% after 20 years. The output energy (E_{PV}) of a solar PV system is expressed as follows [84]:

$$E_{PV} = A_{PV} \times \eta_{PV} \times \eta_{PC} \times Pf \times I_h \tag{3.10}$$

Where:

A_{PV} = total area of the PV panel (m^2);

η_{PV} = PV module efficiency;

η_{PC} = power conditioning efficiency;

p_f = packing factor;

I_h = hourly irradiance (kWh/m^2).

3.5.3. Converter

A converter has been selected to vary DC to AC. The chosen converter consists of a standalone true sine wave inverter, suitable for supplying sensitive electronic appliances. It is the 8kW, 50Hz, 230Vac, with efficiency of 98%. The South African market price of purchasing this converter is US$4.041 [85]. Its O&M cost is assumed to be 1% of its capital cost per year with a lifespan of twenty years [86]. Since the peak-load demand of this study is 7.7kW, this converter may supply up to a maximum of 7.84 kW power demand, when considering its efficiency.

3.6. HOMER Results and Discussion

After the simulation was completed, HOMER selected the most economical configuration for the proposed stand-alone system, to adequately serve the load demand. Due to the fluctuating behaviour of the economy, the prices of various renewable energy technologies may fluctuate over a period, at different rates. For simplicity, it is assumed that the replacement cost is equal to the capital costs, after the lifespan of each component. An assumption is also made for the O&M costs, i.e. they will be evenly distributed over the entire lifetime of the project. In addition, other costs such as installations, cabling, licencing and financial charges by the local government, are excluded during simulations. Therefore, the proposed system was simulated to offer 0% annual capacity shortage, at 6% annual interest rate for a thirty years' period. Meaning, the load demand should be adequately met throughout the year.

Figure 3.5, shows the schematic diagram of the standalone PV pumped hydro storage system, as used in HOMER. From Figure 3.5, it is evident that the primary load-demand to be met is 76kWh/d, followed by a peak load of 7.7 kW.

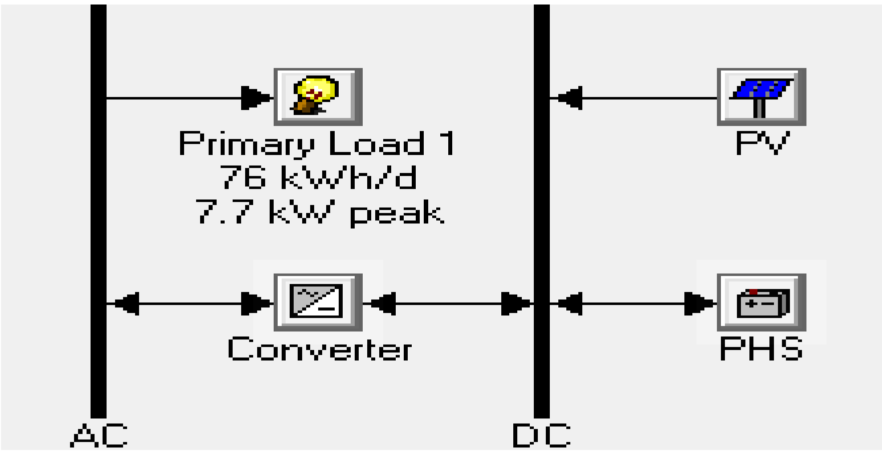

Figure 3.5. Schematic diagram of the stand-alone PV-pumped hydro system

Figure 3.6 shows the first five optimal configuration results. The highlighted row represents the most feasible and optimal configuration. It consists of 127 PV panels, 45 Trojan T-105 batteries and an 8-kW converter, meeting the load demand at the lowest cost. The simulated 45 batteries represent an upper reservoir, consisting of 45 kWh storage capacities, since each battery was set to represent a 1 kWh capacity.

Based on the optimal configuration results, the cost of the energy is found to be ZAR2.32/kWh, at 100% renewable energy fraction, at no capacity shortage for thirty years. This is equivalent to ZAR2.32/kWh. Assuming ZAR is equal to USD$, this is due to the nature of HOMER simulating in USD's however all capital values are entered in values of south African Rands.

PV (kW)	PHS	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Batt. Lf. (yr)
127	45	8	$ 593,500	21,430	$ 891,995	2.322	1.00	30.0
124	47	8	$ 591,500	21,614	$ 892,558	2.324	1.00	30.0
121	49	8	$ 589,500	21,798	$ 893,121	2.325	1.00	30.0
129	44	8	$ 596,000	21,378	$ 893,780	2.327	1.00	30.0
126	46	8	$ 594,000	21,562	$ 894,343	2.328	1.00	30.0

Figure 3.6. Overall optimization results

The system's operational characteristics, such as the PV and inverter output power performances, PV electricity production profile, overall unmet and excess electric power, as well as the inverter upper reservoir state of charge, are shown in Fig. 3.7-3.12.

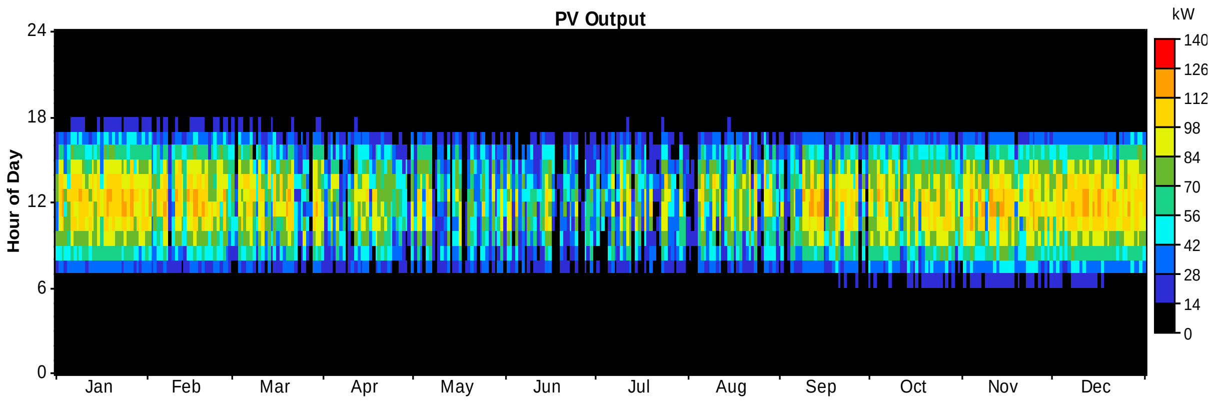

Figure 3.7. Output power generated by a PV system

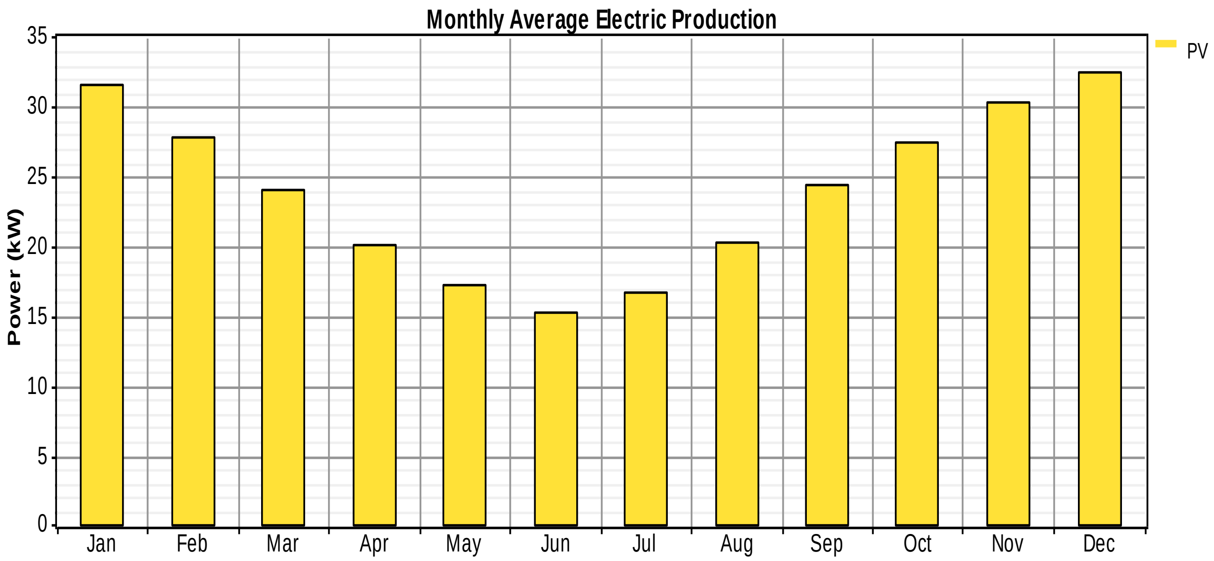

Figure 3.8. Monthly average electricity production

The yearly output power generated by the PV panels is shown in Fig. 3.7, the majority of the generated solar power takes place during day time due to the availability of sunlight. Throughout this time, the solar PV system may adequately meet the load-demand, without allowing the PHS to discharge. Close to a maximum of 126 kW is generated, at approximately 12h00, in majority of the days. As shown in figure 3.8, the monthly average generation level is significantly low during the May, June and July months of the year, due to the low solar radiation level. This shows that HOMER was led to oversizing a few of the components of the system preventing the unmet load-demand (shown by the small red line in Figure 3.9), particularly throughout the low solar radiation months (May, June, July). This led to the high level of excess power during the high radiation months, as shown in Fig. 3.9. The reason for oversizing is that the radiation level is low, whilst the load demand reaches exceptionally high levels, during the low radiation months.

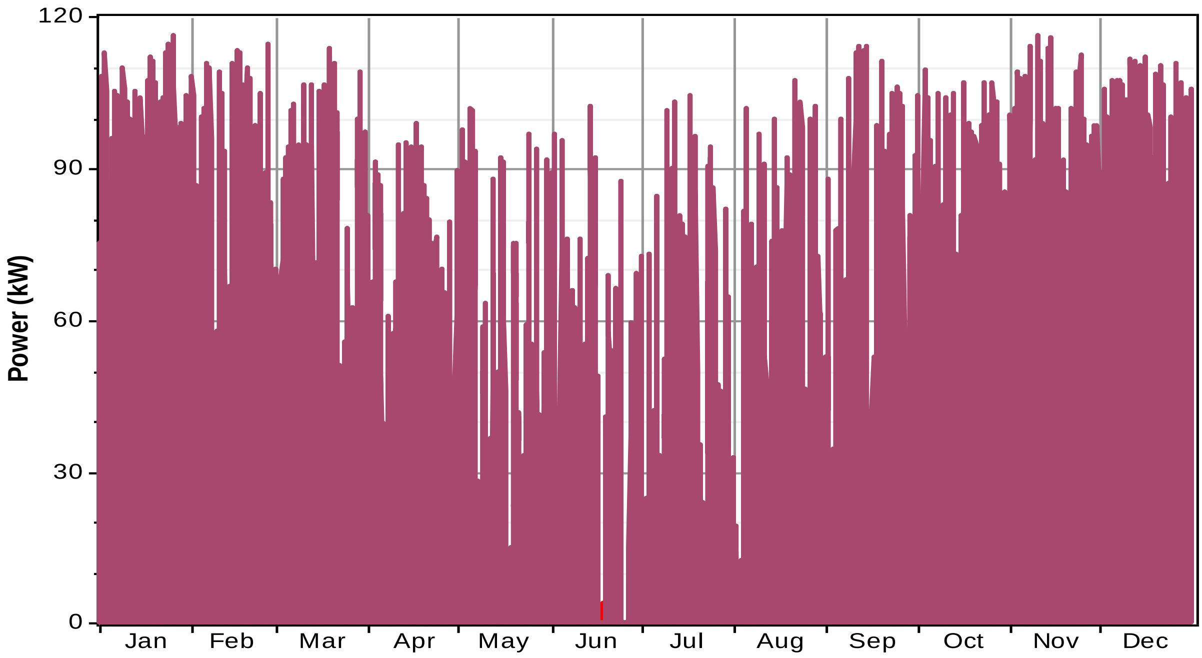

Figure 3.9. Excess electric power production

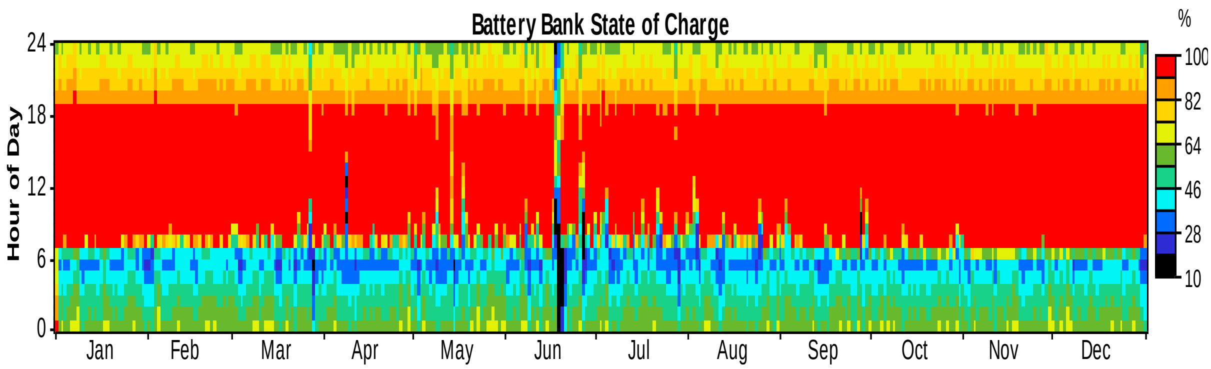

Figure 3.10. Upper storage state of charge

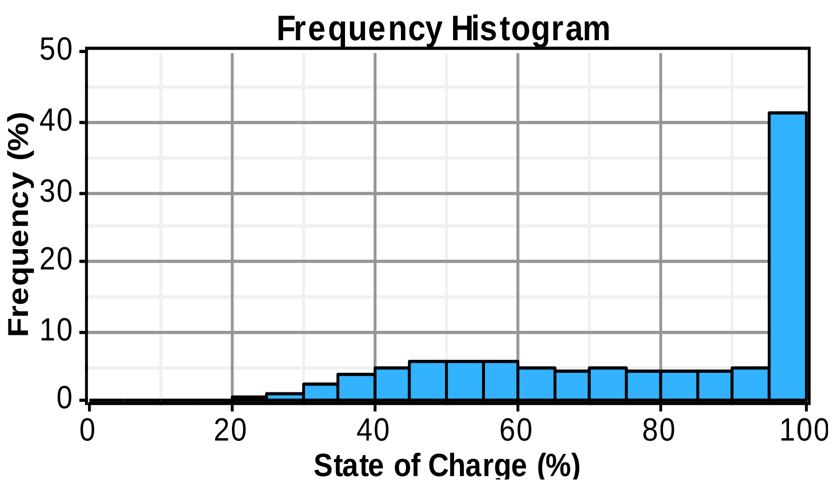

Figure 3.11. State of charge frequency histogram

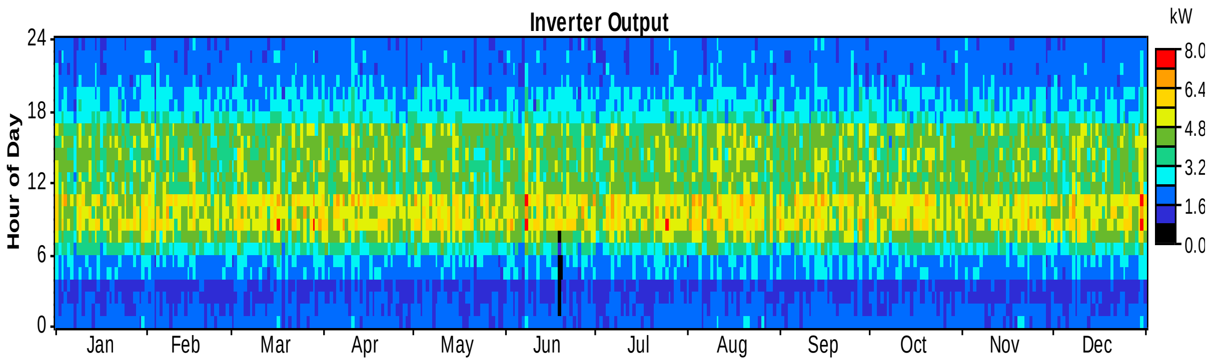

Figure 3.12. Invertor output power

The hydro-generator system is not frequently utilized during the day, depending on whether the PV managed to generate sufficient power, to adequately meet the load. Therefore, the upper reservoir discharges after 18h00, until 6h00 in the morning, to meet the load demand, due to the lack of sunlight for power generation by the PV. Hence, its state of charge level mainly remains at 100% during the day, as shown in Figure. 3.10. From Figure 3.11 above, it is considered that the upper reservoir could reach a minimum of 20% and, thereafter, it gradually begins to recharge once again. It is fully charged for at least 42% of the time.

Figure 3.12 represents the inverter output power of the system. The converter follows the load demand in the morning, from 6h00, when the farm starts operating, until 17h00, when the inverter converts the DC power generated by both PV and Pumped hydro system feeding the AC load demand. it converts maximum output in the mid-month of march, June, July and the last few days of December.

3.7. Conclusion

This Chapter performed a feasibility analysis of an off-grid PV-UPHS hybrid system, meeting the farming load demand, using HOMER software. During the simulations, the optimal configuration was selected to incur at least NPC, at a minimal cost of energy (COE). HOMER permitted the load demand to be reliably met throughout the year, at zero capacity shortage. Nevertheless, HOMER led to excessive energy generation, to supplement the low radiation season months, meeting the high demand with no shortages. The simultaneous occurrence of low solar radiation and high-power demand, led to a significantly large amount of wasted/excess energy, during high radiation months.

To attempt to overcome the oversizing problem, this study has led to the future work of designing an optimal energy management model. It is recommended that the model should be developed, allowing the proposed system to meet the load demand, at no capacity shortage and, further, at a reduced system size. Both the PV and the storage system sizes should be reduced, so that the excess energy is well-preserved and utilized. This should lead to a less NPC, due to reduced COE and O&M costs. Hence, less payback periods should be achieved.

CHAPTER 4: OPTIMIZATION MODEL FORMULATION AND PROPOSED ALGORITHM

4.1. INTRODUCTION

The main objective of this Chapter is to develop a mathematical model for optimally managing and controlling the daily operation of the proposed grid-connected renewable energy-based system. This is achieved by maximising the use of the renewable resources, whilst minimising the utilisation of the grid, to supply the required energy to the load demand, without a shortage or load rejection. In this Chapter, the mathematical expression of the system's optimal operation control problem, will be derived. Furthermore, the various constraints of the system's components and operating limits are also expressed.

In this Chapter, a solar tracking device is considered, due to the nature of weather conditions at the selected site. The proposed system considered in this work, consists of a solar PV system, hydro turbine system and water storage tank. The load demand is met by the three power sources, namely, a PV system, PHS system and the local grid (when necessary). The proposed system is non-interactive grid connected, i.e. to enable the energy use during off peak periods and during renewable power deficit. However, the consumer is not legalised to sell the excess electricity back to the grid. The developed models are applied into the MATLAB software, to perceive the energy cost savings and operation. The results are discussed in Section 4.5. The *linprog* solver, is used to solve the optimization problem, since the problem consists of linear constraints.

4.2. Schematic layout of the system

The schematic diagram, presenting the power flow of the proposed system, is shown in Figure. 4.1. The arrows illustrate the direction of the power flow in the system. In this system, the PV power will be used to supply the pump and the load, respectively. The Grid may further be used for supplying the water pump and a portion of the load, when the electricity price is more affordable. Therefore, the water should be pumped during the off-peak period and may be discharged during peak period. Lastly, the power from the turbine generator will constantly be used to supply the load. Furthermore, the load demand should constantly be met from all three sources, without a shortage. P_1 is the solar PV generated power supplying the load; P_2 is the PV generated power to the motor pump unit; P_3 is the minimum amount allowed to supply the motor pump unit; P_4 is also the minimum amount of power permitted from the grid, supplying the load and lastly, P_5 is the power generated by the turbine generator to the load.

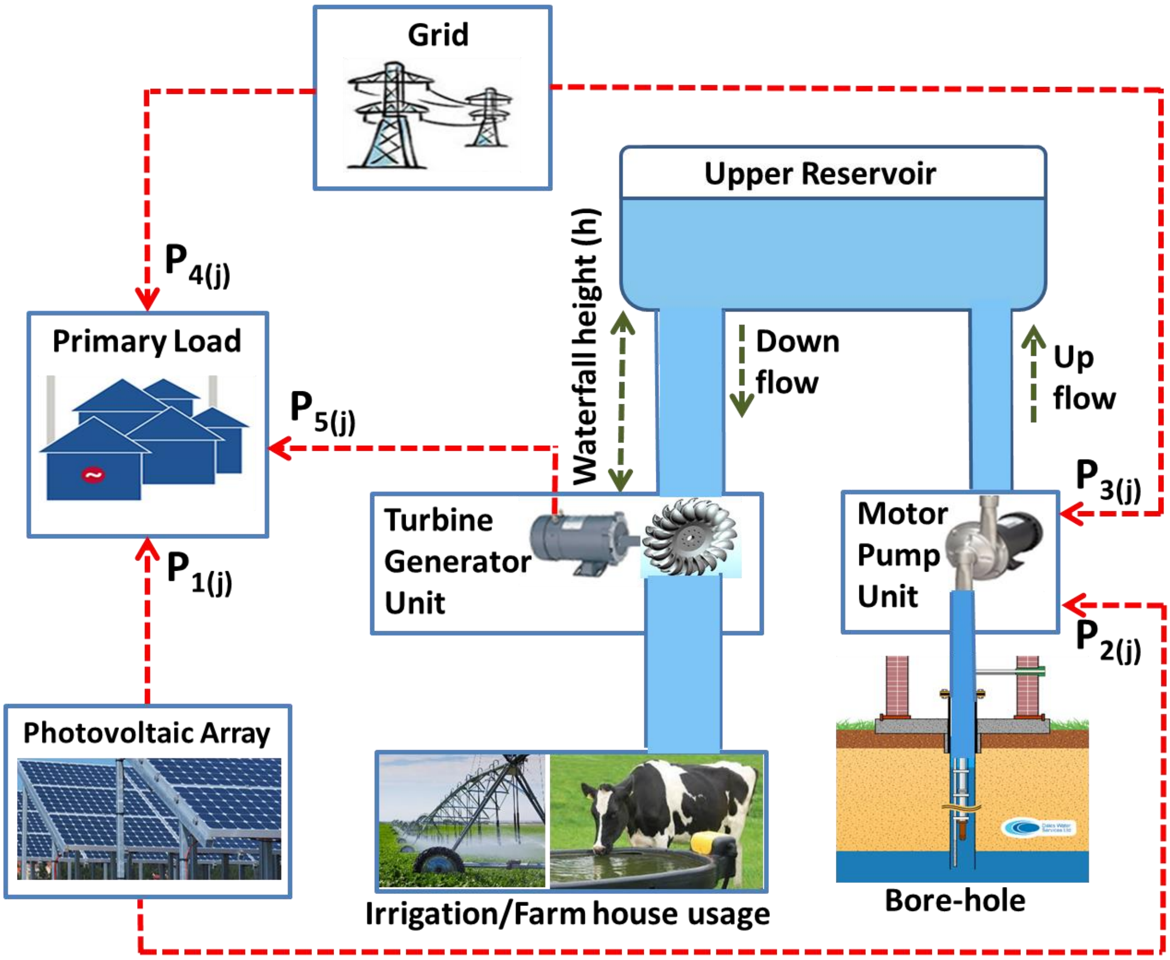

Figure 4.1. Schematic diagram of the proposed system

4.2.1. Pumping system

The power required to extract water from the source to the upper reservoir (P_{MP}) in kW, is expressed as follows:

$$P_{MP} = \frac{\rho_W \times g \times h \times Q_{MP}}{\eta_{MP} \times t} \quad (4.1)$$

Where:

Q_{MP} is the rate of the flowing water through the pump (m^3/s);

h is the head at which the water is pumped (m);

g is the gravitational acceleration (9.8 m/s^2);

η_{MP} is the overall pumping efficiency (%).

4.2.2. Hydro turbine

The electrical power generated from the hydro turbine system P_{TG}, is formulated as:

$$P_{TG} = \frac{\rho \times g \times h \times Q_{TG}}{\eta_{TG}} \quad (4.2)$$

Where:

η_{TG} is the efficiency of the hydro generating system;

Q_{TG} is the rate of the flowing water for generation purposes (m^3/s).

4.2.3. Hydro storage

The turbine produces the electrical power output P_{TG}, with efficiency η_{TG}. Therefore, the rated output would be achieved with a water power input $P_{In\text{-}TG}$ of:

$$P_{In-TG} = \frac{P_{TG}}{\eta_{TG}} \quad (4.3)$$

Water is pumped from a water reservoir at the height h above ground level, to the turbine located at ground level. Taking the density of water ϱ and the acceleration due to gravity g, the water volume V required by the turbine of power P (watts) is as follows:

$$V = \frac{P_{In-TG}}{h \times \rho \times g} \quad (4.4)$$

The available volume of water stored in the tank (*V*), is directly linked to the potential energy (E_R), available. This may be formulated as [87]:

$$E_R = \rho \times v \times g \times h \qquad (4.5)$$

Where:

E_R is the potential energy of water stored (kWh);

v is the capacity of the reservoir m^3.

With the water resource available on site, the size of a motor-pump, turbine-generator and the capacity of the PHS system, may depend on the funding availability and the energy saving target.

4.3. Model development

4.3.1. Objective Function

The objective is to produce an optimum algorithm design problem, to lower the operation costs, by minimizing the power purchased from the grid and maximising the use of renewable energy sources, using the TOU tariff. Therefore, the total cost will be formulated, as shown in Eq. (4.6) below:

$$F = \sum_{j=1}^{N} C_j \cdot (P_{3(j)} + P_{4(j)}) \cdot \Delta t \qquad (1 \le j \le N) \qquad (4.6)$$

Where:

j is the considered sampling interval;

N is the considered number of sampling intervals;

Δt is the sampling time;

C_j is the TOU electricity tariff.

4.3.2. Constraints

In the optimization problem, there is an existence of both equality and inequality constraints. The equality constraints will be used to enforce the power balance between the load demand (primary and pumping load) and supply. The inequality constraint is applied for the generation and storage limits. Hence, the objective function will be solved under the following equality and inequality constraints:

4.3.2.1. Equality constraints

a. Equality constraint for power balancing

The load power balance constraint is critical to ensure that the primary load demand is constantly satisfied. Hence, the sum of the power supplied by the grid, PV system and PHS turbine-generator unit should be equal to the load power consumption. This is mathematically expressed as follows:

$$P_{Load(j)} = P_{1(j)} + P_{4(j)} + P_{5(j)} \qquad (1 \leq j \leq N) \tag{4.7}$$

Where:

$P_1(j)$ is the power from the PV to the primary load at jth sampling interval (kW)

$P_4(j)$ is the power from the grid to the primary load at jth sampling interval (kW).

$P_5(j)$ is the power flow from the turbine generating system to the primary load at jth sampling interval (kW).

b. Equality constraint for fixed-final state condition

For appropriate planning and operation purposes, taking into consideration repetitive application of the developed algorithm to the grid-interactive PHS's operation, the final state of potential energy of water stored in the reservoir should be equal to the initial state of the of the potential energy carried by water at the beginning, for the considered simulation period. This may be modelled as follows:

$$\sum_{j=1}^{N}(P_{2(j)}+P_{3(j)})-\sum_{j=1}^{N}P_{5(j)}=0 \qquad (1\le j\le N) \qquad (4.8)$$

Where:

P2(j) is the power flow from the PV to the pump at jth sampling interval (kW)

P3(j) is the power flow from the Grid to the pump at jth sampling interval (kW)

c. *Control variable limits constraints*

The power from the PV system, the power generated by turbine generator, as well as the grid, are modelled as adaptable power sources, manageable in the range of zero to their maximum rated power, for the 24 hours of a day. Therefore, the variable limits should be the output limits of all the different power sources. These constraints may be determined by the characteristics of each power source and may be stated as:

$$0\le P_{1(j)}\le P_{1(j)}^{\max} \qquad (1\le j\le N) \qquad (4.9)$$

$$0\le P_{2(j)}\le P_{2}^{\max} \qquad (1\le j\le N) \qquad (4.10)$$

$$0\le P_{3(j)}\le P_{3}^{rated} \qquad (1\le j\le N) \qquad (4.11)$$

$$0\le P_{4(j)}\le P_{4(j)}^{rated} \qquad (1\le j\le N) \qquad (4.12)$$

$$0\le P_{5(j)}\le P_{5}^{rated} \qquad (1\le j\le N) \qquad (4.13)$$

Where:

$P_{(j)}^{max}$ is the maximum power generated by the PV at j^{th} sampling interval (kW);

$P_{(j)}^{rated}$ is the the rated power of the component (kW).

4.3.2.2. Inequality constraints

The inequality constraints are critical for power generation limits of the system. For instance, the PV system is used to supply power to the load (P_1) and/or, to the motor-pump unit (P_2), as shown in Figure. 4.1. Hence, at any given sampling interval, the sum of the above-mentioned powers should not exceed the maximum generated output power of the PV system. This inequality constraint is expressed as follows:

$$P_{1(j)} + P_{2(j)} \le P_{PV(j)}^{\max} \qquad (1 \le j \le N) \qquad (4.14)$$

The power supplied to the load from the turbine generator should always be equal, or less than the rated output power of the turbine generator. This may be expressed by:

$$P_{5(j)} \le P_{T:G}^{rated} \qquad (1 \le j \le N) \qquad (4.15)$$

The power from the PV and the minimum power permitted from the grid should be less or equal to the rated input power of the pump. Therefore, it is expressed as:

$$P_{2(j)} + P_{3(j)} \le P_{M:P}^{rated} \qquad (1 \le j \le N) \qquad (4.16)$$

4.3.2.3. Dynamics of PHS water level

The excess energy from the PV system may be stored within the upper-reservoir. The grid power may further be used to refill the upper reservoir. The stored potential energy is used during peak demand, or when it is uneconomical to use the grid-power for supplementing the unmet primary load demand. The storage level is restricted, to be within the design storage limits, based on the size of the upper reservoir. The upper reservoir water level state (Vol(j)) may be used as a decision variable, preventing overcharging. In cases whereby the upper reservoir is entirely filled up, the maximum capacity is represented as 1. Therefore, the constraint for the storage limit level has been imposed on the upper reservoir as follows:

$$Vol^{\min} \le Vol_{(j)} \le Vol^{\max} \qquad (1 \le j \le N) \qquad (4.17)$$

Where:

$Vol^{\min}$ is the minimum allowable capacity of the upper reservoir;

$Vol^{\max}$ is the maximum allowable capacity of the upper reservoir.

The state of the water level changes when the water is pumped into the upper reservoir, or the turbine-generator unit generates electricity. As the motor-pump unit is supplied with electricity (using P_2 and/or P_3), it allows the storage level to increase. Hence, the sum of P_2 and P_3, at any given time, is made positive, revealing the charging process. Whenever the turbine-generator unit generates electricity to supply the unmet load demand (using P_5). This allows the storage water level to decrease. Hence, P_5 is made negative implying the discharging process. The water level dynamic state in the upper reservoir, may therefore be expressed as follows:

$$Vol(j) = Vol_{(t-1)} + (P_{2(t)} + P_{3(t)}) \times \frac{\eta_p}{E_{pot}} - P_{5(t)} \times \frac{1}{\eta_g . E_{pot}} \quad (4.18)$$

Where:

$Vol_{(t)}$ is the water level in the upper reservoir at the end of time t;

$Vol_{(t-1)}$ is the water level in the upper reservoir at the end of the following time period t-1;

η_p is the overall pumping efficiency;

η_g is the overall efficiency of the turbine generator unit;

E_{pot} is the nominal potential energy in the upper reservoir (kWh).

Hence, the discrete water level dynamic state at any sampling interval (j), is then expressed as follows:

$$Vol_{(j)} = Vol_{(0)} + \sum_{j=1}^{N} [P_{2(j)} + P_{3(j)} \times \frac{\eta_p . \Delta t}{E_{pot}}] - \sum_{j=1}^{N} P_{5(j)} . \frac{\Delta t}{\eta_p . E_{pot}} \quad (4.19)$$

Where:

$Vol_{(0)}$ is the initial water level state.

Eq. (4.19), may further be substituted in (4.17), yielding the following boundary limit equation:

$$Vol^{\min} \leq Vol_{(0)} + \sum_{j=1}^{N} [P_{2(j)} + P_{3(j)} \times \frac{\eta_p.\Delta t}{E_{pot}}] - \sum_{j=1}^{N} P_{5(j)} . \frac{\Delta t}{\eta_p.E_{pot}} \leq Vol^{\max} \tag{4.20}$$

By letting: $Y = \frac{\Delta t}{C \times \eta D}$ and $Z = \frac{\eta c \times \Delta t}{C}$ equation 4.20 may be written as:

$$Vol^{\min} \leq Vol_{(0)} + \sum_{j=1}^{N} [P_{2(j)} + P_{3(j)} \times Y] - \sum_{j=1}^{N} P_{5(j)} \times Z \leq Vol^{\max} \tag{4.21}$$

4.3.3. Proposed solver

The optimal control method will be used in the system. Therefore, the developed objective function and constraints are linear; that is, the optimization problem may be solved, using linear programming in MATLAB [88]:

$$\min g(x), st \begin{cases} Ax \leq b \\ A_{eq} x = b_{eq} \\ Ib \leq x \leq ub \end{cases} \tag{4.22}$$

Where:

$g(x)$ represents the objective function;

A_{eq} and b_{eq} represent the equality constraint parameters;

A and b represent the inequality constraint parameters;

l_b and u_b represent the inferior and superior limits of the variables.

4.4. Case study

To assess the effectiveness of the developed energy management model, a grid connected PV with PHS, was considered in a small farm in the Mangaung municipality of Bloemfontein, in South Africa. The South African case was selected, as the electricity costs have increased drastically over the years. Given the current electricity costs in South Africa, the proposed supply system, with the developed energy control model, has the potential of reducing the operation cost. This may positively affect the economic profit of farmers, who may opt to use this grid connected supply option. Data, related to the demand and component's size of the considered system, are given in the section below.

4.4.1. Load data and size of the proposed system

The load demand profile and data are used as discussed in Chapter 3, Section 3.3., Figure 3.2. and 3.3. The size of the proposed PHS, with minimum grid power allowance, is mainly constrained by the funds available to implement the project, energy saving target, the specifications of the site where the system should be built and the maximum amount of power to be fed into the electrical network. In this study, the maximum amount of power to be fed into the utility grid, is considered as the sizing criteria.

4.4.2. Electricity tariffs

Optimal scheduling of the modelled hybrid system aims to minimize electricity costs within the outline of DSM. Therefore, the TOU program is a typical program of DSM. Due to electricity price changes over different periods, according to the electricity supply cost, as shown in Table 4.1. In this study, the daily electricity price for both high demand and low season is given as [89]:

$$\rho(t) = \begin{cases} \rho_k; t \in T_k, T_k = [6,9) \cup [17,19) \\ \rho_0; t \in T_0, T_0 = [0,6) \cup [22,23) \\ \rho_s; t \in T_s, T_s = [9,17) \cup [19,22) \end{cases} \tag{4.23}$$

$$\rho(t) = \begin{cases} \rho_k; t \in T_k, T_k = [7,10) \cup [19,20) \\ \rho_0; t \in T_0, T_0 = [0,6) \cup [22,23) \\ \rho_s; t \in T_s, T_s = [6,7)(10,18) \cup [20,22) \end{cases} \tag{4.24}$$

Where:

ϱ_k is the price of electricity in R/kWh for peak periods;

ϱ_0 is the price of electricity R/kWh for off-peak periods;

ϱ_s is the price of electricity R/kWh for standard periods.

The TOU tariff structure and pricing layout is illustrated in Table 4.1. The tariff is enforced by Centlec (electricity distribution and managing company for Bloemfontein and surrounding areas). From the Table, the high demand season, with the costliest electricity prices, falls in winter season (June to August), while the low demand season is between September and May. Additionally, the low and high demand season's peak, off-peak and standard periods, begin and end at different hours throughout the day. The highest electricity price for all seasons at R3.56, is effective in the peak period of the high demand season, while the lowest is R1.28, during the off-peak period of the low demand season. Therefore, a difference of 278%, from the lowest electricity price to the highest electricity price, takes place within one year.

Table 4.1

Comflex single phase TOU tariff structure and pricing

Season	Months	Period	Time	Rate (ZAR)
High Demand (Winter)	June - August	Off-peak	00:00-06:00, 22:00-24:00	2.101
		Standard	09:00-17:00, 19:00-22:00	2.182
		Peak	06:00-09:00, 17:00-19:00	3.557
Low Demand (Summer)	September - May	Off-peak	00:00-06:00, 22:00-24:00	1.281
		Standard	06:00-07:00, 10:00-18:00, 20:00-22:00	1.431
		Peak	07:00-10:00, 18:00-20:00	2.251

4.5. MATLAB Simulation results and discussion.

The variable load demand data is used, as in Chapter 3 (Section 3.3). It is used to evaluate the effectiveness of the proposed energy management model. It is designed to meet the demand of a local commercial farming load profile. The simulation has been carried out for high demand season, as the worst-case scenario. Simulation was carried out for 24 hours, analysing the performance of the proposed model throughout the most unfavourable winter's day. The sampling time (Δt), is presumed to be 30 min, leading to a total of 48 sampling intervals. A 24 hours load profile data has been selected from the variable load data, generated by the HOMER software in, Chapter 3. The optimal size of the proposed system, when meeting the load, has been determined using the HOMER software. However, HOMER has led to oversizing, as revealed by the excess energy production, discussed in Chapter 3. Hence, to minimize the initial capital cost, the sizes of both the PV and PHS systems have been reduced for simulations in this Chapter. To study the effectiveness of the developed model, the baseline grid energy cost incurred by load in demand if solely supplied by the utility grid, is compared to the net energy cost achieved during optimal energy control of the proposed PV-PHS system. Furthermore, for appropriate comparison, the fixed-final state condition is used, allowing the upper reservoir's water level state, at the start of the control horizon, to be equal at the end of the control horizon.

4.5.1. Component size and simulation model parameters

A baseline model, in Section 4.5.2, is adapted from the proposed PV-PHS system model, shown in Figure 4.1, Section 4.1.1, to simulate electricity consumption, without solar irradiance and PHS system as input. Therefore, the sole energy input to the system will be from the grid. The baseline model is hence simulated with the same component sizes and input data, as the proposed system. The component sizes and parameters of the proposed system and the baseline are shown in Table 4.2.

Table 4.2

Simulation parameters for the proposed system

Item	Value
Sampling time (Δt)	30 minutes
PHS nominal capacity (PT:G= 3 kW and PM:P= 3 kW)	5 kWh
PHS maximum volume	100%
PHS minimum volume	10%
Initial upper reservoir capacity	50%
Overall efficiency of the PHS η_{TG}= 81% and η_{MP}= 82%)	66.4%
PV system rating	8 kW

4.5.2. Baseline

To validate whether the optimal model reduces energy costs to the consumer, a baseline should be established. The baseline model is a direct supply of electricity from the grid, without contribution from the solar and PHS system. Grid electricity should be expected to supply the load for 24 hours, without load rejection, irrespective of the TOU period (peak, standard or off-peak). A high demand season is simulated to represent a winter case. The electricity consumption of the proposed load demand is presented in Figure. 4.3-4.10, for the winter season. Based on the simulation results, an amount of R79.61 during winter is spent on grid electricity daily, satisfying the load. Figure 4.2 illustrates the power flow of grid supplied power to the load, for the high demand season.

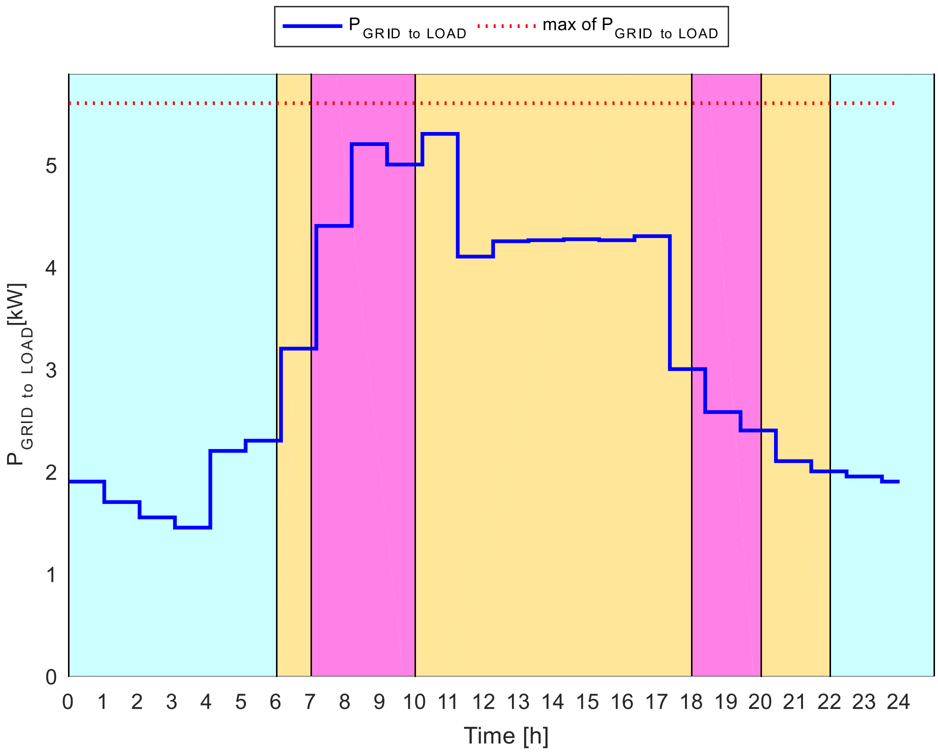

Figure 4.2. Baseline Grid power flow for both high demand season

4.5.3. Optimal scheduling of the proposed PV-PHS system for high demand season

The results for the high demand season, are presented in Figures. 4.3-4.10. Figure 4.3. represents the load demand profile. Figure 4.4 shows the average sun radiation for the

10th of July, with July being the prominent in low temperatures of the winter season, in the year 2018.

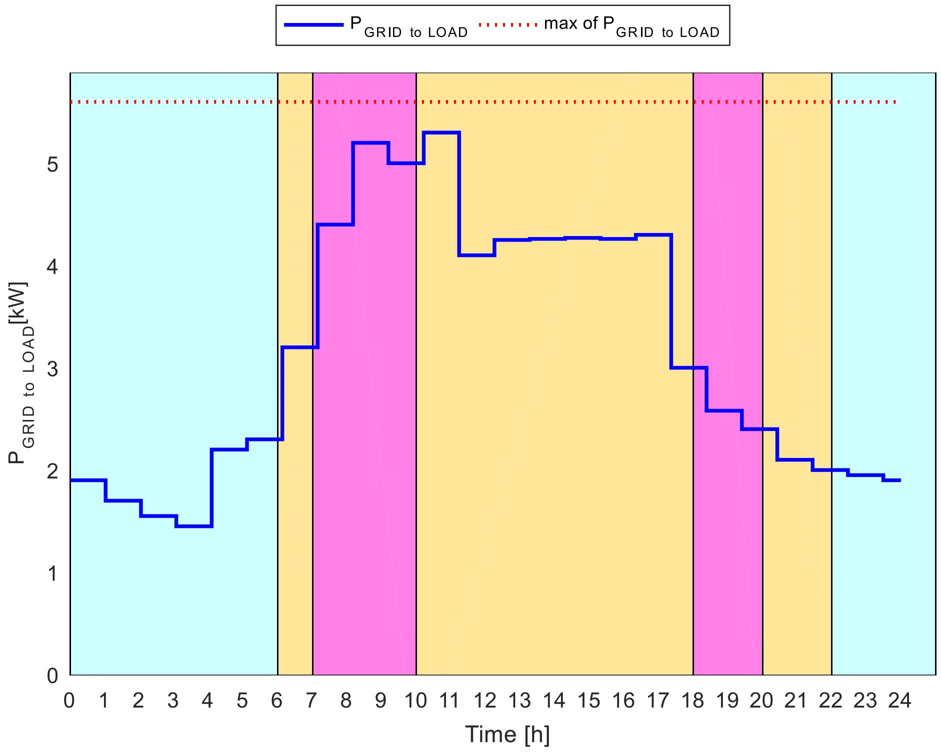

Figure 4.3. Load profile

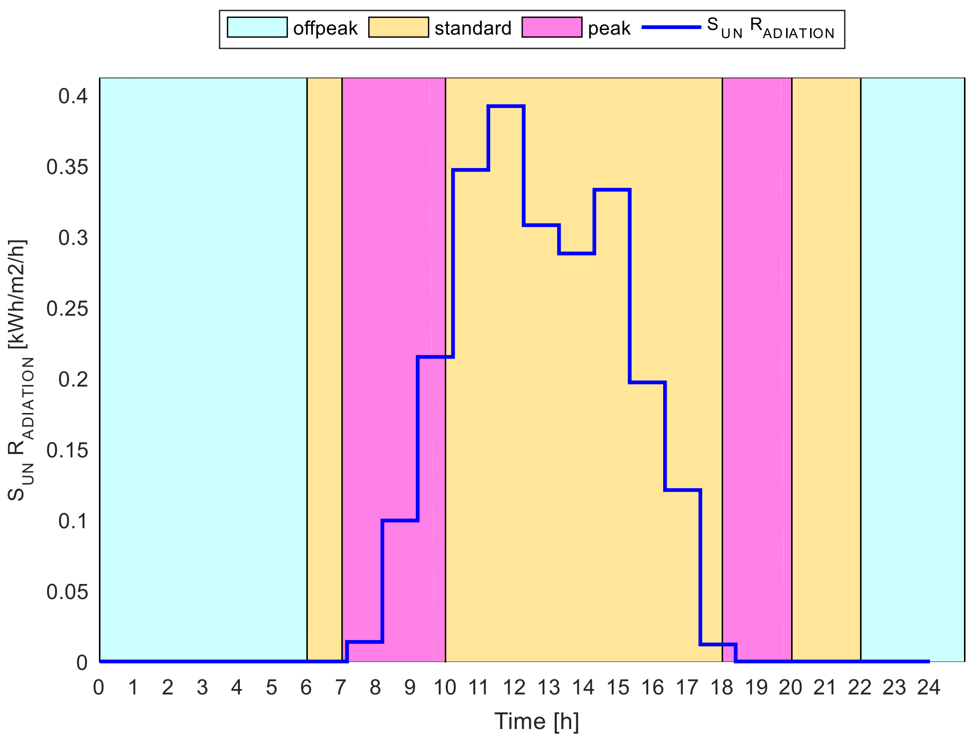

Figure 4.4. Sun radiation

Due to very low temperatures, the PV begins generating from 08h00 and ends at 18h00, unlike during low the demand season. Therefore, as shown in Figure 4.5. and 4.8, the PV system generates a maximum of 2.1 kW (as denoted by the doted red line). Figure 4.5. shows that the model permits the majority of the PV generated power, to feed the primary load.

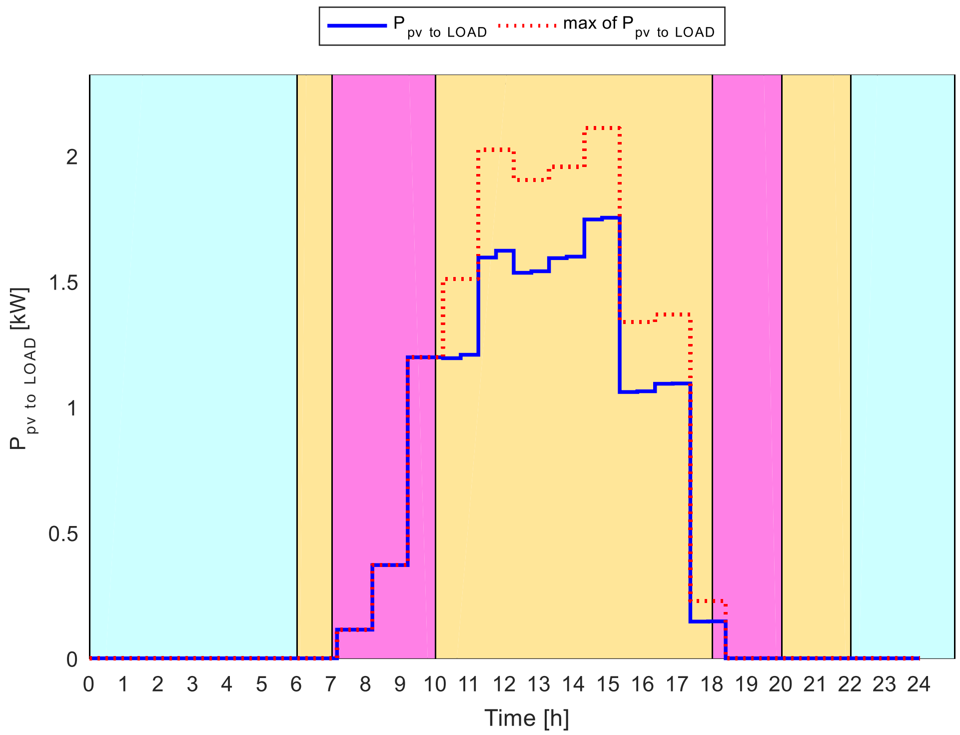

Figure 4.5-PV to load

A portion of the load demand is fed by the turbine generator unit, however, during high demand season, this action happens solely during peak hours, as shown in Figure 4.6. As for the remaining load, the grid power is utilised throughout the day mainly during the morning off-peak hours, when both the PV and PHS systems may not meet the overall demand. This further occurs during peak hours, however, less power is drawn from the grid during that period. As shown in Figure. 4.7, this may be caused by the fact that the study site receives a significantly low temperature in winter, therefore, it takes time in the morning for the temperatures to rise. Hence, the PV power is not as of yet sufficient, to cover the load.

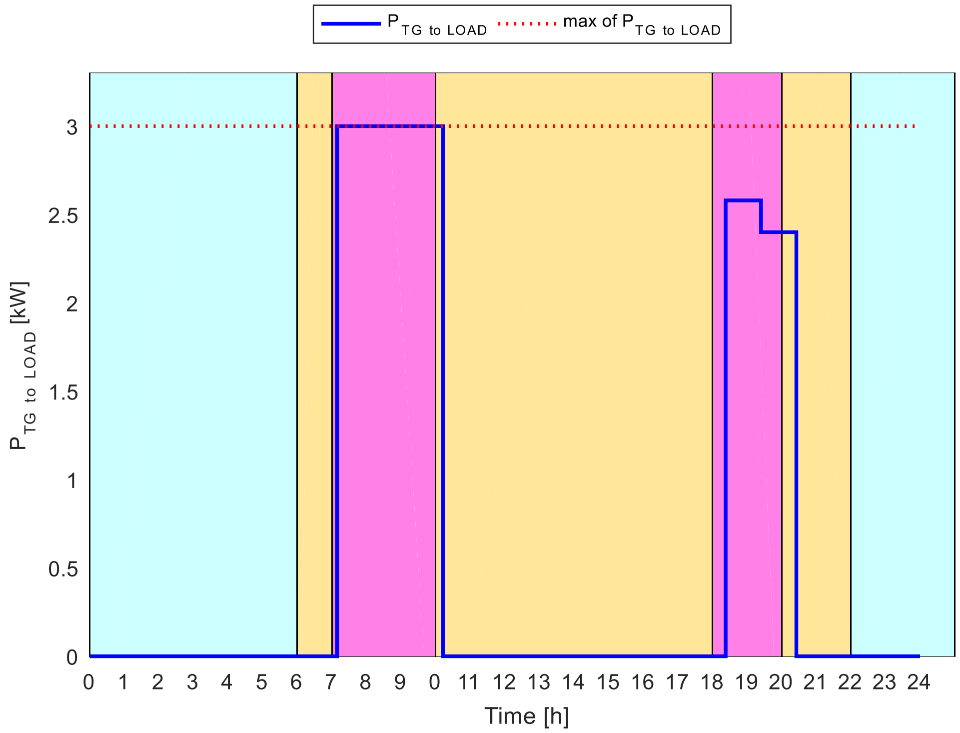

Figure 4.6. Turbine generated power to load

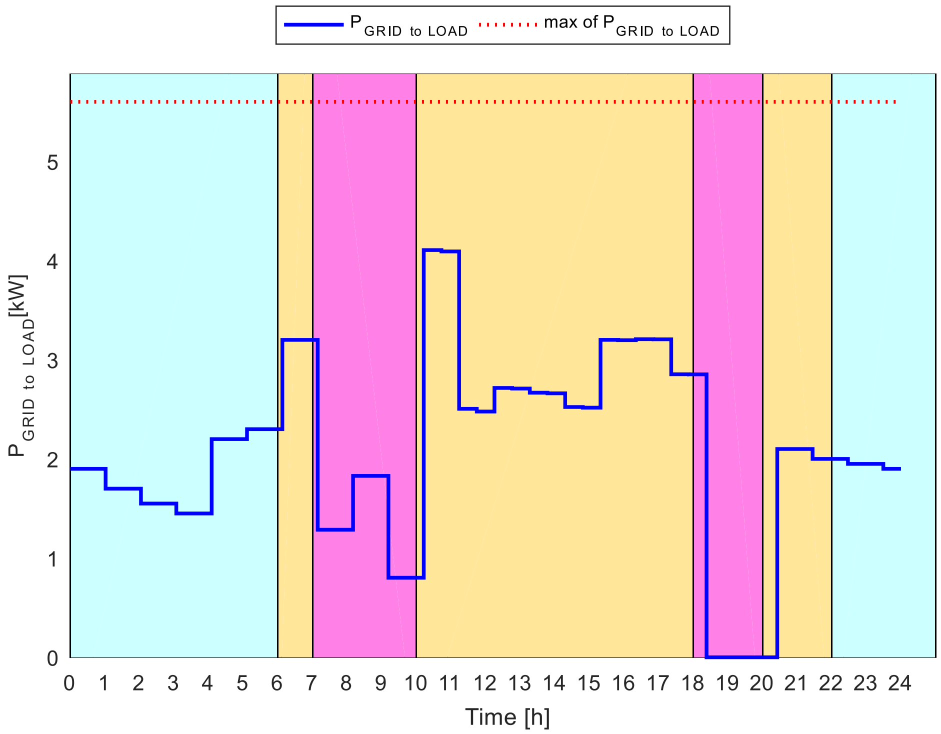

Figure 4.7. Grid power to load

The grid power is further used to meet the pumping demand during cheap off-peak hours throughout the week, as shown in Figure 4.9. The main idea is to store the affordable energy for later use, when the PV and PHS are not able to meet the load demand and during standard and peak periods of the following day. A selected amount of PV power (exceeding small, due to significantly low temperatures), is stored during off-peak periods, as shown in Figure 4.8. Hence, the upper reservoir level charges during the off-peak period, to discharge during peak hours, as shown in Figure 4.10.

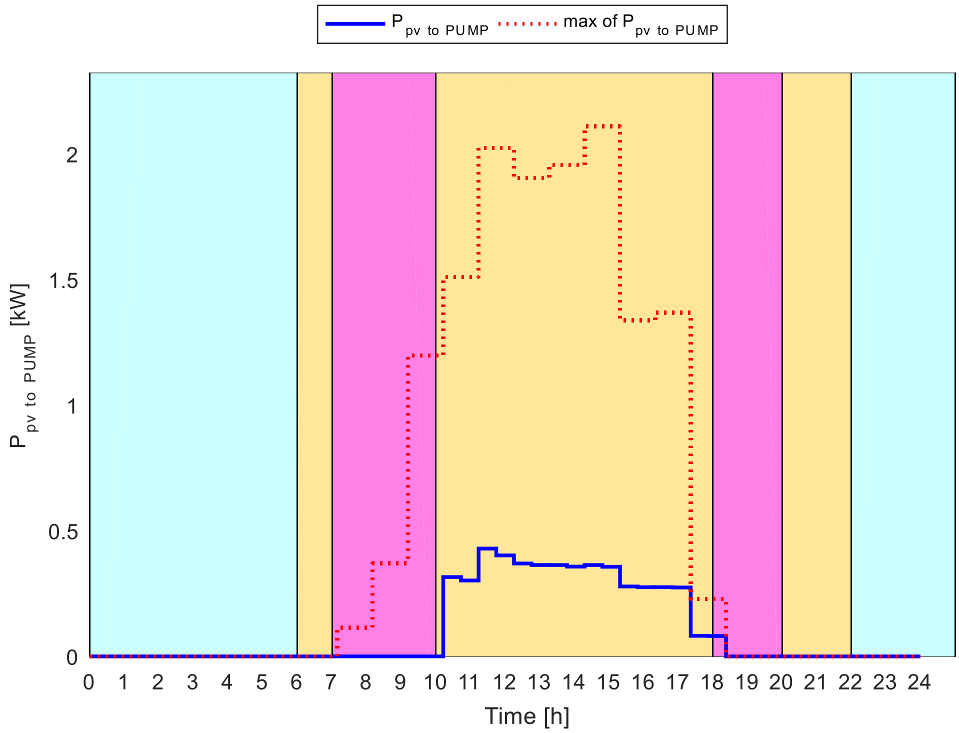

Figure 4.8. PV generated power to Pump

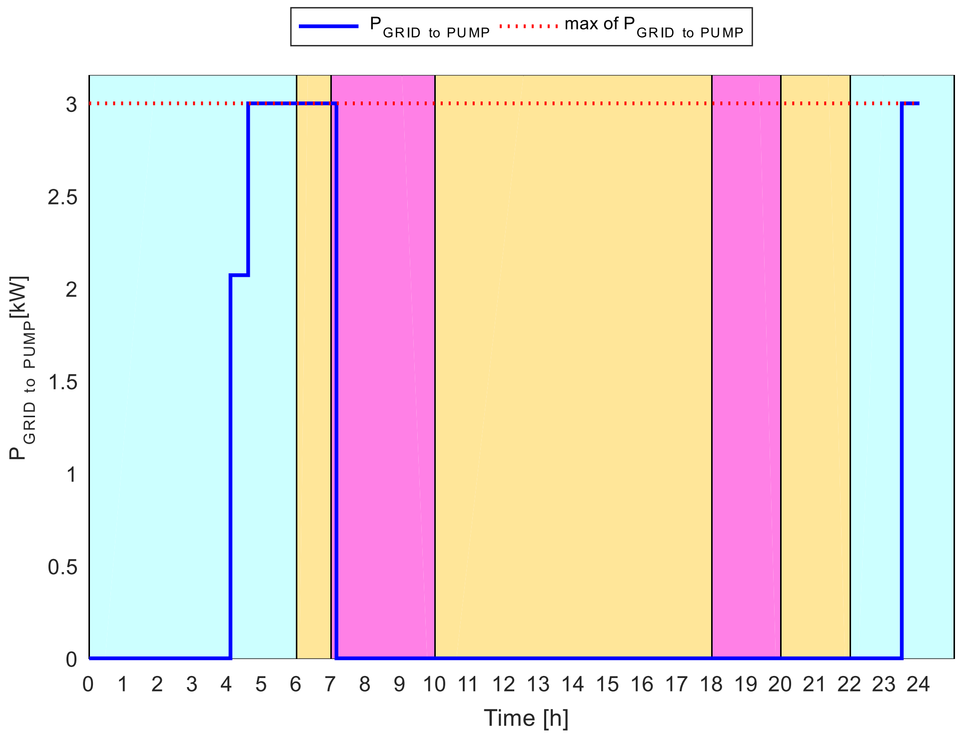

Figure 4.9. Grid power to pump

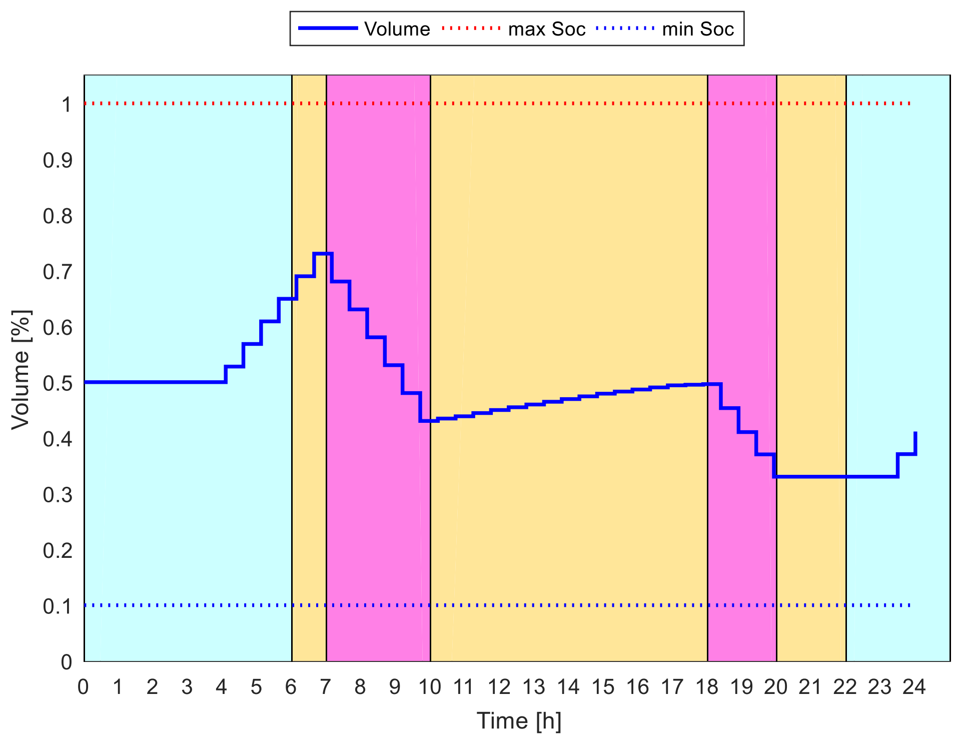

Figure 4.10. Upper reservoir volume profile

4.5.4. Simulation discussion

Simulations for a baseline and PV-PHS based system for winter (high demand season), were performed. The grid consumption cost for the simulated 24 hours, in optimal scheduling, yielded a total cost of ZAR79.61. The baseline utility grid cost of ZAR120.53, during high demand season, is possible if the load demand is solely met by the utility grid company, for the entire 24 hours, as shown by Figure 4.2. Hence, using the optimally controlled PV-PHS system, the consumer merely settles 66.1% of the baseline grid cost, during the high demand season. This proves that a potential of a 33.1% cost saving is possible for those 24 hours. The winter savings may be found to be significantly low, as compared to summer. This may be caused by the high load demand, exceedingly low radiation and sunshine period, for that season. Whereas, on the other hand, summer has significantly high radiation, low load demand and more hours of sunshine in a day, than in winter. Moreover, this may further be influenced by the tariffs plan, as presented in Table 4.2. Nevertheless, including the results obtained during high demand season, it clearly guarantees significantly high savings, during the low demand season, since the temperature should be high, with a decreased low demand.

4.6. Conclusion

This Chapter presented an optimal energy management algorithm for the PV-PHS system, allowing the users to purchase electricity from the utility grid, under Comflex TOU tariffs. The aim of the model was to ensure an optimal power dispatch, by minimizing the use of grid electricity and maximizing the used of RE. Since the nature of the problem was solely linear, *linprog* has been used, solving the optimization problem. The performance of the model has been studied, using the variable commercial farm load. The load type has been studied during the high demand season. The simulations were carried out for twenty-four consecutive hours. To ensure that the developed model is performing effectively, the baseline energy cost, given by the load profile without the use of the PV-PHS system, is compared to the net energy cost, achieved through the optimal energy control of the proposed system. The simulation results have revealed the effectiveness of the proposed model, to optimally control the power flow of the proposed PV-PHS system. The model permitted the effective use of the RE power (PV and PHS), since it is chief in meeting the load demand.

The aim of this Chapter was to further correct the oversizing of the systems components, produced by HOMER in Chapter 3. Referring to Figure 3.6, the system had been designed in a way that it requires 127 kW PV and the capacity of the storage to be 45kW, as compared to the sizes required for the system designed, using MATLAB as shown in Table 4.2, above. In conclusion, MATLAB effectively solved the oversizing problem and it is guaranteed that the operation cost, initial capital and the NPC, will be less than that was calculated by HOMER. The savings and economic contribution of the system are discussed in Chapter 5.

CHAPTER 5: ECONOMIC ANALYSIS

5.1. INTRODUCTION

The purpose of this Chapter is to asses and evaluate the effectiveness of the proposed system, in terms of investment. To achieve the goal set for this Chapter, several economic performance indicators are considered. Indicators, such as benefits to cost ratio (BCR), initial rate of return (IRR), lifecycle cost (LCC), as well as the simple payback period (SPP), are available. Amongst them all, the SPP is uncomplicated to apply, due to its simplicity. However, it is associated with drawbacks, such as the inconsideration of inflation and the project's lifespan. A further indicator, such as payback period is further excluded, since the project's lifespan is not taken into consideration. As a result, this initiates an inaccurate analysis. Therefore, BCR and IRR methods, may be used, due to their level of accuracy when compared to the SPP. With these two methods, inflation and the project's lifespan, are considered. The life cycle cost evaluation and breakeven point (BEP) analysis, forms part of the methods, increasing the level of accuracy. This method is applied in both baseline and the proposed system, for the entire expected lifespan to better the comparison. The expected project lifespan for this case study, is 30 years.

5.2. Initial installation cost of the proposed system

The initial investment cost of the proposed system is shown in Table 5.1. The manufacturers' products all comply with the South African Bureau of Standards (SABS) criteria. The PV panel are accompanied by a solar tracking device, satisfying the four seasons in one day, of Bloemfontein's weather conditions throughout summer and its winter freezing temperatures. The prices in Table 5.1, obtained from [90-92] are average component prices for the year 2018.

Table 5.1

Bill of quantity (proposed system)

Component description	**Quantity**	**Net price (ZAR)**
Upper Storage tank	1	32 133
Tank construction labour	-	17 500
PV Panels	8	64 584
PV installations	-	5900
Solar tracking device	8	21 248
Converter	1	5 499
Low rpm hydrogenator	1	61 245
Series 5 kW submersible pump	1	6 805
Borehole drilling	-	24 000
Total initial investment cost	-	238 914

5.3. Cumulative Cost Calculations

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

5.3.1. Cumulative energy cost

To calculate the daily cumulative energy cost, with the primary objective function, as described in Chapter 4; Eq. (5.1) may be used in this instance:

$$C_{daily-EC} = t_s \cdot \sum_{K=1}^{N} (P_{grid} \cdot C_{TOU_k} \qquad (5.1)$$

Where:

t_s is the sampling time;

P_{Grid} is the power allowed from the grid;

C_{TOU_k} is the time-based cost of electricity at each kth interval.

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

5.3.1.1. Winter cumulative energy cost comparison

The cumulative cost of the winter period is shown in Figure 5.1. As shown from the Figure, it may be observed from the curves that everytime grid electricity is used, the grid cost, in the specific TOU tariff period, increases the total daily cost. The cumulative curves in Figure 5.1, shows a directly proportional relationship between the baseline and optimal control strategy, after the first peak period. The cumulative costs of both systems are approximately the same, at the beginning of the horizon. However, the optimal system's cumulative cost decreases as the baseline increases during the rest of the day. This may be caused by the renewable energy's availability, after the temperature has risen. When comparing the operational cost curves at the end of the horizon, the baseline's total energy cost is approximately 32% higher than that of the optimal system.

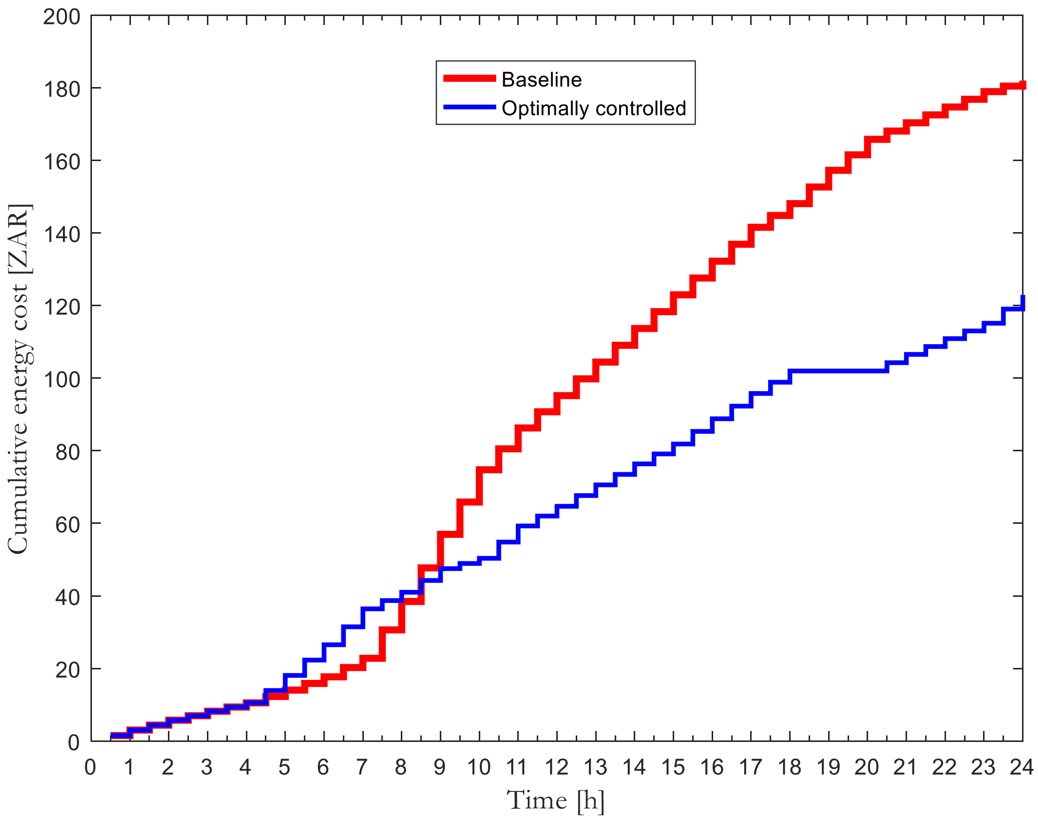

Figure 5.1. Winter cumulative energy cost

5.3.1.2. Summer cumulative energy cost comparison

The cumulative cost of the summer period is shown in Figure 5.2, which is different to the winter cumulative cost curve, in Figure 5.1. The summer electricity usage is low as compared to winter. The energy cost difference of the two systems, is clearly visible, as denoted by the gap between the curves. From the beginning of the first peak period, the cost of the optimal controlled system remains constant, so that its cumulative cost remains under R5.00 for the rest of the control horizon. However, it rises above R5.00, at the end of the horizon. This allows the upper storage to recharge for the following use. The difference in cumulative energy cost, at the end of the control horizon, represents the daily energy cost savings, as in the winter case. The baseline energy cost, compared to the optimal controlled system, shows that the baseline's cost of energy is 95% higher, than that of optimally controlled system. This is significantly higher, as compared to the winter case and, with this, it proves that the optimal system is more effective during the summer season.

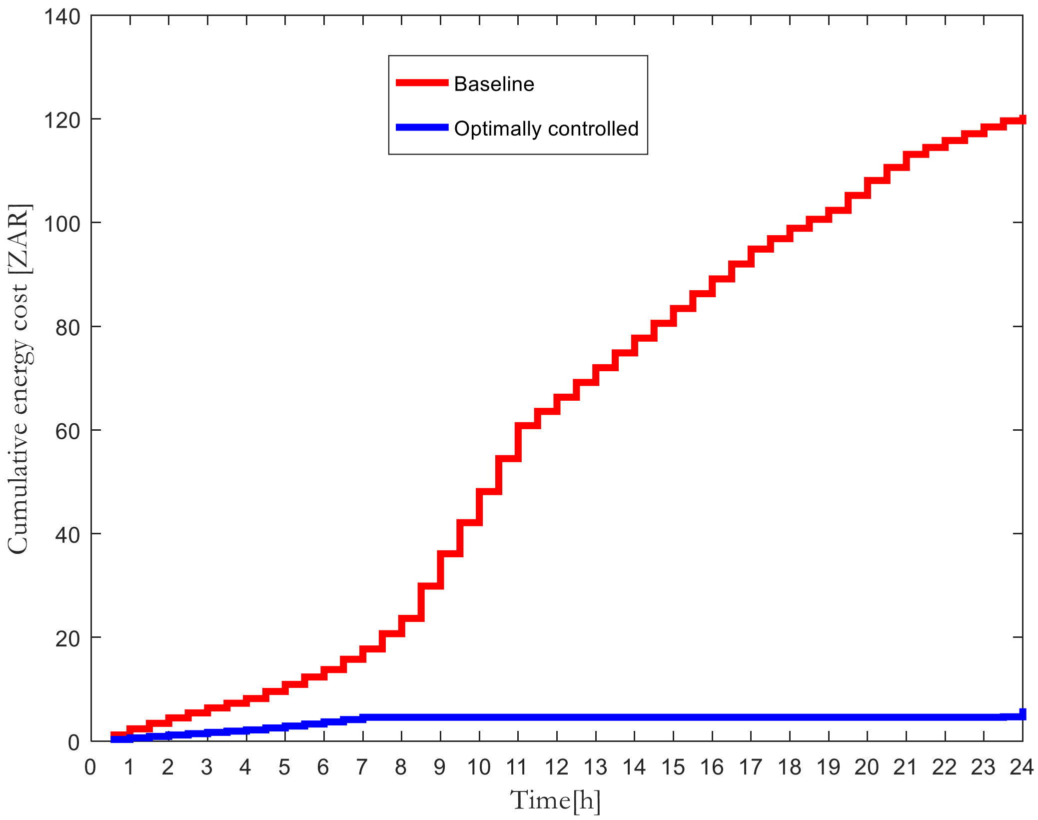

Figure 5.2. Summer cumulative energy cost

5.3.1.3. Daily energy consumption and savings

The cumulative costs and energy consumed after each simulation of the baseline and optimal control strategies, are shown and compared in Table 5.2. A 32% saving of the energy in the winter season is observed, while a 90.64% saving during the summer is noted. With grid electricity being used during standard and off-peak solely for optimal control strategy, a saving of 95% in cost may be observed for the Summer season, while in winter, a total savings as low as 32.4% in electricity cost is observed. The results of this comparison highlight the importance of avoiding the use of electricity, during high demand periods, particularly during winter, when the electricity prices are high.

Table 5.2

Daily energy consumption and savings

Strategy / Season	Baseline (Grid alone)		Optimal control (UPHS)		Daily Savings (ZAR)	Daily Savings (%)	
	Energy (kWh)	Cost (ZAR)	Energy (kWh)	Cost (ZAR)	Cost	Energy	Cost
Winter	51.1	181.9	34.52	122.9	59	32.4	32.4
Summer	50.3	120.78	4.71	6.32	116.07	90.64	95

5.3.1.4. Annual energy consumption and savings

The total cost saving is calculated over the period of one year, by using the data in Table 5.2. Based on the utility company's tariff structure, the winter season has a total of 92 days, while on the other hand the summer season consists of 273 days. The product of the number of days in the seasons and the cost saving for the respective seasons may equate to the total seasonal savings. When adding the savings of the two seasons, an approximate annual saving in electricity cost may be obtained. Using this method, the savings in 2018 were calculated and shown, in Table 5.3.

Table 5.3

Annual energy consumption and savings

Strategy	Baseline (Grid alone)		Optimal control (UPHS)		Annual Savings (ZAR)	Annual Savings (%)	
Season	Energy (kWh)	Cost (ZAR)	Energy (kWh)	Cost (ZAR)	Cost	Energy	Cost
Winter	4 701.2	16 734.8	3 175.84	11 306.8	5 428	32.4	32.4
Summer	13 731.9	32 972.94	1 285.83	1 725.36	31 687.11	90.64	95
Total	18 433.1	49 706.9	4 461.67	13 032.16	37 115.16	75.79	73.78

5.4. Life cycle cost analysis

The system was designed to last for at least 30 years, based on the life expectancy of the upper storage, since it lasts for the longest period of time and is the most expensive to replace.

The salvage costs were taken as 20% of the initial cost of implementation, for both the baseline and the proposed system. This is necessary for the finances that will be used on upgrades, for technological efficiency in the future.

Eq. (5.2) is used to calculate the replacement cost. With the average inflation rate, shown in Figure 5.3, the future costs of components may be predicted, by assuming that the average inflation rate will be equal to the interest rate [93].

$$C_{rep} = \sum_{k=1}^{N_{rep}} C_{cap}.k(1+n.r) \tag{5.2}$$

Where:

C_{cap} is the initial capital cost for each component;

N_{rep} is the number of component replacements of the 30-year lifetime;

n is the lifespan for a specific component (years);

r is the average inflation rate shown as 4.5% in Figure 5.3.

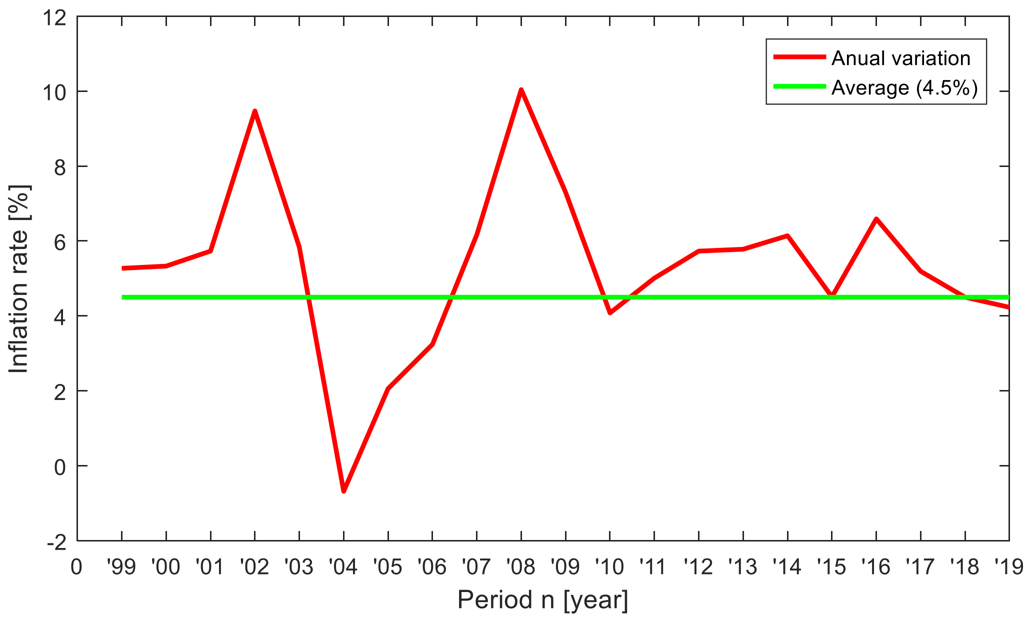

Figure 5.3. Inflation rate of South Africa from 1999 to 2019 [94].

5.4.1. Baseline life cycle cost analysis

The total replacement costs (C_{rep}) over the 30-year lifespan for the baseline, are not calculated as the baseline system solely requires the grid as a component that cannot be replaced. Therefore, the total lifecycle replacement costs are equal to Zero.

The cumulative cost of energy for the first year, was taken from Table 5.3. The cost at the end of year 30, equates to the total cumulative electricity cost C_{EC}, with an increase of 10% annually taken into consideration, as shown in Eq. (5.3).

$$C_{EC} = \sum_{K=1}^{30} C_{initial-EC} \cdot k(1+a) \tag{5.3}$$

Where:

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

K represents the year at which the cumulative cost should be calculated (years);

a is the annual increase of 10%.

The operation and maintenance costs at the end of each year are calculated, using Eq. (5.4). However, in this case, it is assumed to be zero, since the grid does not require maintenance by the end user.

$$C_{OM} = \sum_{k=1}^{30} C_{initial-OM} \cdot k(1+r) \tag{5.4}$$

A salvage cost ($C_{salvage}$), is assumed to be 20% of the initial implementation cost ($C_{initial}$) of the baseline system, as shown in Eq. (5.5). However, the lack of salvage cost will be calculated, since the grid connection to the end user is handled by the utility company. Therefore, the total lifecycle cost for the baseline, is calculated using Eq. (5.4).

$$C_{salvage} = 0.2 \cdot C_{initial} \tag{5.5}$$

$$LCC_{Grid} = C_{initial} + C_{rep} + C_{EC} + C_{OM} - C_{salvage} \tag{5.6}$$

The total lifecycle cost value LCC_{Grid} (ZAR), using Eq. (5.6), is shown in Table 5.4. Over a 30-year project lifetime, a total amount of approximately R 8 177 578.663 will be spent, in the case of the grid supplied electricity.

Table 5.4

Total lifecycle cost of the grid

Cumulative Cost	Value (ZAR)
$C_{initial}$	0
$C_{rep-BTC}$	0
C_{OM}	0
C_{EC}	8 177 578.663
$C_{salvage}$	0
LCC Grid	8 177 578.663

5.4.2. Optimally controlled system's life cycle cost analysis

In the case of the proposed system, further components exist, with various life expectancies. Therefore, the total replacement costs (C_{rep}), may be calculated using Eq. 5.2, over the 30-year project lifespan, for all the proposed system's components, as shown in Table 5.5. These are added, to calculate the total lifecycle replacement costs (C_{rep-TC}) denoted, in Eq. (5.7).

$$C_{rep-TC} = C_{rep-US} + C_{rep-PV} + C_{rep-ST} + C_{rep-HG} + C_{rep-SP} + C_{rep-B} \tag{5.7}$$

Following the same method for cumulative electricity costs, with an annual 10% increment, was calculated for the proposed system using Eq. (5.3) as well as the salvage cost and the cumulative operation and maintenance costs using Eq. (5.5) and (5.4), respectively.

Eq. (5.8) shows the calculation of the lifecycle cost for the proposed system.

$$LCC_{\text{Proposed}} = C_{initial} + C_{rep-TC} + C_{OM} + C_{EC} - C_{Salvage} \tag{5.8}$$

Table 5.5

Total replacement cost for the proposed system

Parameters	Value
Optimally controlled system lifetime (years)	30
Upper storage (US) lifetime (years)	30
$N_{\text{Rep-US}}$ (-)	0
$C_{\text{Rep-US}}$ (ZAR)	49 633
PV panels lifetime (years)	20
$N_{\text{Rep-PV}}$ (-)	1
$C_{\text{Rep-PV}}$ (ZAR)	70 484
Solar tracker (ST) lifetime (years)	10
$N_{\text{Rep-ST}}$ (-)	2
$C_{\text{Rep-ST}}$(ZAR)	21 248
Hydro-generator (years)	20
$N_{\text{Rep-HG}}$ (-)	1
$C_{\text{Rep-HG}}$ (ZAR)	61 245
Submersible pump (years)	20
$N_{\text{Rep-SP}}$ (-)	1
$C_{\text{Rep-SP}}$ (ZAR)	6 805
Borehole lifetime (years)	30
$N_{\text{Rep-B}}$ (-)	0
$C_{\text{Rep-B}}$ (ZAR)	0
C_{rep-TC} (ZAR)	181 030

The total lifecycle cost value (ZAR) was calculated, using Eq. (5.8). The detailed data is presented in Table 5.7. Over a 30-year project lifetime, a total amount of approximately R3 042 619.19, will be spent, in the case of the proposed system is implemented.

Table 5.6

Total lifecycle cost for the proposed system

Cumulative Cost	Value (ZAR)
$C_{initial}$	238 914
C_{rep-TC}	181 030
C_{OM}	7 274.16
C_{EC}	2 648 457.23
$C_{salvage}$	33056.2
LCC $_{proposed}$	3 042 619.19

5.4.3. Break-even point (BEP)

The break-even point is when the total implementation and operating costs of both systems incurred becomes equal at any point during the project's lifespan. In this case, the baseline grid electricity supply is compared to the proposed system, with the optimal energy management scheme, in terms of the total cumulative annual energy cost in the project's lifespan of 30 years. The cumulative cost curves, including the initial investment cost and the total annual costs incurred over this period; the baseline and optimal system is plotted on the same axis, for clear comparison. The point where these two curves intersect, shows the point in time (years), at which the two systems break even.

The initial total implementation cost of the optimal system and the grid connected, is R238 914 and R0, respectively. The values are therefore considered as the starting points of the two curves, in Figures 5.3. After the first year has passed, the sum of total annual cost of energy and the initial investment cost, is the total present cost of energy, shown in Table 5.2. This equates to the total cumulative cost for the first year, after implementation. After the first year of implementation, a 10% increase in the price of electricity is considered, calculating the annual energy costs. This amount is further added to the previous total cumulative cost of the first year. The same method is followed for the remaining years up until year 10, as shown in Fig. 5.4. In this curve, the replacement costs and lifespan of all the components are considered, for increased accuracy of the cumulative cost representation. From Fig. 5.4, a clear observation may be made the break-even point occurs within 7 years, after the project has started. The costs incurred are equal to R 384 400 and the differences in finances used; at the end of the project's lifespan, further presents an important economic performance indicator.

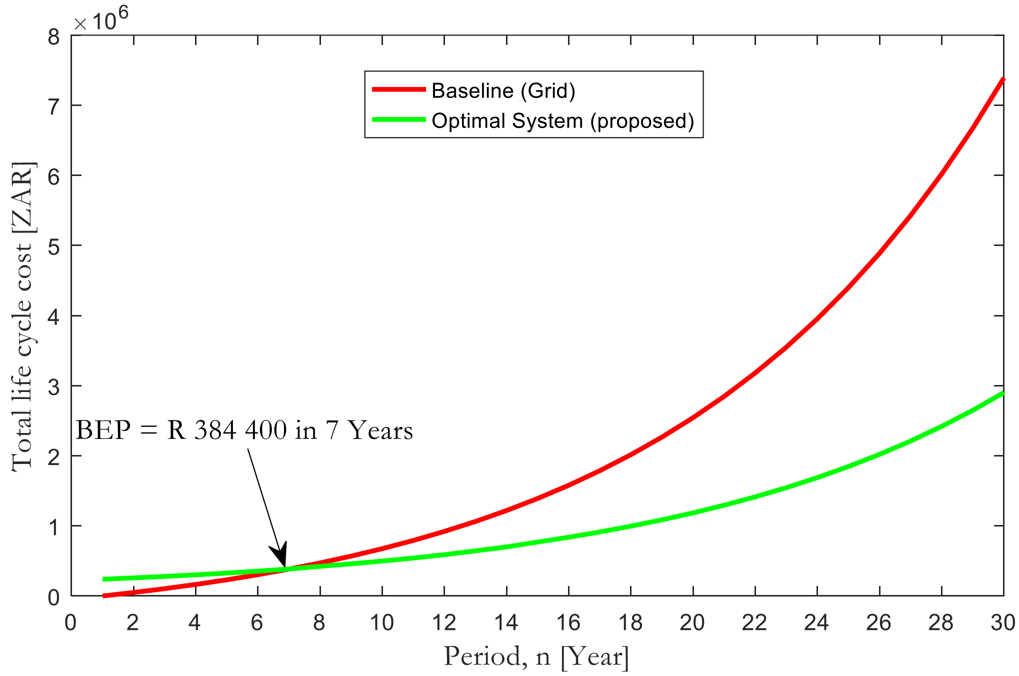

Figure 5.4. Breakeven point

5.4.4. Lifecycle cost comparison

The lifecycle costs for the grid operated system and the system with optimal energy management scheme, are compared in Table 5.8. The break-even point analysis shows the period in which it will take both systems to reach cost equalization. The difference in LCC is calculated, in order to note the savings in cost, at the end of the project lifespan. From the Table below, a conclusion may be made that at the end of the project's lifespan, an approximate saving of R5 134 959.473 may be achieved, if the proposed optimal system is implemented. This translates into a saving of 62.79%.

Table 5.7

Lifecycle cost comparison

LCC	Value (ZAR)
LCC_{Grid} (ZAR)	8 177 578.663
$LCC_{Proposed}$ (ZAR)	3 042 619.19
Total savings over 30 years (ZAR)	5 134 959.473

5.5. Conclusion

The purpose of this Chapter was to asses and evaluate the effectiveness of the proposed system, in terms of investment. The evaluation was a success through BEP analysis. This analysis reveals that, after a period 7 years, the cumulative costs were lower for the proposed system, as opposed to the baseline. It was observed that, after the break-even point, the difference in cumulative costs significantly increased with the baseline cost. The LCC of the proposed system, as compared to the baseline, revealed a R5 134 959.473 saving in cost, over the project lifetime. Therefore, the LCC analysis substantiates the hypothesis in Chapter I, Section 1.6, that in areas with a lack of flowing water, but with an adequate solar resource within South Africa, a non-interactive grid connected UPHES system generates electricity more effectively and affordable, than using the utility grid alone, for the same amount of load demand.

CHAPTER 6: CONCLUSION

6.1. FINAL CONCLUSION

This Chapter presents a summary of conclusions and potential future works to be carried out, based on the proposed PV-UPHS system. This research work was encouraged by the current state of electrical energy in our country, such as random electricity blackout experiences, caused by increasing energy demand. This has led to a rising electricity cost, due to the rising global fossil fuel prices. Underground pumped-hydro system technology has been researched, yet, is lacking implementation in South Africa. The research study aimed to demonstrate the technical and economic viability of the proposed system for farms served by the grid electricity, using UPHS technology. Hence, an optimal energy management model has been developed, with the objective of minimizing the grid consumption cost, whilst maximizing the use of renewable energy resources, meeting the load demand.

Chapter 2 has revealed that majority of the pumped hydro storage studies have mainly focused on the common sources of water, such as rivers and dams. Considerably limited studies have concentrated on energy management of an underground (borehole) based hydro generating system. Majority of the energy management studies have mainly focussed on solely using solar PV and WT technologies, limiting the use of grid electricity.

In Chapter 3, the optimal size of the proposed PV-PHS system was determined, using HOMER software, as main optimization tool. The optimal configuration results revealed that the size of the load has no effect on the size of the system design, or the amount of energy to be produced. Instead, it affects the size of the storage system components. However, the optimal configuration results led to a large amount of redundant annual excess energy generation. Although the system is grid connected, no excess energy could be sold back to the grid, since it was not as yet permitted at the study area. This challenge has led to the recommendation of designing an optimal energy management model, assisting with the reduction of the PV-PHS system size. The model should be able to permit the system to store excess energy during the affordable off-peak period and use it at a later stage, during the costly peak periods. Additionally, it should constantly be able to minimize the grid consumption costs and maximize the use of renewable energy, to satisfy the load.

Chapter 4 demonstrated the behaviour of the developed optimal energy management model for the PV-UPHS system, supplying a commercial farm. A high demand season has been used as the worst-case scenario and specific TOU tariffs for that season have been considered during the analysis of the model. The model ensured an effective flow of power, by utilizing the RE power as a priority, when meeting the load demand. The grid power was utilized during inexpensive off-peak periods, or to supplement the unmet load demand, where the renewable energy could not meet the demand during peak periods.

Chapter 5 presented an economic analysis, based on the cost savings obtained in Chapter 4. The bill of quantities of the PV-UPHS system, with all the relevant components were included, with the aim to determine the life cycle cost and break-even point. The analysis revealed that the proposed system was economically feasible, with a potential cost saving of 62.79% and a break-even point of 7 years.

The main objective of this research was to develop a model that permits the optimal utilisation of solar photovoltaic with pumped hydro storage, through open wells (borehole), for minimization of electricity cost of farming activities in a dynamic electricity pricing environment. A model has been developed; it minimizes the level of reliability on grid electricity. While on the other hand, maximizing the usage of renewable energy. The simulation results in Chapter 4, revealed that using the developed model to optimally manage the power generated by PV and the PHS, the cost of electricity for farm operation may be reduced.

In Chapter 5, the economic analysis was carried out for a period of 30 years. The simulation was carried out for both high and low demand (winter and summer) seasons. The initial investment cost of the developed model was R238 914 and Zero Rands, for the grid. A total amount of R8 177 578.663 was obtained, in terms of money spent on grid electricity alone and R3 042 619.19 was obtained for the case of the developed model, for a 30-year period of the project's lifespan. Therefore, a 32.4% and 95% saving in costs is observed, for both winter and summer seasons, respectively. Furthermore, a breakeven point of R384 400 in 7 years is further observed. This means that once the 7 years have elapsed after the start of the project, merely savings may be noticed, for the entire lifecycle of the project. Therefore, from the analysis and evaluation reports above, it may be noticed that the system is economically feasible and technically viable, in a South African context.

6.2. Suggestions for further research

Now that the objective (model development) has been achieved, the next step is implementation. However, this will depend on the availability of funds and permission by the farm owner.

This dissertation is not the conclusion on optimal control of PV-UPHS; several questions still remain. Since the study focused on Bloemfontein, the research could be adapted to fit other geographical locations with different input parameters, which may in turn, change the configuration of the proposed system.

The economic analysis was carried out based on the full period of the project's lifespan. The savings are acceptable, however, further sensitivity analysis, in terms of project's lifespan may be necessary to increase the savings.

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APPENDICES

APPENDIX A: ONE DAY SUN RADIATION DATA AND GRAPHS

Table A1

24-hour sun radiation data (Summer)

Date	Time	GHI_Avg W/m² Avg	DIF_Avg W/m² Avg	DNI_Avg W/m² Avg
20/12/2018	00:00	0	0	0
20/12/2018	01:00	0	0	0
20/12/2018	02:00	0	0	0.11479
20/12/2018	03:00	0	0	0
20/12/2018	04:04	0	0	0
20/12/2018	05:00	0	0	0
20/12/2018	06:00	43.20971	12.64141	270.1084
20/12/2018	07:00	244.4972	35.97787	747.007
20/12/2018	08:00	491.246	49.09532	900.6012
20/12/2018	09:00	724.4757	52.36248	981.9835
20/12/2018	10:00	922.0294	56.0018	1024.021
20/12/2018	11:00	1058.121	61.20162	1039.738
20/12/2018	12:00	1139.667	61.83218	1047.924
20/12/2018	13:00	1160.694	61.01998	1056.618
20/12/2018	14:00	1102.709	65.17064	1044.767
20/12/2018	15:00	992.2538	66.38932	1029.399
20/12/2018	16:00	814.9387	64.35567	991.0381
20/12/2018	17:00	594.3667	55.47336	936.5825
20/12/2018	18:00	345.4515	44.79202	814.5192
20/12/2018	19:00	111.8668	26.14346	518.7736
20/12/2018	20:00	1.771426	0.992537	17.47751
20/12/2018	21:00	0	0	0
20/12/2018	22:00	0	0	0
20/12/2018	23:00	0	0	0.00274
20/12/2018	24:00	0	0	0

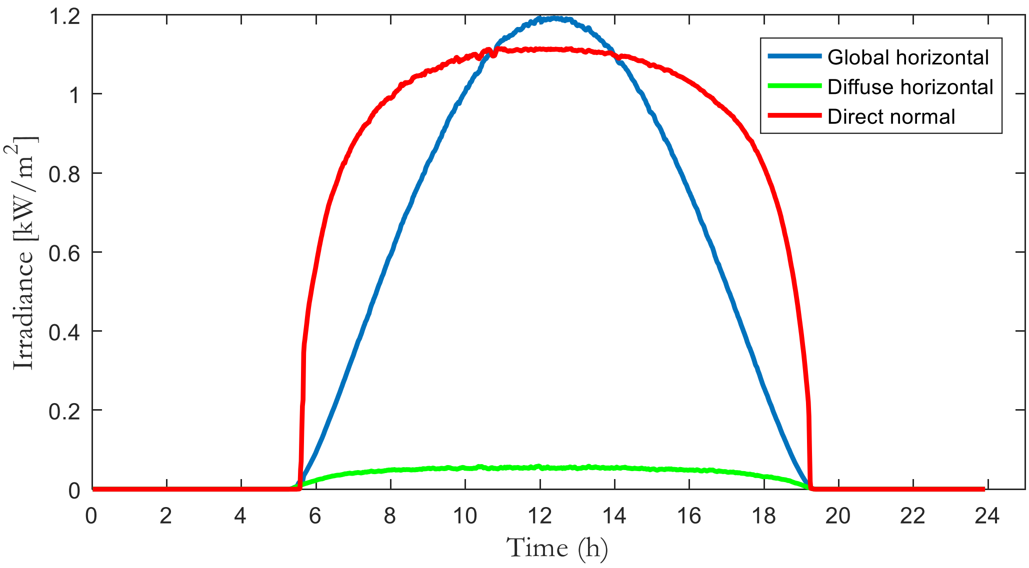

Figure A1: Sun radiation curve (Summer)

Table A2

24-hour sun radiation data (Winter)

Date	Time	GHI_Avg W/m² Avg	DIF_Avg W/m² Avg	DNI_Avg W/m² Avg
10/07/2018	00:00	0	0	0
10/07/2018	01:00	0	0	0
10/07/2018	02:02	0	0	0.044901
10/07/2018	03:00	0	0	0.043187
10/07/2018	04:04	0	0	0.000114
10/07/2018	05:00	0	0	0.020566
10/07/2018	06:00	0	0	0.005827
10/07/2018	07:00	0	0	0.001257
10/07/2018	08:00	13.79257	13.81156	1.214303
10/07/2018	09:00	99.54277	99.95614	0.051414
10/07/2018	10:00	214.5939	208.4429	17.11597
10/07/2018	11:00	346.5211	331.0024	29.56049
10/07/2018	12:00	392.4931	365.1743	45.62051
10/07/2018	13:00	308.518	302.6681	11.19728
10/07/2018	14:00	288.1663	290.2164	1.578107

10/07/2018	15:00	333.8734	257.6718	149.3065
10/07/2018	16:00	197.8865	174.6317	54.80763
10/07/2018	17:00	121.2569	75.23914	236.8407
10/07/2018	18:00	12.68401	10.8893	21.39304
10/07/2018	19:00	0	0	0
10/07/2018	20:00	0	0	0.000914
10/07/2018	21:00	0	0	0
10/07/2018	22:00	0	0	0
10/07/2018	23:00	0	0	0
10/07/2018	24:00	0	0	0

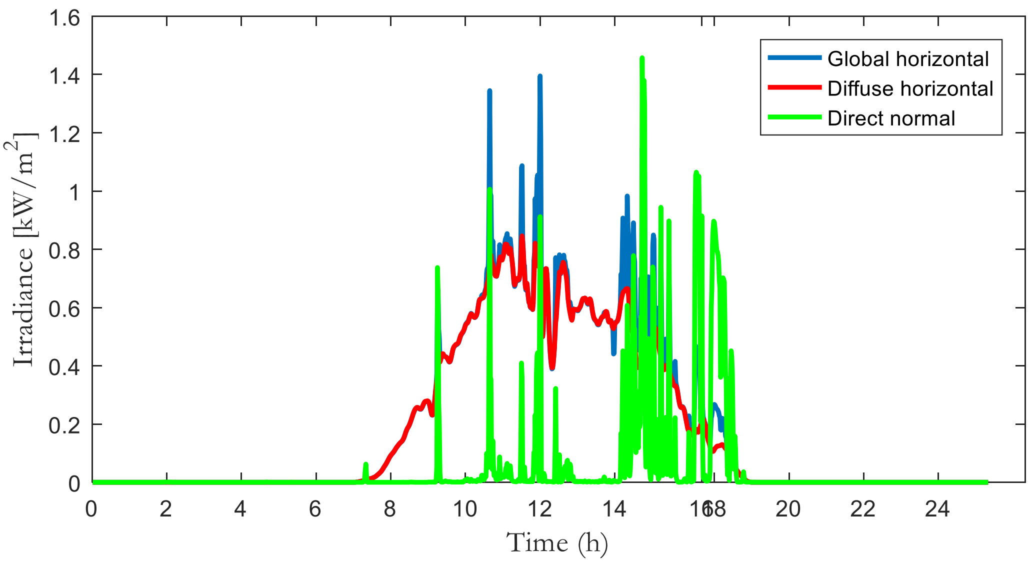

Figure A2: Sun radiation curve (Winter)

APPENDIX B: ONE DAY OF EACH MONTH PV OUTPUT POWER

Table B1:

PV output power (kW)

Time	Total PV output power Winter			Total PV output power Summer							
	Realtime data extrapolated with reference to 20 December 2018.										Data
	Jun	10-Jul-18	Aug	Jan	Feb	Mar	Apr	May	Sep	Oct	Nov	20-Dec-18
00:00	0	0	0	0	0	0	0	0	0	0	0	0
01:00	0	0	0	0	0	0	0	0	0	0	0	0
02:00	0	0	0	0	0	0	0	0	0	0	0	0
03:00	0	0	0	0	0	0	0	0	0	0	0	0
04:00	0	0	0	0	0	0	0	0	0	0	0	0
05:00	0	0	0	0	0	0	0	0	0	0	0	0
06:00	0	0	0	2.244	1.842731	1.443591	1.222984	1.166585	1.92415	2.082345	2.240539	1.22
07:00	0.127662	0.114	0.187988	5.004	4.109192	3.219131	2.727189	2.601421	4.290751	4.643517	4.996283	2.502
08:00	0.415463	0.371	0.611785	5.776	4.743144	3.715768	3.147931	3.00276	4.952714	5.359903	5.767093	2.888
09:00	1.341	1.198	1.97552	5.814	4.774349	3.740213	3.168641	3.022515	4.985297	5.395166	5.805034	2.907

	574		2									
10:00	1.690966	1.51	2.490016	5.84	4.795699	3.75694	3.182811	3.036031	5.007591	5.419293	5.830994	2.92
11:00	2.266566	2.024	3.337611	5.866	4.81705	3.773666	3.196981	3.049548	5.029885	5.44342	5.856954	2.933
12:00	2.132185	1.904	3.139729	5.954	4.889314	3.830277	3.244941	3.095296	5.105342	5.52508	5.944818	2.977
13:00	2.190417	1.956	3.225477	5.9	4.84497	3.795538	3.215511	3.067223	5.059039	5.47497	5.890901	2.95
14:00	2.362873	2.11	3.479426	5.776	4.743144	3.715768	3.147931	3.00276	4.952714	5.359903	5.767093	2.888
15:00	1.498353	1.338	2.206385	5.688	4.67088	3.659156	3.099971	2.957011	4.877257	5.278243	5.679228	2.844
16:00	1.531948	1.368	2.255855	5.592	4.592046	3.597398	3.04765	2.907104	4.79494	5.189158	5.583376	2.844
17:00	0.255532	0.228	0.375976	5.368	4.408102	3.453297	2.92557	2.790653	4.602868	4.981295	5.359722	2.796

	5											
18:00	0	0	0	4.466	3.667396	2.873029	2.433978	2.321732	3.829435	4.144274	4.459113	2.684
19:00	0	0	0	1.192	0.978848	0.766827	0.649642	0.619683	1.022097	1.10613	1.190162	2.233
20:00	0	0	0	0	0	0	0	0	0	0	0	0
21:00	0	0	0	0	0	0	0	0	0	0	0	0
22:00	0	0	0	0	0	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0	0	0	0	0	0	0