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Forecasting Photovoltaic Electricity Generation at a Private Dwelling in Tshwane, South Africa: A Case Study

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Abstract: ***Green House Gas (GHG) emission and its detrimental effects are by now a well-known phenomenon. Many countries are focussing on reducing their carbon footprint as a result. This has become evident in the move towards alternative, green energy sources such as wind, biogas and solar energy applications. In this paper, the forecasting of solar power generated through a solar installation at a private house in Tshwane, South Africa is discussed. The system comprised 12 photovoltaic (PV) panels, an inverter, two lithium batteries and one solar thermal geyser. Weather data from a nearby weather station was used to develop a model for the prediction of solar energy generated. The inverter provides a web-based interface where output and usage of the electricity is recorded. This data was used of over a one-year period and analysed, to develop a PV electricity forecasting model. The variables included ambient temperature, cloud opacity, Global Horizontal Irradiance, Global Tilted Irradiation (Gti) - Fixed Tilt and Gti Sun Tracking. Both multiple linear regression and Long Short Term Memory (LSTM) models were used to assess their ability to forecast PV electricity generation. The potential PV electricity to be generated for the previous five years was then calculated using historical weather data. Based on the assumption that the next five years would have similar weather patterns, the PV electricity forecasted was calculated. The savings potential and break-even time for the installation were then calculated based on the forecasted PV electricity generation. The break-even periods were calculated for a 5%, 10% and 15% electricity increase per year and ranged from 8 years to 12,3 years. The additional benefits of the systems and possible areas for improvement are also discussed.***

Keywords: PV power, solar power generation prediction model, domestic PV, off-grid domestic power

1. Introduction

The world-wide climate change challenge has placed emphasis on alternative energy sources including solar systems. Although, the southern region of Africa particularly has an abundance of solar radiance, very little of the power generation comes from solar sources. South Africa's energy generation capacity is about 51 megawatts of which 91% is from coal-fired thermal power stations and only 8,8% from renewable energy sources [1]. In addition, the South African power generation infrastructure fleet is aged with frequent breakdowns [2]. This situation combined with inadequate maintenance and management has placed South Africa in an electricity crisis since 2008. Since then the main electricity provider ESKOM has been using intermittent load shedding ("rolling blackouts") to cope with the electricity demand due to the requirement to keep at least 15% of generation capacity in reserve for network stability [3]. The impact of load shedding on the South African economy has been severe and it was projected that growth will be as little as 0.5% in 2020 - before the Covid-19 pandemic [4]. Consequently, in 2020 South Africa has been downgraded to below investment grade by Moody's [5]. Load shedding has had a serious impact on business and households. Small businesses in particular, are struggling due to a loss of operational time or alternatively the high cost of using generators. The Covid-19 pandemic in South Africa caused energy demand to reduce in March 2020 with an estimated 7500 MW to 9000 MW, alleviating the load shedding [6]. However, as the government started opening up the economy the load shedding resumed in June/July 2020.

With the focus on climate change, alternative, green energy has become critical and energy sources such as wind and solar is projected to provide 30% of all energy use by 2040 [7]. A number of authors have discussed the use of solar energy in private dwellings and showed that the results can vary significantly depending on the type of system and the local weather [8]. Hybrid photovoltaic (PV) and thermal storage systems have been shown to be effective in houses when utilising both batteries and a hot water thermal storage system to replace energy use partially [9]. The performance of solar systems in houses depend on the solar radiance at the particular location as well as factors such as the slope of the roof [10].

This paper discusses the benefits of and payback period for a solar power system combined with a solar geyser in a private house in Tshwane, South Africa as well as the prediction of expected solar power generation based on predicted weather data.

2. Literature

South Africa is not the only country with an energy crisis - this is a global problem. The literature review aims to highlight the benefits of renewable energy sources, with a focus on solar energy.

2.1 Energy challenge

The energy problem is complex and multifaceted when one considers the continued increase in the global energy demand, stagnant oil production, price instability, economic growth and an awareness of the health and environmental implications of greenhouse gasses [11],[12]. The solution to many of these problems can be provided by renewable energy sources by producing a secure and reliable energy supply with lower carbon emissions [13]. Renewable energy sources, however, only suppled 26% of the world's total energy in 2018 [14]. Therefore, the development of these renewable clean energy sources should be a top priority.

One of the sectors with the highest demand for energy is the building sector. About 40% of the primary end-use energy is consumed by building in both the USA and European Union [15]-[17] and account for nearly 40% of the total direct and indirect CO_2 emissions globally [18]. This makes buildings and the building construction sector, sources of unexploited energy efficiency. One of the main focuses in residential buildings has been reducing energy consumption and increasing energy performance through sustainable building designs [19]. Coupling this with renewable energy sources has led to the development of Energy Efficient Buildings. Energy Efficient buildings draw energy from outside equal to or less than the energy produced on site, these buildings are known as Zero Energy Buildings (ZEB) [20].

Several renewable energy systems are available for buildings including small wind and hydro electrical generators and solar panels (thermal and electric). Globally extra effort, on a technological and political front, have been directed to solar energy systems due to its potential to deliver clean sustainable energy [19].

2.2 Solar energy system classification

According to [21] solar energy systems can be classified into the following continuum:

- Passive and active;
- Thermal and photovoltaic; and
- Concentrating and non-concentrating.

Passive solar energy systems collects energy without altering the heat or light into any other form for example through the design of a building maximizing the use of daylight or heat [22]. Active solar energy systems harness solar energy by transforming or storing it for other applications and can be classified into photovoltaic (PV) or solar thermal systems.

PV systems transform radiant energy into electrical energy when light falls on a semi-conductor material. Crystalline silicon-based PV cells and thin film technologies with different semi-conductor material are the types of PV systems available in the market today. In contrast, solar thermal systems use heat from the sun for direct heat or thermal application or electricity generation [21]. Over the past few years researchers have also developed a hybrid photovoltaic-thermal (PV-T) systems.

PV-T system help to maintain a low cost of solar energy production by maximizing the energy generated per square meter of roof coverage. This system generates both useful thermal energy and electricity from the same contact area. It can also be integrated with conversion or energy storages devices to provide multiple outputs [13].

2.3. Advantages of using solar energy

Solar energy from a primary energy perspective is abundant, sustainable and clean [13]. It addresses the energy problem on an economic, health, environmental and security level [23].

The potential annual technical energy supply that can be generated form solar energy is significant, especially in Sub-Sahara Africa where there is an abundance of annual clear sky irradiance and clearance with large patches of available land. From Table 1 it is clear that the technical potential solar energy supply in Sub-Sahara Africa alone is significantly greater than the primary energy demand for the whole of Africa.

Table 1: Annual technical minimum and maximum potential of solar energy and primary energy demand in Million tonnes of oil equivalent (Mtoe) [21], [24]

	Annual technical minimum	*Annual technical maximum*	*Primary energy demand 2008*	*Primary energy demand 2018*	*Primary energy demand 2040*
Sub-Sahara Africa	8 860	227 529	505	-	-
Africa	-	-	-	831	1300

Solar energy systems are also resilient to political instability and oil or gas price fluctuations since their cost is an upfront investment and running cost like operating and maintenance is minimal [13]. Solar PV systems for example can operate for more than 20 years with little deterioration for example, researchers have observed only a 0.5% power output loss per year on average [25].

A study comparing life cycle costing effectiveness of PV solar systems for residential dwellings in eight major cities in Australia, conducted over 25 years, found significant financial saving for residential owners. The study showed that all residential owners not only covered the initial installation cost, but also benefitted from the life cycle cost saving within the first 15 years [19]. The researchers observed savings of between $273 and $53 021 on the life cycle cost, with percentage of between 0.35% and 123%. Capacity ranges of the PV system investigated was 1.5kW to 5 kW in relation to the number of occupants in the dwelling and the researchers compared different types of grid connections. These grid connections included gross-feed-in-tariff (GFIT)[1], net-feed-in-tariffs (NFIT)[2] and a buy-back scheme[3].

[1]Homeowners sell all the renewable energy generated form the PV to the electricity retailers. All electricity consumed by the household is bought form the retailers.

In Tehran a four-member family home, utilizing both passive and active solar energy strategies, was investigated by [26]. The annual electricity consumption was 4 105 kWh while the electricity generated by solar system was 11 543 kWh. The household sold the excess electricity to the grid. An economic analysis conducted by the researcher found that with the price of electricity close to that of the European Union and interest rates at 4.9%, the payback period for this system was 10 years. Unfortunately, due to high interest rates and low price of energy in Iran the researchers deemed the investment in this system as unjustified. For South Africa, this may not be the case due to the instability of electricity supply due to the rolling back outs as well as the expected increase in electricity prices over the next few years.

The potential of PV systems for residential homes in Lagos, Nigeria was conducted by [27]. Nigeria accounts for one of the lowest per capita electricity consumption in the world, about 3% of South Africa's. Despite this the study found that the levelized cost of electricity (LCOE) for a PV system range between 0.395 USD/kWh and 0.743 USD/kWh and estimated a 31.24kgCO_2eq to 7456.44 kgCO_2eq annual reduction of green house gas emissions.

A study conducted by [28] looking at the average economic performance of solar water heaters for low density dwelling across South Africa found an average payback period of eight year for the system. Using data from 2015 the author noted that solar savings rapidly overtook labilities, such as maintenance and mortgage repayments.

Usually financial gains are achieved through limited or no interaction with the electricity grid known as self-consumption or independence, in other words the user generates the energy required onsite, thus reducing the electricity bill [13]. According to [29] total grid disconnection (off-grid systems) for individual households with the technology available is difficult to achieve from an economic viewpoint. This is due to season and daily disparity between energy demand and renewable energy supply. The power output from renewable energy sources cannot be controlled, thus resulting in a mismatch between peak generation and consumption, especially with solar systems not generating energy during the night or reduced generation during winter months [30],[31]. In an off-grid set-up, the additional renewable energy generated during the summer or day is wasted and not used to supplement energy needs during the winter or night. Households can diminish the seasonal disparity with a long-term energy storage device, but this approach with current technologies is not economically viable.

A grid connected ZEB on the other hand does not require on-site long-term energy storage. In this case additional energy is injected into the grid or withdrawn from the grid during periods of insufficient production. [20]. This is called Nett ZEB (NZEB) in other words on an annual basis the building requires no energy input.

Self-consumption[4] and self-sufficiency[5] for NZEBs can be improved with the installation of short-term energy storage devices, thus diminish the daily energy disparity. Studies done in Sweden by [32] and [33] found that PV installations coupled with energy storage devices increased self-consumption substantially. A 5kW per person PV installation with a 3kWh battery increased self-consumption by 614kWh/year. Doubling the size of the battery increased self-consumption by an additional 358 kW/h per year [32]. A battery installation with a capacity range of 5-24kWh with a PV installation of 5.2 kWper person was investigated by [33]. The extreme cases of 5kWh and 24 kWh showed an 18% and 33% increase in self-consumption respectively. Researchers conducted similar studies in the following countries:

- Germany [34]-[39]
- Belgium [40],[41]
- Sydney, Australia [42]
- California, USA [43]
- Spain [44] and
- Tokyo, Japan [45].

The studies above found that batteries had the ability to increase PV electricity self-consumption and self-sufficiency. These studies differed in the degree to which self-sufficiency and self-consumption increased. This was due to differences in applied methods of analysis, the number of households and geographical locations. [46] and[47] point out the need for studies that involve different latitudes and climates and representative sample of buildings and end-users.

A number of benefits to domestic electricity storage exist not just increased self-consumption. Energy storage devices help maintain constant energy supply during outages, result in a lowered grid demand and reduces the household's energy bill [31]. [31] investigated 74 private dwellings with battery connected PV systems. The authors found that batteries not only increase self-consuption by an average of 6% depending on the surplus PV energy and size of the battery and PV system, but that the batteries contributed up to 11% of the household's electricity resulting a maximum annual saving of £45.52 ($68.28).

Energy storage devices not only provide benefits to the user by increasing self-consumption, but also to the operator of the distribution grid. These include reducing peak energy, allow for deferral of infrastructure upgrades, reduce the need for grid expansion and help with voltage regulation[6][47]-[49].

[2] Homeowners are allowed to consume PV generated energy and excess energy sold to the retailers. Therefore, the homeowner only buys electricity if the system does not generate enough.

[3] This scheme is similar to the NFIT but is not regulated by the state or territory government

[4]Self-consumption as defined by [46] is the PV-generated electricity consumed by a household.

[5] Self-sufficiency is defined as the fraction of consumed electricity not bought from the grid [46].

[6] Voltage regulation is achieved through excess energy being stored during the middle of the day on low voltage networks and avoiding high voltage issues on low voltage networks [50].

In conclusion, the increased focus on climate change caused by carbon emissions and the looming energy crisis in some countries make solar power systems attractive and they can assist in solving the problem. Household solar systems may hold the key to success, due to the high demand buildings place on energy supply. Household solar systems will not only help solve the problem but hold many benefits for operators of distribution grids and the household itself. The benefits for individual households, which include stable energy supply and financial gain, depend on many factors. These include the type of grid connection, energy storage devices, geographical location and climate just to name a few. In this case study enhances understanding of the potential benefits that can be obtained from a solar system in a private dwelling.

2.4. Forecasting of PV generation

Meteorological factors such as atmospheric and module temperature, humidity, wind pressure, wind direction and solar irradiance play a major role in the generation of PV power. Variability of environmental factors results in power output changes for PV systems, this therefore, makes forecasting PV power generation difficult. Accurately forecasting power generated by PV systems can reduce uncertainties of PV power on the gird, maintain the quality of the power, ensure system reliability and increase the infiltration level of PV systems. Two broad classes for forecasting models exist namely direct and indirect models [51].

For the indirect model, researchers forecast solar irradiance on different time scales by using methods such as statistical, image-based and hybrid artificial neural network (ANN) or numerical weather prediction (NWP) [52]-[56]. The predicted solar irradiance is input data for commercial PV simulation software packages that include for example TRNSYSM, HOMER and PVFORM [57]. Industry then use these software packages to forecast power generation by PV systems. The direct model on the other hand forecasts power generation by PV systems directly using historical data samples that include meteorological and associated PV power output data [51].

Using both direct and indirect methods, [58] showed that the direct method was better at forecasting the next-day power generation of a PV system. Direct forecasting can therefor achieve accurate forecasting of the power generated by PV systems and a comprehensive literature review on short-term direct forecasting was conducted by [51]. The authors emphasized the importance of the correlation between input (meteorological) and output (PV power generation) values for an accurate forecasting model. PV output and meteorological data can contain peaks, non-stationary components and gaps that may result in forecast errors. To overcome this, preprocessing of input data is required and using one of several available methods. These include normalization [51], stationary, historical lag identification [59], wavelet transform (WT) [51], trend-free time series [60], and self-organizing map [61]. Solar data is usually subjected to both preprocessing and post-processing. For PV power forecasting anti-normalization and wavelet reconstruction are the most popular methods [51].

PV power forecasting methods can be classified into four types based on historical PV power generation outputs. These include (1) persistence, (2) statistical, (3) machine-learning and (4) hybrid methods.

Persistence models are used as a benchmark and only uses PV power output data for forecasting. In this model, the PV output is equal to the output of the previous day at the same time interval and for similar sunny weather [51]. The accuracy for this model however, decreases significantly with time intervals greater than one hour and increased cloud cover [62].

The statistical method uses statistical analysis to forecast power generation using different input variables. Autoregressive moving average (ARMA) and Autoregressive integrated moving average (ARIMA) models are examples of linear statistical methods. ARMA extracts statistical properties form stationary time-series data while ARIMA can handle non-stationary data [63].

Machine-learning models are intelligent and can handle linear, non-linear and non-stationary data patters. This model however requires larger data sets compared to persistence and statistical methods to forecast accurately [51]. Artificial neural network (ANN) method is an example of a machine-learning model. This method is popular due to its increased accuracy, self-adaptively, robustness, fault-tolerance and inference capabilities [61]. Despite this, the method is complex due multi-layered network architecture and may have a reduced reliability due to its requirement of a random initial data set [51].

3. Method

The project objective was to evaluate, through a case study, the performance of a solar electricity supply system that had been installed in a private house in Tshwane, South Africa located at coordinates: -25.774202, 28.343655 (Smit *et al.*, 2020). The solar panels were orientated North 40^o East, at a 26.5^o elevation. The system was monitored and output was recorded over a one-year period. The PV generation was correlated with weather variables recorded at a close-by weather station on an hourly basis. The weather data recorded over a 12-month period was used to construct models for forecasting PV generation at the location. The models were based on simple linear regression analysis as well as Long-Short-Term Memory Recurrent Neural Network methodology.

These models were developed using the following variables:
- Ambient temperature;
- Cloud opacity;
- Global Horizontal Irradiance;
- Global Tilt Irradiation (GTI) Fixed Tilt, and
- GTISun Tracking.

Global Horizontal Irradiation/Irradiance (GHI) is defined as the sum of direct and diffuse radiation received on a horizontal plane. GHI is a reference radiation for the comparison of climatic zones; it is also an essential parameter for calculation of radiation on a tilted plane.

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Global Tilted Irradiation/Irradiance (GTI) is the total radiation received on a surface with defined tilt and azimuth, fixed or sun-tracking. This is the sum of the scattered radiation, direct and reflected. It is a reference for photovoltaic (PV) applications and can be occasionally affected by shadow.

The temperature variable was included because high temperatures have a negative effect on PV generation and PV output can be reduced by 10 to 25% in high temperatures [64].

The predicted versus actual PV was plotted for each of the models and the best fitting model used for further computations. This model wasthen used to predict PV generation for the past five years (2015 to 2019). It was assumed that the PV generation pattern for the next five years from 2019 to 2024 and beyond would be similar. This forecasted PV generation was then used to calculate the savings potential from the installation as well as the forecasted economic benefit per annum to allow the calculation of the payback period for the investment into the installation. The average PV pushed back to the grid as well as the self-use of PV generated electricity was used to calculate potential direct savings. Total direct savings were then used to calculate the potential payback period for the installation. The research method included:

- Review of literature;
- Description of system;
- Recording of data using the GoodweSems portal for 12 months;
- Data analysis and development of prediction models;
- Comparison of the results from different prediction models;
- Prediction of potential PV generation over a five-year period;
- Benefit cost analysis;
- Analysis of functional performance, and
- Analysis of lessons learnt.

The research objective focused on the payback period for installation of a PV power generation system at a private house in Tshwane and the evaluation of its performance and effectiveness.

4. Description of the system

4.1. Hardware

The installed system is depicted in Figure 1. It consisted of the following:

- 12 photo voltaic polycrystalline panels – *Canadian Solar CS6U 325*;
- One *Goodwe* inverter with 4,6 kW output – GW5048D-ES;
- Two *Pylontech* lithium batteries – US 2000 2,4 kW (later upgraded to four batteries), and
- One solarised geyser – *Geyserwise TSE*.

The scullery, stove and second geyser remained connected directly to the Eskom grid only to prevent the inverter from being overloaded beyond its maximum capacity of 4,6 kW. Overloading can occur when appliances such as a kettle and an iron are used simultaneously. Overloading causes a temporary cut in power and the system will only re-boot after 10 minutes provided that an external power source is available (solar panels or grid power). In the absence of an external power source, the system will remain dormant until such source is restored.

The inverter can draw power from the Eskom grid as well as feed excess PV generation back into the grid. This was possible due to the "dual way" meter that was installed at the house and allowed by the electricity metering company. The *Goodwe* inverter comes with a wi-fi radio that allows for wi-fi connection to the house's internet router. The limitation on a good wifi connection is for the inverter to be less than 5 meters from the router.

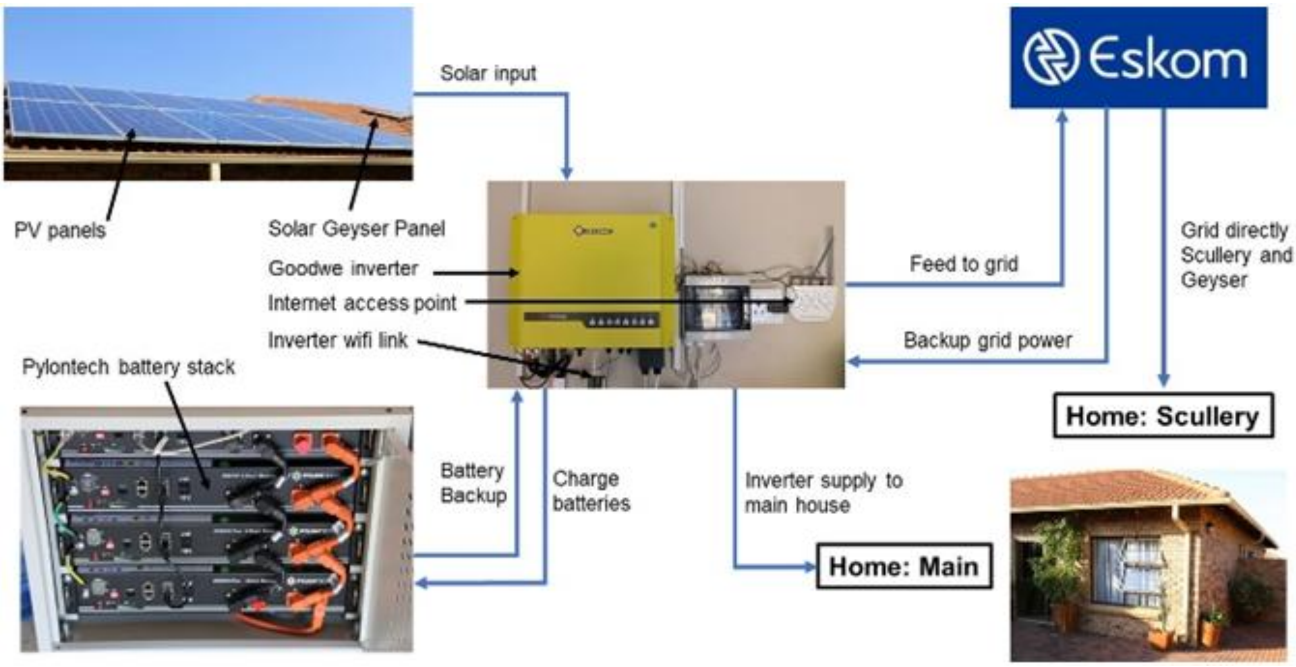

Figure 1: Layout of the solar system

4.2. The SEMS portal

The *Goodwe* inverter comes with a portal (and associated mobile App) that records performance data of the system through the wi-fi connection that can be downloaded and analysed. Several standard graphs are available on the system. These are described below.

The landing page of the SEMS app provides information on the real time PV generation as well as the tatus of the system. This is usually in a typical bell-shape unless there are periods of cloud cover. The information is also available for the past month or year.

The second page in the *SEMS* App is shown in Figure 2. It contains information on:
- Continuous PV generation for the day (blue curve);
- The state of charge (SOC) of the batteries (green curve);
- The total power consumption at the dwelling (red curve);
- The meter reading (yellow curve) which can be negative when power consumption is more than the PV supply or positive if the PV supply exceeds consumption, and
- The power used to recharge the batteries (purple curve).

The figure shows two instances of load shedding. Firstly, during the day when the PV generated power supplied the demand and secondly, during the night when the batteries supplied the demand. The drop in battery reserve (State of Charge or SOC) is indicated by the green curve. This is followed by an increase in SOC as the batteries were recharged from the grid after the load shedding was discontinued. For safety reasons, when the grid is down, the *Goodwe* inverter automatically does not push excess power back to the grid.

Figure 3 shows the data collected by the system during a period with a longer power break due to an ESKOM grid failure. Figure 4 shows that the Sate of Charge of the batteries (two *Pylontech* batteries at that stage) reduced to 50%. It is shown that the system provided continuous power during the event. In the five hours of power break, the batteries used 50% capacity of the 4,8 kW storage. The *Pylontech* batteries can only discharge to a minimum of 10% of SOC. This implies that the system can supply power for about 7 to 8 hours using only fridges, lights, TV and the kettle.

The data in the *SEMS* App can also be displayed over a period of a month or a year as depicted in Figures 4 and 5.

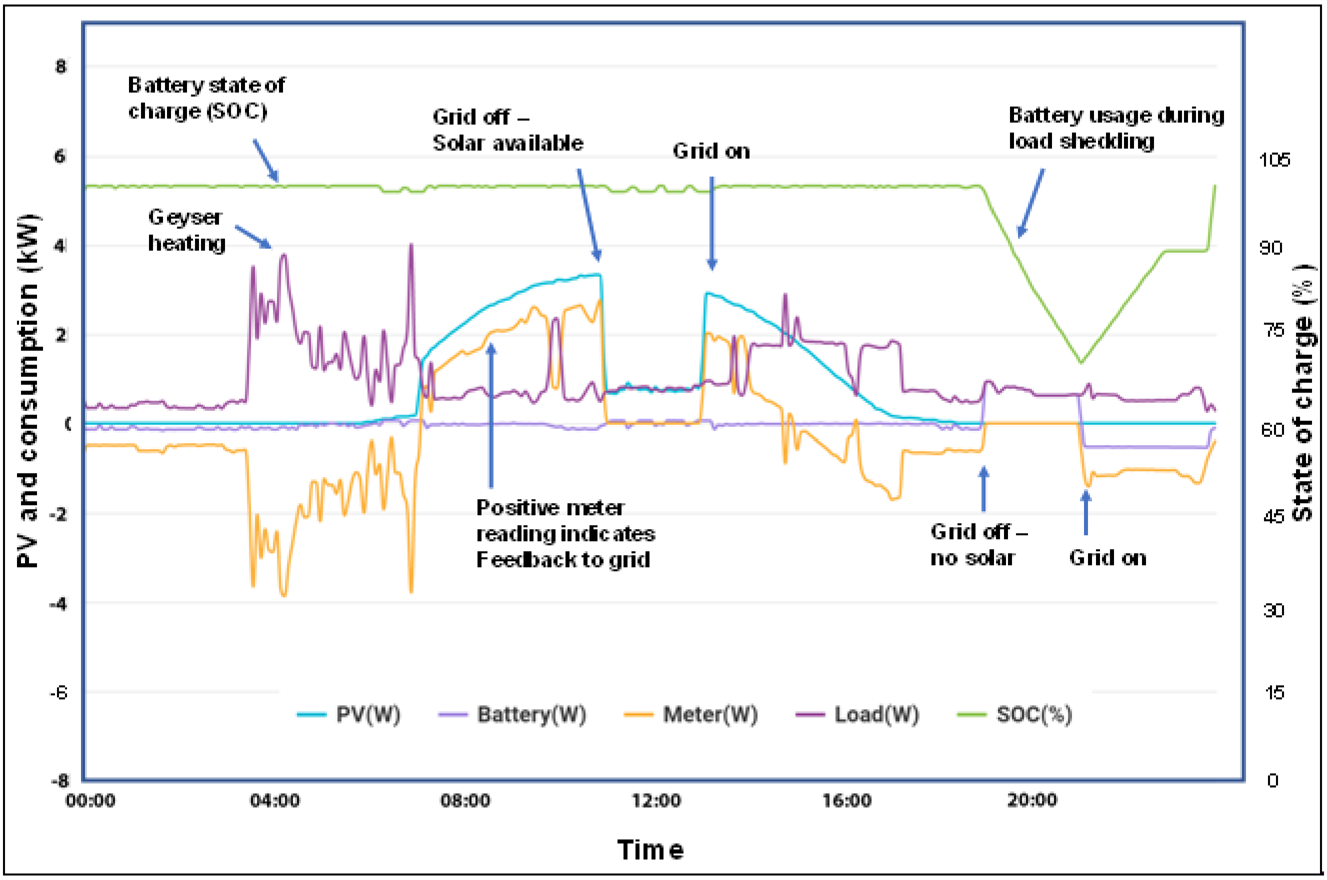

Figure 2: *SEMS* App graph indicating generation and usage in the system[65]

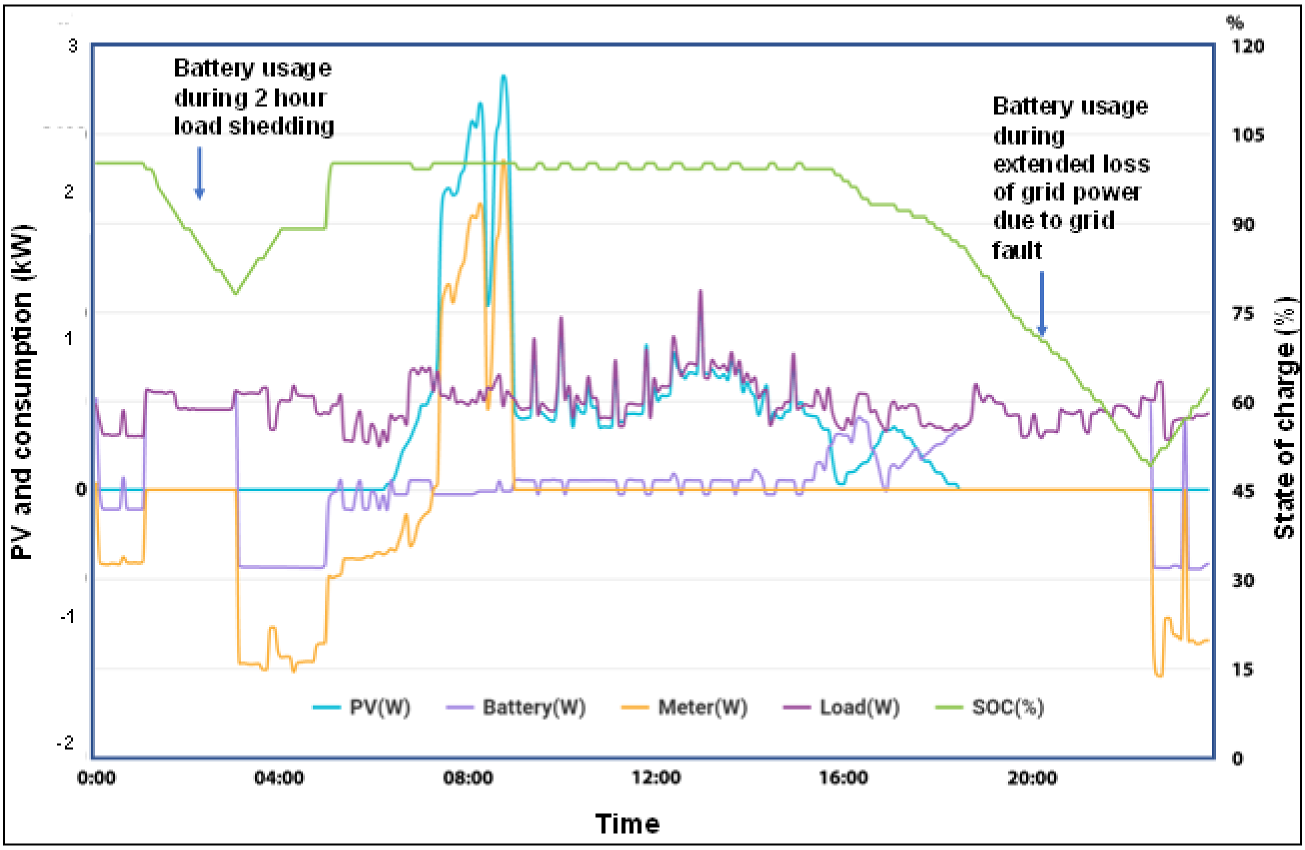

Figure 3: System performance during a long power break [65]

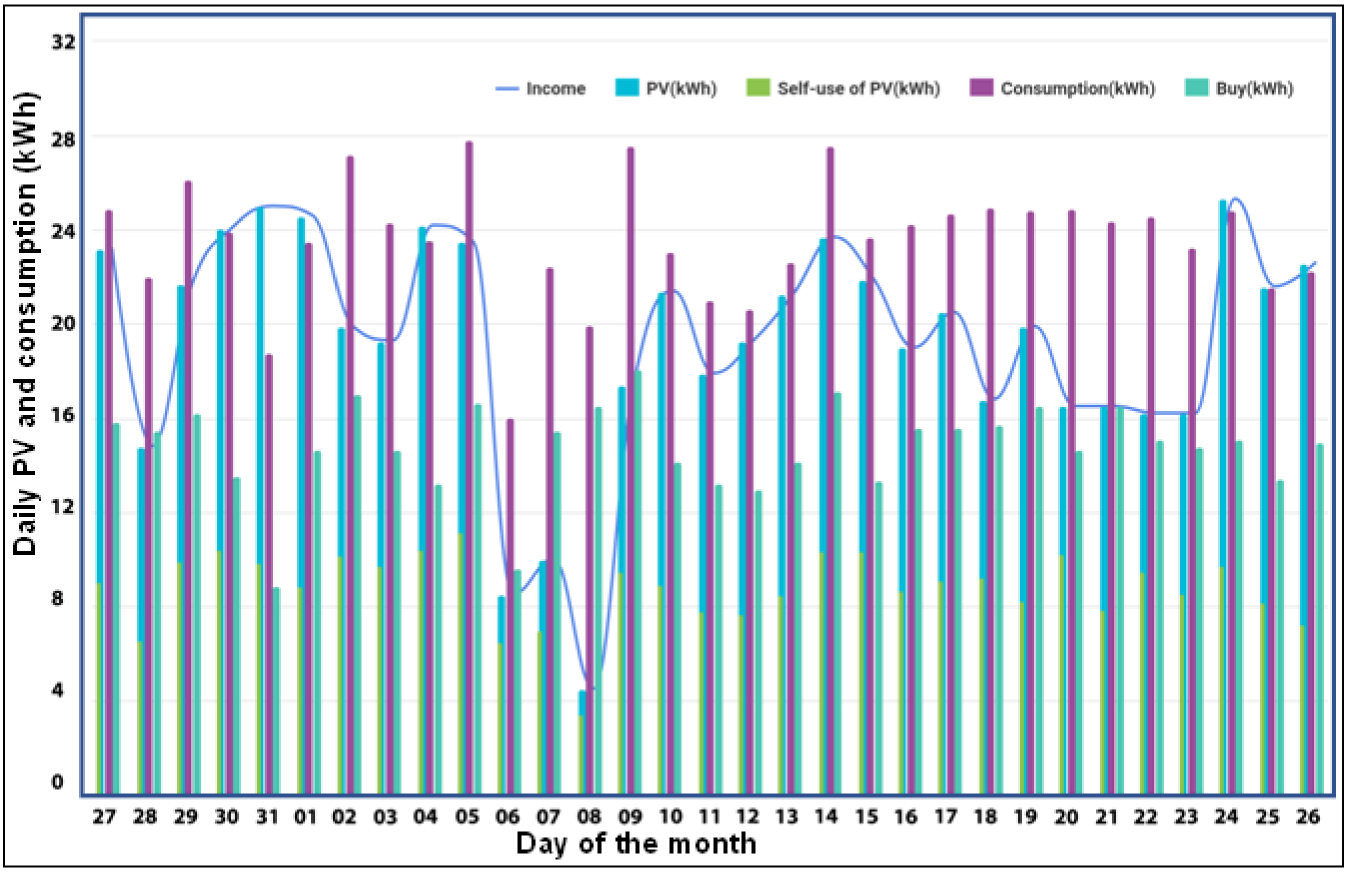

Figure 4: Daily display of PV generation, self-use and consumption [65]

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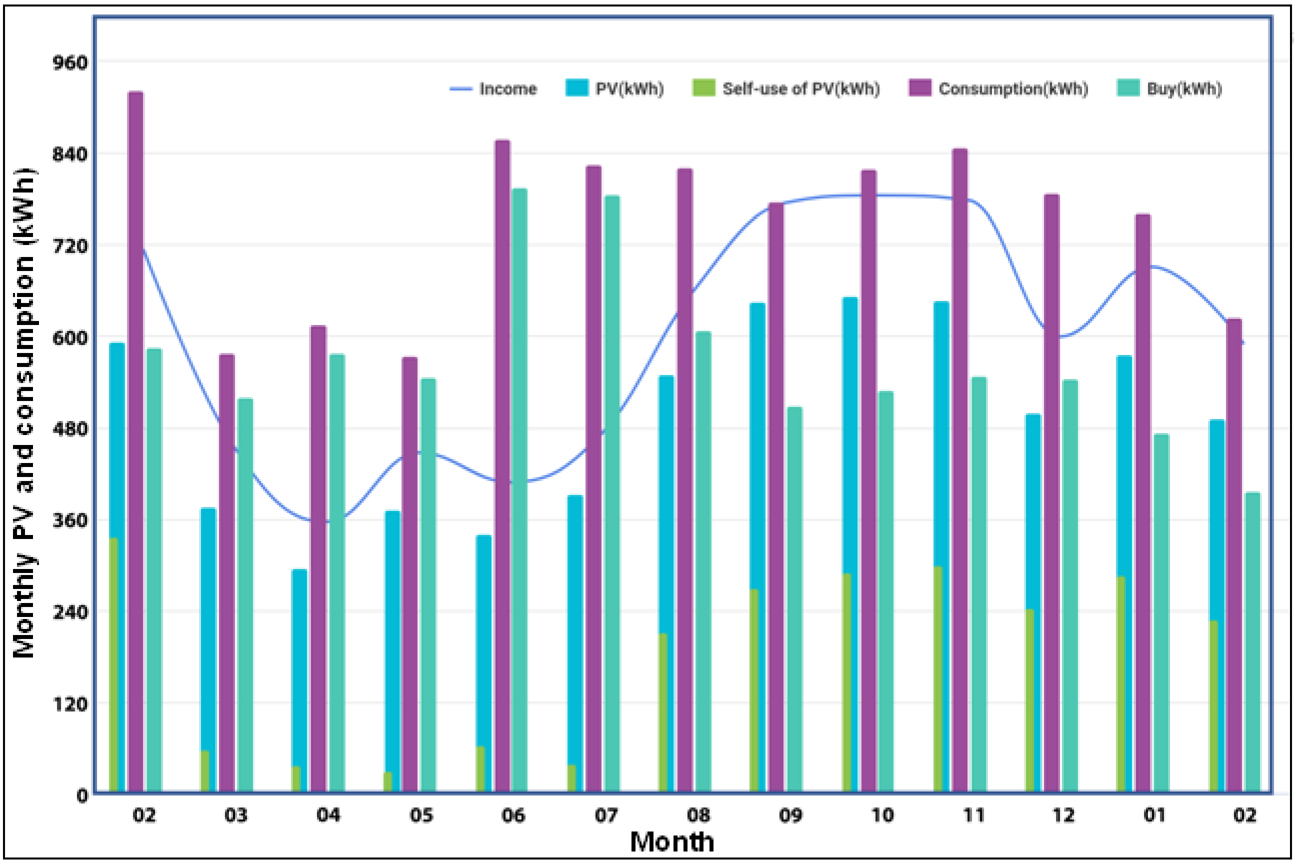

Figure 5: Monthly display of PV generation, self-use and consumption [65]

5. Forecasting of PV generation

In this study the authors used the following analysis methods to develop predictive models that can be used to forecast the PV generation:

- Multiple linear regression using Excel;
- Long-Short-Term-Memory Recurrent Neural Network methodology [66] with hyperparameter tuning at 50 epochs (LSTM1);
- Long-Short-Term-Memory Recurrent Neural Network methodology with hyperparameter tuning at 100 epochs (LSTM2), and
- Long-Short-Term-Memory Recurrent Neural Network methodology with hyperparameter tuning at 150 epochs (LSTM3).

The Adam optimizer with a learning rate of 0.01 and a categorical cross-entropy was used for the Recurrent Neural Network analysis of the 50 and 100 epoch models. For the 150 epochs model a learning rate optimizer was used with a decay step of 100 and a decay rate of 0,3.

The weather data collected from a weather station near the dwelling was analysed to determine possible variables that can be used to predict PV generation.

A *Python* pvlibsoftware library was used to determine a heatmap of correlation between PV generation and the variables. The heatmap indicated some correlation between PV generation and the following weather variables:

- Ambient temperature;
- Cloud opacity;
- Global Horizontal Irradiation (GHI);
- Global Tilt Irradiation (GTI) - Fixed Tilt, and
- GTISun Tracking.

It was found that the LSTM3 option provided a better correlation than that of the LSTM1 and LSTM2 option. The results of the regression analysis for the multiple regression and the LSTM3 option are shown in Table 2.

Table 2: Results from multiple linear regression analysis

	Multiple regression	*LSTM3*
Multiple R	0.858470829	
R Square	0.736972165	
Adjusted R Square	0.736581104	
Standard Error	0.511742883	
Observations	3369	3369
Variable	*Coefficient*	*Coefficient*
Intercept	-1.1511746	-0.37155658
Tamp	0.059056549	0.02355061
Cloud opacity	-0.001532649	-0.00232762
GHI	0.000943837	0.00236510
GtiFixedTilt	0.001943403	-0.00087740
GtiTracking	-0.000549336	-0.00073156

The multiple regression analysis of the 3 369 observations of hourly data of PV generation data correlated with the weather data provided a R^2 value of 0.74 which is reasonable. The actual measured PV generation vs the predicted PV generation is plotted in Figure 6.

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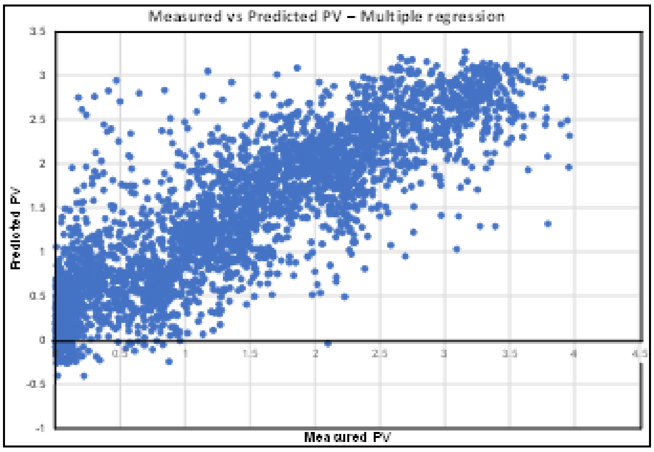

Figure 6: Measured vs predicted PV generation from multiple regression

The result of the correlataion using the LSTM3 model is shown in Figure 7.

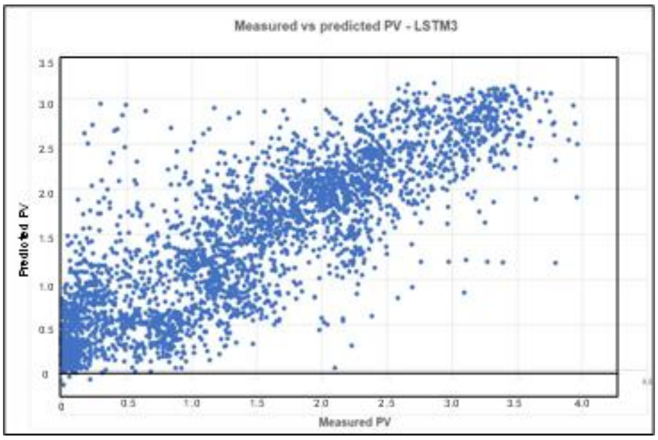

Figure 7: Measured vs predicted PV generation from the LSTM3 model

The results from the two approaches were similar and the multiple regression data was used for further calculations. The predicted monthly PV generation over a 5-year period from 2014 to 2018 was then calculated as shown in Figure 8 and in Table 3.

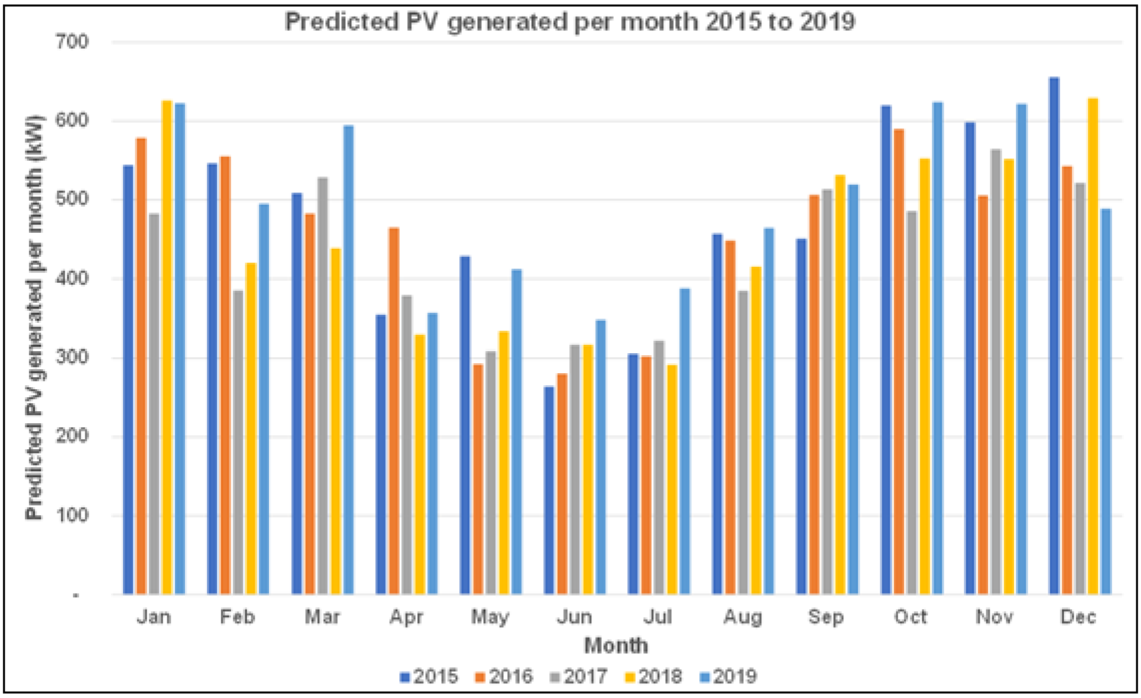

Figure 8: Predicted PV generation based on model in Table 2 [65]

Table 3: Detail predicted monthly PV generation from 2015 to 2019 (kW)

	2015	*2016*	*2017*	*2018*	*2019*
Jan	544	579	483	626	623
Feb	546	555	385	420	495
Mar	509	483	529	439	594
Apr	354	465	379	329	357
May	428	293	309	334	412
Jun	264	280	316	316	348
Jul	305	303	321	291	388
Aug	457	448	385	416	464
Sep	451	506	514	531	519
Oct	620	590	486	552	624
Nov	599	506	564	552	622
Dec	655	543	522	629	489

As indicated above, it was assumed that the next five-year period (2019 to 2023) and beyond will experience similar weather conditions and therefore result in similar PV electricity generation. The data in Table 3 was therefore used to calculate the potential savings for the future.

The savings due to self-use of the PV generated electricity as well as push back into the grid was calculated based on a cost of electricity for the Tshwane municipality of R2.04 per kWh (2019). Due to expected annual increases of between 10% and 15% per annum [67], the cost was escalated at 5% (inflation), 10% and 15% respectively to calculate the break-even point for the initial investment of R107,000 (2018). The interest lost due to the investment was calculated at 6% per annum. The savings due to PV power generation is indicated in Table 4 assuming a 10% annual increase in electricity cost. The break-even point calculations for the 5%, 10% and 15% scenarios are shown in Figure 9.

The break-even point for cost recover shown in Figure 9 was 8 years, 9,55 years and 12,33 years for the respective annual increase scenarios. In addition, there was also the additional advantage of being able to continue operations during load shedding and grid failure. This case study result compares well with findings from other studies in literature as indicated above. Studies in Australia indicated a cost recovery period under 15 years and in Tehran cost recovery period of 10 years was found [19], [26].

Table 4: Savings due to PV self-use and "sell" to the grid at 10% increase of cost of electricity (Rand)

	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
Tariff (10% increase)	2.04	2.24	2.47	2.72	2.99	3.29	3.61	3.98	4.37	4.81
Jan	623	544	579	483	626	623	544	579	483	626
Feb	495	546	555	385	420	495	546	555	385	420
Mar	594	509	483	529	439	594	509	483	529	439
Apr	357	354	465	379	329	357	354	465	379	329
May	412	428	293	309	334	412	428	293	309	334
Jun	348	264	280	316	316	348	264	280	316	316
Jul	388	305	303	321	291	388	305	303	321	291
Aug	464	457	448	385	416	464	457	448	385	416
Sep	519	451	506	514	531	519	451	506	514	531
Oct	624	620	590	486	552	624	620	590	486	552
Nov	622	599	506	564	552	622	599	506	564	552
Dec	489	655	543	522	629	489	655	543	522	629
TOTAL	5,935	5,733	5,551	5,192	5,436	5,935	5,733	5,551	5,192	5,436
Savings (Rand)	12,108.42	12,865.13	13,700.87	14,097.02	16,236.52	19,500.73	20,719.42	22,065.39	22,703.39	26,149.09
Interest	6,420.00	6,420.00	6,420.00	6,420.00	6,420.00	6,420.00	6,420.00	6,420.00	6,420.00	6,420.00
Cum Savings (Rand)	5,688.42	12,133.55	19,414.42	27,091.44	36,907.97	49,988.69	64,288.12	79,933.51	96,216.90	115,945.99

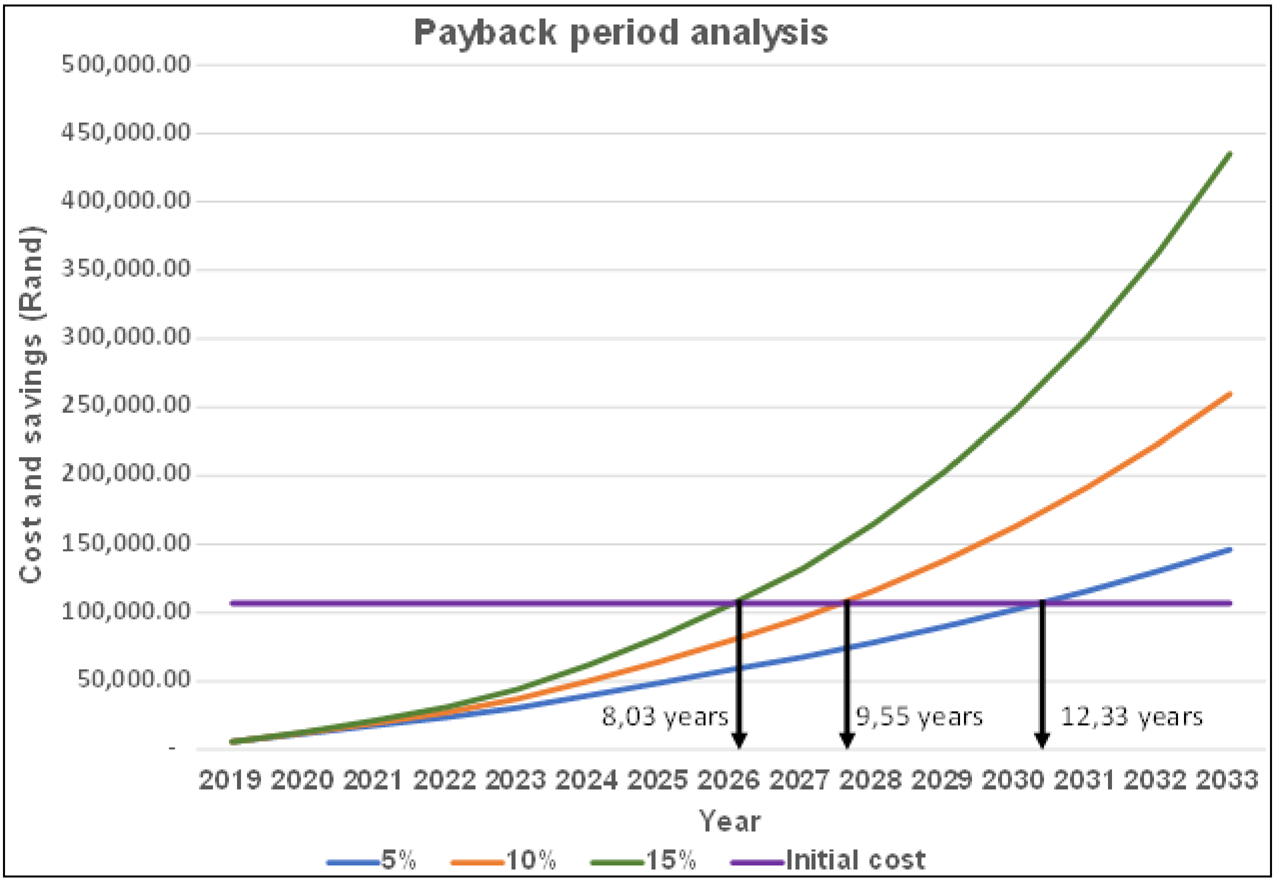

Figure 9: Calculation of payback period for 5%, 10% and 15% annual increase in cost

6. Functional Performance

The system performed well over the evaluation period of 18 months. Power supply was continuous during many load shedding periods as well as through a number of grid breakdown periods. Seeing that the occupants of the house work from home, this provided a significant benefit. Some aspects of the installation can, however, be improved. [65] summarised these aspects as follows:

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- After an overload, improving the rebooting of the system from battery power when both the solar source and the grid is off;
- Providing the solar geyser with a timer, so as to ensure that the solar water pump does not start up to early at sunrise when the water in the solar heating system is still cold, thus cooling the water stored in the geyser;
- Improving the wi-fi connection of the inverter to ensure that recorded date and a real time view of the performance of the system is not lost, and
- The specific installation evaluated initially has only two lithium batteries that were sufficient for load shedding but not for prolonged periods of grid power loss. The system was subsequently upgraded by adding two extra batteries.

7. Concluding Remarks

The solar energy system installation was shown to be a viable option for this building in Tshwane, South Africa. The break-even period for paying back the investment is reasonable and a number of additional benefits were realised. This included the possibility to work from home during frequent period of load shedding and grid breakdowns. A PV electricity forecasting model was developed that can be improved with future data collection. The system performed very well, although a few improvements are proposed.

The initial installation cost for the system described was relatively high and can be a barrier for most households in South Africa, unless there is a trade off with economic activity at the same location. Financial incentives used by other countries should be investigated to enable and facilitate the use of such technology to alleviate pressure on the grid and environment. This also implies that regulation and practice in South Africa should allow household installations to feed power back into the grid thus assisting in the alleviation of South Africa's energy crisis. Nevertheless, solarising a private house remains an attractive option in the current scenario of load shedding and grid breakdowns.

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