Comparison of Photovoltaic and Solar Thermal Hot Water Systems in the South African Context

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Abstract

This study provides a comparison of photovoltaic- (PV) and solar thermal- (solar water heater, SWH) hot water systems for residential use in South Africa. The study was carried out as a financial feasibility analysis using the performance and cost data recorded from the 1.56 kW_p PV and 2.4 m^2 SWH hot water systems installed at 2 separate houses on Mariendahl Farm, Stellenbosch, South Africa. Performance data recorded from these systems, from 1 May 2018 to 30 April 2019, was also used to investigate the financial feasibility of another inexpensive PV water heating system locally available on the South African market. The study compares the performance and financial feasibility of the 4 different alternatives of solar water heating systems over a 25-year period. Financial factors including; capital costs, total savings, net present value (NPV), internal rate of return (IRR) and levelized cost of heat (LCOH) was determined and compared for all of the solar solutions. The SWH and PV hot water systems produced a total of 2 219 kWh_{th} and 1 403 kWh_{th}, respectively, indicating a 45% difference in the annual thermal energy yield. The SWH and PV hot water systems produced annual heat gains of 925 kWh_{th}/m^2 and 140 kWh_{th}/m^2 over the same period, respectively. When comparing the financial outcomes of the study, it can be seen that the 2.4m^2 SWH system provides the largest benefits from a cost perspective, with a payback period of 6 years and a LCOH of 0.04 USD/kWh_{th} over the 25-year period.

Keywords: Photovoltaic, solar thermal, solar hot water, financial feasibility, system performance.

1. Introduction

This study provides a comparison of photovoltaic- (PV) and solar thermal- (solar water heater, SWH) hot water systems for residential use in South Africa. The technical performance and lifetime costs are evaluated and compared. A financial feasibility analysis is carried out using the data gathered from the PV hot water and SWH systems installed at Mariendahl Farm, Stellenbosch, South Africa. The data gathered from these system is also used to investigate the financial feasibility of other inexpensive PV water heating alternatives available on the South African market. Over the years, there has been a noticeable reduction in the cost of solar PV technologies globally, sparking interest in the use of the technology for hot water production within the residential sector, as opposed to SWH systems. In addition, the ease of retrofitting existing hot water storage tanks in residences with the necessary PV panels and immersion heaters, when compared to the labor and plumbing work expected with retrofitting of solar collectors, further drove interests and presumptions that PV alternatives could serve as a more cost-effective solution. This study aims to address the questions relating to this matter within the local context.

The dual alternating and direct current (AC/DC) powered immersion heaters used for hot water production in homes is a relatively new technology in the South African market. An increase in installations of this technology was observed over the past few years as an alternative to conventional SWH systems. These electric immersion heaters, or elements, commonly makes use of Positive Temperature Coefficient (PTC) chips, as opposed to the traditional internal resistance wire, which offers advantages of better safety, greater reliability and lower operating costs (Dulzer,E., n.d.). These dual AC/DC immersion heaters are typically integrated with a maximum power point tracking (MPPT) device and installed in conjunction with a suitable capacity PV system to offer a low-cost solution for producing hot water using solar energy. Dual AC/DC heating elements operate by using solar PV panels to produce DC electrical power during the day that powers the heating element to produce hot water. When there is no solar irradiation, AC power from the grid is used to power the immersion heater to produce hot water. Due to the relatively low cost of solar PV modules and the added benefit of not requiring inverters (direct coupled PV to immersion heater), lower maintenance cost, ease of installation and relatively simple integration into existing tanks available on the market, these PV hot water systems has the potential to be a highly cost competitive alternative to conventional SWH systems for households.

Over recent years, the PV panels, controllers, batteries and dual AC/DC immersion heaters have become more common on the market as a single packaged, low-cost product. However, battery storage incorporated systems are not included in this study. Many of these systems include suitable battery storage solutions to effectively utilize solar energy, however, the feasibility of these types of systems would need to be investigated as capital investments could significantly increase with the inclusion, maintenance and replacement of batteries over the entire system's lifespan.

2. System Description

A PV powered hot water system and a SWH system were installed on two separate residences at Mariendahl Farm outside Stellenbosch in the Western Cape, South Africa, during November 2017. These installations were installed through the Southern African Solar Thermal Training and Demonstration Initiative (SOLTRAIN) and co-funded by the Austrian Development Agency (ADA). The key purpose of the installations was to measure, compare and report on the performance of the types of technologies within the local climate and gain insight on the efficiency, operation and technical and financial feasibility of PV driven hot water systems. The installed systems were designed with a similar thermal capacity, capable of effectively supplying a household with 3-4 residents with hot water. The small-scale residential systems were specifically designed and intended for domestic applications.

Figure 1: PV hot water and SWH system installed at Mariendahl Farm residence in Western Cape, South Africa (SketchUp Free)

The PV hot water system consists of a 1.56 kW_p PV system (6 x 260 W_p poly-Si modules) that powers a 2 kW dual AC/DC immersion heater with MPP tracking. This immersion heater is used to heat the water in a 200 ℓ hot water storage tank. The element is supplied with AC electricity from the grid as a secondary energy source when solar energy is unavailable. The indirect SWH system consists of 2.4 m^2 flat-plate collector which heats a 200 ℓ hot water storage tank. This system is fitted with a 2 kW AC immersion heater which acts as the secondary energy source. Both 200 ℓ tanks were roof mounted with the intention of creating identical environments for both systems.

The systems were equipped with performance monitoring equipment capable of measuring the thermal energy input from both solar technologies supplying each system as well as the heat consumed within the households. The performance data of both systems, measured from 1 May 2018 to 30 April 2019, and cost information of the systems was used in this study to evaluate the performance of the technologies and furthermore to investigate the financial feasibility thereof. Figure 2 and Figure 3 present the schematic layouts of each of the systems, including the monitoring equipment integration used to measure the performance of the systems. The monitoring equipment measures all the required parameters of the systems at 5-minute intervals, allowing for detailed analysis of the system performance. During the monitoring period, the household installed with the SWH had 3 residents, while the household with the PV hot water system had 1 resident occupying it for most of the time.

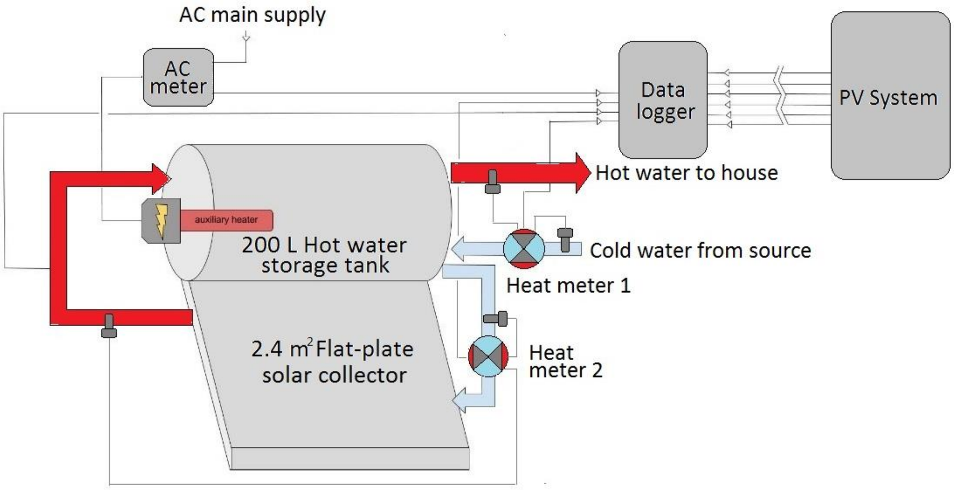

Figure 2: 2.4 m^2 SWH system schematic layout with monitoring equipment

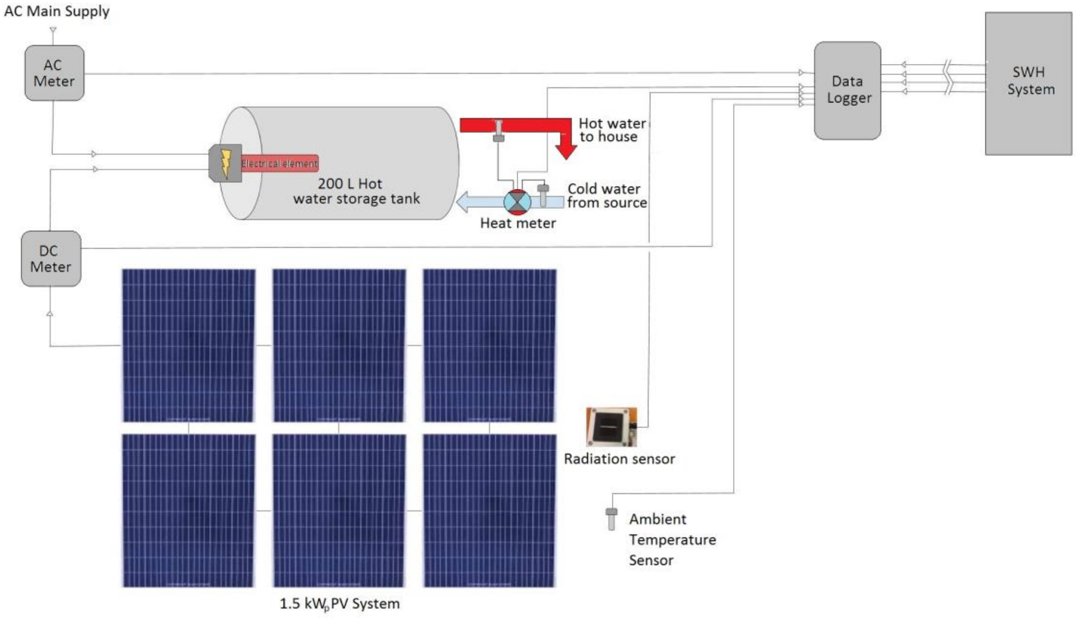

Figure 3: 1.5 kW$_P$ PV driven hot water system schematic layout with monitoring equipment

As seen in Figure 3, the 1.56 kW$_p$ PV system is fitted with a DC meter that measures the DC power supplied to the immersion heater. The PV modules have a total area of 10.05 m^2. In order to simplify the analysis of this study, it was assumed that all DC and AC power supplied to the immersion heaters was converted into heat within the tank (1 kWh$_e$ = 1 kWh$_{th}$). The indirect thermosiphon SWH system, as well as the hot water consumption lines of both households, was fitted with heat meters to measure the heat input and output, respectively. The electricity supplied to secondary AC elements in each system was measured using AC electrical meters. All measurements were recorded on the data logger. The ambient temperature and solar irradiation in the area was also measured.

3. Motoring data evaluation

3.1. Solar thermal energy production

In order to accurately investigate the performance of both types of solar hot water systems, the heat produced by each system was measured and characterized over the annual period from 1 May 2018 to 30 April 2019. Figure 4 presents the monthly heat produced by each of the systems alongside the average daily specific yield based on the total collector/PV area installed.

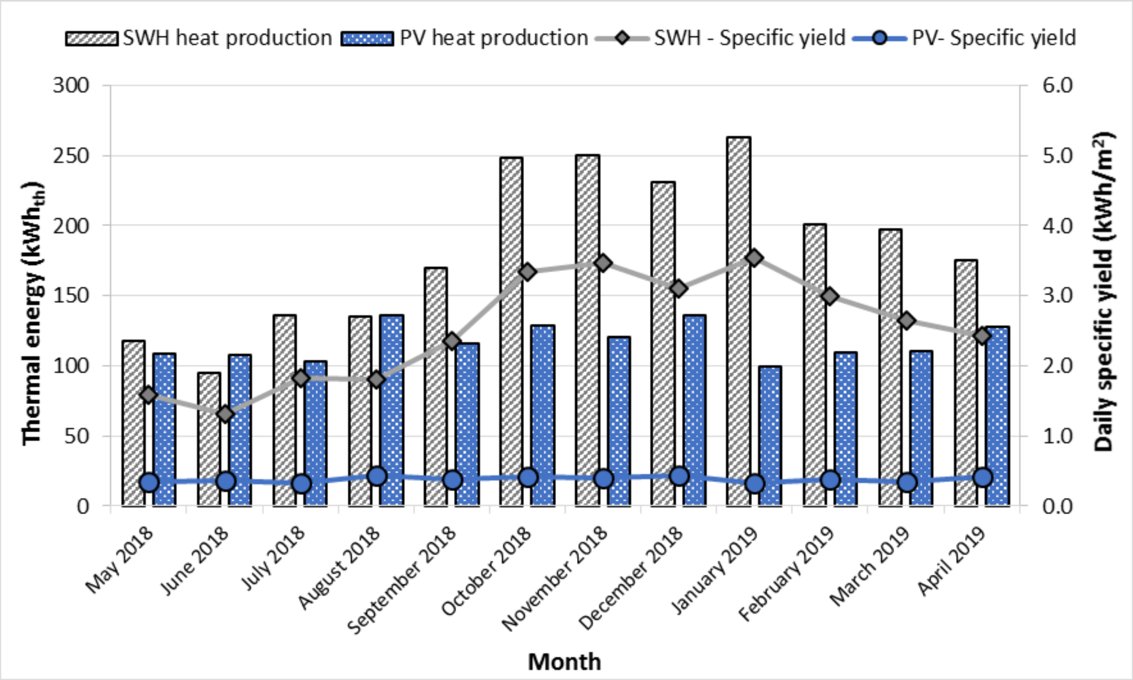

Figure 4: Monthly thermal energy production and average daily specific yield for both system from May 2018 to April 2019

The SWH and PV hot water systems produced a total of 2 219 kWh$_{th}$ and 1 403 kWh$_{th}$ of thermal energy over the annual period from 1 May 2018 to 30 April 2019, respectively. The large difference in heat production is largely attributed to limited performance of the PV driven hot water system, which is set to heat the water to a maximum of 55 °C, irrespective of the available solar energy, and the lower hot water draw-off from the tank on a daily basis. The SWH system is allowed to supply heat to the tank in excess of 55 °C, which allows more heat input from the collector and harnessing more solar irradiation for hot water production.

The SWH and PV hot water systems produced annual heat gains of 925 kWh$_{th}$/m^2 and 140 kWh$_{th}$/m^2 over the measured period, respectively. Figure 4 also shows that the SWH system performed at an average daily yield of 2.53 kWh$_{th}$ /m^2, significantly higher than the 0.383 kWh$_{th}$ /m^2 of the PV hot water system over the year it was monitored. This is primarily due to the lower efficiency characteristics of PV hot water systems (10 – 15%) when compared to SWH systems (35 – 68%) on average, as shown by (Matuska and Sourek, 2017). The lower efficiency largely affects the excessive amount of PV area required to power AC/DC immersion heaters when compared to SWH systems. In this case, roughly 4 times more roof area was required to adequately power the immersion designed for a household of 3 to 4 persons which closely matches the thermal capacity of the 2.4 m^2 SWH system, yet it results in a significantly lower thermal energy yield per m^2.

3.2. Solar resource and system efficiency

The monthly solar irradiation, in kWh/m$_2$, and the monthly efficiency of both systems was investigated and plotted in Figure 5 below. The efficiency values plotted in this figure indicate the systems' ability to produce heat in relation to the total amount of solar irradiation received by the collector/PV area over the entire month

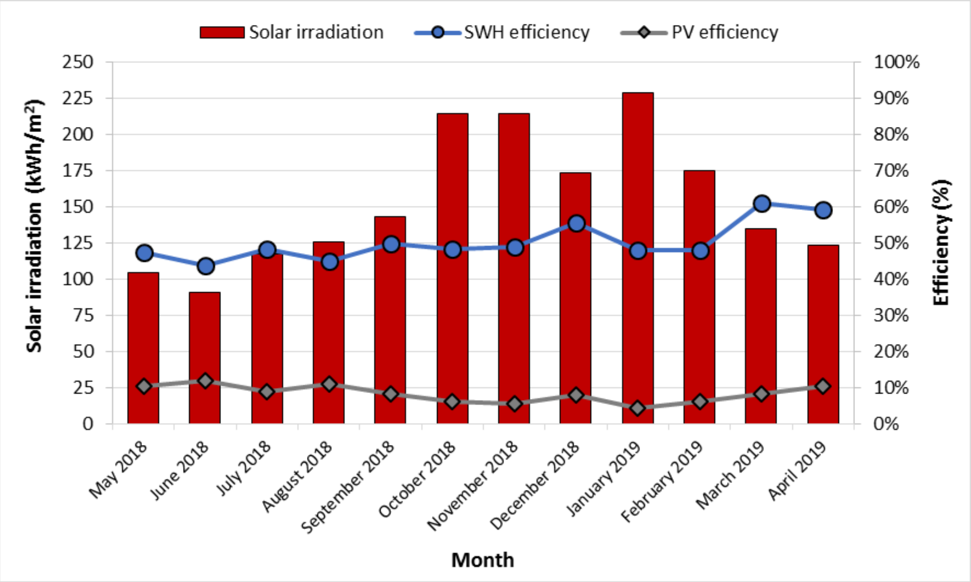

Figure 5: Monthly solar irradiation and system efficiencies for both systems from May 2018 to April 2019

A total solar irradiance of 1 843 kWh/m^2 was measured in the area from 1 May 2018 to 30 April 2019. Figure 5 shows that the SWH and PV hot water systems performed at an annual efficiency of 50.2% and 7.5%, respectively, when based on the total collector/PV area available for harnessing solar irradiation and converting it into heat. The study by Matuska and Sourek (2017) showed that efficiencies ranging from 13 to 15% is achievable with PV hot water systems which includes advanced MPP tracking in European climates. The significant inconsistency of the measured PV efficiency is attributed to a number of factors, primarily, the lower hot water consumption from the household (1 as opposed to 3 residents), limited heat input capability and the omittance of batteries for electrical energy storage.

3.3. Heat demand and hot water consumption

In order to accurately investigate the performance of both types of solar hot water systems, the hot water and thermal energy consumption was measured and characterized using heat meters over the annual period. Figure 6 shows the monthly hot water volume used in each of the households and the thermal energy consumed through this hot water usage.

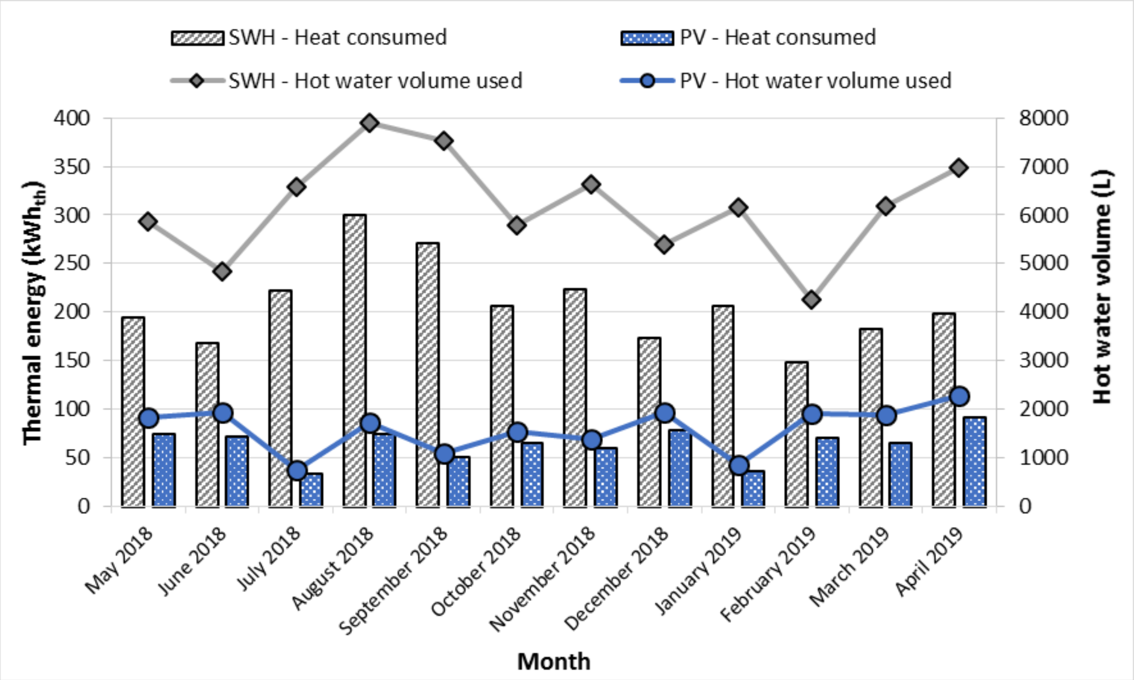

Figure 6: Monthly heat consumption and hot water volume used in each household from May 2018 to April 2019

As mentioned, 1 resident occupied the household installed with the PV hot water system, as opposed to the 3 residents in the household with the SWH system. The sole resident making use of the PV hot water system resulted in a large variation in the day-to-day hot water consumed within the household, which in turn affected the performance of PV hot water system to an extent.

The household with the SWH system used a total of 74 111 ℓ of hot water, amounting to a heat consumption of 2 497 kWh_{th} over the annual period from 1 May 2018 to 30 April 2019. The household with the PV hot water system used a total of 19 126 ℓ of hot water, amounting to a heat consumption of 775 kWh_{th} over the same period. In order to better understand the hot water consumption and heat demand of each household, the average daily hot water usage and attributed heat consumption per person was evaluated, as shown in Figure 7 below.

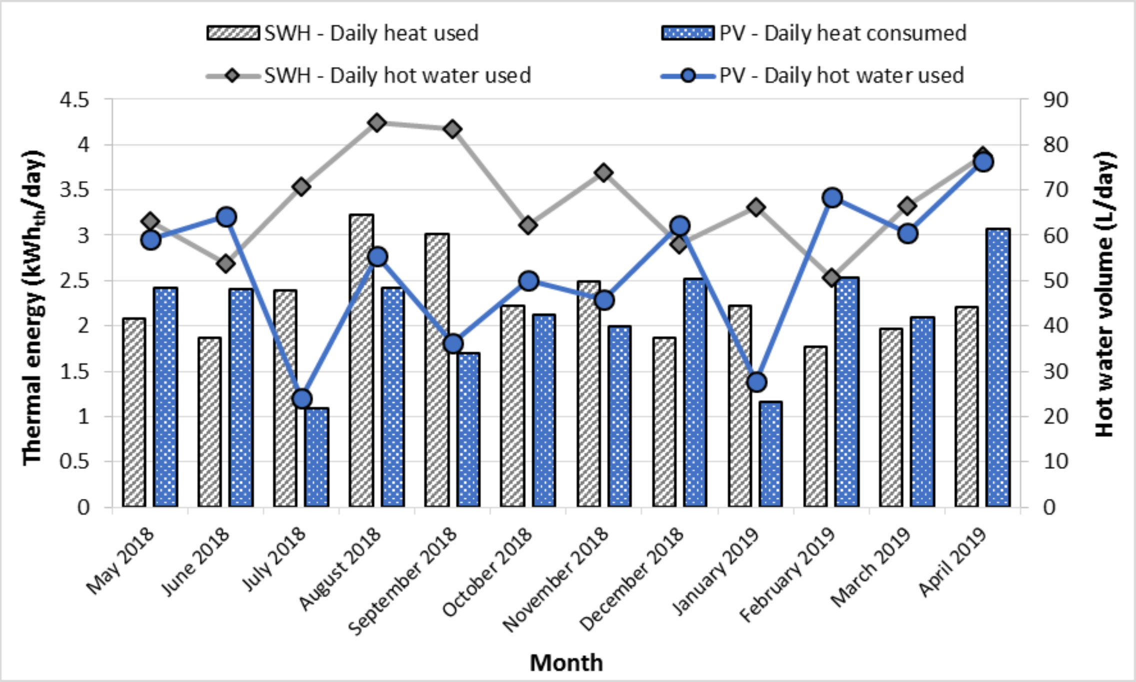

Figure 7: Average daily heat consumption and hot water volume used per person in each household from May 2018 to April 2019

The measurements presented in Figure 7 shows more comparable results in contrast to the overall hot water usage of the households. The residents making use of the SWH system used 67.6 ℓ of hot water per person per day on average, with a heat consumption of 2.28 kWh_{th} /day over the annual period. Similarly, the resident making use of the PV hot water system used 52.6 ℓ of hot water per day on average, with an average heat consumption of 2.13 kWh_{th} /day over the same period.

3.4. Thermal energy balance

The measurements of the energy input for hot water production from the solar technologies and secondary AC immersion heaters as well as the heat consumption from the households allows for accurate thermal energy balances of each system's performance to be determined. The monthly energy balance and solar fraction for the household installed with the 2.4 m^2 SWH system is shown in Figure 8 below.

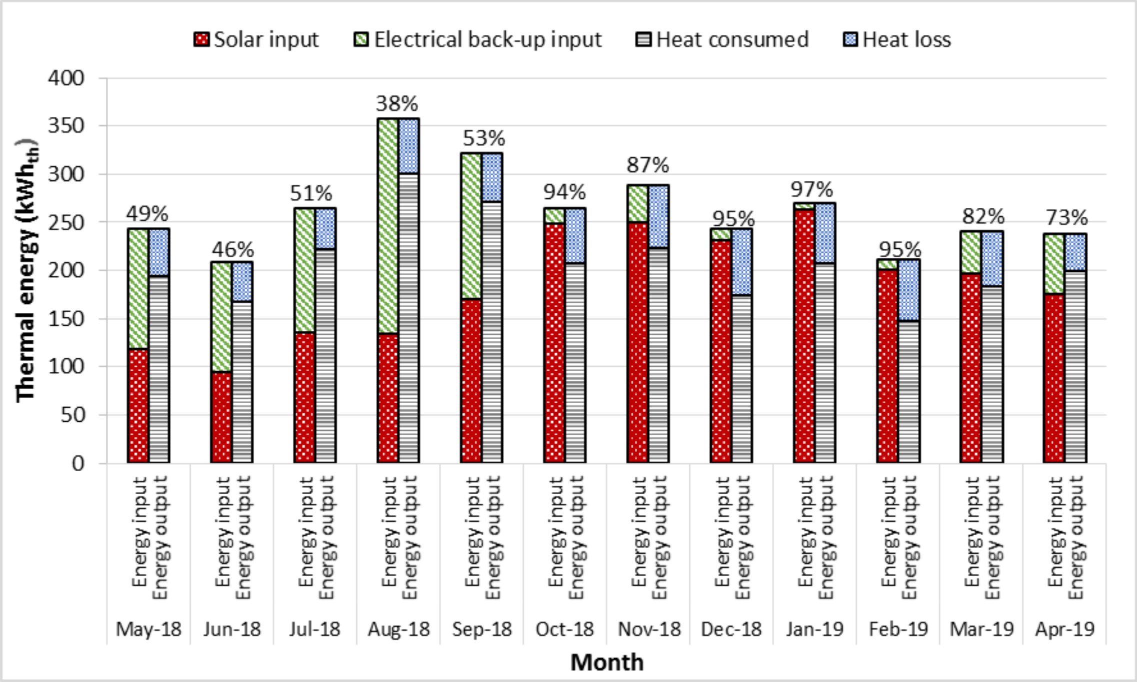

Figure 8: Monthly thermal energy balance and solar fraction for the 2.4 m^2 SWH system household for May 2018 to April 2019

Over the annual period from 1 May 2018 to 30 April 2019, the thermal input from the SWH system and secondary AC heater was 2 219 kWh$_{th}$ and 934 kWh$_{th}$, respectively, while the total heat consumed from the tank was 2 497 kWh$_{th}$. This indicates that the system had a solar fraction of 70.4% over the year. The total heat input to the 200 ℓ tank was 3 153 kWh$_{th}$ and heat losses from the system amounted to 656 kWh$_{th}$ over the year.

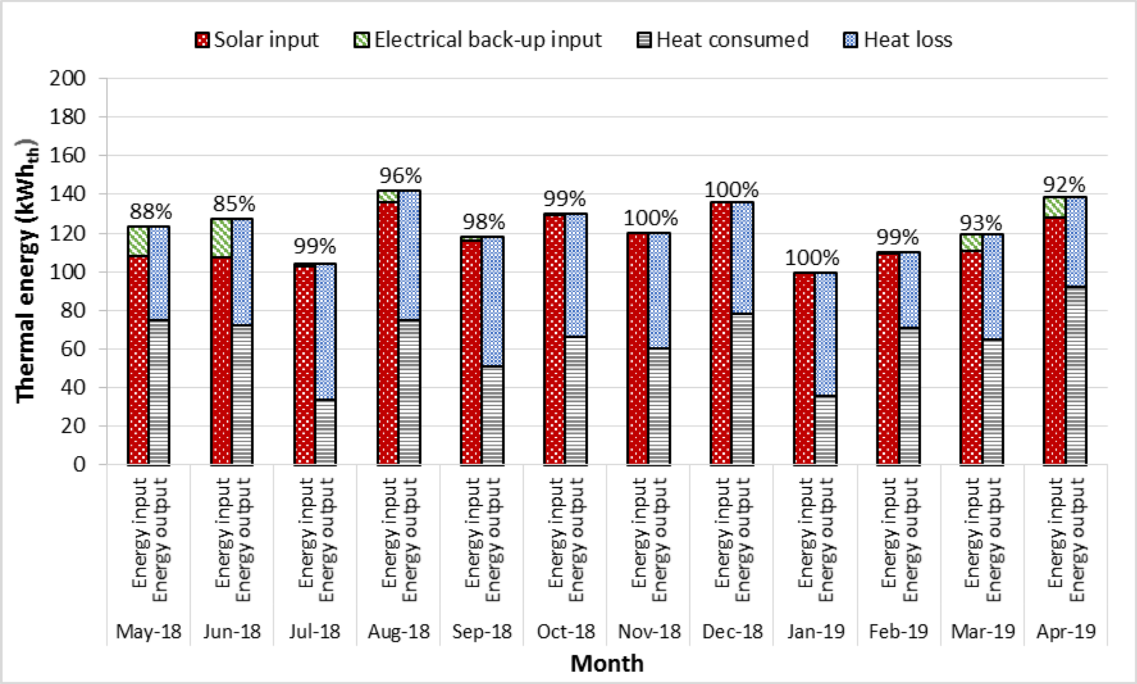

Figure 9: Monthly thermal energy balance and solar fraction for the 1.56 kW$_P$ PV driven hot water system household from May 2018 to April 2019

Over the annual period from 1 May 2018 to 30 April 2019, the thermal input from the PV and secondary AC heating function was 1 403 kWh$_{th}$ and 65 kWh$_{th}$, respectively, while the total heat consumed from the tank was 775 kWh$_{th}$. This indicates the system had a solar fraction of 95.6% over the year. The high solar fraction, when compared to that of the SWH system, is primarily influenced by the lower hot water consumption and the system being designed for a larger usage. The total heat input to the 200 ℓ tank was 1 468 kWh$_{th}$ and heat losses from the system amounted to 693 kWh$_{th}$ over the year.

3.4. Low cost PV water heating systems

Over recent years, there has been large growth in the interest and market penetration of PV hot water systems, and more specifically dual AC/DC type PTC immersion heaters. As a result, solar technology suppliers and installers have introduced PV hot water alternative products onto the South African market that are highly cost competitive with conventional SWH systems. The capital cost of the 1.56 kW$_p$ PV hot water systems installed as part of this study is considerably higher than that of the 2.4 m^2 SWH system and similar technologies currently available on the market. For this reason, it was decided to include the performance and financial feasibility of a lower cost PV hot water alternative currently available on the local market as part of this study.

For the purpose of this study, the performance of a 900W DC/2kW AC PTC immersion heater with a 200 ℓ hot water storage tank was estimated using the performance measurements of the PV hot water system currently installed at Mariendahl for the equivalent hot water consumption of the household over the year. This system makes use of a 900 W$_p$ PV system to power the element. The energy balance of the system is shown in Figure 10.

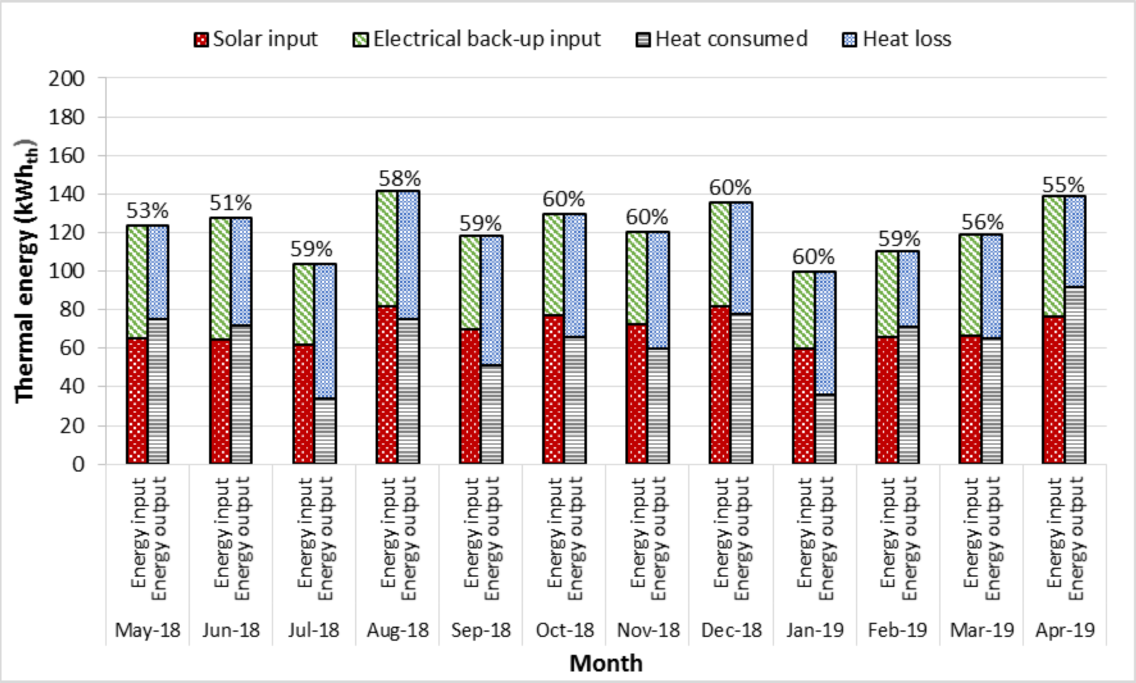

Figure 10: Adapted monthly thermal energy balance and solar fraction for the 0.9 kWp PV driven hot water system from May 2018 to April 2019

Based on the performance computations of this lower cost PV hot water system for the period of 1 May 2018 to 30 April 2019, the thermal energy input from the PV and secondary AC element function would be 842 kWh$_{th}$ and 626 kWh$_{th}$, respectively, for the same volume of hot water consumed by the current resident occupying the household. This indicates a solar fraction of 57.4% for the year.

3.5. System capital cost

The capital cost of a solar hot water system is a key influencing factor for the financial feasibility thereof. The SWH market of South Africa is well developed when compared to that of the solar PV water heating technologies. Therefore, cost and performance expectations of SWH systems within the local context is relatively well understood based on the hot water demand of the household or application in question. In contrary, the interest and understanding of PV hot water systems have only started growing over recent years, which has led to an identifiable growth in the market. Local solar technology suppliers now offer inexpensive “off-the-shelf” PV hot water system packages that can be installed in new-builds and retrofitted to existing hot water storage tanks. All financial calculations were based on the average exchange rate of 13.29 ZAR/USD for the year 2018 (www.irs.gov). For this study, four solar water heating alternatives as listed below was financially analyzed.

1. 1.56 kW_p PV system, 2kW Dual AC/DC immersion heat and 200 ℓ storage tank
2. 2.4 m^2 flat-plate thermosiphon SWH system and 200 ℓ storage tank
3. 0.9 kW_p PV system, 900W DC/2kW AC PTC immersion heater (low cost) and 200 ℓ storage tank
4. 0.9 kW_p PV system, 900W DC/2kW AC PTC immersion heater (low cost) retrofit to an existing tank

This low-cost alternative system was investigated as a complete system which includes a 200 ℓ storage tank for new builds as well a retrofit solution that excludes the costs of the 200 ℓ hot water storage tank, its associated components and installation. Both alternatives exclude battery storage, which is commonly offered with these types of systems. The capital cost breakdown of the systems is shown in Figure 11.

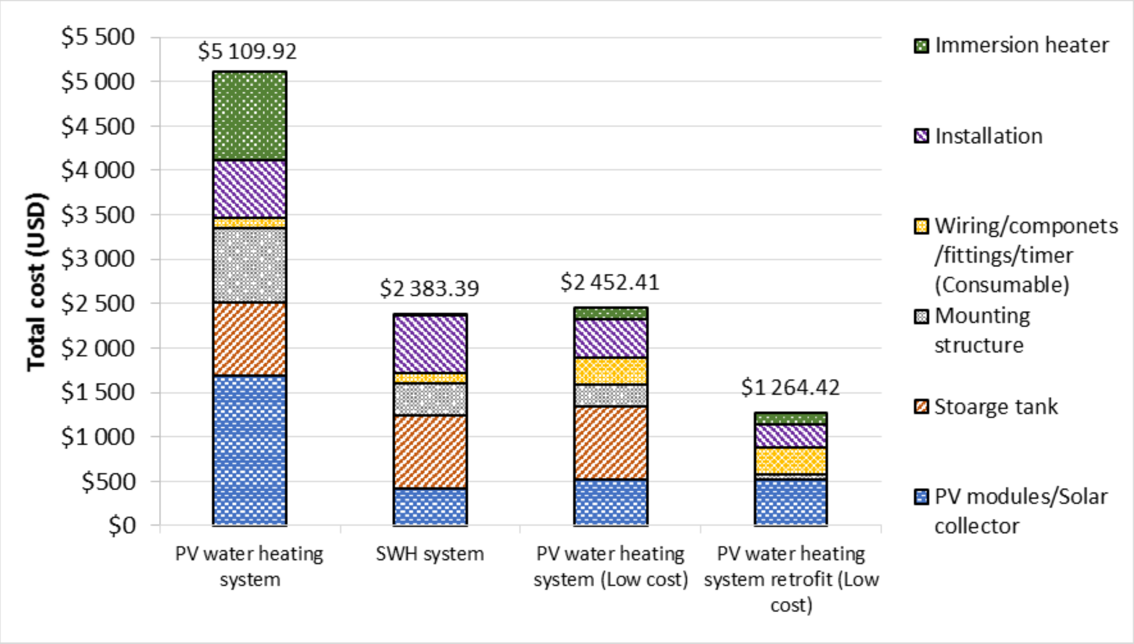

Figure 11: Capital cost breakdown, in USD, of each of the solar water heating systems

4. Financial Feasibility Analysis

The analysis of the performance data made it possible to characterize the annual heat production capabilities of both types of systems. This data also provided a means of characterizing the performance of similar technologies, specifically the aforementioned lower cost 0.9 kW_p PV hot water system with different electrical and thermal capacities. The cost information of these systems can be used to better understand the feasibility of these systems within the local context. The financial outcomes of low-cost PV water heating systems currently available on the local market was also investigated to cover all bases and realize the competitive impact these technologies could have on conventional SWH systems on the market.

Financial indicators determined in this study includes the system's payback period, IRR, NPV, total savings and LCOH. The finances were investigated by adopting a number of assumptions. For the financial calculations, an electricity price of 1.74 ZAR/kWh_e (excl. VAT) (= 0.1315 USD/kWh_e) was used for the first year. The electricity price is based on the Stellenbosch Municipality's tariffs for 2018/2019, which is the tariff applicable to residential customers consuming less than 600 kWh per month on average, representative of the households of this study (Stellenbosch Municipality Tariff Booklet 2019/2020). This electricity cost is assumed to an adequate representation of the average residential electricity cost in the country. The electricity price increase after year 1 was set at 7.32%, which is the increase implemented the following year by the municipality for the specific tariff. After this, a more conservative approach was adopted, assuming an annual increase of 8.6% year-on-year, calculated from the average electricity price increase applied by the national utility, Eskom, over the past 6 years.

Furthermore, the assumptions used in this study was a capital cost rate of 9.25%, inflation rate of 6.7% and capital funded systems. The financial feasibility for systems were investigated over a 25-year period and it was assumed that the PV modules have a degradation rate of 0.5%/year, adopted from the findings of Jordan & Kurtz (2012). Figure 12 shows the annual financial savings generated by each system over the 25-year period.

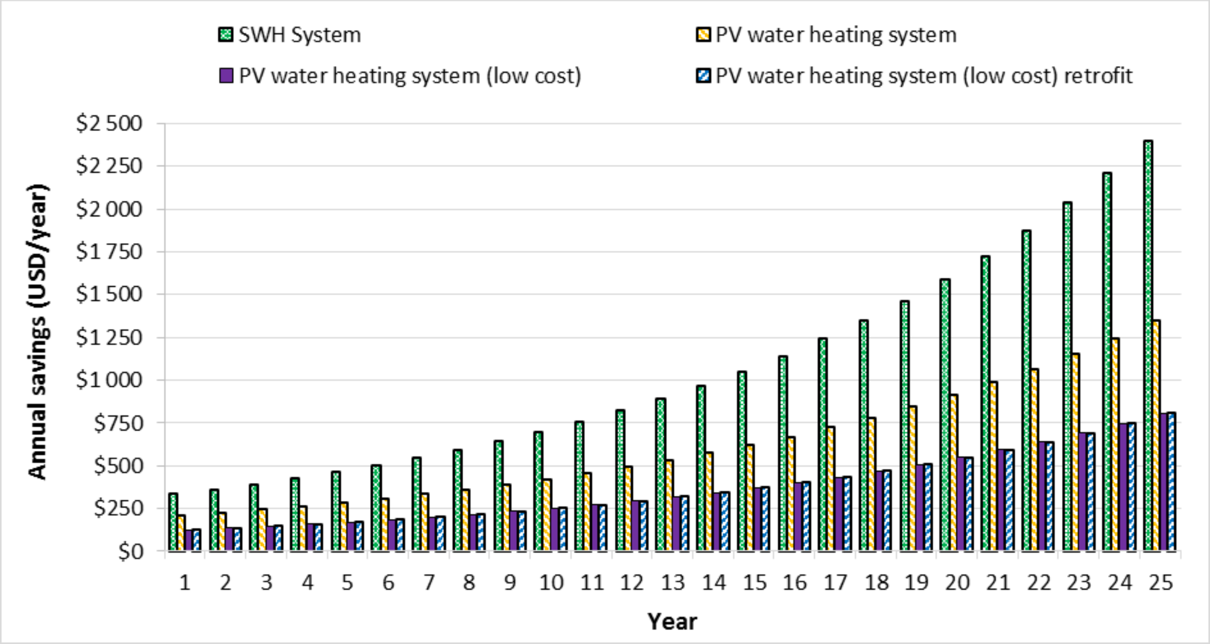

Figure 12: Annual generated financial savings for each of the solar water heating systems over 25 years

Figure 12 shows significantly larger annual savings generated by the SWH system when compared to the PV driven hot water alternatives. This results from the larger thermal energy input from the SWH system. Savings associated with the lower cost PV hot water alternatives presents lower annual savings, which can be expected, since the system has a low thermal capacity and in turn, a lower annual heat production when compared to the system monitored in this study. The annual cash flows for the systems are presented in Figure 13.

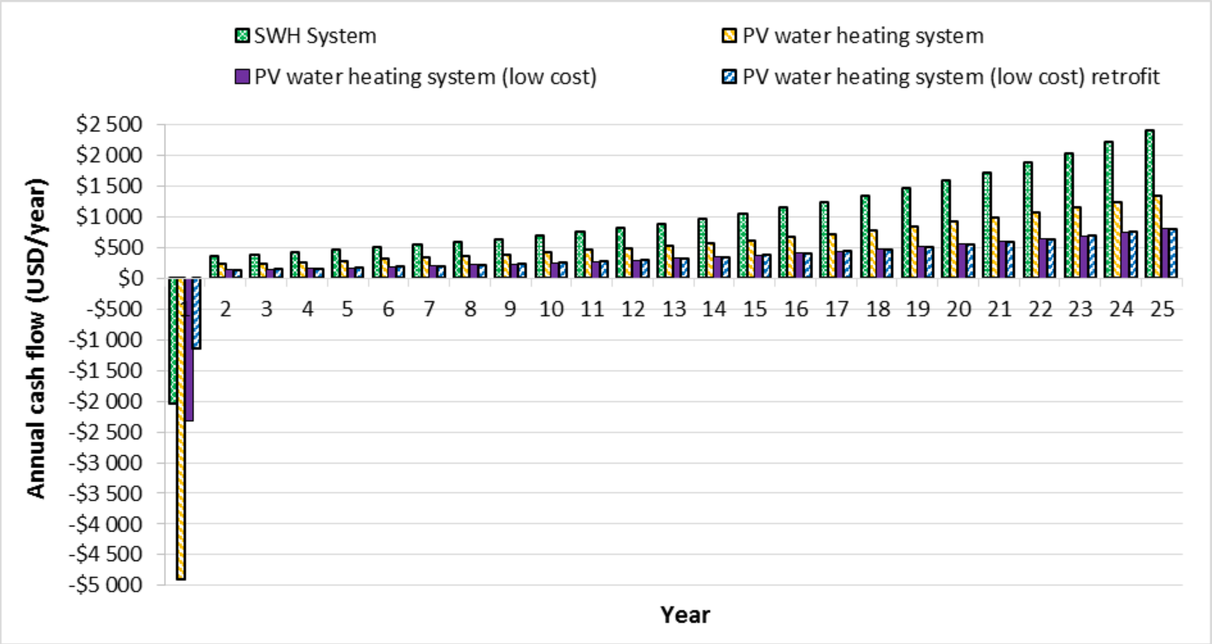

Figure 13: Annual cash flows associated with each of the solar water heating systems over 25 years

The negative cash flow generated in year 1 is attributed to the initial capital cost of the systems at the start of year 1. As a results of the larger annual savings, it can be seen that conventional SWH system presents the largest cash flow year-on-year with a relatively low investment cost in year 1. The SWH system outmatches the PV hot water systems investigated in this study with respect to annual cash flows generated. The cumulative net cash flows generated by each of the technologies is presented in Figure 14.

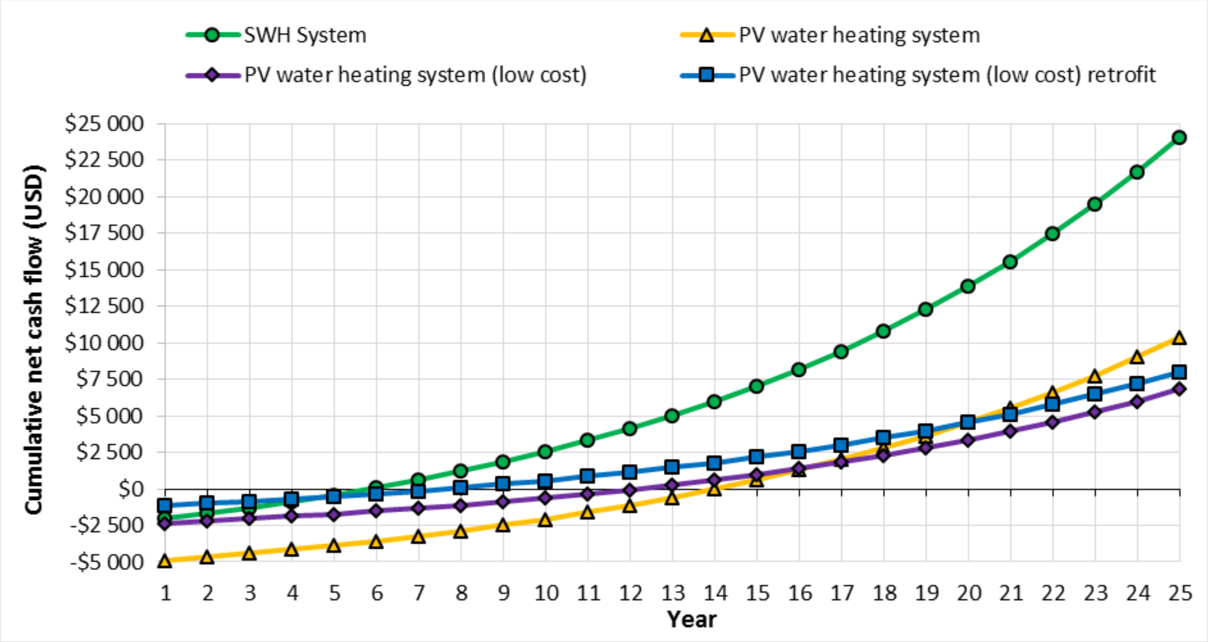

Figure 14: Cumulative net cash flows generated with each of the solar water heating systems over 25 years

Figure 14 shows that the SWH system generates significantly more cash over the 25-year period and reaches break-even point sooner than the solar PV alternatives. The point at which the cumulative net cash flows reach 0 USD indicates the payback period of the investigated systems. The key financial outcomes of the feasibility analysis are presented in Table 1 below:

Table 1: Results of financial feasibility analysis over 25 years

Financial results	SWH system	PV water heating system	PV water heating system (Low cost)	PV water heating system (low cost) retrofit
Initial capital cost	2 383 USD	5 110 USD	2 452 USD	1 264 USD
Total energy offset	55 475 kWh_{th}	33 052 kWh_{th}	19 834 kWh_{th}	19 834 kWh_{th}
Total financial savings	24 093 USD	10 349 USD	6 824 USD	8 012 USD
LCOE	0.36 USD/kWh_{e}	0.36 USD/kWh_{e}	0.36 USD/kWh_{e}	0.36 USD/kWh_{e}
IRR	26%	8%	10%	19%
Payback period	6 years	15 years	13 years	8 years
LCOH	0.04 USD/kWh_{th}	0.15 USD/kWh_{th}	0.12 USD/kWh_{th}	0.06 USD/kWh_{th}
NPV	4 892 USD	- 456 USD	288 USD	1 376 USD
Cost of business-as-usual	26 476 USD	15 459 USD	9 277 USD	9 277 USD

5. Results

When comparing the financial outcomes of the study, it can be seen that the conventional SWH system provides the largest benefits from a cost perspective. The 2.4 m^2 SWH system presents a payback period of 6 years and a LCOH of 0.04 USD/kWh_{th} over the year 25 period. This system vastly outperforms the PV alternatives from a technical and financial perspective. The study by Matuska and Sourek, (2017) showed that when used to its full potential, a SWH system and PV hot water system of approximately the same thermal capacity, will produce almost the same of heat annually. This particular study showed the SWH system producing 15% more thermal energy than the PV hot water system (excl. MPPT) over an annual period, as opposed to the 45% difference measured in this study (Matuska and Sourek, 2017).

It was initially expected that competitive finances would be achieved through the investigation of the lower cost "off-the-shelf" PV hot water system when compared to installed 2.4 m^2 SWH system. In this case, the lower cost PV hot water system is most competitive from a financial perspective to conventional SWH systems when considered as a retrofit to an existing tank within a household, as seen in the results of Table 1. Foreseeably, retrofitting of solar collectors to existing residential hot water storage tanks would have the potential to provide the most desirable financial outcomes. Retrofitting existing tanks with PV powered PTC immersion heaters largely reduces capital costs, providing more attractive financial outcomes with payback periods of 8 years, IRR of 19% and LCOH of 0.06 USD/kWh_{th}, which is competitive to SWH systems and substantially less than the LCOE from the grid for hot water production over the 25 year period.

6. Recommendations

A number of clarifications and concerns have been identified during the course of this study; the first is the significantly larger area required for the PV panels when implementing the dual AC/DC immersion heaters with storage tanks in households, when compared to the solar collectors of SWH system of similar thermal capacity. The larger roof space requirement may limit the application for local households, especially for low- to middle-income households where roof space may be limited. Furthermore, the theft of PV modules is a common occurrence in South Africa and may pose a risk for these types of systems. The difference in the number of residents living in each monitored household contaminated the performance results of the PV hot water to an extent. With a larger hot water consumption, it would be expected that more solar radiation would be used to produce hot water in the tank. Therefore, it is critical that solar hot water systems be designed correctly based on the hot water demand of the household.

7. Conclusion

This study shows that SWH systems out-perform PV hot water systems with respect to performance and financially. The 2.4 m^2 SWH system considered in this study presented the most attractive investment opportunity to reduce the electricity consumption for hot water production for households. In comparison to the lowest cost solution for a PV water heating system, retrofitting existing tanks with the necessary components, SWH systems offer the shorter payback periods (6 years) while producing more thermal energy over the 25-year period at a LCOH of 0.04 USD/kWh_{th}. This is substantially less than the 0.36 USD/kWh LCOE for utility supplied electricity over the same period.

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