Potential of Photovoltaics for Water Heating in South Africa

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ABSTRACT

Electric water heating (EWH) is the most common technology used to heat water in residential and commercial buildings in the country of South Africa. Water heating typically accounts for roughly 40% of the energy consumption of a typical South African home. The high capital costs of solar thermal water heating (SWH) systems in South Africa have made implementation of this technology very expensive. Recent reductions in the costs of solar photovoltaic (PV) systems have made them economically competitive with conventional electrical systems. The relatively steady annual electrical generation output of the PV systems when compared with the seasonal performance of the conventional SWH has created opportunities for solar PV to capture a larger share of the local water heating market. This article reviews and assesses the three primary water heating technologies currently used in South Africa and provides an energy and financial analysis of each technology.

SOLAR WATER HEATING IN SOUTH AFRICA

South Africa has been experiencing serious electricity generating capacity shortages for some time. Load shedding has become a constant threat in South Africa and new ways of providing energy storage and alternative electricity supplies are necessary to resolve this problem. The residential and commercial sectors use a substantial amount of electricity for water heating. The primary technologies for water heating available are electric water heating and thermal applications of solar water heating. South Africa has one of the world's highest solar thermal potentials. However, SWH has not evolved to be the country's preferred water heating option. The reasons for this are financial, technological, legislative, economic, cultural and social.

The recent decline in the costs for solar photovoltaic modules and improvements in module efficiencies create opportunities for PV to be used for water heating. However, additional research and publicity are needed to develop, adapt, and apply this technology in South Africa [1]. The National Solar Water Heating Program (NSWHP) was launched in 2009 by the South African government with a goal of encouraging the installation of one million SWH systems by 2015 [2,3]. Its primary objectives were:

- Reduce electricity demand and greenhouse gas emissions.
- Protect the economically disadvantaged from higher electric rates.
- Facilitate a local manufacturing industry.
- Create employment.

Over 400,000 systems were installed in residential dwellings by the conclusion of the NSWHP. Some of the problems that developed included:

- The intended reduction in electricity usage was not achieved since it focused on locations with comparatively low electricity consumption.
- Low quality imported products have dominated installations.
- Poor quality installations due to lack of training.
- Unreliable verification of number and location of installed systems due to lack of monitoring.
- Lack of maintenance support which resulted in users reverting to electric systems.

Two new goals have now been adopted. The Department of Energy (DoE) has set an intermediate aggregate target of 1.75 million SWH installations by 2019. The National Development Plan established a cumulative target of five million installed SWHs by 2030 [2]. These goals were based on a revised framework that emphasized local content requirements for new SWH installations and aimed to achieve more sustainable SWH systems [2].

Despite these goals, solar water heating in South Africa has received inconsistent support from the government in restructuring its SWH policies. The technology failed to become a preferred solution for consumers considering alternative technologies and renewable energy solutions. The main cause of the low penetration of SWH technologies is their extremely high price. This is linked with the higher cost of capital in South Africa when compared to countries with similar solar energy potential. Affordable solar hot water heating systems are underdesigned and incapable of providing adequate energy and monetary savings to offer an acceptable return on investment.

Another major obstacle to SWH development in South Africa is the absence of a developed market for quality (preferably locally-made) solar collectors, storage tanks and other components that allows customers to assemble a system that matches their requirements. Repair and replacement of faulty system components is difficult. As a result, the market offers predominantly compact solar water heating units at inflated prices [4].

Compared to solar alternatives, electric water heating (EWH) is an established and regulated business in South Africa. It is supported by favorable legislation and the involvement of insurance companies. Appliance prices are very low [4].

CONVERTED OR MODIFIED WATER HEATERS

Conventional EWHs are easily replaceable and usually for a low cost. EWH manufacturers do not provide options for easy conversion of EWH hot water tanks into similar SWH storage tanks which increases the costs of solar conversions. This often justifies the relatively high electricity costs for consumers reluctant to scrap their still operational EWHs.

Regardless, there are commercial methods to convert conventional EWHs into solar but the conversion costs are higher than comparable new SWHs [6].There are also commercial solutions to convert an existing EWH into a hybrid one using solar photovoltaics [3]. The technology replaces the flanges of an EWH with a dual heating element: one 900W for the direct current (DC) output from a PV array and a titanium electric water heater (3kW) for 230 volt alternating current (VAC). The unit uses a maximum power point tracker and a controller that allows system performance to be optimized in the absence of solar DC input from the PV array. However, all these additions increase the unit's costs comparable to the cost of a SWH [4,7].

Typically, the price of converted solar water heaters is comparable to conventional SWHs. The cost comparisons among EWHs, SWHs, converting EWHs into SWHs and converting EWHs into PV water heaters for 100 liter to 300 liter units are provided in Figure 1. The prices shown are averages at the middle range of the market. The extreme high and extreme low prices were not considered in this comparison [4,6].

OPTIONS FOR RESIDENTIAL WATER HEATING APPLICATIONS

Our study was conducted on behalf of the secretariat of the South African-German Energy Partnership managed by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH and funded by the

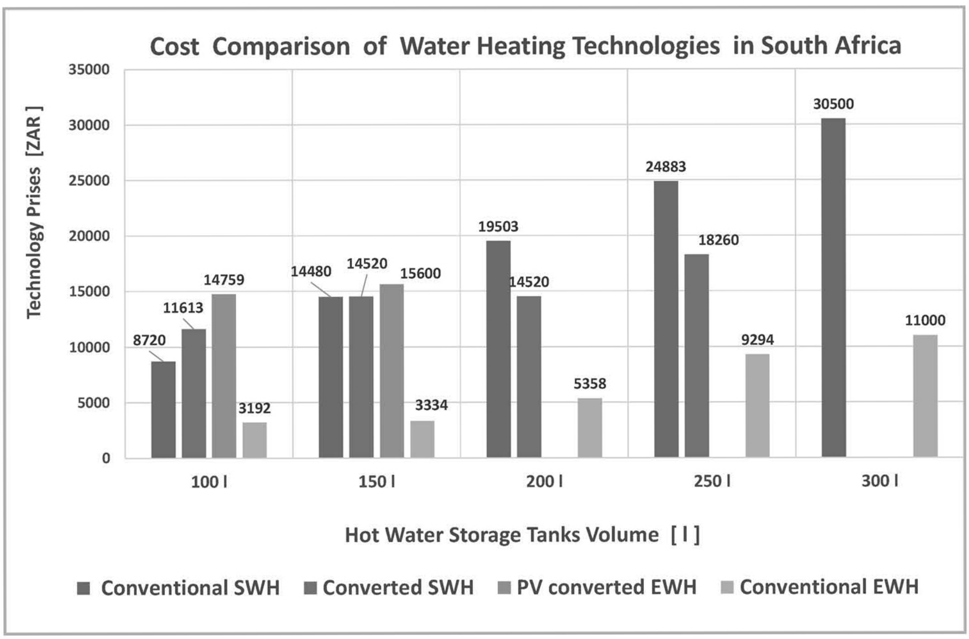

Figure 1. Cost comparison of water heating technologies in South Africa ($1 U.S. = 14 ZAR in January 2017).

German Federal Ministry for Economic Affairs and Energy. Its principle objective was to compare the three options for residential water heating (electric water heater/geyser, solar water heater, solar PV system powering existing electric geyser) in terms of thermal performance, efficiency and cost [1].

The selected systems investigated used specifications typical for the medium cost market in South Africa.

The methodology of the study was based on validating the simulation models by physical "back-to-back" testing of the three technologies.

STUDY RESULTS

Physical Back-to-Back Testing

This testing was intended to show how the three technologies perform given similar conditions. The test results were valid for the days of testing during the summer month of December 2015. Considering the time of the year, temperature and weather conditions, the following parameters were measured, recorded and tabulated in Table 1.

Table 1. Test performance results

Parameter	Unit	Technology		
		Electric Water Heater	Solar Water Heater	PV Water Heater
Thermal Energy Output per day	kWh	6.76	6.36	4.91
Performance (EWH as 100%)	%	100.00	94.08	72.65

SIMULATION RESULTS

The three water heating systems were individually simulated. To validate the simulation model, the system specifications were comparatively similar to the systems physically tested. The simulations were performed using the 2015/16 version of Polysun 8.1 simulation software [5]. The simulated energies were: 1) the grid input fraction for the EWH and as back up energy for SWH and PV water heating; 2) the solar fraction yield for heating water for the SWH; and 3) the solar yield of the PV array at the AC inverter output terminals. The simulations were limited to the specific designs and typical selections of the three technologies at a specific location in Pretoria, South Africa and the results and findings should not be considered to be representative for EWH, SWH and PV water heating technologies. The simulated system specifications are presented in Table 2.

Table 2. Specification of simulated water heating systems.

System Geographic Location: Pretoria, South Africa Latitude: -25.75 °, Longitude:28.2 °, Elevation:1,402 m				
No	**Item**	**Electric Water Heater**	**Solar Water Heater**	**PV Water Heater**
		Specifications		
1	Hot water storage tank Volume	150 l	150 l	150 l
2	Electric Heating element	230 V, 50 Hz, 3 kW	Back up: 230 V, 50 Hz, 3 kW	230 V, 50 Hz, 3 kW
3	Standing losses over 24 h	2.59 kWh	2.59 kWh	2.59 kWh
4	Thermostat settings	50 °C	50 °C	50 °C
5	Solar Collector		1x flat plate, gross area:2m ^{2}	
6	Circulation pump		Eco, small 72 l/h	
7	PV Modules			3 x 300 W PV modules
8	Grid-tied inverter			2.2. kW
	Purchase Price	R 3,000.00	R 20,515.00	R 23,412.00

The annual simulated energy performances of the EWH, SWH and PV water heating are illustrated in Figures 2, 3 and 4. The simulations were performed with the arrangement that the three technologies deliver the same amount of hot water.

WATER HEATER COMPARISONS

Performance comparisons are shown in Figure 5. It is evident that the PV solar yield of 1,538 kWh/a is higher than the corresponding SWH yield of 1,218 kWh/a. The percentage of annual grid electricity consumption of the PV water heating system (35%) is less than the corresponding fraction of the SWH (56%). The solar component of the PV water heater is superior to that of the SWH.

The grid energy input saved (not used) for water heating is shown in Figure 6. Both the SWH and the PV water heater use less energy from the grid than the EWH.

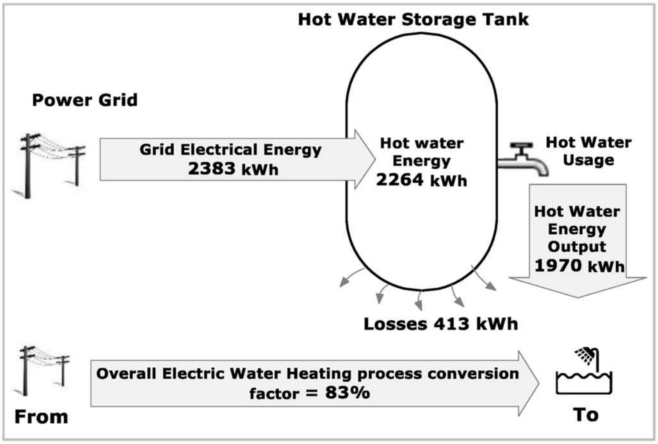

Figure 2. Annual simulated thermal performance of the electric water heater.

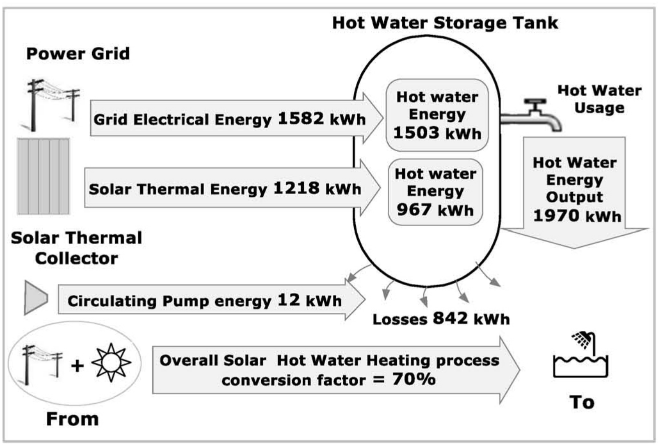

Figure 3. Annual simulated thermal performance of the solar thermal water heater.

The PV annual yield is not as dependent on the seasonal conditions as is the SHW. When compared annually, the PV solar yield is 10% superior, with a yield of 55% compared to the SWH's corresponding yield of 45%.

Annual average daily PV AC yield is shown in Figure 7 together with the corresponding average daily hot water usage. It is evident that only 60% of the PV AC yield is used directly for heating water while the balance is exported to the grid.

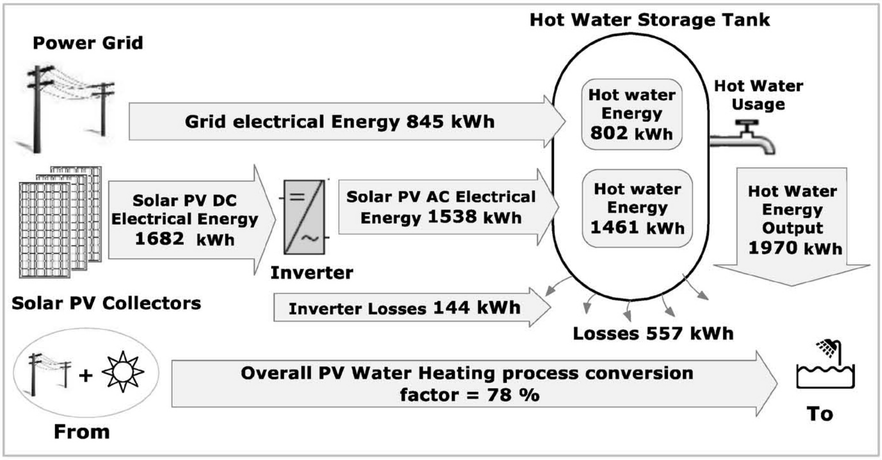

Figure 4. Annual simulated thermal performance of the solar PV water heater.

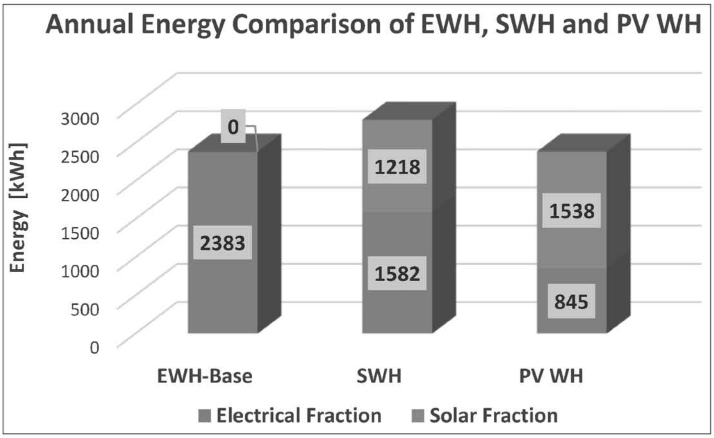

Figure 5. Annual energy balance comparisons for water heating using the three technologies.

ENERGY AND FINANCIAL ASSESSMENTS

Comparing the SWH to the PV Water Heater

The financial analysis of the SWH and PV water heating technologies was based on identical assumptions [7]. The same parameters obtained from the simulations are used as inputs/drivers to the financial analysis (see Table 3). The financial drivers per system are the grid input per system saved and related monetary costs [7].

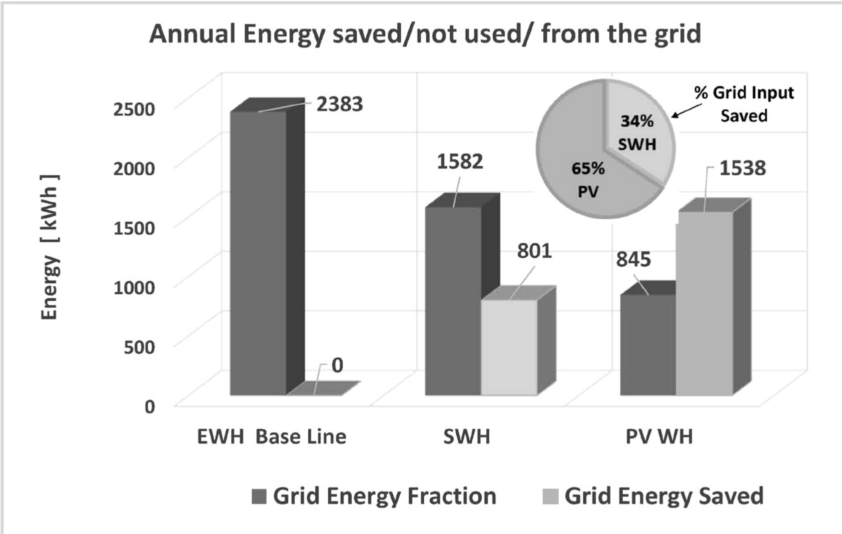

Figure 6. Annual electrical energy saved from the grid as compared to the baseline of the electric water heater.

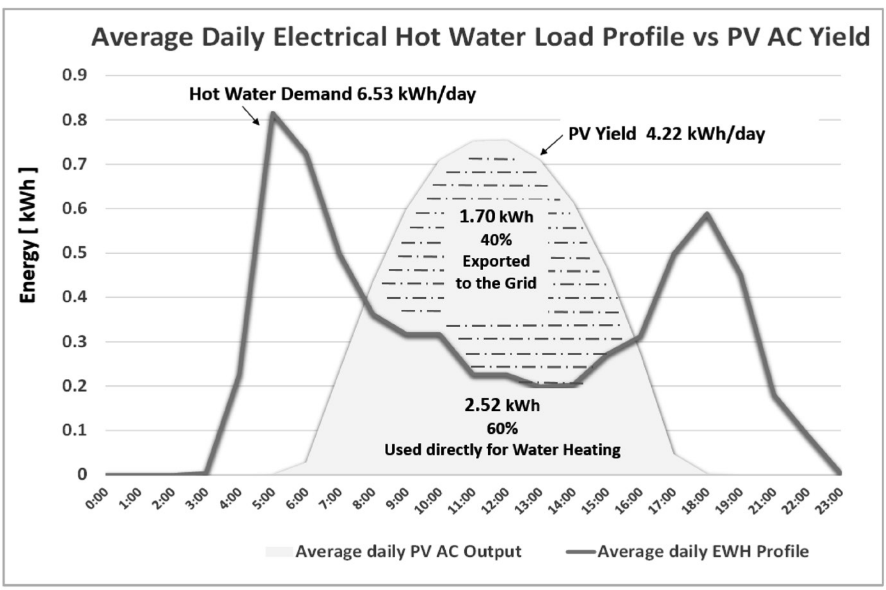

Figure 7. Annual average daily PV AC yields with corresponding hot water usage.

Table 3. Macro and per system drivers.

Drivers - Macro	Unit	Macro Driver	
Household HW consumption	liters / annum	54470	
Grid input for WH - without any system	kWh / annum	2383	
Grid electricity unit cost - current	ZAR / kWh	1.50	
Current Interest rate	% / annum	9.50%	
Current Inflation rate	% / annum	5.00%	
Current Grid electricity inflation rate	% / annum	15.00%	
Drivers - Per System	**Unit**	**SWH**	**PV**
Purchasing cost - once off	ZAR	20,515	23,412
Installation cost - once off	ZAR	1,000	1,000
Maintenance cost coefficient	% / annum	2%	1%
Expected useful life	years	15	20
Grid input for WH - with system	kWh / annum	1582	845
Grid input saved	kWh / annum	801	1538
% of Grid input saved	%	34%	65%

Energy Performance

From the simulations and comparisons it is evident that the SWH's total energy used for water heating is greater than the EWH's and PV water heater's counterpart when producing the same quantities of hot water. This is due to the fact that the losses of the SWH are higher than the losses of the other two technologies.

As shown in Figures 2 and 3, the annual grid electricity consumption of the PV water heater is less than the corresponding fractions of the SWH and the solar fraction per yield of the PV water heater is greater than those of the SWH. Figure 6 shows that grid input energy saved by the PV water heater is greater than the thermal SWH.

The annual electricity saved (not used) from the grid of the two technologies for water heating demonstrates the superiority of the PV water heater—1,538 kWh compared to 801 kWh for the SWH. The percentage of energy savings of the two technologies compared to the EWH are 65% and 34% respectively (see Figure 6).

The solar energy performance comparison indicates that the thermal SWH output is affected by the climate whereas the PV WH performs steadily throughout the year. Also, the PV annual solar yield (55%) is higher than that of the SWH (45%).

In summary, for the specific selected South African conditions, the PV water heating technology offers better energy performance than the SWH. This results from its greater solar energy harvesting potential and its relatively constant energy output during the year. It is also easier to install than existing residential electric water heating systems.

Lifecycle Costs and Savings Analysis

Next considered are lifecycle financial analysis methodologies that include the simple payback period, net present value, return on investment and internal rate of return. Each offers a methodology to perform lifecycle financial analysis. A summary of the financial outputs is shown in Table 4. An interactive decision tree was developed to compare the financial performance of the three technologies during their useful life. The cost per liter of heated water is calculated by considering the solar and grid fractions for water heating as shown in Table 5.

Simple payback period (SPP)—The SPP is the total installation costs divided by the difference of annual savings less annual costs. The result is positive when annual savings exceed annual costs. The SPPs for the SWH and PV water heater are 10.5 and 6.9 years respectively. The PV water heater is superior by 3.6 years (see Table 4),

Net present value (NPV)—The NPV is the difference between the present value of cash inflows and the present value of cash outflows. The discontinued NPV payback periods for the SWH and PV water heater are 16.0 years and 9.6 years respectively, making the PV water heating superior by 6.4 years. The SWH fails to achieve a payback of its investment within its useful lifecycle. Over the lifecycle of the SWH, the NPV is negative value (R-2,056) while the PV water heater is a positive value (R43,466). The PV water heating system with its higher NPV of R43,446 provides better financial performance system as it returns a greater monetary sum. The PV water heater is superior by a difference of R45,522 or 2,214% (see Table 4).

The cost per heated liter of water is calculated on a NPV basis as

Table 4. Financial analysis outputs.

Analytic Criteria	Unit	SWH	PV	Amount	%	Preferable
Efficiency						
Grid Input saved	%	34	**65**	31		PV
Payback						
Payback - simple, theoretical	years	10.54	**6.96**	-3.59	-34	PV
Payback - discounted, theoretical	years	15.98	**9.57**	-6.41	-40	PV
Achieves NPV payback over useful life	Y/N	**NO**	**YES**			PV
Life Cycle						
Implementation cost (initial capital outlay)	ZAR	**21,515**	23,412	1,897	9	SWH
Useful life	years	15	**20**	5.00	33	PV
Cost per heated liter - system only	ZAR	0.09	**0.04**	0.06	-60	PV
System NPV (ROI amount)	ZAR	2,056	**43,466**	45,522	2214	PV
ROI coefficient	%	-7.98	**164.85**	172.83	2166	PV
IRR	% / annum	8.33	**20.86**	12.53	150	PV

Performance omparison		Margin
Higher proportion of grid input saved	PV	92%
Lower initial capital outlay	SWH	-9%
Shorter simple payback period	PV	-34%
Shorter discounted payback period	PV	-40%
Longer useful life	PV	33%
Lower cost per heated litre	PV	-60%
Higher NPV	PV	2214%
Higher ROI	PV	2166%
Higher IRR	PV	150%

system total costs (including purchase, installation, plus the NPV of the annual system maintenance costs adjusted for inflation) divided by total system output (liters of hot water supplied during the system's useful life). The SWH and PV water heater have values of R0.09/l and R0.04/l respectively, making PV water heater superior with R0.06/l (see Table 5).

Return on investment (ROI)—The ROI can be used to calculate the proceeds received from an income source as a proportion of all costs attributable to the same source of income. The ROIs for the SWH and PV water heaters have values of –8.0% and 164.9% respectively. The ROI of 164.9% means that for the useful lifecycle of the PV water heating

Table 5. Interactive decision tree.

1 Item / Option	Unit	Grid (EWH)	SWH	PV
a. option useful life-years	Years	n/a	15	20
b. adopted useful life-years	Years	15		
c. grid unique startup costs	ZAR	3,000		
d. grid unique recurring costs (annual)	ZAR	200		
2 Life-Cycle		**Grid**	**SWH**	**PV**
a. startup costs	ZAR	3,000	21,515	23,412
b. life cycle costs NPV(total costs of system)	ZAR	72,231	4,259	2,955
c. kWh grid supplement(cost paid to utility)	ZAR	0	49,002	41,038
d. option total cost NPV	ZAR	75,231	74,776	67,405
e. option per annum cost NPV (15,15,20ys)	ZAR	**5,015**	**4,985**	**3,370**
f. liters heated	kl	817	817	1,089
g. cost per liter (solar+grid)	ZAR/l	**0.092**	**0.092**	**0.062**

system, the income generated exceeded all system costs by a factor of roughly 1.7. The PV water heating system is the better performing system as it returns an amount which is greater in proportion to all costs divided by the funds invested.

Internal rate of return (IRR)—The IRR is the annual return received on the investment during the product lifecycle (also known as the discount rate) expressed as a percentage. The IRR for the SWH is 8.3%. The IRR for the PV water heater is 20.9%. The SWH's yield is less than a risk neutral interest bearing investment. The IRR of the PV water heater is greater than the SWH by 12.5% and is higher than the macro interest rate of 9.5%.

CONCLUSIONS

Data from Table 4 indicates which water heating system meets each comparative criterion and by what percentage margin it outperforms the other system. The PV water heating system demonstrates better performance in most criteria:

- The PV water heater supplies more total output. Based on the higher proportion of grid input saved, the PV water heater outperforms the SWH by a margin of 90% (i.e., the proportion of grid kWh saved exceeds that of the SWH by a factor of 0.9).

- The PV water heater pays back its investment quicker in both SPP and NPV terms. The SWH fails to achieve a discounted payback over its useful life.
- The PV water heater returns more in terms of IRR and ROI. It demonstrates a lower per heated liter of water cost over a longer lifecycle.
- The PV water heater's initial capital outlay is 13% higher than that of SWH. This is the single criterion for which PV can be deemed as "underperforming." If the cost of the storage tank (electric water heater) in PV water heater is not included in the purchase price (the household uses an existing electric water heater) then solar PV water heating would be superior in all criteria.

Based on the above comprehensive energy and financial analysis including parameter constraints and calculations, when compared to SWH, the PV water heating system constitutes the best capital investment for the specific South African conditions that were considered.

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