

BRIEFING NOTE

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AN IN-DEPTH COMPARISON OF THE PERFORMANCE OF A HEAT PUMP POWERED BY SOLAR PV COMPARED TO SOLAR WATER HEATING WHEN APPLIED IN THE RESIDENTIAL AND COMMERCIAL SECTORS

Tshiamo Segakweng^{1*}, Muhammad Sheik¹, Karen Surridge²,

¹CSIR, Meiring Naude Road, Brummeria, Pretoria, South Africa; Phone: 012 841 3436; Email: TSegakweng@csir.co.za

²SANEDI Block C, Upper Grayston Office Park, 152 Ann Crescent, Strathavon, Sandton, 2146: karenst@sanedi.org.za

KEY FINDINGS

An in-depth comparison of a large scale solar thermal system and a heat pump was conducted. Solar energy can be used to produce hot water, either directly through a Solar Thermal (ST) system or indirectly through a solar photovoltaic panel that produces electricity to drive a heat pump (SHP). The heat pump and solar thermal systems, despite their initial costs and challenges, have proven to be efficient solutions for heat generation and energy cost savings. Both systems have demonstrated significant monthly energy production and savings, with the heat pump system having a return on investment (ROI) period of approximately 7.3 years, and the solar thermal system having a shorter ROI period of approximately 3.4 years.

The comparative performance of these systems suggests that a hybrid system, combining the strengths of both, could potentially outperform each individual system. The solar thermal system excels during warmer months, while the heat pump system is more efficient in colder months and offers a more consistent and reliable hot water supply.

INTRODUCTION

Solar thermal and solar PV heat pump equipment was purchased and installed on the CSIR campus with a thermal rating of 15-20 kW. Heat rejection equipment was also added to simulate real-world load profiles for demand in hot water. The CSIR already operates a sophisticated weather station that will provide data on the available solar radiation. Then, back-to-back performance tests were performed over a 12-month period. This project aims to evaluate and compare the performance of two distinct solar-based heating systems: a heat pump powered by photovoltaic (PV) panels and a solar thermal water heating system. The study focusses on evaluating the efficiency, energy savings, environmental impact, and economic viability of both technologies in a residential setting. Key parameters such as energy consumption, heat output, system reliability, and lifecycle costs will be thoroughly examined and compared.

The overall objective of the project is to provide empirical data to inform homeowners, policymakers and industry stakeholders on the benefits and drawbacks of each solar technology (ST and S-HP) for generating clean and affordable hot water at scale. The collected data will also be used to validate thermodynamic models, which will be utilized within the TSSP for conducting feasibility and design studies on behalf of industry and the solar thermal sector to improve the uptake of these technologies.

Energy consumption, heat production, efficiency, and energy savings were monitored and evaluated at the end of the 12-month testing period. During the duration of the experiment, temperatures never dropped to a point where the electric heaters had to turn on.

METHODOLOGY

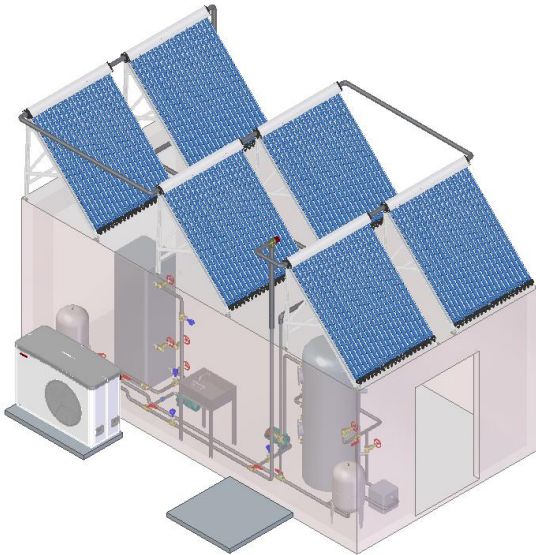


Figure 1: Thermal lab 3D design

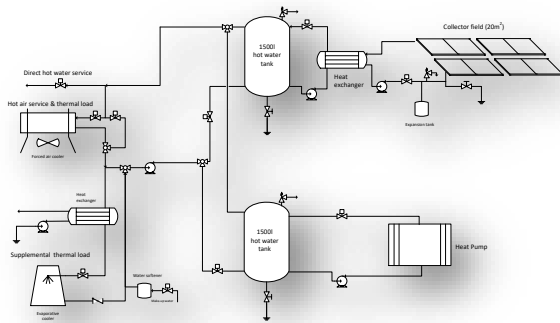


Figure 2: Solar thermal water heating versus solar photovoltaic Experimental design

The system is designed so that the energy demand and performance on any connected heat source, currently solar thermal and heat pump, can be recorded through multiple flow and temperature measurements. A heat rejection circuit allows the hot water demand to be simulated according to different industrial scenarios.

To evaluate the performance of solar thermal (ST) Evacuated Tube Collectors (ETC) against Photovoltaic (PV) driven heat pumps, we will observe the ETC's effectiveness each season. Afterward, the heat pump will operate according to a timetable based on available solar energy during the equivalent timeframe. We will compare the daily average total energy output as a benchmark.

The 1000L and 400L can be used interchangeably to simulate the performance of various hot water storage tank sizes as a buffer for meeting process demand and limiting standing losses.

Water heating system design

Before comparing the solar thermal and PV heat pump systems, it is important to understand the difference between direct and indirect solar thermal water heating systems. Direct systems use the same fluid, usually water, to collect and transfer heat from the sun to the storage tank or the point of use. Indirect systems use a separate fluid, such as glycol or a refrigerant, to collect the heat and then transfer it to the water through a heat exchanger.

Direct systems are simpler and cheaper, but they have some drawbacks. They are more prone to freezing, scaling, and corrosion, especially in cold or hard water areas. They also have a higher risk of overheating and boiling, which can damage the system or cause safety hazards. Indirect systems are more complex and expensive, but they have some advantages. They can prevent freezing, scaling, and corrosion by using a suitable heat transfer fluid. They can also regulate the temperature and pressure of the system more easily and avoid mixing potable water with potentially contaminated fluids.

Depending on the climate and water quality, different types of solar thermal water heating systems may be more suitable. For example, direct systems are more common in warm and sunny regions, where freezing and overheating are less likely. Indirect systems are more common in cold and cloudy regions, where freezing and overheating are more frequent.

Two interlinked systems were developed for this facility: a solar water heater (SWH) connected to a 1000L tank, and a heat pump linked to a 400L tank. The plan was altered due to availability constraints on donated equipment. These systems can function interchangeably with either tank as needed, and both dissipate heat through a heat exchanger into a secondary loop with a cooling tower. For our testing purposes, we maintained the setup as described and monitored all inflow and outflow temperatures and volumes in each system.

Solar thermal system

The ST system consists of six manifolds with 20 tubes each giving a total of 120 tubes. Each with a length of 0.0167 m and a diameter of 0.058 m, mounted on a south-facing roof at an angle of 30°. The manifolds are connected in a 3x2 arrangement with water as the heat transfer fluid. A pump circulates the fluid from the manifold to a coil in the tank which acts as a heat exchanger, where it

transfers heat to the water in the 1000 L tank. The tank is insulated with 50 mm of polyurethane foam and has an electric backup heater that can be activated in the event that there is insufficient solar energy to heat the water to the desired temperature using solar energy alone (the electric back up heater was not connected in this study). A controller monitors the temperature difference between the manifold and the tank and adjusts the pump speed accordingly. The design parameters and performance indicators of the ETC system are shown in Table 1.

Table 1: ST system parameters

Parameter	Value
Collector area	3.48 m ²
Collector efficiency	0.75
Manifold flow rate	0.06 kg/s
Heat exchanger effectiveness	0.85
Tank heat loss coefficient	0.6 W/K
Pump power	50 W
Maximum water temperature	70°C
Solar fraction	0.8
Coefficient of performance	9.8

PV heat pump system

The PV heat pump system consists of 20 photovoltaic modules, each with a peak power of 250 W and a conversion efficiency of 0.15, connected in series to a DC-AC inverter. The inverter supplies power to a 5 kW air-to-water heat pump, which uses R134a as the refrigerant. The heat pump has a compressor, a condenser, an expansion valve, and an evaporator. The condenser transfers heat to the water in the 400 L tank, while the evaporator absorbs heat from the ambient air. The tank is insulated with 50 mm of polystyrene foam and has an electric backup heater that can be activated if the water temperature drops below 40°C. A controller monitors the water temperature and the solar

irradiance and switches the heat pump on or off accordingly. >on or off the heat pump accordingly. The design parameters and performance indicators of the PV heat pump system are shown in Table 2.

Table 2: Heap Pump system parameters

Parameter	Value
Heat pump capacity	6.9 kW
Heat pump COP	3.5
Tank heat loss coefficient	0.8 W/K
Maximum water temperature	60°C

Performance analysis
Heat pump scheduling.

This experiment was intended to compare a heat pump powered by solar PV but unfortunately the heat pump was not connected to solar PV. Instead, a calculation was made on the size of solar PV field required to power the heat pump with either a 20 % or 50 % oversize on the PV panels. The costs (+/- R50000) and performance implications associated with each were looked at and it was decided to use a 50% oversize as the remaining power would go to other utilities in the facility the heat pump would be installed in.

The performance of both sizes was compared using Solar Panels SUNTECH STP445S-B72/Pnj+ PV panels. Their characteristics are as follows:

Rated Max Power 445 W

Tested a STD condition AM =15, E = 1000W/m² , Tc = 26 °C [1].

Calculations for the heat pump solar PV requirements

Table 3

Rated Max Power	445 W
Tested Condition	AM =15, E =1000W/m ² , Tc = 26 °C

Heat Pump	Steibel Eltron WPL 25 ACS
Max Consumption	6.9 kW
Starting Current	10 A
Starting Power	230v * 10 A = 2300 W

With a PV field that's 50% larger than necessary,

- You would require a 10.35 kW capacity, calculated from half of 6.9 kW.
- This would mean installing 24 panels.
- Considering the average Direct Normal Irradiance (DNI), 600 W/m²,
- The power output would be 60% of the size of the PV collector field.
- This results in an energy yield of 6.21 kW,

Which is 90% of the maximum usage by the heat pump, Assuming the current system operates with an inverter-driven compressor.

This allowed the heat pump to begin running as early as possible in both winter and summer.

Observations made from the experiment are as follows:

Start of day running. In the summer months, the DNI would reach 600 W.m² as early as 7 AM and this would move to 8 AM in the summer winter months.

The one issue of possible loadshedding was always a looming factor when working with heat pumps. Compressor driven heat pumps however, would offer an opportunity to overcome this when using batteries. The time for each period of lead shedding in Pretoria has been 2 hours at a time, if this occurs when heat water is needed, then the heat pump could be run at 50% capacity [2]. This would allow hot water to still be produced albeit at a slower rate.

Number of batteries needed for back up on the heat pump to enable it to run at 50% capacity during potential load shedding or power shut down periods. Based on 90% inverter efficiency and utilizing 12 volt cells. Just over 4,000 Amp-Hours worth of batteries are needed to go 10 hours at 3500 watts:

$$3.5 \text{ kW} \times 10 \text{ Hrs} = 35 \text{ kWh}$$

$$35 \text{ kWh} \text{ divide that by } 12 \text{ volts} = 2917 \text{ AH}$$

$$2917 \text{ AH} \times 90\% = 3241 \text{ AH.}$$

Utilizing deep cycle solar batteries would give the best capacity, therefore taking the average 12V battery with 200 AH capacity, 16 batteries would be needed for 10 hours, therefore this would be more than sufficient for the maximum 4 hours of loadshedding [3].

MAIN RESULTS/EXPECTED OUTCOMES

Solar thermal system

Heat generated.

The solar thermal system was tested from February to July 2024. The amount of heat generated for each month was calculated and is presented in Figure 3.

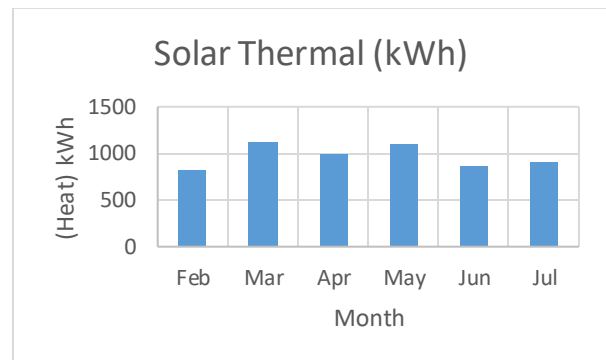


Figure 3: Heat generated by the solar thermal system

Savings

The solar thermal system generates on average about a 1000 kWh of energy monthly.

In the time that it has been operational, it has produced 5845 kWh.

Cost savings

The power produced is just under 5845 kWh.

Therefore, the total savings in energy cost is:

Assuming an average cost per kWh of R2.80:

$$\text{Cost} = \text{Energy (kWh)} \times \text{Cost per kWh}$$

$$\text{Cost} = 5845 \text{ kWh} \times \text{R}2.80/\text{kWh}$$

$$\text{Cost} = \text{R} 16366$$

$$\text{Monthly average savings} = \text{R} 16366 \div 6$$

$$\text{Monthly average savings} = \text{R} 2727$$

The total savings achieved from the heat pump over the past 6 months are R12600.

Return on Investment (R.O.I)

With a total cost of R 185400 for the heat pump system, the R.O.I period is calculated as follows:

$$\text{R} 111974 \div \text{R} 2747 = 41.06 \text{ months}$$

Which is equivalent to 3.4 Years.

Heat pump system

Heat generated.

The amount of heat generated by the heat pump for each month for was calculated and is presented in Figure 4. The heat pump did not function every day in February and March due to technical issues with the heat rejection system. Further issues were encountered in April which also lead to downtime.

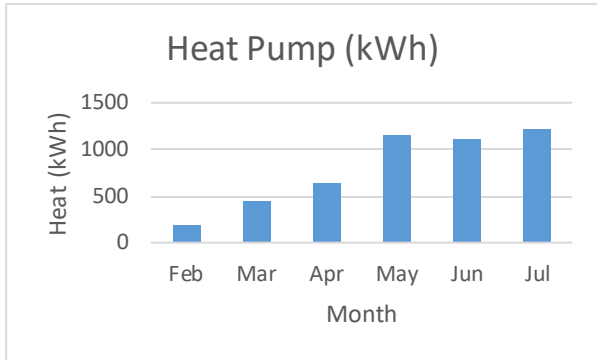


Figure 4: Heat generated by the heat pump system

Savings

The heat pump generates on average about a 1000 kWh of energy monthly.

In the time that it has been operational, its has produced 5952.271 kWh and it's total power consumption is 1 453 kWh. This gives a COP of 4.01.

Cost calculation

Table 4: Cost of Heat pump system

Heat pump and heat pump manager and pump	R 75000 installed
Tank 1000L	R 55000
PV collectors	R 38400
Inverter	R 10000
Batteries	R 7000
Total	R 185400

The access power produced is just under 4500 kWh.

Therefore, the total savings in energy cost is:

Assuming an average cost per kWh of R2.80 [4]:

Cost = Energy (kWh) × Cost per kWh

Cost = 4500 kWh × R2.80/kWh

Cost = R 12600

Monthly average savings = R 12600 ÷ 6

Monthly average savings = R 2100

The total savings achieved from the heat pump over the past 6 months are R12600.

Return on Investment (R.O.I)

With a total cost of R 185400 or the heat pump system, the R.O.I period is calculated as follows:

$R\ 185400 \div R\ 2100 = 88.3\ \text{months}$

Which is equivalent to 7.3 Years.

Combined Heat pump solar thermal combined system

The aim of a hybrid or combined system is to maximize the hot water delivery, energy efficiency and sustainability by using both renewable and energy efficiency sources of heating.

The combined system aims to maximize the hot water delivery while minimizing the energy consumption by using both the heat pump and the solar collectors as complementary sources of heating. The heat pump can provide a stable and consistent heating output regardless of the weather conditions, while the solar collectors can harness the free and abundant solar energy when it is available. By using both sources, the system can reduce the reliance on grid electricity and lower the carbon footprint of the hot water production.

Depending on the configuration of the system, the combination can also enhance the efficiency and performance of the individual components. For example, in the system with two independent coils, the heat pump can be switched off when the solar collectors are able to provide sufficient heating for the tank, thus saving energy and prolonging the lifespan of the heat pump. Alternatively, in the system with a single coil, the heat pump and the solar collectors can work together to heat the same coil, thus increasing the heat transfer rate and reducing the heat losses in the tank.

Taking the learnings from each system, a combined system was hypothesized and assembled. This system would use half of each system's components to allow the coil in the 1000L tank to be heated by both the heat pump and solar collectors. There are two possible configurations for this system:

- A system where the tank has two independent coils, one for the heat pump and one for the solar collectors, respectively.

- A system that combines the two heating lines into a single coil within the tank.

To keep the system cost-competitive, we can assume that the configuration where the two heating lines merge into a single coil within the tank would be the least expensive. This setup would allow for a collector field half the size of the current one (60 tubes) and a heat pump with half the capacity of the current unit ($\pm 3.5\text{KW}$). This change would reduce costs and allow the system to remain completely off-grid, with the heat pump acting more efficiently.

Table 5: Cost of a hybrid system

Collectors and manifold	R (8176*6) = R49074
Heat pump and heat pump manager and pump	R 75000
Tank 1000L	R 55000
Geyzerwise 12v controller	R 1500
Geyzerwise 12v pump	R 1700
Auxiliary parts	R 5000
PV collectors	R 38400
Inverter	R 10000
Batteries	R 7000
Total	R 235674

A combined heat pump and solar thermal system offers several advantages compared to using either a heat pump or solar thermal system alone. Here's a comparison of the key aspects:

- Energy Efficiency and Cost Savings

Heat pumps are highly efficient, typically with COP values in the range of 3-4. However, they still rely on electricity, which can be costly depending on the local energy prices. A PV powered heat pump can help improve the efficiency of heat pumps with the back up offered by batteries.

Solar thermal systems use solar energy to heat water, providing significant cost savings since they rely on a free energy source. However, their performance is dependent on weather conditions and the availability of sunlight.

A combined system leverages the strengths of both technologies. The solar thermal component can preheat water, reducing the load on the heat pump, which then only needs to raise the temperature by a smaller amount. This leads to higher overall efficiency and lower energy costs, as the system relies less on electricity and more on solar energy and will conserve the batteries.

- Reliability and Availability of Hot Water

A solar PV powered heat pumps provide reliable hot water when there is enough sunshine to provide the solar PV energy with batteries available when there is insufficient sunshine. It will also provide hot water in very cold weather.

Solar thermal systems can struggle during cloudy days, at night, or in winter months when sunlight is limited, potentially leading to inconsistent hot water supply.

The combined system offers a more reliable hot water supply by using the heat pump as a backup when solar energy is insufficient. This ensures a consistent supply of hot water year-round, regardless of weather conditions.

- Environmental Impact

A combined system will further enhance the environmentally friendly aspect of both systems as there will be very little reliance on grid electricity.

- Installation and Maintenance Costs

Installation of a heat pump can be costly, and maintenance includes servicing the mechanical and electrical components. For a solar thermal system, installation costs vary, but they often require roof space for solar collectors. Maintenance involves keeping the collectors clean and checking for leaks. From the above calculations, a combined system will have lower costs as it will use only half of each system and these savings will further be enhanced by the long-term savings from reduced energy bills and potential incentives for renewable energy. Maintenance cost will also be much less.

- Scalability and Customization

A combined system will offer flexibility by adjusting the balance between solar collectors and heat pump

capacity, allowing for tailored solutions based on specific energy needs and climatic conditions. In summary, a combined heat pump and solar thermal system offers a balanced approach, leveraging the benefits of both technologies to provide efficient, reliable, and environmentally friendly hot water heating. It generally results in greater energy savings and lower environmental impact compared to using a heat pump or solar thermal system alone.

Return on Investment (R.O.I)

With a total cost of R 235674 for the combined system, the R.O.I period is calculated as follows : Assuming the monthly savings will be the savings of both systems combined

$$R\ 2100 + R\ 2747 = R\ 4847$$

$$R\ 235674 \div R\ 4847 = 48.7\ \text{months}$$

Which is equivalent to 4.01 Years.

Although such a system would cost more in the beginning, its payback period will be much less and you would have hot water available all the time. The payback period may even be less as the heat pump will not be required to work as much.

System comparing

The solar system performs better than the heat pump system in the warmer/summer months while the heat pump outperforms the solar in the colder months as shown in Figure 5.

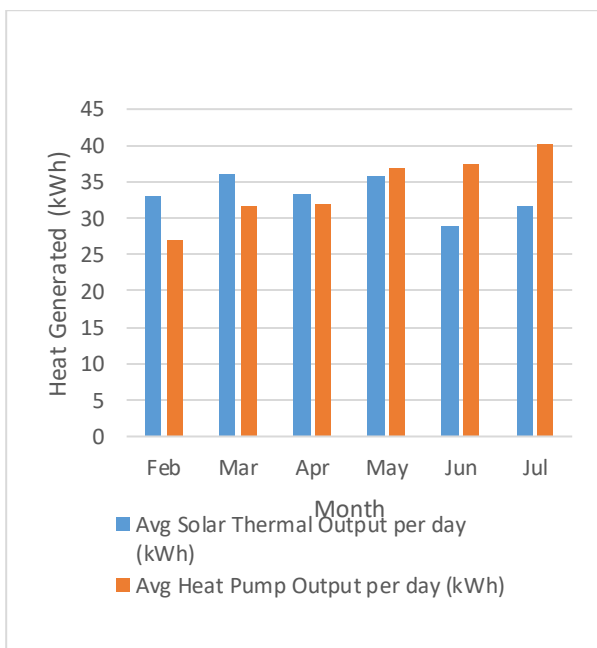


Figure 5: Average monthly heat generated by both systems

CONCLUSIONS

The heat pump and solar thermal systems, despite their initial costs and challenges, have proven to be efficient solutions for heat generation and energy cost savings. Both systems have demonstrated significant monthly energy production and savings, with the heat pump system having a return on investment (ROI) period of approximately 7.3 years, and the solar thermal system having a shorter ROI period of approximately 3.4 years.

The comparative performance of these systems suggests that a hybrid system, combining the strengths of both, could potentially outperform each individual system. The solar thermal system excels during warmer months, while the heat pump system is more efficient in colder months and offers a more consistent and reliable hot water supply [2].

The project underscores the potential for both systems to be deployed in an industrial setting, suggesting that further testing in larger environments could provide more comprehensive insights. Despite the initial costs, the performance and financial savings offered by both systems make them worthwhile investments in the long run, affirming their potential in promoting sustainable and efficient energy solutions.

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