Comparative analysis of solar thermal and PV-assisted heat pump technologies for industrial process heat in Southern Africa and Central Europe

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Abstract

Industry is the largest energy consumer, with most demand occurring as direct heat input. For low to medium-temperature industrial processes (≤160°C), heat pumps and solar technologies offer significant opportunities to reduce industrial carbon emissions. This work presents a comprehensive comparison of solar thermal energy systems and photovoltaic-assisted heat pump technologies for industrial process heat applications, specifically contrasting their performance in Southern Africa and Central Europe.

Three distinct scenarios from the beverage industry, each representing different operational scales, are examined to highlight the trade-off between economic viability and environmental sustainability. Hybrid solar thermal configurations achieve high solar fractions, but the heat pump pathway proves very viable in both regions for deep, cost-effective CO_2 reduction. While Southern African solar systems yield substantially higher energy output per square meter of collector area, the relatively higher cost of natural gas in Central Europe provides favorable economic returns. Significant CO_2 reductions are enabled by a combination of measures, including public funding to offset initial capital costs, rising fossil energy prices, and decreasing technology costs.

Keywords: process heat, solar thermal, photovoltaics, heat pumps, Southern Africa, Central Europe, techno-economic analysis, CO_2 emissions

1. Introduction

Solar thermal (ST) energy systems and heat pump (HP) technologies are essential for enhancing sustainability in industrial process heat applications (Kosmadakis, 2019; Meyers, Schmitt & Vajen, 2018). In 2019, the German Solar Association coordinated an assessment of the potential for solar-generated process heat in South Africa (Solar Payback, 2019). The report included a review of potential technologies across temperature ranges and identified the food and beverage sector as a promising focus area given the large number of steam boilers in use (Solar Payback, 2019). More recently, researchers estimated the energy usage across the beverage sector at 3-terawatt hours per annum with CO_2 emissions of two million tonnes per annum (Rozon, McGregor & Owen, 2024). Further work estimated the levelised cost of heat (LCOH) of solar thermal energy systems for steam production, in Cape Town and Johannesburg, at between US$38-70/kWh$_{th}$, 2–3× the cost of steam generated from coal boilers (Rozon, Koke, McGregor, *et al.*, 2023).

Saini *et al.* (2022) compared the technical and economic benefits of solar thermal systems and high-temperature heat pumps (HTHP) for industrial processes requiring steam. The competitiveness of industrial HTHPs was shown to be highly dependent on electricity prices, initial capex and asset utilisation (Saini, Ghasemi, Arpagaus, *et al.*, 2023). Furthermore, for HTHP to play a role in decarbonising steam production in South Africa, green electricity from renewable energy sources would be necessary, given the high carbon emission footprint of the electricity grid at 0.94 tonnes/MWh (South African Department Forestry, 2025). Green electricity third-party supply agreement indicative prices are at US$70/MWh. In comparison, utility-scale photovoltaic supply is as low as US$30/MWh, which would make heat pumps viable at least during daytime (Department of Mineral Resources and Energy, 2024). Furthermore, the availability of waste heat streams, often available in industrial processes, should be prioritised and can improve the efficiency or

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coefficient of performance (COP) of high temperature heat pumps, making these technologies highly attractive (Arpagaus, Bless, Uhlmann, *et al.*, 2018; Niknam, 2025; Oliveira, Iten & Matos, 2022).

Process redesign should also be considered, as process heat temperatures often do not require steam-driven systems. Hot water or hot oil systems operating at less than 120°C benefit from lower losses, larger energy yields from solar thermal collectors and higher COPs from heat pump systems (Liescheidt, 1992; Rozon *et al.*, 2023; Seck & Guerassimoff, 2011). For the Food and Beverage sector, several case studies have been developed highlighting the opportunity for a given plant, environment or technology solution (Bobbo, Lombardo, Menegazzo, *et al.*, 2024; Holler, Winkelmann, Pelda, *et al.*, 2021).

This paper contrasts the performance of renewable and sustainable thermal energy systems across various scenarios in Southern Africa and Central Europe. The beverage industry, with its diverse temperature requirements ranging from 40°C for washing processes to 160°C for distillation, is used to frame boundary conditions and process heat analyses and simulations. Three distinct environments are examined: a small brewery, a medium-sized brewery with returnable bottle washing facilities, and a large soft drink factory with steam boilers.

2. Methodology

The analysis employs a combination of simulation-based modelling and techno-economic analysis to evaluate renewable heating technologies across different applications. The Polysun® software platform is used to model and simulate various system configurations, including flat plate collectors (FPC), parabolic trough collectors (PTC), high-temperature heat pumps, air-source (AHP) and waste-water type (WWHP) with and without PV integration. For the heat pump models, pre-calculations using Chemcad® software were performed earlier to parameterise performance across various temperature ranges (Koke, Rozon & McGregor, 2024).

Generic and actual production data from beverage facilities were used to create representative load profiles for demand modelling.

2.1 Economic assessment methodology

The economic evaluation focuses on the Levelised Cost of Heat (LCOH), a standard metric for determining the true cost of energy production over a system's lifespan. The analysis incorporates regional differences in energy pricing and potential feed-in tariffs for surplus PV electricity. The LCOH calculation combines the total costs from the applied solar thermal (or heat pump) system and the conventional fossil fuel backup. The cost of abatement c_a refers to the cost incurred to reduce or eliminate one unit of CO_2 emissions relative to the fossil baseline. e_{CO2} is the specific emission per kWh of heat.

$$c_a = \frac{\Delta\text{cost}}{\Delta\text{emissions reduced}} = \frac{\Delta LCOH}{\Delta e_{CO2}} \qquad \text{(eq.1)}$$

2.2 Case studies

This section presents a comparative analysis of three distinct use cases from the beverage industry, each serving as an example of a specific type of industrial heat user. The cases, presented in Table 1, are modelled and evaluated with a dedicated focus on contrasting the performance of renewable heating solutions—Solar Thermal, High-Temperature Heat Pumps, and Photovoltaics (PV) —in two fundamentally different climate zones:

- Cape Town, South Africa (SA): Representing Southern Africa (high solar irradiance).
- Würzburg, Germany (GER): Representing Central Europe (moderate, seasonal solar irradiance).

The objective is to gain robust insights into the transferability and techno-economic viability of these technologies for industrial heat decarbonisation across diverse global settings. The three selected cases differ critically in operational scale, process type, heat demand characteristics, and required temperature level.

Table 1. Overview of the investigated use cases (HFO: Heavy Fuel Oil)

	Case 1	**Case 2**	**Case 3**
Type	*Small brewery*	*Medium-sized brewery*	*Large soft drink factory*
Considered process	*Brewing*	*Washing of bottles*	*Washing of bottles*
Exemplar Type	*Small-Scale Core Process*	*Medium-Scale Returnable Logistics*	*Large-Scale Steam Heating System*
Annual heat demand	*155 MWh*	*953 MWh*	*3,057 MWh*
Reference fuel	*HFO (SA); Gas (GER)*	*Coal (SA); Gas (GER)*	*Coal (SA); Gas (GER)*
System Integration	*Hot process water*	*Hot process water*	*Steam system*
Process temperature	*85°C*	*75°C*	*160°C*
Technology focus	*Flat plate ST, Air heat pump*	*Flat plate ST, high-temperature heat pump*	*Parabolic trough ST, Wastewater heat pump*

Table 2 provides an overview of the two locations selected for this comparative study, highlighting their contrasting climatic conditions, solar resource availability, and representative regional characteristics.

Table 2. Overview of the locations

	Cape Town, South Africa (SA)	**Würzburg, Germany (GER)**
Region / Climate	*Southern Africa / High-Irradiation*	*Central Europe / Temperate Zones*
Climate Zone	*Mediterranean Climate*	*Temperate Oceanic/Continental Climate*
Annual Global Irradiation (GHI)	*Very High (>1,900 kWh/m2/a)*	*Moderate (Approx. 1,000 kWh/m2/a)*
Mean Winter Temp.	*Mild (Coldest month approx. 9°C)*	*Cold (Coldest month approx. -2 to 0°C*
Comparable Regions	*Europe: Iberian Peninsula (South Coast), North America: US Pacific Coast (South), Australia: South/ West Coasts, America: Central Chile Valley*	*North America: Midwestern Industrial Belt, Asia: North China Plain Europe: Central-Western Regions*
Solar Seasonality	*Low. High solar yields are stable and available almost year-round.*	*High. Severe drop in solar radiation during winter.*
Grid Water Temp.	*High & Variable: ≈14°C to 25°C*	*Low & Stable: ≈ 6°C to 16°C*

2.3 Applied Technology

Solar thermal technology is of interest due to its relatively high efficiency and significant potential for CO_2 reduction. However, solar thermal systems typically cannot fully replace fossil fuel systems; they commonly require a fossil fuel backup to ensure a consistent energy supply, especially during periods of low solar irradiance. Flat-plate collectors are an established technology for solar heat generation and are particularly cost-effective in Germany compared to vacuum tube collectors. They are well-suited for providing low-temperature heat <100°C. For applications requiring higher temperatures, specialised vacuum flat-plate collectors, evacuated tube collectors, or parabolic trough collectors (PTC) are suitable alternatives (Rozon *et al.*, 2023). PTCs appear to be relatively cost-efficient and are therefore selected for this study. These collectors concentrate sunlight onto an absorber tube, enabling higher temperatures to be achieved for industrial processes, such as steam production.

Heat pumps can transfer more energy in the form of heat than the electrical energy they consume, making them highly efficient. They can utilise renewable energy sources, such as ambient air, ground, or water, reducing reliance on fossil fuels. Nowadays, high-temperature heat pumps can provide high temperatures even for steam applications. In contrast to conventional applications, HTHP are engineered to elevate heat to 150-160 °C (Kosmadakis, 2019; Meyers *et al.*, 2018). In this paper, it is assumed that the heat pump completely replaces the fossil fuel boiler.

Using heat pumps in industrial processes offers a means to harness the significant potential of waste heat, thereby enhancing process efficiency and mitigating CO_2 emissions. Waste heat presents a valuable resource owing to its relatively elevated temperature range, typically between 30 and 70°C. 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 (Rozon *et al.*, 2023). This cooling has traditionally been achieved with large industrial ammonia compressors, which generate heat.

It is important to note that heat pumps still contribute to CO_2 emissions due to their electricity consumption, particularly if the grid electricity is not generated from renewable sources. By integrating photovoltaic systems, the share of renewable electricity used by the heat pump is increased, thus reducing its overall carbon footprint. Currently, polycrystalline and monocrystalline solar modules, as used in this paper, represent the state of the art in the photovoltaic industry. These modules are known for their high efficiency and durability and are widely used.

2.4 Cost and CO_2 Assumptions

The specific capital costs are listed in Table 3, distinguishing between flat plate collectors (FPC) and parabolic trough collectors (PTC). Similarly, the annual CO_2 emissions are calculated by multiplying the respective heat flows, taking into account the boiler efficiency, by the CO_2 factors. Since all numerical values can fluctuate in practice, this work assumes representative values to enable a relative comparison. The specific cost and CO_2 emission factors are listed in Table 4.

When subsidies are considered, it is distinguished between ST and PV:

- Solar Thermal: 50% of Capital Expenditure subsidised.
- Photovoltaics: A feed-in tariff (FIT) of 0.07US$/kWh applied.

Table 3. Specific system prices, including installation. Exponential scaling method for solar thermal.

Photovoltaics	Solar thermal FPC	Solar thermal PTC	Heat pumps	Storage tank (<100°C)	Storage tank (>100°C)
570 $/kW$_p$	505 $/m^2 @300m² Scaling n=0,85	336 $/m² @2000m² Scaling n=0,85	500 $/kW$_{th}$	750 $/m^3	1700 $/m^3

Table 4. Specific cost and CO2 emissions for fuels (2024 H2 reference)

	Coal (SA)	HFO (SA)	Gas (GER)	Electricity (SA)	Electricity (GER)
Cost US$ per MWh$_{th}$	24	68	52	120	188
Optional feed-in tariff US$ per MWh$_{th}$				70 (contracted)	73 (feed-in tariff)
CO2e kg per MWh$_{th}$	464	326	225	942 (2023)	321

Boilers assumed to be operating at 70% efficiency for coal and HFO and 80% for gas; RSA coal export monthly price with transport adjustment at ZAR1.18/tonne-km (Braun, 2018; IndexMundi, 2024); United States heating oil reference price (IndexMundi, 2024); South African 2024/25 Megaflex variable electricity tariffs (Eskom, 2025) German gas (YChart, 2025); German Electricity prices (SMARD, 2025); Exchange rate Nedbank (Nedbank, 2024); Domestic grid generation emission factor (South African Department Forestry, 2025); RSA feed-in tariffs based on indicative wheeling agreements from interviews; German feed-in tariff (Enkhardt, 2025). Further assumptions for the LCOH calculation, in real terms: Weighted Average Cost of Capital (WACC)=6.5%; Price increase rate for electricity and fossil fuels 3%; Inflation 0%; Average system life: ST 20 years; HP and PV 15 years. Since the electricity generated by the PV system is not always fully consumed by the process, surplus electricity is fed into the grid. Whether this fed-in electricity is compensated depends on the contracts with the energy suppliers. Typically, no feed-in tariff is taken into account unless stated otherwise. For comparison purposes, a scenario is also considered in which the fed-in electricity is compensated at the same rate as it would be purchased for Germany and in South Africa using indicative wheeling rates contracted between independent power producers and energy users. The calculation of CO_2 emissions is solely based on the consumption of fossil fuels and electricity. The annual heating costs are calculated based on the relevant LCOH.

3. Results

As a baseline, Figure 1 compares the total LCOH and CO_2 emissions across the three scales of beverage processes in Germany and South Africa, using different energy sources for heat supply. The total LCOH is calculated, encompassing all energy sources utilised, including both fossil fuels and renewable solar energy (Solar Thermal and PV-driven systems). The analysis reveals a clear trade-off between economic efficiency and environmental impact. South Africa offers compelling cost advantages of 60-70%, but at the expense of significantly higher carbon emissions, particularly for larger operations using coal. Germany's natural gas approach provides a more consistent environmental profile across all scales, though at substantially higher cost. The specific CO_2 emissions are significant for all cases.

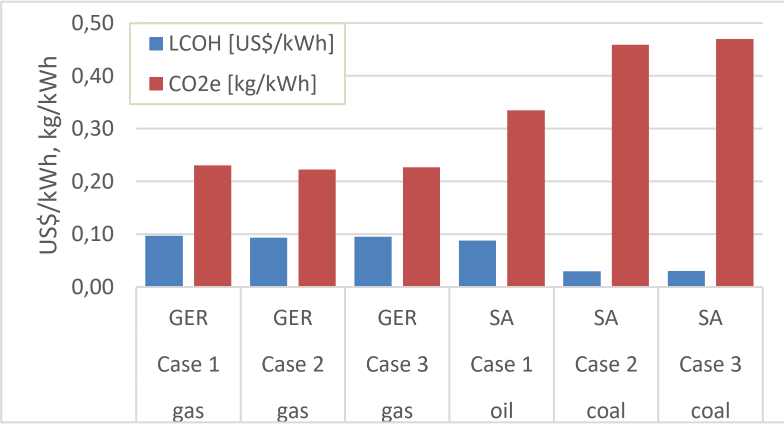

Figure 1: Baseline LCOH and CO2 emissions for each case and country, representing 100% for further results

The CO_2 emissions are significantly higher in SA due to the use of fossil oil, while the LCOH are lower compared to GER. The Reference Processes (100%) for this analysis are defined for each case and country by the existing industrial heat generation methods before any decarbonisation efforts are implemented (Figure 1).

3.1 Case study 1: Small brewery using gas in Germany and heavy fuel oil in South Africa

Figure 2 illustrates the performance of Solar Thermal integration. CO_2 emissions (orange line) decrease rapidly with increasing solar-thermal collector area in both Germany and South Africa, indicating high technical effectiveness for emission reduction. However, the economic viability, represented by the relative LCOH (solid blue line), differs significantly by location.

Germany (Gas Baseline): The total LCOH remains relatively stable and increases slightly for the actually available roof area. Larger ST installations lead to a steeper increase. Crucially, the introduction of subsidies (dashed blue line) drives the LCOH below baseline, highlighting the necessary role of policy support to make ST economically competitive against natural gas.

South Africa (Oil Baseline): The LCOH actually decrease slightly for the available roof area, making it economically competitive to oil. Large installations lead to higher LCOH; however, the CO_2 emissions could be significantly lowered. Subsidies make it a very favourable business case for industrial ST integration compared to the oil baseline, as shown in Figure 2.

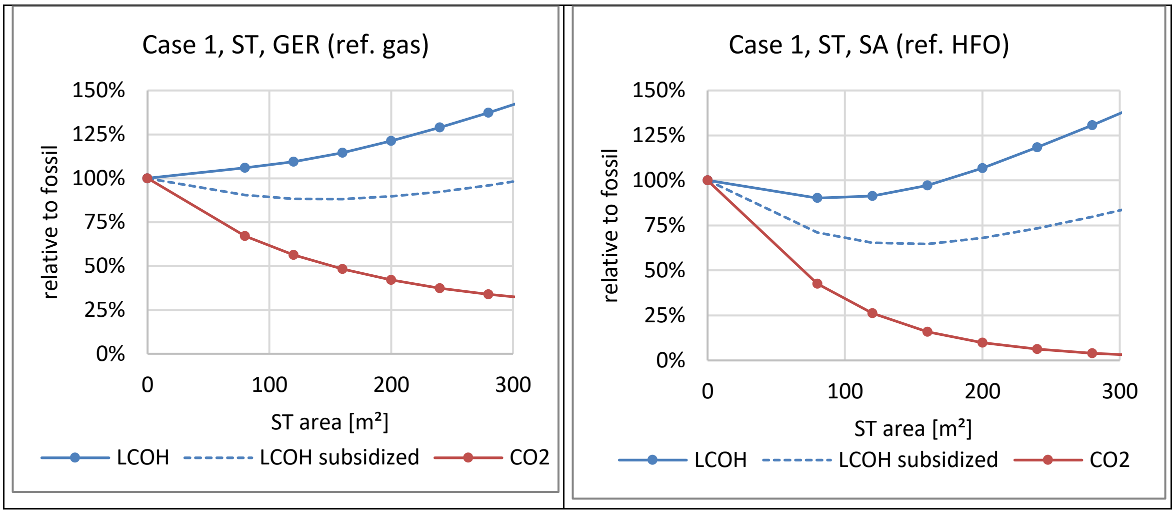

Figure 2: Solar thermal heat generation in Germany and South Africa for Case 1 (Small brewery). LCOH and specific CO_2 emission over the ST area. Subsidies 50% on capital cost.

In Germany, the LCOH with a heat pump is only slightly higher than that of a gas heating system, as shown in Figure 3. However, with a feed-in tariff for excess PV electricity, the LCOH decreases slightly with an increase in PV panel area. The reduction in CO_2 emissions is significant (over 50%) because the share of renewable electricity in Germany is relatively high. In South Africa, the use of a heat pump significantly reduces both the LCOH and CO_2 emissions. However, the implementation of a PV system increases the LCOH slightly, as a noteworthy amount of excess electricity cannot be utilised effectively. Introducing a feed-in tariff or enabling the sale of excess electricity would greatly enhance the economic viability of the system. In conclusion, while ST is technically effective for initial CO_2 reduction, its economic viability is highly dependent on subsidies in Germany or is challenged by rising LCOH at high coverage ratios in SA. AHP+PV, however, provides a path to deep, cost-effective decarbonisation in both locations, proving especially advantageous in South Africa, where it delivers the lowest LCOH values for near-complete CO_2 abatement.

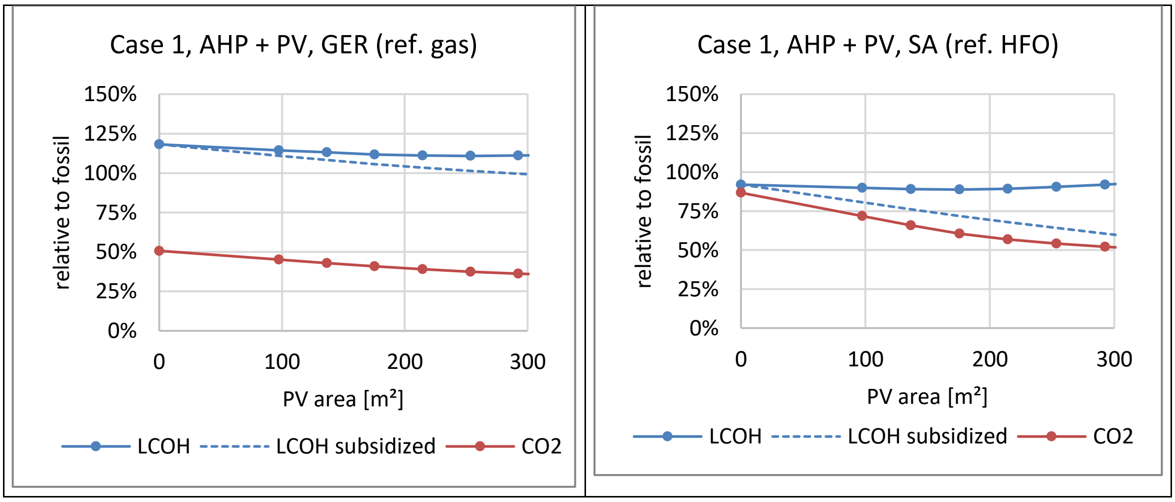

Figure 3: Air heat pump heat generation in Germany and South Africa for Case 1 (Small brewery). LCOH and specific CO2 emission over PV area. Subsidies by feed-in tariff.

3.2 Case study 2: Medium-sized brewery using gas in Germany and coal in South Africa

For the case of a medium-sized brewery, using ST to produce high-temperature heat for factories is currently not cost-effective in either Germany or South Africa, as can be seen in Figure 4. Although specialised, high-performance vacuum tube collectors exist, they do not result in an economic advantage. Thus, we focus on cheaper flat plate collectors because their lower purchase price better reflects economic reality. In South Africa, solar thermal technology is currently not economically competitive with coal-fired heating, which dominates the industrial sector due to significantly lower fuel costs under the assumptions applied in this study. For Germany, the high initial investment means that ST only becomes financially neutral—meaning it costs the same as a traditional system—if a substantial government subsidy of 50% is provided. This demonstrates that for industrial heat, solar technology requires and justifies strong financial incentives in Germany and faces insurmountable price competition from coal in South Africa.

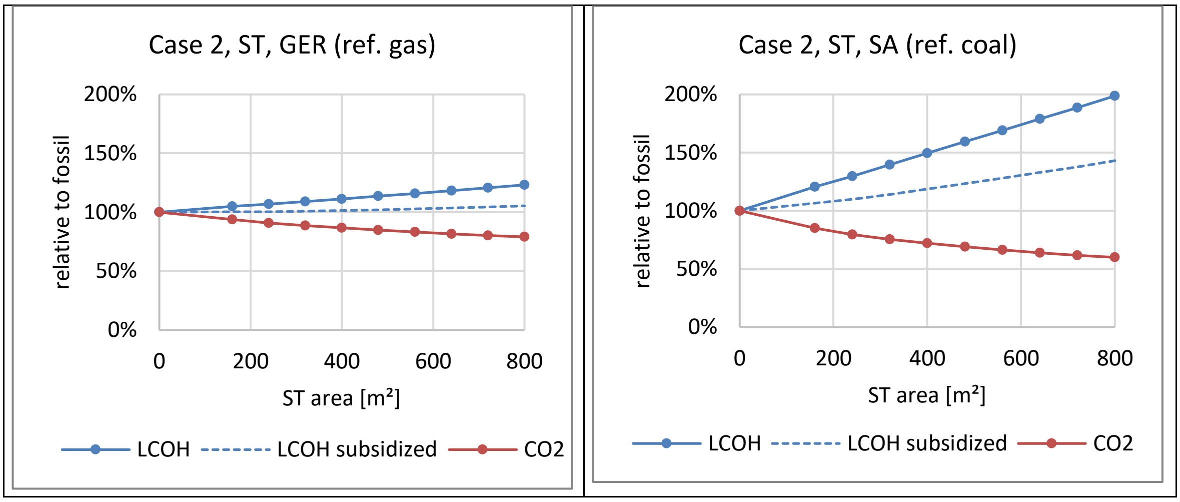

Figure 4: Solar thermal heat generation in Germany and South Africa for Case 2 (Medium brewery). LCOH and specific CO2 emission over the ST area. Subsidies 50% on capital cost.

The application of Air Heat Pumps (AHP) for high industrial process temperatures is typically challenged by a significant temperature lift, resulting in a low COP and high operating costs. However, utilising waste heat significantly changes the economic viability, as depicted in Figure 5. While low-grade waste heat at 20°C is insufficient to make the technology competitive, using medium-grade waste heat at 60°C proves highly profitable. In Germany, this approach drastically lowers the LCOH well below the conventional reference. Conversely, in South Africa, LCOH reduction is limited, moving only slightly from the unfavourable baseline, still struggling to overcome the cheap coal reference. Crucially, the CO_2 abatement potential is high across all technologies but is particularly maximised by the heat pump pathway, demonstrating that while technically superior for decarbonisation, the economic feasibility of AHP remains deeply tied to both the temperature of the available heat source and the local energy price structure.

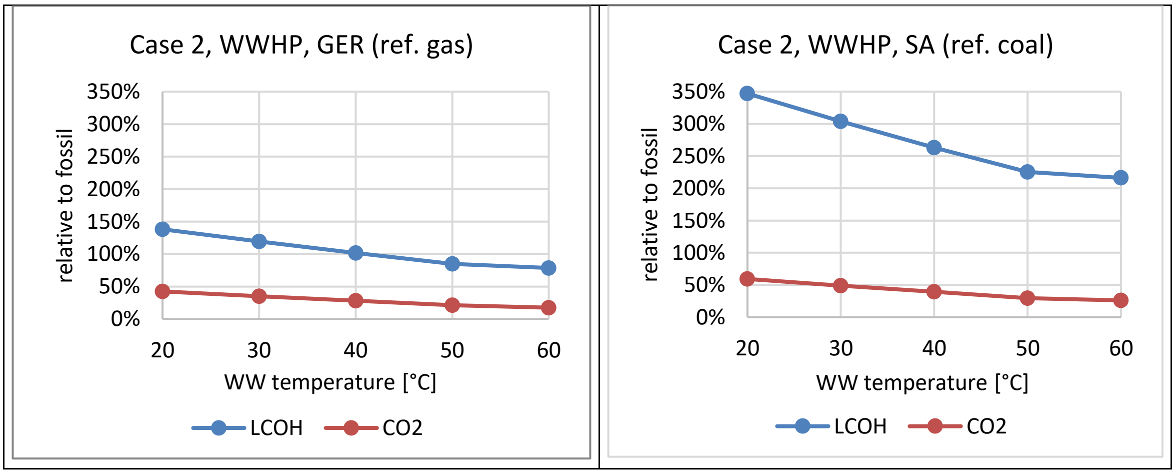

Figure 5: Waste-water heat pump (WWHP) heat generation in Germany and South Africa for Case 2 (Medium brewery). LCOH and specific CO2 emission over waste-water temperature. No PV

Integrating Photovoltaics with the Heat Pump system allows for further reduction of CO_2 emissions across both regions. This is particularly valuable in lowering the system's reliance on grid electricity, thus enhancing its overall environmental profile. However, despite these environmental gains, the impact of PV on the LCOH is found to be marginal, even with a heat source temperature of 40°C, as shown in Figure 6. This indicates that the initial economic case for renewable heat is primarily determined by the heat pump's efficiency and the availability of high-grade waste heat, with the self-generation of electricity from PV offering a necessary CO_2 benefit but minimal additional financial advantage.

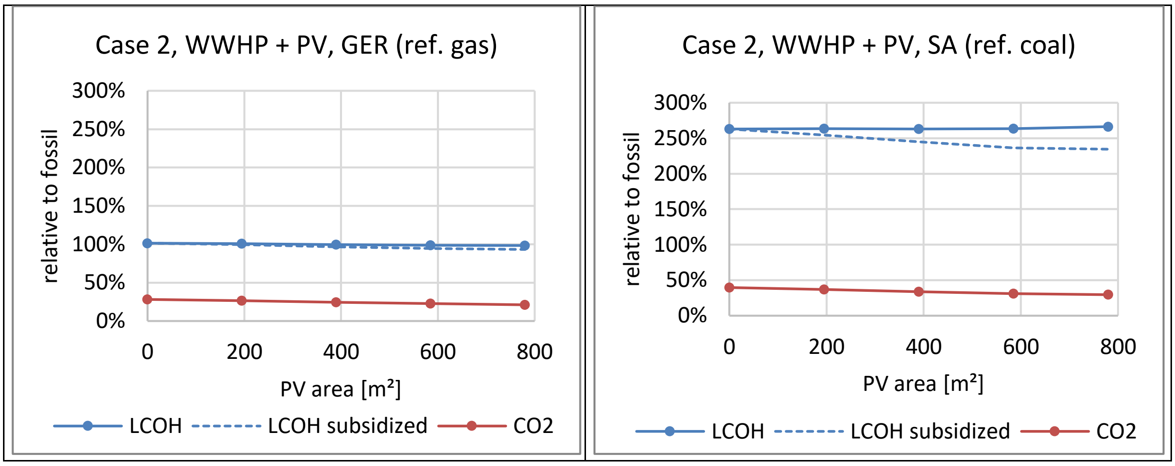

Figure 6: Waste-water heat pump heat generation in Germany and South Africa for Case 1 (Medium brewery). LCOH and specific CO2 emission over the PV area. Waste-water temperature 40°C. Subsidies by feed-in tariff.

3.3 Case study 3: Large soft drink manufacturer burning gas in Germany and coal in South Africa

The scenario for Case 3, characterised by an even higher process temperature lift, largely mirrors the economic challenges of Case 2, with technology choice again being highly sensitive to subsidies and heat source. For Solar Thermal, the increased temperature requirement necessitates the use of Parabolic Trough Collectors. However, even with this high-performance technology, ST remains uneconomical without public funding, as can be seen in Figure 7. Similarly, the Heat Pump pathway is only financially viable when integrated with an available waste heat source, which is crucial for maintaining an acceptable Coefficient of Performance, illustrated in Figure 8. Despite these economic barriers, the heat pump technology is of particular interest due to its high potential for CO_2 abatement. Finally, integrating Photovoltaics provides minimal additional cost relief, as it does not significantly lower the Levelized Cost of Heat, confirming that the primary economic drivers for deep decarbonisation are high-grade waste heat availability and targeted investment subsidies.

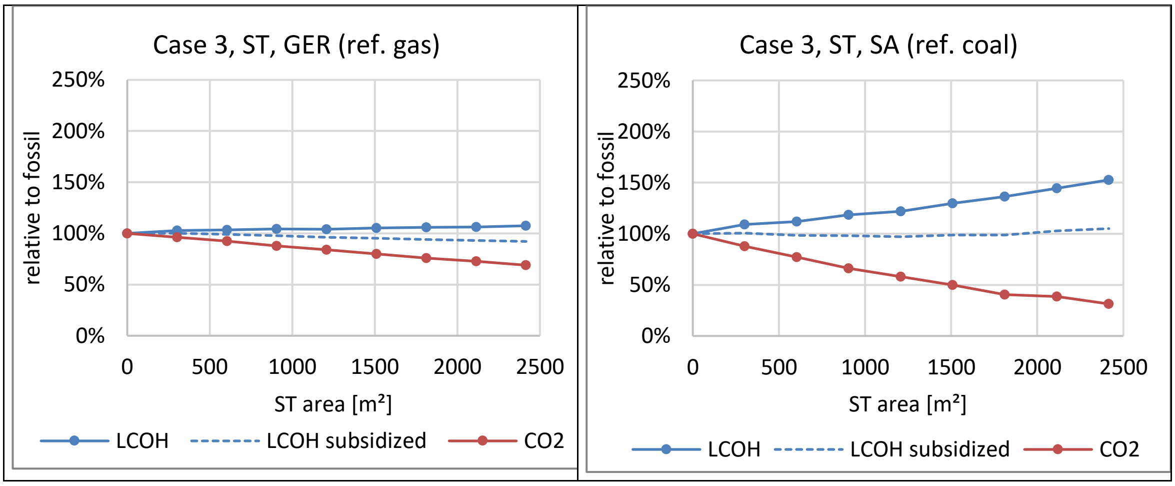

Figure 7: Solar thermal heat generation in Germany and South Africa for Case 3 (Large soft drink factory). LCOH and specific CO2 emission over the ST area (PTC). Storage tank scales with ST area appr. 50 l/m². Subsidies 50% on capital cost.

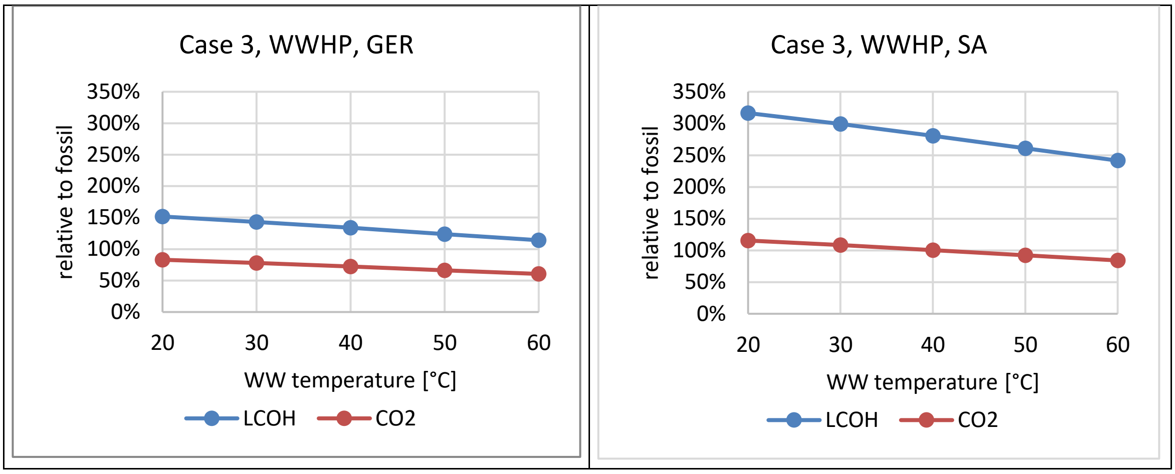

Figure 8: Waste-water heat pump heat generation in Germany and South Africa for Case 3 (Large soft drink factory). LCOH and specific CO2 emission over waste-water temperature (heat pump source). No PV.

4. Discussion

The analysis considers the unique climate conditions, electricity pricing structures, and industrial energy landscapes of both regions. In Southern Africa, abundant solar resources and rising electricity costs make renewable heating systems—particularly solar thermal and HP+PV—highly attractive for reducing both operational expenses and CO_2 emissions when compared to oil-fired boilers. While competing economically with inexpensive coal remains challenging, the potential for substantial CO_2 savings is significant. In contrast, Central Europe's lower solar irradiation and more reliable electricity grid infrastructure favour PV-assisted heat pump systems, especially for low-temperature applications. However, solar thermal systems remain advantageous for CO_2 reduction and can achieve economic viability through optimal storage sizing and incentive programs.

Optimal system configurations vary significantly across regions and temperature requirements. For small facilities with moderate temperature demands (<90°C), heat pumps supplemented by PV systems prove particularly cost-effective in Southern Africa, delivering low heating costs as demonstrated in Figure 3. Conversely, in Germany, subsidised solar thermal systems present a favourable option for similar brewery applications. However, their viability depends critically on current electricity prices and the renewable energy content of the grid, as illustrated in Figure 2.

For high-temperature processes, solar thermal systems remain competitive in Southern Africa, with parabolic trough collectors offering high technological performance. However, in Central Europe, achieving economic viability for solar thermal at high temperatures requires substantial subsidies or carbon pricing mechanisms.

The COP of heat pumps is highly dependent on the source heat temperature. For high-temperature applications, access to significant waste heat sources is essential for maintaining efficiency. Economic viability is closely tied to electricity prices, making the integration of PV systems particularly beneficial, also in order to effectively reduce CO_2 emissions and transition toward sustainable production. Integration with cooling processes could also improve overall system efficiency.

While the preceding techno-economic analysis has demonstrated the varying economic performance of renewable heating systems across different regions and applications, it does not fully capture their effectiveness in achieving the primary goal of decarbonisation. To bridge this gap and provide a more comprehensive evaluation framework, the cost of carbon abatement is introduced as a key metric. This indicator combines both economic and environmental performance by calculating the cost per ton of CO_2 avoided, enabling direct comparison of climate mitigation efficiency across different technologies and regional contexts. Unlike simple payback periods or levelized costs, abatement cost analysis reveals which systems deliver the greatest emission reductions per unit of investment, thereby supporting informed policy decisions and investment prioritisation. Subsidies are not considered in the following evaluation.

Figure 9 evaluates the cost of abatement against annual CO_2 savings for Case 1, presenting a marginal abatement cost curve comparison for renewable heating technologies in Germany and South Africa. The abatement costs are plotted against the annual CO_2 savings to illustrate and weigh the significance of each system's decarbonisation potential. The analysis focuses on air-source heat pumps combined with PV and solar thermal systems, revealing significant divergence in cost-effectiveness based on local energy contexts.

In South Africa, both AHP+PV and ST demonstrate highly favourable economics, with predominantly negative abatement costs (net savings). This is driven by the country's exceptional solar yield and the displacement of oil-based heating. Solar thermal systems, in particular, achieve exceptionally high CO_2 savings in this context. In contrast, Germany exhibits a less favourable profile: ST systems show positive, higher abatement costs due to lower solar resources and competition with natural gas, while AHP+PV systems are more competitive, offering a mix of negative and slightly positive costs depending on electricity prices and grid carbon intensity.

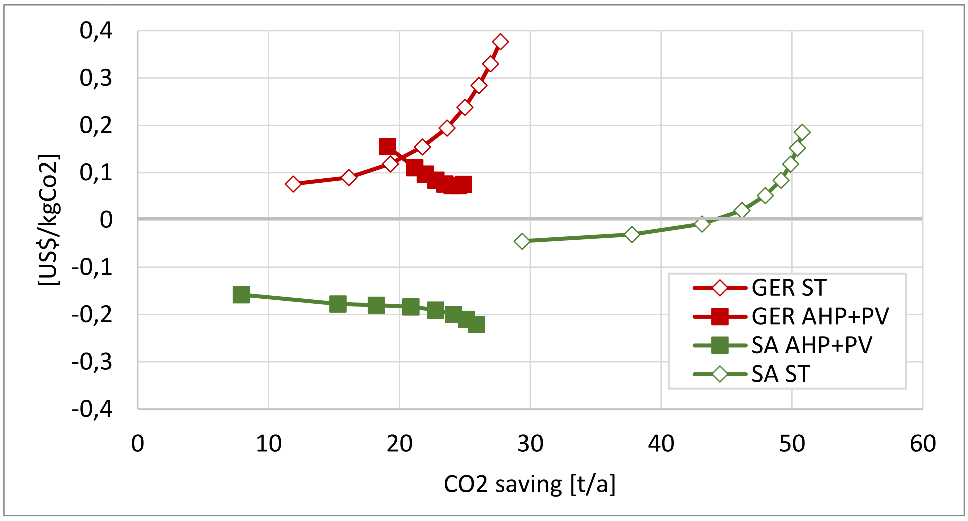

Figure 9: Cost of abatement curves for case 1 in GER, SA. No subsidies.

The abatement cost curves visually represent the correlation between the cost of carbon abatement and annual CO_2 savings for various renewable heating technologies across different regions and cases. For each distinct case evaluated (e.g., C1, C2, and C3 for both Germany and South Africa, and for both Solar Thermal and Heat Pump systems), the lowest abatement cost and corresponding annual CO_2 saving have been selected and plotted in Figure 10. This allows for a streamlined comparison of the most efficient system configurations under each scenario. The blue bars indicate the annual CO_2 saving in tons per year. The red line shows the cost of abatement in US$/kWh.

Cases involving South Africa generally show higher CO_2 savings (taller blue bars) and often negative abatement costs (red line below zero). This signifies that in South Africa, these renewable heating systems not only significantly reduce carbon emissions but also provide a net economic saving. This strong performance is likely driven by the displacement of high-carbon electricity generation (e.g., coal) and excellent solar resources, making solar thermal and heat pump systems partly economical and environmentally beneficial. Noticeable instances include "C1, SA, ST" and "C1, SA, HP," which both exhibit substantial CO_2 savings alongside negative abatement costs. "C3, GER, HP" results in the highest CO_2, with positive abatement cost.

Cases in Germany present a more varied picture. While some cases, such as "C2, GER, HP," show negative abatement costs, many others, particularly those involving Solar Thermal ("C1, GER, ST," "C2, GER, ST"), exhibit positive and sometimes high abatement costs. "C3, GER, HP" stands out with the highest CO_2 saving in the dataset, albeit with a slightly positive abatement cost. This suggests that in Germany, due to factors like lower solar irradiation and competition with natural gas, the economic case for specific renewable heating systems is less compelling than in South Africa, even if they still contribute to CO_2 reduction. The "C2, GER, ST" case shows a relatively low CO_2 saving with a high positive abatement cost, indicating lower cost-effectiveness in decarbonisation for this specific scenario. Heat Pumps in Germany generally appear to be competitive in this study, if waste heat is available, often showing lower abatement costs or even negative ones compared to solar thermal in Germany, particularly for "C2, GER, HP."

"C3, SA, GER" yields the highest CO_2 saving, while "C3, SA, HP" also shows significant savings, albeit with a positive abatement cost. In conclusion, the figure effectively illustrates that the cost-effectiveness of carbon abatement through renewable heating systems is highly dependent on regional factors, the specific technology chosen, and underlying case conditions. South Africa consistently demonstrates a more favourable environment for cost-effective decarbonisation, particularly when displacing high-carbon energy sources. At the same time, Germany presents a more nuanced landscape where heat pumps often prove to be economically viable for abatement and offer good potential for even greater CO2 savings as the electricity supply becomes more renewable

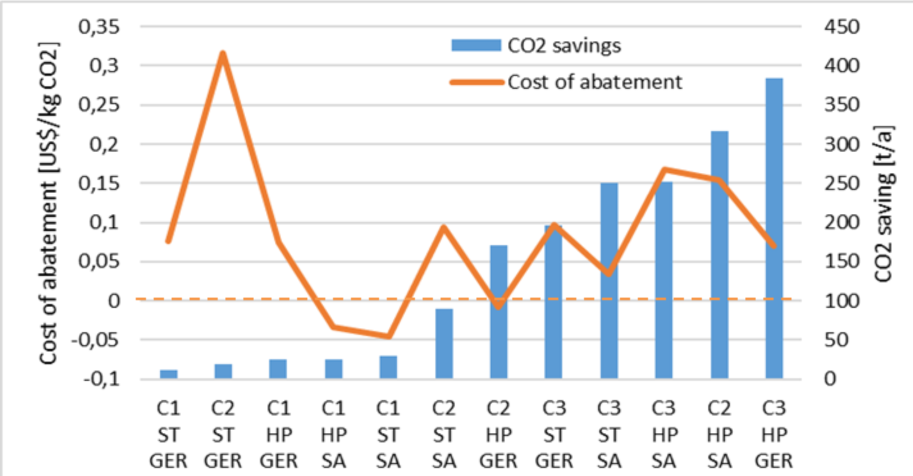

Figure 10: Cost of abatement and potential of CO2 reduction. No subsidies.

5. Conclusions

The target of this work was to conduct a comprehensive, comparative evaluation of Solar Thermal and PV-assisted Heat Pump systems for industrial process heat, specifically contrasting their techno-economic performance between Southern Africa and Germany. By moving beyond traditional economic metrics, the study established a robust, policy-relevant framework using the cost of carbon abatement (€/t_{CO2} avoided), which integrates the Levelized Cost of Heat with the annual CO_2 emission reduction. This methodology, which intentionally excluded subsidies to capture the intrinsic market performance, yielded profound insights into the true climate mitigation efficiency of these technologies. The core finding is the critical and contrasting influence of the existing regional energy structure on the viability of the transition. The potential of waste heat and energy efficiency measures should be utilized. In South Africa, both systems demonstrated low or even negative abatement costs (net savings), while simultaneously achieving high annual CO_2 reductions. This result is crucial, as it confirms that in high-carbon markets, where renewables displace coal-based energy, the savings generated from avoided fuel consumption can often offset the annualised capital investment. Consequently, for these regions, the industrial heat transition is not necessarily a financial burden but also a net economic gain. In contrast, the German profile was more complex. AHP+PV systems proved competitive, showing a mix of negative and slightly positive abatement costs, while ST systems generally faced higher positive abatement costs without subsidies. This divergence underscores how lower solar resources, lower grid carbon intensity, and competition from existing natural gas infrastructure create a tighter financial landscape. The study concludes that subsidy policies remain important and must be tailored to regional specifics.

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