ISEC 2024 – 3rd International Sustainable Energy Conference
Solar Thermal and Energy Efficiency for Sub-Saharan Africa's Industry and Commerce
https://doi.org/10.52825/isec.v1i.1227

Published: 23 Apr. 2024

Analysing the Techno-Economic Viability of Different Solar Heating Systems in South African Beverage Plants

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Abstract. With ongoing real-term reductions in the cost of renewable energy technologies, opportunities to reduce carbon emissions within industry have improved. While the South African industrial sector has been investing in photovoltaics to meet electricity requirements, little has been done to replace fossil fuels used for the generation of process heat, representing two-thirds of the energy consumed. While previous studies have demonstrated the benefits and limitations of solar thermal (ST) energy solutions for industrial applications, recent developments in high-temperature heat pumps (HTHP) offer opportunities for novel configurations, including the use of renewable energy like photovoltaics (PV). This study compares the techno-economic benefits of solar thermal energy systems with PV-supported HTHP systems within the South African beverage sector. After a general consideration, simulation calculations are presented for selected applications. The cost of heat is determined for PV-heat pump systems operating on a stand-alone basis and with heat storage. The study finds that the levelised cost of heat of US$0.050-0.073/$kWh_{th}$ is at least twice that of coal-fired steam boilers. The study, therefore, calls for further work on optimising systems minimising steam requirements, and thereby improving the economics of heat pumps and for a coordinated effort to support the development and financing of high-temperature heat pumps for industrial applications.

Keywords: Industry, Renewable Energy Solutions, South African Beverages, High-Temperature Heat Pumps, Techno-Economic Analysis

1. Introduction

South Africa's mature beverage sector, with large production facilities, is a significant energy user, representing 3020 GWh/annum [1]. The majority of energy needs, approximately 60 %, is process heat [1]. Steam boilers burning mainly coal, gas and heavy fuel oil are widely used to meet these process heat requirements, with associated carbon emissions of nearly one million tonnes. While there have been shifts towards a more sustainable electricity supply from renewable energy technologies, South Africa's national electricity network continues to depend on coal-fired power stations, which compounds the problem. As a result, the beverage sector generates an estimated 2,060,000 tonnes of CO_2 equivalent or 0.4-0.5 % of the South African annual emissions [1], [2].

To meet electrical energy requirements, offset high tariff increases, and mitigate power outages due to load shedding and the high cost and emissions associated with diesel backup generators, the industrial, commercial, and residential sectors have accelerated investments in solar photovoltaic (PV) installations. A recent study estimated the 2023 installed capacity at 5.0 GW_{peak}, double the 2022 estimates [3]. In the coming twelve months, these PV unlicensed "rooftop" installations will overtake the 6.3 GW of licensed renewable energy capacity brought into operation under the Renewable Energy Independent Power Producer Programme [4]. Furthermore, an electricity wheeling framework has been introduced, paving the way for large-scale, offsite electricity generation installations [5]. As a result, industrial operators are expected to lower their energy costs and reduce their carbon footprints.

Ready-to-drink beverage plants, producing soft drinks, juices, water, beer and cider, typically use steam (160-180 °C at 4-8 bars) as the primary heat working fluid. However, packaging hall processes, such as cleaning, washing and sterilisation, usually require temperatures at or below 80 °C. A previous study demonstrated that solar thermal projects would be viable alternatives to heavy fuel oil, diesel, gas, and even coal - should the cost of coal be above US$250/tonne (2020 real-term values) [6]. While steam boilers using fossil fuels are expected to continue to be the norm, it was demonstrated that up to half of fossil fuel consumption could be displaced by solar thermal collectors using parabolic trough collectors [6]. However, despite such potential, few large-scale projects have been commissioned to date and continue to require large subsidies [7]. Should low-cost electricity from renewable energy sources be available, heat pumps could be a lower-risk alternative.

Heat pumps have benefited from increasing policy support resulting from pressures to reduce carbon emissions from the direct use of fossil fuels in heating and cooling systems coupled with a drive to improve energy efficiency [8]. Global installed capacity has increased steadily to reach 1000 GW_{th} (nearly 200 million units) [8], [9]. While the global market for heat pumps dropped in 2020, growth has bounced back in 2023 with reported growth of 34% in Europe, 7% in China and 15% in the USA [9]. This includes domestic and district heating schemes and industrial applications [10]. Combined with thermal storage, heat pumps can provide flexibility to electric usage profiles, which can be attractive where the electricity supply is unreliable or electricity tariffs vary throughout the day [11]. High-temperature heat pumps (HTHP), an industrial subset, have also become options to provide steam, especially when a waste heat stream or solar thermal energy is available [12], [13].

Despite these dynamics, there has been limited adoption by industry, given high capital costs and the variable cost of heat due to high electricity costs, low waste heat availability or both [14]. While some studies have provided techno-economic comparison across thermal renewable energy solutions, the precise quantification requires three main inputs: 1) the cost of electricity, 2) the quality and quantity of waste heat available as input, and 3) the heat energy demand profile and operating temperatures. This study aims to provide a detailed assessment of the levelised cost of heat (LCOH) for beverage plant packaging hall operations, specifically where returnable glass bottles are cleaned and filled in conjunction with the production of PET formats. The results point to an LCOH of less than US$0.050/kWh where waste heat of 60 °C is available for large-scale PV systems and US$0.073/kWh where half of the electricity requirement is replaced by PV using heat from ambient air at an average of 20 °C. These results, in line with solar thermal system simulations for South Africa, remain at twice the current cost of heat from coal.

2. Method and materials

Given the prevalence of steam boilers within ready-to-drink beverage operations, this study has modelled high-temperature industrial heat pumps operating up to 160 °C [1]. This section provides an overview of high-temperature heat pumps and their capital costs. As was done in a previous study on solar thermal, the narrower but replicable energy demand profile of a typical soft drink packaging hall has been selected and is presented in this section [2]. Finally, an overview of South African energy costs is provided for comparative purposes.

2.1. High-temperature heat pump performance

Nowadays, high-temperature heat pumps can provide high temperatures for steam applications. Typical heat sources for heat pumps are surrounding air, geothermal energy stored in the ground, or nearby water sources or waste heat from a factory. The coefficient of performance (COP) of a heat pump strongly depends on the required supply temperature T_{sink} and the heat source temperature T_{source}. The rated COP can be calculated as the COP efficiency modifier η_{COP} multiplied with the ideal COP (Carnot).

$$COP = \frac{Q_{th}}{W_{el}} = \eta_{COP} \cdot \frac{T_{sink}}{T_{sink} - T_{source}} \quad (1)$$

Using heat pumps in industrial processes offers a means to harness the significant potential of waste heat, thereby enhancing process efficiency and mitigating CO2 emissions. Waste heat presents a valuable resource owing to its relatively elevated temperature range, typically between 30 and 70°C. In contrast to conventional applications, High-Temperature Heat Pumps are engineered to elevate heat to 150-160 °C [3], [4]. This necessitates robust compressors and suitable refrigerants with low environmental impact, such as those with minimal global warming potential. The range of high-capacity heat pumps capable of delivering elevated temperatures has experienced steady expansion in recent years.

The choice of the refrigerant depends primarily on the temperature level of the process to enable high efficiencies. The critical temperature usually gives the upper application limit for subcritical cycle processes (with condensation). To ensure efficient heat pump operation, a differential of 10 to 15K (depending on the refrigerant) from the critical temperature should be maintained [5]. Typical refrigerants for high-temperature heat pumps include R245, R365mfc. Alternative refrigerants with very low global warming potential are, for example, R600 (butane up to 135°C) or R601 (n-pentane up to 180°C). Water would also be conceivable as a safe refrigerant, but its high boiling point can only be used at high waste heat temperatures. Certain HTHP combine a refrigeration cycle with an additional vapour compression unit (Kobelco).

Waste heat availability and fluid operating temperature are critical drivers of heat pump performance and are usually plant-specific. Typical filling temperatures for soft drinks are between 5-10 °C, the lower temperature being favoured to retain carbonation and reduce foaming. To achieve these filling temperatures, ambient water at an average temperature of 16 °C (Cape Town and Johannesburg) must be cooled, especially in summer when average temperatures are above 20 °C [6]. This cooling has traditionally been achieved with large industrial ammonia compressors, which generate heat. Alternatively, heat pumps could be used to extract heat from incoming water as a source of quality waste heat. Another source of waste heat is from the blow moulding of PET bottles at a temperature that averages around 90 °C using an infrared heating lamp oven [7]. Well-controlled systems would have an ambient temperature differential estimated to be 10 °C [8]. For this simulation, a range of waste heat between 20 °C and 60 °C were selected.

2.2. Capital expenditure assumptions

Industrial heat pump capital costs are a function of unit size, with 2021 costs of less than US$400/kW for larger units of 4500kW or more and US$550 for units of 1000kW in capacity [9]. These one to five-megawatt units would be similar in capacity to the large backup diesel generators used in bottling packaging halls. While there are local manufacturers of heat pumps in South Africa, high-temperature heat pumps still need to be readily available, and global benchmark capital costs are therefore used for this study.

Costs are expected to come down with the acceleration in global deployment. Long-term forecasting of renewable energy costs depends on global capacity growth and learning rates [10]. Applying a temporal quadratic regression on historical capacity growth for heat pumps suggests a twofold increase in capacity by 2030. If the requirements of the International Energy

Agency's net zero scenario are met [11], the capacity for heat pump generation could triple. Using published learning rates of 10–15 % [12], [13], the resulting heat pump Capex would reduce 10–20 % by 2030 (in real terms).

Similarly, leading global manufacturers import photovoltaic solar panels and solar thermal collectors for large- and small-scale installations in South Africa. This study uses 2020 cost benchmarks and 2030 cost projections previously published [10]. Table 1 summarises the capital cost expectation for photovoltaic, solar thermal (parabolic trough collector systems) and high-temperature heat pump technologies with representative LCOE and LCOH. The solar thermal and heat pump Capex and LCOH for 2023 assume no inflationary increase from 2020 costs, hence a decrease in real terms. Photovoltaic installation capex has, however, continued to reduce in nominal terms, with late 2023 and early 2024 data obtained from representative large-scale installations of >100kW$_p$. While PV-generated electricity for projects being commissioned in 2024 will be at less than half of the average electricity tariffs, project financing, network charges and operator returns will increase this value.

Table 1. *2020 and 2023 Capex, LCOE and LCOH estimates (2023 US$)*

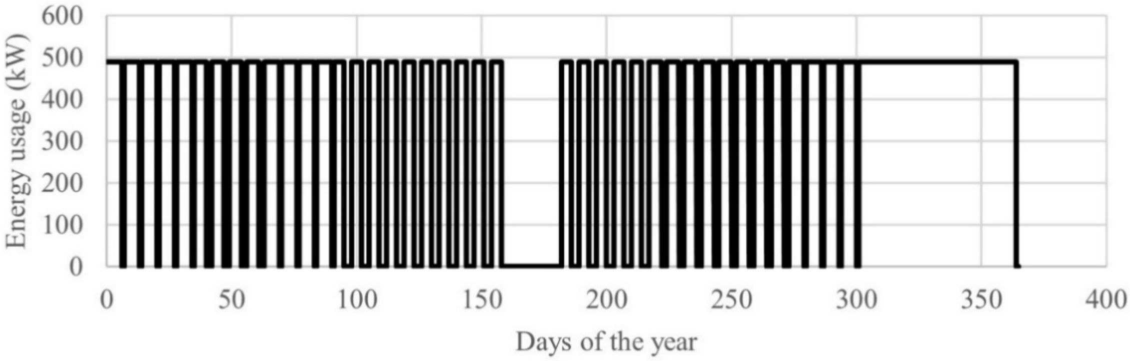
2023 US$ values	Photovoltaics		Solar thermal (PTC)		Temp Heat Pumps
	Capex (US$/kW$_p$)	LCOE (US$/MWh)	Capex (US$/kW$_{th}$)	LCOH (US$/MWh$_{th}$)	Capex (US$/kW)
2020 Global	1007	65	570	46	570
2020 RSA - Gauteng		46	515-735	50-80	
2023 RSA - Gauteng	700	32	450-650	45-70	500

2020 data is inflated by 1.14 to 2023 US$ values [14]; 2020 PV global average capex of US$883/kW and LCOE of US$57/MWh from IRENA [15]; 2020 PV RSA LCOE from REIPPP window 5 [16], [17]; 2020 solar thermal large industrial systems from IRENA with global capex of US$500/kW and US$40/kWh$_{th}$ [18]; 2020 solar thermal Gauteng estimates from previous solar thermal techno-economic study [2]; 2020 heat pump capex of US$500/kW from literature [19]; 2023 PV Capex and LCOE are based on early 2023 and early 2024 data; 2023 solar thermal and heat pump capex and LCOH assume no nominal cost increase.

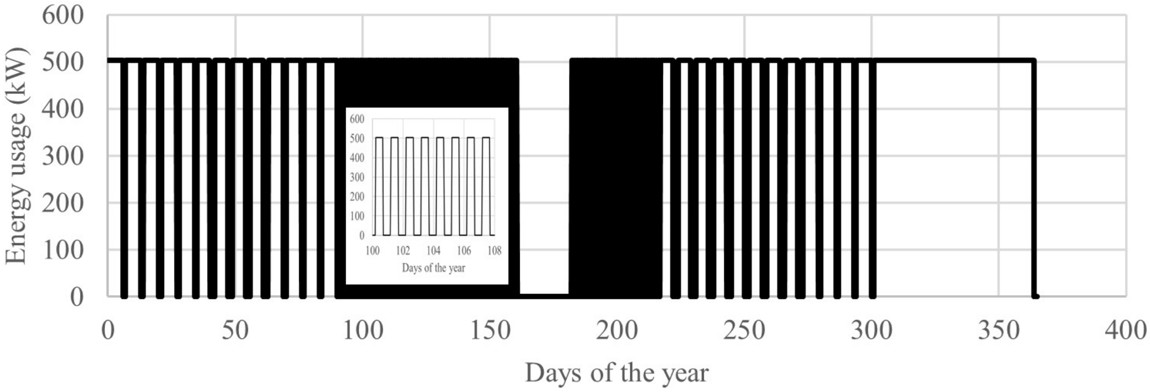
2.3. Thermal energy demand profile

A previous solar thermal study proposed generic process heat requirement profiles for packaging halls, which are used again to develop a baseline techno-economic assessment [2]. These energy demand profiles were found to be highly seasonal, with seven days a week of operation in summer and variable operation regimes in winter. South African soft drink production facilities are typically large sites (with several high-speed bottling lines). Polyethylene Terephthalate (PET) and returnable glass bottle (RGB) lines usually co-exist. Similarly, large-scale breweries are the norm, with most production being returnable glass bottles and the rest being one-way glass bottles. Typical packaging hall demand would be 0.2 kWh$_{th}$/litre in process heat requirements, given the need for pasteurisation, bottle washing, and sterilisation [20], [21].

The process heat energy requirement in Figure 1, replicated from a previous study, would be representative of an annual operating regime for a large soft drink facility of 200 million litres in annual production that combines one-way PET and returnable glass bottles (or a smaller regional RGB facility with ~55 million litres in annual production) [2]. Case A assumes 24-hour operation with fewer working days in lower-demand periods with an average hourly process heat consumption of 500 kW$_{th}$ (excluding 1500 kW of electricity). Case B's 12-hour operating regime for winter months would require similar hourly energy consumption with additional working days throughout winter. In both cases, the annual heating load is 3057 MWh_{th}.



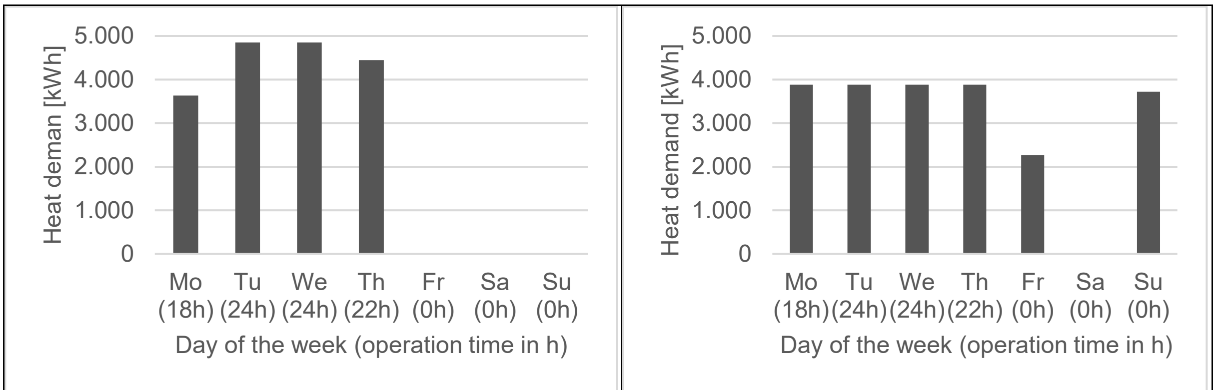
a) Case A: 24-hour-per-day operating regime, with a 3-week shutdown in June



b) Case B: 24-hour- per-day operating regime with 12h per day operation when necessary, with a 3-week shutdown in June

Figure 1. *Hourly process heat requirement profile for typical soft drink plants*

For comparison, the heat consumption of a middle-sized brewery in Germany for bottle washing is included in Figure 2. With a maximum capacity of 32.000 bottles per hour, the heat demand profile presents similar variations between peak and off-peak seasons.



Off-peak season	*Peak season*

Figure 2. *Daily process heat requirement profile for German medium-sized brewery*

2.4. The cost of heat from fossil fuels in South Africa

In recent years, fossil fuel markets have experienced increased volatility, first due to the COVID-19 pandemic demand disruptions followed by the war in Ukraine supply disruptions. As a result, global oil prices and South African export-grade coal prices have reached peaks of three to five times their decadal low before oil settled on an average of US$80/barrel in 2023 and coal averaged US$100/tonne in 2023 [22]. For South Africa, the LCOH for 2017, as reported by the Solar Payback project, are presented in Table 2, together with 2023 average LCOH, assuming a steam boiler energy conversion of 80 %. While gas was historically commercially available in certain provinces (Gauteng and Kwazulu-Natal), new contracts are no longer available due to insufficient supply [Sasol].

Table 2. *The nominal cost of heat from traditional fuels 2017-2023 (excluding capex)*

	Unit	**2017Q2 Costs**	**2023 Costs**	**2017H1 Heat cost @80%**	**2023 Heat cost @80%**
Fuel		(US$)	(US$)	(US$/MWh$_{th}$)	(US$/MWh$_{th}$)
Coal–Gauteng	tonne	68	120	11	20
Coal–Western Cape	tonne	114	200	19	33
SASOL gas C3 Gauteng/KZN	GJ	9.4	12.6	42	57
Heavy Fuel Oil (HFO)	litre	0.39	0.80	42	87
Diesel 0.05 %	litre	0.88	1.15	105	135
Electricity–Average Megaflex variable	kWh	0.06	0.10	60	100

Mid-year data for 2017 from the Solar Payback project [23] converted back to US$ at the 2017 exchange rate of ZAR13.20/US$ [24], except for electricity tariffs as per Eskom historical data for comparison to Megaflex average variable rate [25]. 2023 data from the following sources: Coal: RSA coal export monthly price [22]; Coal Western Cape with transport adjustment at ZAR1.18/tonne-km [26]; HFO; United States heating oil reference price [22]; South African diesel price [27]; 2023 Megaflex variable electricity tariffs [25]; Sasol gas as reported (linked to coal, diesel and electricity prices); 2023 average of ZAR18.44/US$ [24]; Heat cost estimates assume boiler efficiencies of 80 % but for electro-boilers at 100 %

3. Simulation model overview

As the Polysun software lacks a dedicated model for high-temperature or exhaust gas heat pumps, initial parameterisation of such a model was necessary. This involved conducting pre-calculations for analysis using Chemcad® software with two models, a single-stage model for typical temperature swings (Tsink 40°C, Tsource 120°C) and a two-stage model that is able to use low-temperature (Tsink <=20°C) heat as source and transfer this to high-temperature heat up to 160°C as required by the introduced process. Both models feature an internal regenerator. These calculations entailed determining the COP (Coefficient of Performance) across various refrigerants and temperature ranges.

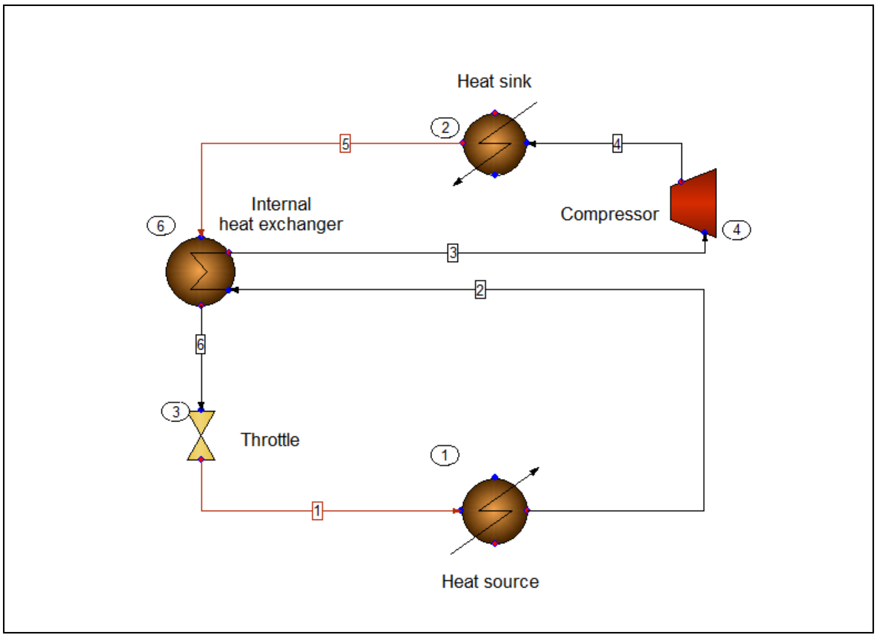


Figure 3. *Heat pump schematic in Chemcad ®. Single-stage model.*

The single-stage heat pump with internal regenerator is presented in Figure 3. The temperature levels for heat source and heat sink can be adjusted by throttle and compressor outlet pressures. The evaporator at the heat source produces saturated steam, while the heat sink is adjusted produce saturated liquid phase. In the preliminary study three different refrigerants were used for different pressure levels: R365mfc (1,1,1,3,3-pentafluorobutane), R245fa (1,1,1,3,3-Pentafluorpropan) and R601 (n-pentane). Figure 4 illustrates COPs calculated for various operating parameters and working fluids with the single-stage model. The left diagram depicts the COP as a function of sink temperature and source temperature for R365mfc. As expected, the COP was found to be strongly dependent on both the source temperature (waste heat) and the temperature swing. For instance, with a waste heat source temperature of 60°C and a temperature swing of 100K, the COP was calculated to be 2.5. This aligned reasonably well with the performance of commercially available heat pumps within this temperature spectrum. Typical COPs are in the range of 2.0-4.7 [2,3]. Ambient air or geothermal energy is generally used for lower sink temperatures, while solar thermal or PV-Thermal energy systems could also be used to increase source temperatures. The right diagram in Figure 4 illustrates the COP at a constant source temperature for the three different working fluids. R365 is notably more suitable for high sink temperatures compared to R245. N-Pentane performs similarly to R365, with a significantly lower Global Warming Potential (GWP). However, it is critical to consider the flammability of N-Pentane in this context.

Figure 5 shows the model of the two-stage heat pump with vapour compressor. To realize the high temperature difference between the above described source temperatures (20°C) and sink temperatures (160°C), one would need a refrigerant with a sufficiently low boiling point at low pressure and a sufficient distance from the critical point at high temperature (pressure). Such refrigerants are rather rare, which is why a two-stage approach with a heat pump and vapour compressor is proposed. Low-grade waste heat is utilized in the evaporator (1) to vaporize the refrigerant. Butane (R600) was chosen as a suitable refrigerant with a low GWP. The vaporized refrigerant is preheated via an internal heat exchanger before being fed to the compressor. The superheated vapor is completely condensed at high pressure, with the heat being transferred to the feedwater under pressure via heat exchanger (2). The saturated vapor generated during expansion in the flash tank (8) is then compressed from atmospheric pressure to the target pressure. To produce saturated vapor, feedwater is additionally supplied to the already superheated vapour (flash tank 9). The process simulation for such a system yields a coefficient of performance (COP) of approximately 1.7–1.8 (heat source 20°C inlet temperature, 10°C outlet temperature; feed temperature 90°C, isentropic compressor efficiency of

0.75). Based on the calculated performance data, a model for an HTHP was parameterised in Polysun and adjusted to match the performance of commercially available products

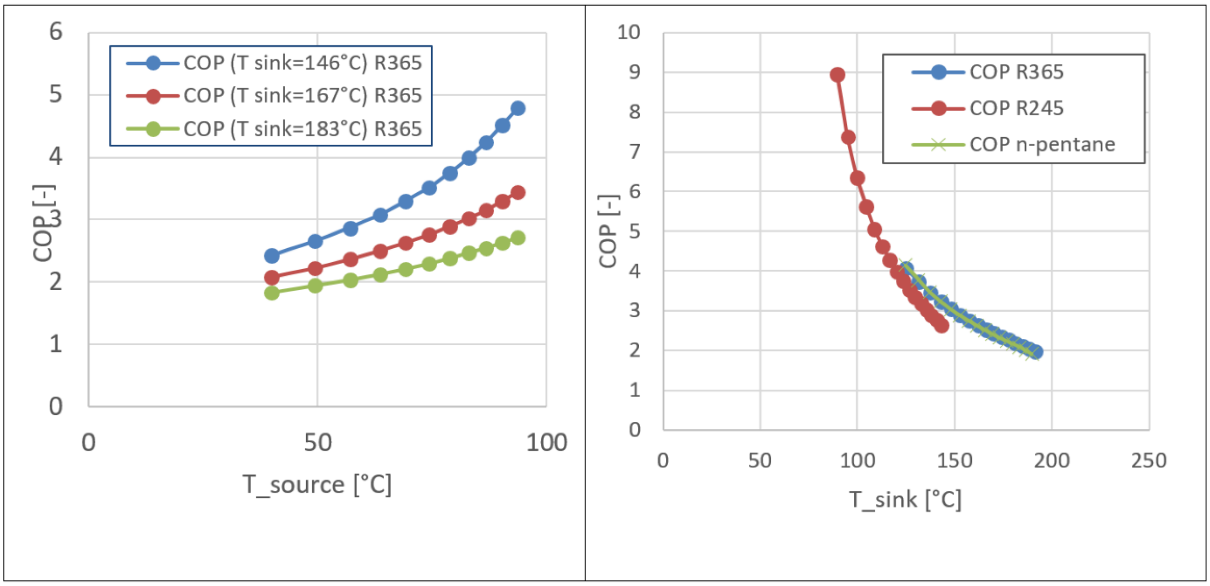


Figure 4. *COPs as simulated with Chemcad®. Left: Results with refrigerant R365 for different sink and source temperatures Right: COP for different refrigerants (R245, R65, n-pentane) at various sink temperatures with source temperature T_source=63°C.*

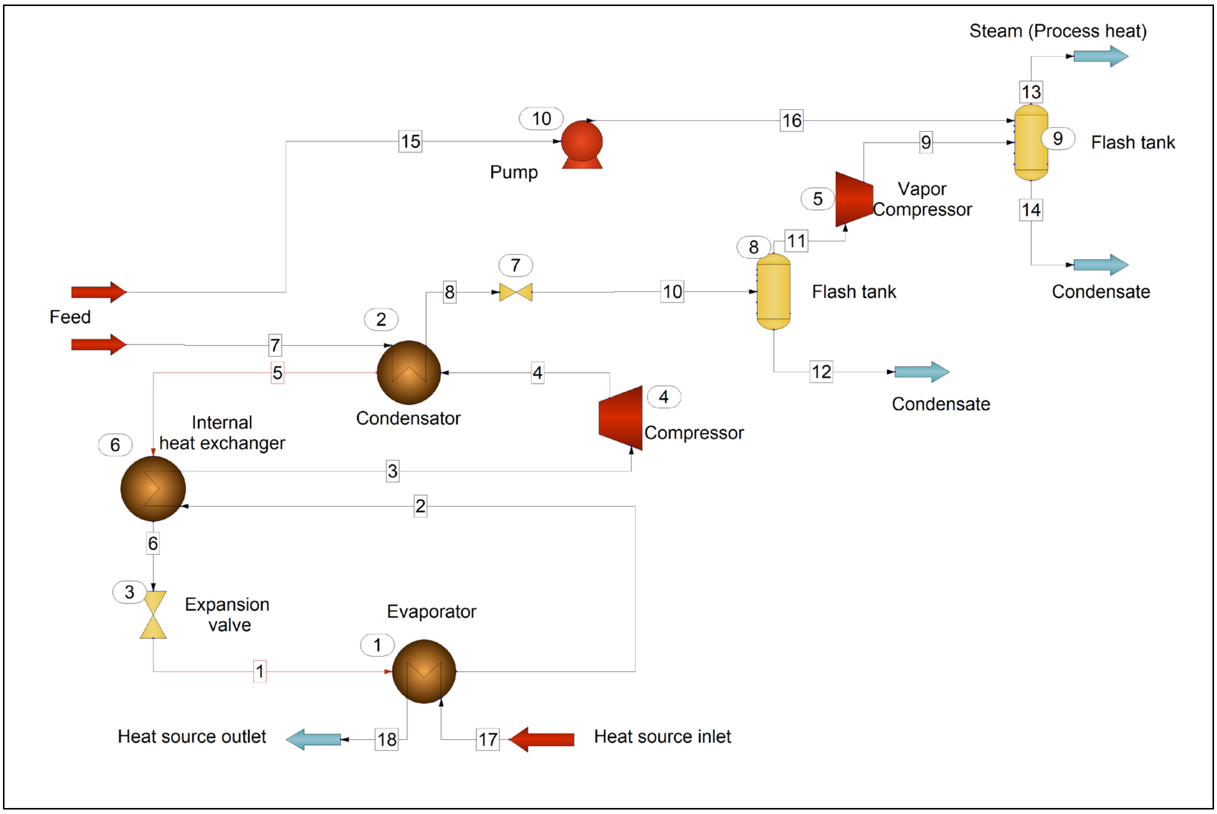


Figure 5. *Two-stage model with heat pump and vapor compressor in Chemcad®.*

From the Chemcad simulation, an approximate COP efficiency modifier of $\eta_{COP} = 0.6$ as a good general fit over a large temperature range with an isentropic compressor efficiency of 0.75. However, the comparison to a commercial heat pump would be better fit with an $\eta_{COP} = 0.54$ which was finally used to calculate the COP as a function of any temperature set. The results should be slightly underestimated and conservative for smaller temperature swings.

Figure 6 illustrates the COPs that were used as the basis for the Polysun heat pump model. The dependence on source and sink temperature is very pronounced. The COP drops significantly with increasing temperature swing.

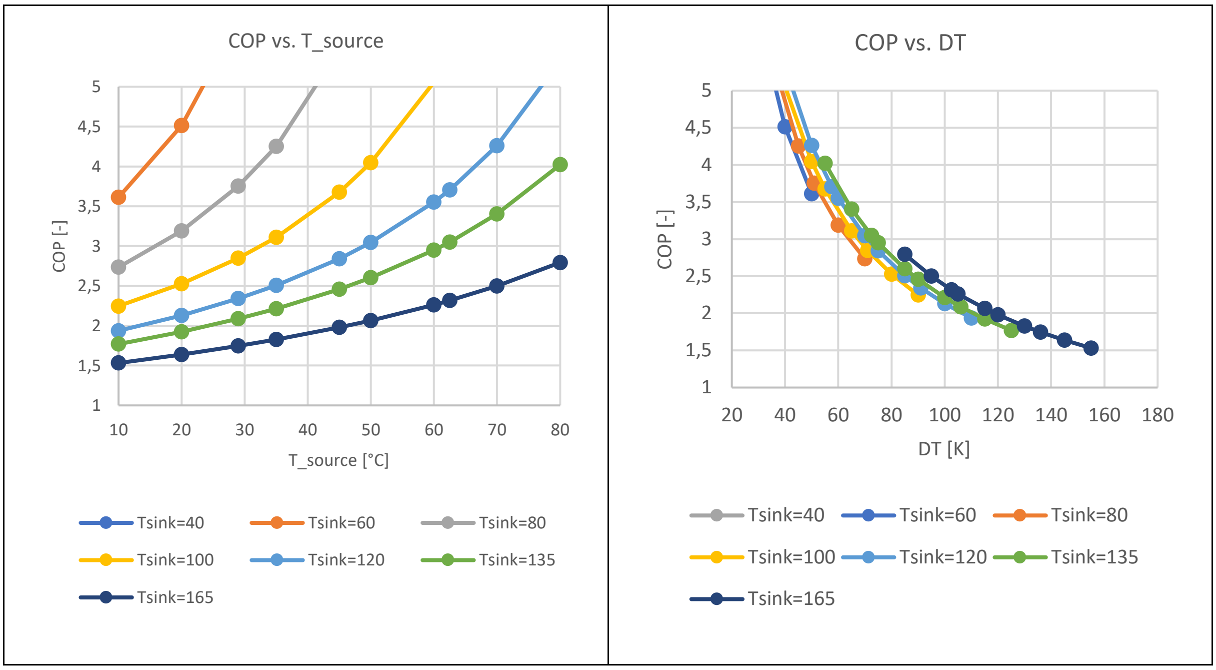


Figure 6. *Heat pump COP data as used in Polysun.*

Left: COP vs. Source temperature for various sink temperatures.

Right: COP vs. Temperature swing for various sink temperatures.

The full process model in Polysun® is presented in Figure 7. It includes a heat pump that extracts its source heat from waste heat that can be adjusted as available. The heatpump model allows for inclusion of individual data, which is, in this case, based on the above calculations. The generated high-temperature heat is stored in a pressure vessel and can be reheated by a conventional fossil fuelled boiler if necessary. The demanded process heat can be defined by individual load profiles. The heat pump can be powered by the electrical grid or by photovoltaics if included. As an additional feature load shedding-profiles can be included, so that in case of a grid shut-down the heat pump will be still powered by PV power if available. The backup boiler is not used in the subsequent simulations. All paramteres can be changed for further analysis.

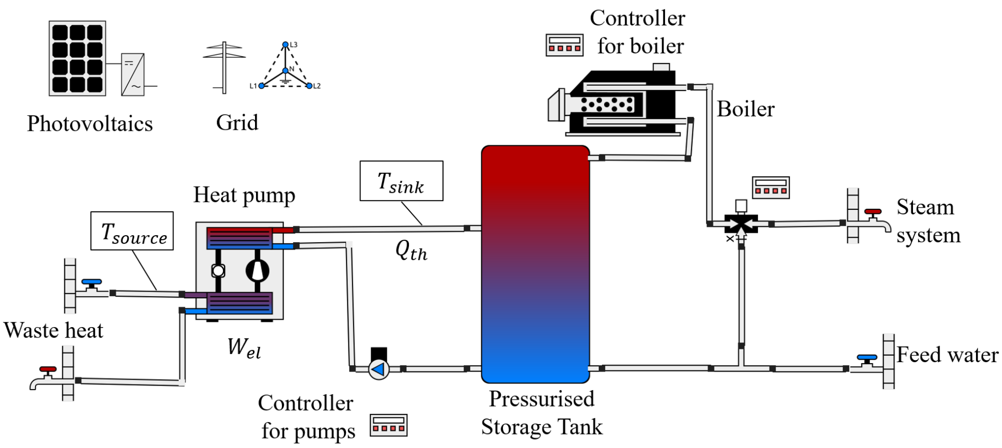


Figure 7. *HTHP and PV process schematic modelled in Polysun*

4. Results

4.1. Yield of Photovoltaic and solar thermal energy collectors

This section compares the solar yield of solar thermal (ST) and PV systems. For photovoltaic installations, modules can be installed with a fixed tilt angle or with tracking. Simulation results show that the optimal fixed tilt angle in South Africa is 30°. Parabolic trough collectors (PTC) were selected from various alternatives for solar thermal yield calculations, in line with a previous study [2]. Figure 8 compares the area-specific yields with the north-south tracking system, which is advantageous for PTC compared to east-west tracking. For this study, racked systems with NS-tracking are modelled.

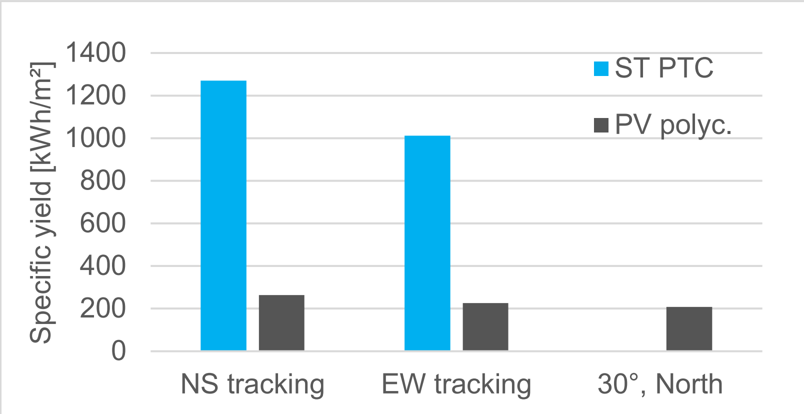


Figure 8. *Specific yield of PV vs ST for Cape Town*

4.2. Reference case

The reference case is specified for the cleaning of returnable glass bottles (RGB) and PET bottles:

- Load profile Case B: 24-hour- per-day operating regime with 12h per day operation when necessary, with a 3-week shutdown in June
- Steam temperature: 160 °C
- Annual heat demand: 3058 MWh/a
- Maximum heat rate: 500 kW_{th}
- Location Cape Town
- Heat pump peak power: 624 kW
- No active steam boiler (only backup)
- Storage tank: 5 m³
- Location: Cape Town
- PV modules: polycrystalline, NS tracking, 250 Wp, gross area 1.95 m²

The baseline economics are derived using the real-term weighted average cost of capital (no inflation). Two cases are presented in Table 3 with Higher and Lower Capex values for PV and storage.

Table 3. *Low and High Capex scenario assumptions*

		Low Capex	**High Capex**
Heat pump cost	$/kWth	500	500
Storage cost	$/m³	1700	2000
PV system cost	$/kWp	700	1007
Average system life HTHP (ST)	Years	15 (20)	15 (20)
Weighted average cost of capital (WACC)	%	6.5	6.5
Annual operation costs	% of Capex	2	2
Inflation	%	0	0
Electricity tariff	$/kWh	0.1	0.1
Electricity tariff increases above inflation	%	3	3

4.3. High-temperature heat pump with PV system

To assess heat pump performance and costs, numerous scenarios are considered. The source temperature is varied, which affects the COP of the heat pump. Furthermore, photovoltaic systems of different sizes were also taken into consideration. The influence of the PV-system on the process can be characterised by the degree of self-sufficiency and the self-consumption rate. Figure 9 shows that both values depend strongly on the PV peak power and source temperature. The degree of self-sufficiency describes the share of the electricity consumption that is covered by the photovoltaic system either by simultaneous consumption of the generated solar electricity or by discharge of a battery. Due to high investment costs, batteries are not considered in this paper. The degree of self-sufficiency naturally starts from 0 if no PV is installed and goes up to around 50%. This means that grid independency cannot achieved without significant storage capacity, either battery or thermal storage.

The solar self-consumption rate is given as a percentage and refers to the total amount of PV energy consumed in relation to the total amount of energy generated. The self-consumption rate should be high for smaller PV installations. From the right chart, one can derive that the maximum self-consumption fraction is about 70% for the given case. This is due to non-conformous heat demand and solar yield. It drops for PV sizes bigger than 400 kWp which is disadvantageous if the unused PV electricity cannot be used elsewhere or being sold to electric grid.

The LCOH are calculated for low and high capex cases, as shown in Figure 10. Without PV the LCOH are in the range of 0.65–0.85 $/kWh, depending on the available heat source. The cost can be reduced by using PV. A certain flattening or saturation occurs at around 500 kW_{peak}, with the lowest LCOH achieved with systems of 500 to 600 kW_{peak}. The conclusion is the installed PV size should be in the equal range as the maximum demanded heat rate.

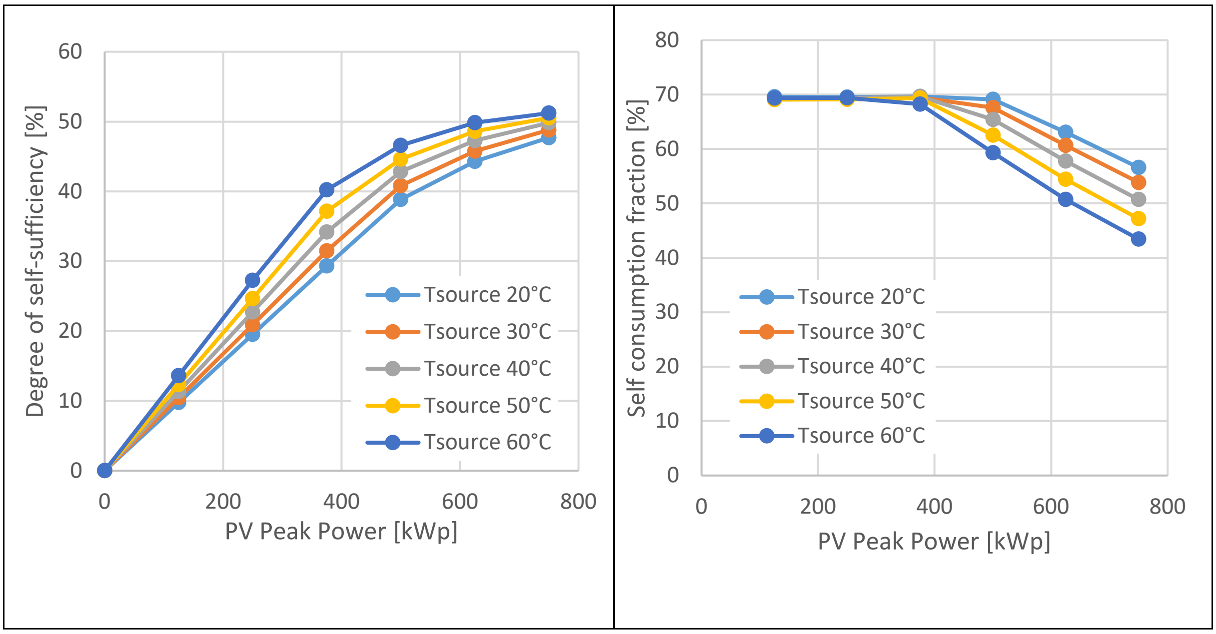


Figure 9. *Sensitivity to PV power and source temperature for process heat temperature of 160°C*

Left: Degree of self-sufficiency | Right: Self-consumption fraction

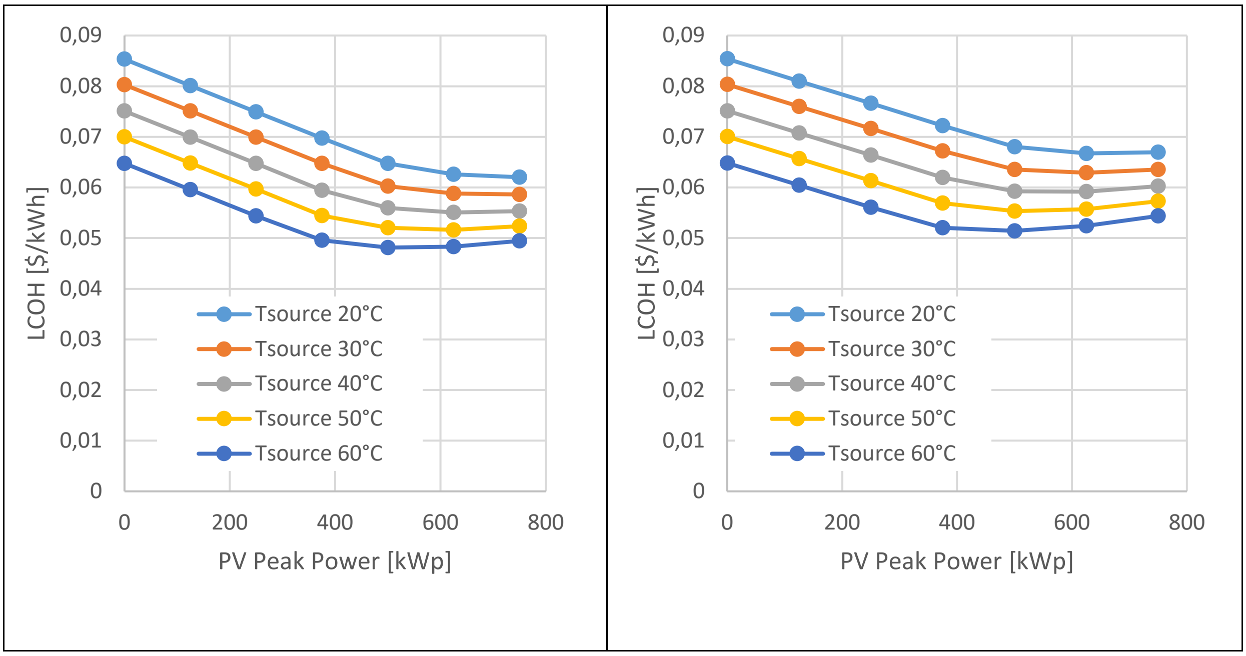


Figure 10. *HTHP+PV system LCOH as a function of PV generation capacity.*

Left: Low capex, right: High capex

4.4. High-temperature heat pump LCOH with varying electricity tariffs

From approximately 500 kWp, PV systems generate surpluses, which were assumed to be lost in the previous section. Generally, municipality or third parties would be willing buyer of electricity during the day. Given the variability of supply a discounted feed-in tariff would be expected for surplus electricity. Figure 11 illustrates how excess PV generation capacity could reduce the LCOH by 10–15% using US$0.05/kWh feed-in tariffs and up to 20% with feed-in tariffs of US$0.010/kWh, which would be in line with Eskom Megaflex variable tariffs for day-time hours.

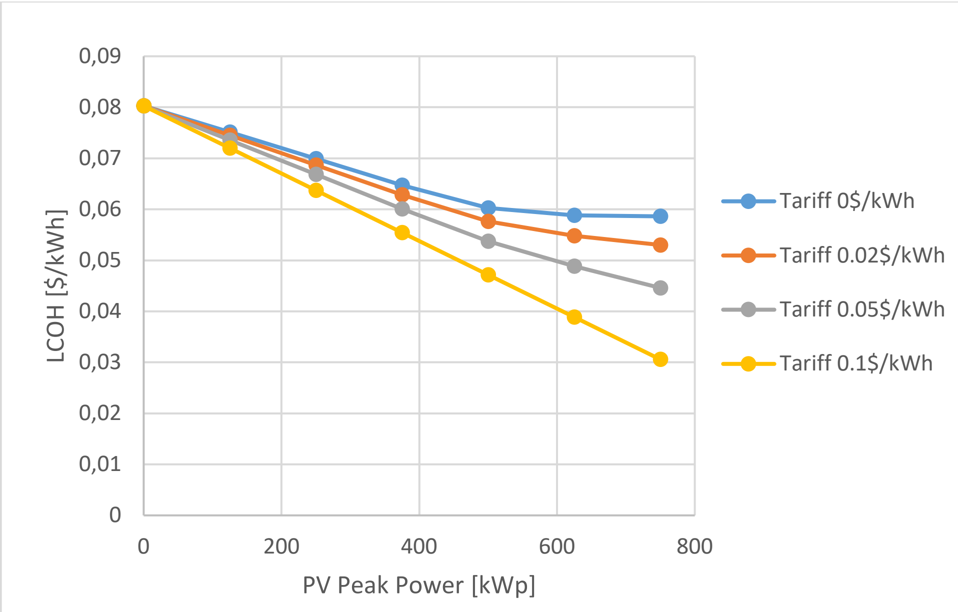


Figure 11. *Effect of feed-in tariffs on LCOH (Process heat temperature 160°C, Tsource=30°C, Tank 5m³)*

4.5. Process coverage during shutdown of electrical power

Over the last few years, South Africa's economy and production facilities have been impacted by frequent load-shedding periods with daily power supply interruptions. The impact of load shedding was simulated by lifting network availability between 7:00–9:00 am and 6:00–8:00 pm. The reference system has a supply coverage of just under 92 %. To raise the supply to a level of over 99 %, the use of electrical, thermal storage, or diesel generators is required. This paper analyses a cost-effective solution through thermal storage. In Figure 12, the effect of storage on supply security is depicted. With a 150-200 m³ storage capacity, thermal supply can be improved to over 99 %. However, the LCOH presented in Figure 13 is US$0.005-0.010/kWh higher than the reference system.

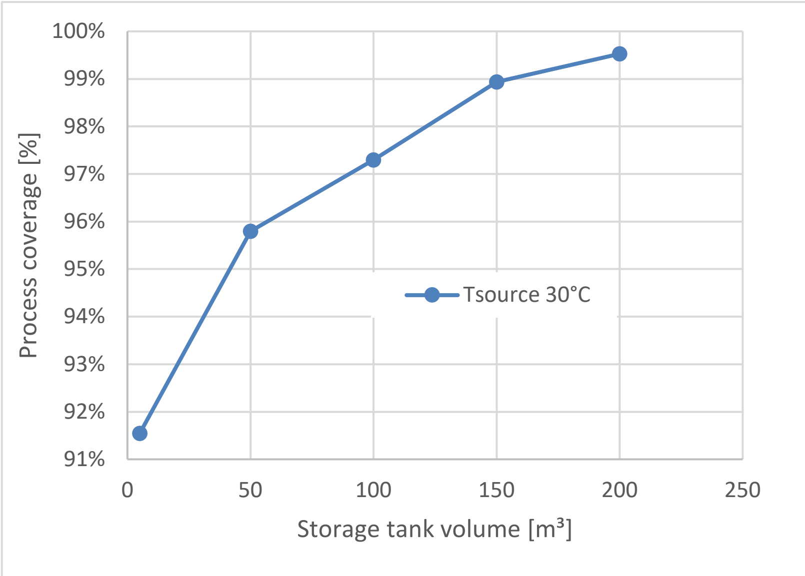


Figure 12. *Impact of storage on process coverage in heat supplied from PV. Source temperature 30°C. Process heat temperature 160°C.*

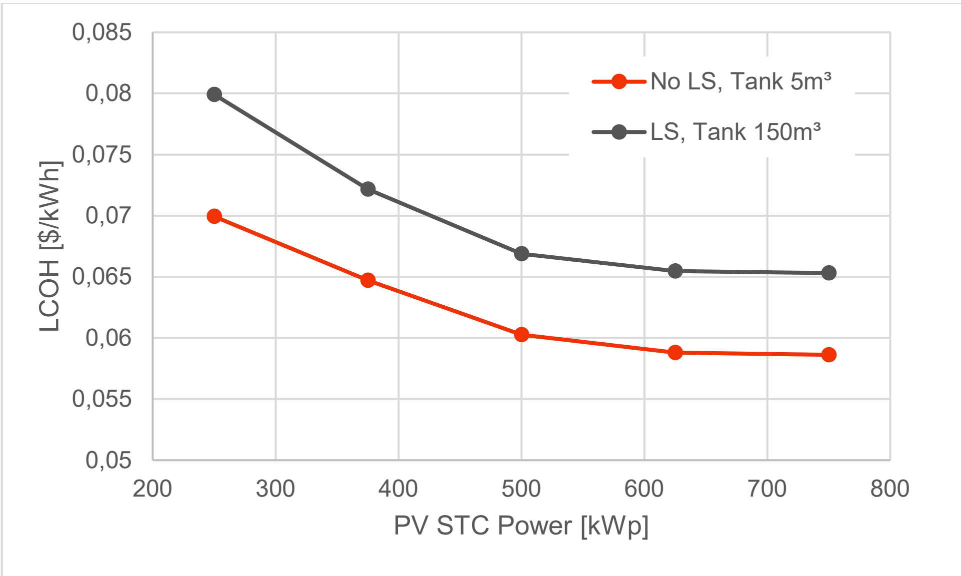


Figure 13. *Impact of storage and Loadshedding (LS) on LCOH. Process heat temperature 160°C.*

4.6. High-temperature heat pump and different steam temperature

One way to increase the COP of the heat pump and the overall efficiency of the system would be the decrease of the steam pressure. This effect is studied by simulating and comparing identical heat demand at two different steam temperatures and presented in Figure 14. When using steam at 120°C instead of 160°C the LCOH can be decreased approximately by 0.01 $/kWh. Although the advantage of lower steam pressure and temperature is obvious, decreasing the pressure of a given system needs to be carefully analysed because there could be unexpected correlations with other process parameters. The pressure decrease leads to an increase of specific volume and steam velocity in the pipes resulting in increased pressure drop. The higher velocities and bigger bubbles could also lead to entrainment of liquid droplets, thus reducing the quality of steam. Other aspects are the influence on pressure reducing stations, flowmeters and even on the feedwater pumps that could be affected by cavitation at the higher flow rates.

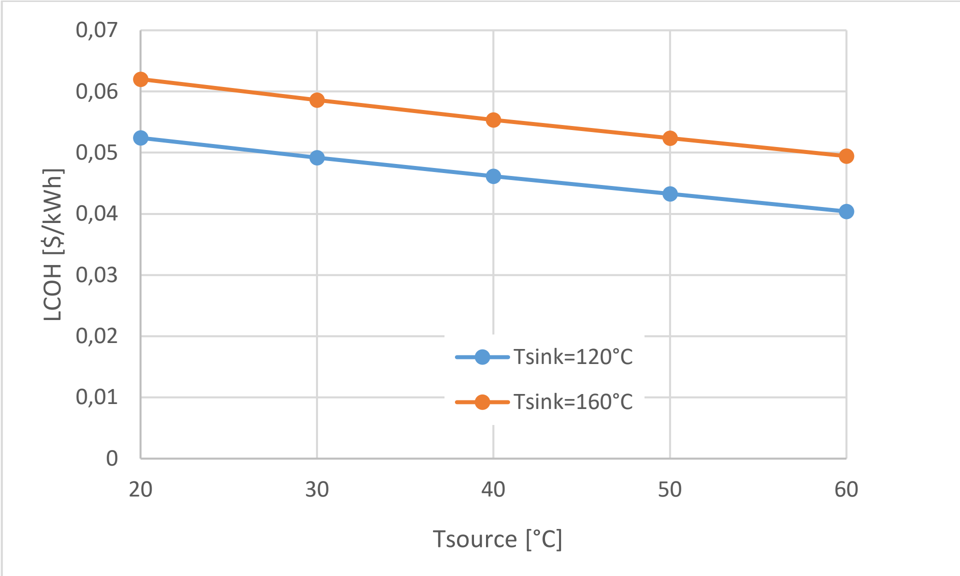


***Figure 14.** Impact of process heat temperature on LCOH (750 kWp PV, 5 m³ tank)*

5. Discussion

This study estimated the cost of heat at US$0.048/kWh$_{th}$ from high-temperature heat pumps powered by a 0.5 MW$_{peak}$ PV installation using waste heat at 60 °C. This is somewhat lower than estimates from international benchmark studies and in line with the LCOH from heat pumps using electricity tariffs of US$0.07/kWh. In 2023, Saini et al. [19] calculated the LCOH of a typical industrial high-temperature heat pump with a coefficient of performance of 2.5, delivering steam at 140 °C. The resulting LCOH for heat pumps with a high-capacity factor (>6000 hours per annum) is summarised in Table 3 for different utilisation levels (24 hours a day operating seven days a week as well as 24 hours a day running five days a week) and variable electricity tariffs. The Capex value of US$500/kWh$_{th}$ used in their modelling was also selected in this study as it represents the cost of larger heat pump systems [28]. According to Table 3, using the current average cost of electricity in South Africa at US$0.10/kWh, the base-line LCOH of heat pumps operating at a Coefficient of Performance (COP) of 2.5 would be around US$0.06/kWh$_{th}$. The results obtained in this analysis are in real costs which would explain the lower LCOH calculated.

***Table 3.** LCOH of heat pumps costing US$500/kW$_{th}$ with COP of 2.5 [19]*

LCOH (US$/MWh$_{th}$)		**Electricity costs** (US$/kWh)		
		0.07	0.10	0.15
Utilisation (Hours per annum)	8760 (24/7)	45	59	84
	6264 (24/5)	49	63	88

In a previous study, the optimal LCOH for solar thermal heating systems were obtained by varying storage capacity for a given field size, as shown in Figure 15 [2]. The optimal solar thermal energy system cost for Cape Town yielded an LCOH of US$0.038-0.053/kWh$_{th}$ for a 12h winter operating regime, depending on the capital expenditure cost assumptions. Without any subsidies, as of 2023, solar thermal energy solutions could be more cost-efficient over the life of the projects than high-temperature heat pumps. However, both solutions are heavily influenced by the initial capital expenditure costs.

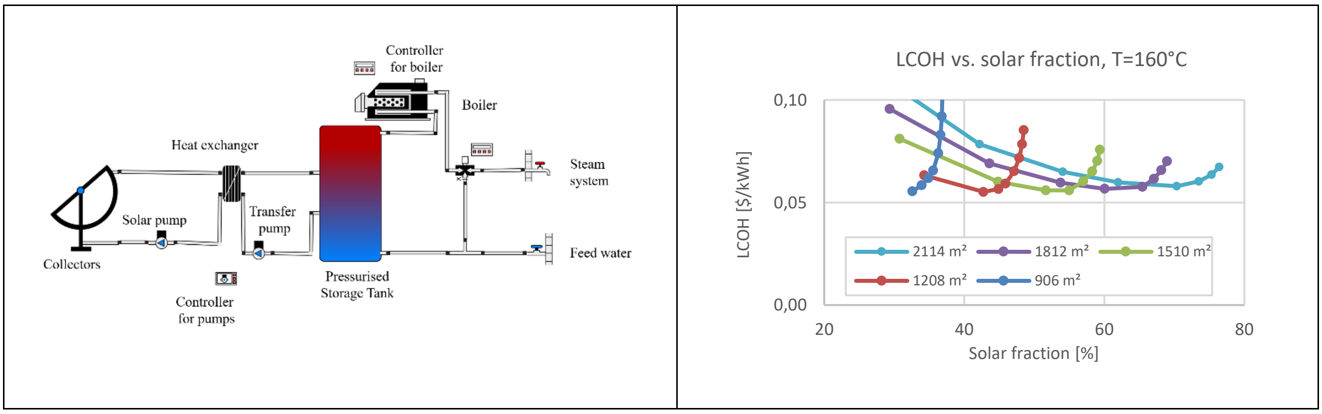


Figure 15. *Solar thermal process schematic and LCOH and solar fraction as a function of aperture area for Cape Town*

Figure 16 compares the cost of an illustrative solar thermal systems for Capetown with low and high capex values which differ by a factor of approximately 3:4. This is similar to the PV cost differential, which make up only a portion of the heat pump PV driven system. The low cost differential between low and high capex scenario for heat pumps is linked to the self-sufficiency of the system which requires high cost electricity input from the grid for at least half of the time when systems LCOH are optimal. For heat pump systems to match the cost of solar thermal system, the cost of electricity would need to be less than US$0.07/kWh.

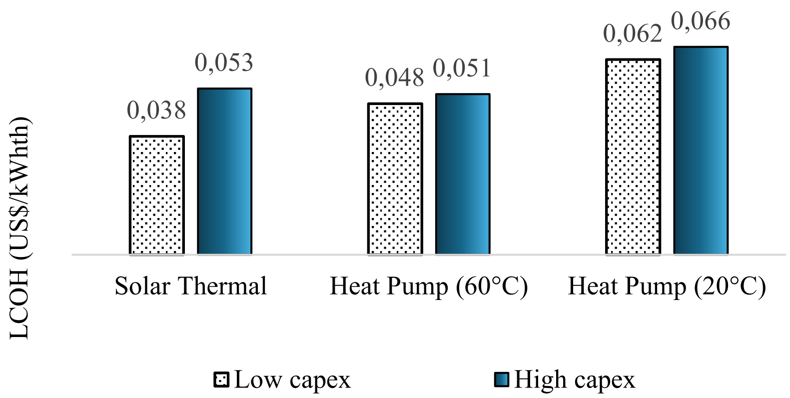


Figure 16. *LCOH comparison between solar thermal and heat pump energy systems*

Compared to traditional fossil fuels, high-temperature heat pumps and solar thermal energy systems would yield LCOH roughly twice that of coal for the Gauteng province (Johannesburg and Pretoria). However, they could be competitive in the Western Cape (Cape Town), specifically when including the capital cost of new coal boilers. Against liquid fossil fuels, heat pumps and solar thermal energy systems would deliver better life cycle costs than the US$0.09/kWhth variable cost of heat from heavy fuel oils.

The simulation in this analysis assumes that excess power generated by the PV installation can be sold back to municipalities or the national power operator. In South Africa, the feed-in tariff rates vary from municipality to municipality. The viability of PV powered heat pump system would, therefore, be influenced by feed-in tariff agreements over the project's life and given the 10-20% impact on LCOH is a critical parameter in any feasibility study.

Another critical success factor is the quality of waste heat available. Higher-quality waste heat from chilling compressors or PET bottle blowing could be used to pre-heat the sink water stream. A site-specific study regarding the quantity of liquid needing to be chilled for bottling purposes and the chilling temperature differential required over the year would be necessary to provide a better understanding of waste heat availability.

The modelling of a water cooling and heating unit presented in Section 3, provided low COPs. Further work would be required to compare the economics of such system to prevailing chilling compressors, which drive a substantial electricity usage in packaging halls. However, these analyses went beyond the scope of this paper. Another mean to boast heat pump COP would be to use solar thermal energy systems which should be part of further configuration developments.

Finally, the potential to lower the steam pressure and temperature should be considered, given that from a thermodynamic viewpoint, lower temperatures would increase the solar thermal efficiency and the heat pump COP. Ultimately, packaging halls should introduce a hot water bottle cleaning systems to improve system performance. Further work is, therefore, necessary to better understand potential energy efficiency initiatives and the potential impact on system viability and integration points.

6. Conclusions

In South Africa, where the cost of electricity has increased well over inflation over the last decade, energy efficiency and renewable energy solutions should receive increased attention. While industry has accelerated investment in power generation, coal-fired steam boilers remain the primary source of process heat, at least in the beverage sector. Ready-to-drink production facilities use bottle washing and sterilising equipment in most large-scale packaging halls, where pressures are mounting to reduce reliance on fossil fuels.

This study indicates that high-temperature heat pumps powered by PV-generated electricity offer a credible alternative to traditional steam boilers. The economics are similar to solar thermal energy systems, depending on capital expenditure assumptions and the availability of waste heat stream. At face value, project risks for heat pumps are lower, which may influence decision-makers. However, in the short term, given the low cost of coal, policy support, subsidies, or pressures to reduce carbon emissions will be necessary for large-scale projects to be commissioned.

Further work will be necessary to optimise systems, namely by assessing the need for steam systems against very hot water systems and by firming up the cost of conversion, namely for bottle washers. Lower process heat temperature would indicatively reduce capital costs to the lower capex of US$400/kW or even lower for large systems. Improvements to COP from 2.5–3.0 to more than 5.0 would also have substantial impact on lowering the system LCOH.

Data Availability Statement

Analyses data available on request.

Author Contributions

Conceptualisation, JK; Methodology, JK; Validation, JK; Formal Analysis, JK; Writing—original draft preparation, FR and JK; Writing—review and editing, FR and JK; supervision, CM. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Funding

This research received no specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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