Electrification of Industrial Process Heat Using Heat Pumps and Photovoltaic Systems

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Abstract

Recent studies have shown that solar and heat pump technologies are viable solutions for reducing carbon emissions in industries. Uncertainties regarding system performance, process integration, operational schemes and high capital cost for installation significantly increase the investment risk, which can be considered a barrier for small and medium-sized industries. Therefore, more detailed analyses should be carried out to gain a clear view of the economic and technical feasibility of these solutions. This study considers computer simulations of solar heating systems, such as (i) a photovoltaic system with an electrical heater, (ii) a photovoltaic system with thermal accumulation, and (iii) a photovoltaic aided high temperature heat pump with thermal accumulation, all of which for supplying hot water for industrial processes in Brazil. Each system was designed to provide minimal LCOH values and are compared against two reference cases, a standard gas-based heater, commonly used in Brazilian industry, and a flat plate SHIP system. While all three analyzed systems proved to be economically better over a gas-based system, none demonstrated competitiveness against the flat plate collector for solar heat in industrial processes.

Keywords: Process heat, Solar photovoltaic energy, Heat pumps, Simulations, Economic analysis

1. Introduction

The pursuit of sustainable and low-carbon energy solutions has become a priority considering the growing energy demand in the industrial and commercial sectors (IEA, 2021). Since 80% of the global primary energy demand is associated with combustion of fossil fuels (EI, 2024), it is evident that solutions, such as electrification, will undoubtedly take place in the next couple decades (Leicher et al., 2024). Technologies such as solar systems and high-temperature heat pumps (HTHPs) hold significant potential to replace fossil fuels in process heat generation, particularly in the medium temperature range (90–160 °C) (Arpagaus et al., 2018). Although technically feasible, these solutions still face economic, structural, and dissemination barriers (AEE, 2024). Considering Brazil's high solar irradiation levels, its established tradition in solar energy utilization, a highly renewable energy matrix, and the commitments under the Paris Agreement, it becomes strategically important to assess the feasibility of integrating these technologies into the industrial sector. This study aims to analyze heat pump systems integrated with photovoltaic power plants and thermal accumulation (HTHP+TES+PV system) and compare their performance against simple solutions, such as a photovoltaic system with an electrical heater (PV system), and a photovoltaic system with thermal accumulation (PV+TES system). In this sense, detailed computational simulations are performed, considering the systems described and further depicted in Figure 1.

In the first system (PV system), an electric flow heater is primarily powered by a photovoltaic (PV) array. If the PV generation exceeds the amount of energy required, the extra is sent to the grid as a credit. In cases where the PV generation is not enough, electricity is drawn from the grid consuming credits. If the energy generated by the PV plant (instantaneity or as credits) is insufficient to achieve the target temperature, the existing auxiliary gas heater provides the supplemental heat.

The second system uses electricity generated by the photovoltaic system in an electric heater inside a water storage tank. To avoid vaporizing the water in the reservoir, a controller will automatically stop feeding electrical energy to the heater at the temperature of 93 °C until the temperature goes down, which is done by a simple thermostat with a deadband of 5 °C. Therefore, the system can store thermal energy in the reservoir to be used later, avoiding dispatching energy into the grid. This is an important aspect to be considered in Brazil because of the modifications in the electricity pricing system occurring in the coming years (ANEEL, 2023). Briefly, Brazilian law n. 14,300, institutes a partial Net Energy Metering (NEM), instead of the current full NEM (energy is compensated by a one-

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to-one retail price). The new partial-NEM will compensate for the generated energy by a value lower than retail price, charging a tariff concerning the use of the electricity grid.

In the HTHP+TES+PV system, an air-to-water heat pump is used to heat the water in the reservoir instead of the electrical heater. The cold water from the bottom of the tank is circulated through the heat pump, receiving heat from the equipment, returning to the top of the tank at a higher temperature. A thermostat with a setpoint of 95 °C and a deadband of 10 °C is used to control the heat pump. The benefit of using a heat pump relies on the coefficient of performance (COP) of the heat pump, set as 3.88 in the present study, which results in significantly less modules to meet the total energy demand. The energy generated by the PV system supplies the energy demand of the heat pump, with the excess electrical energy being supplied to the grid. In the cases where the PV generation is not enough to attend to the equipment demand, it is necessary to use energy credits or purchase it from the grid.

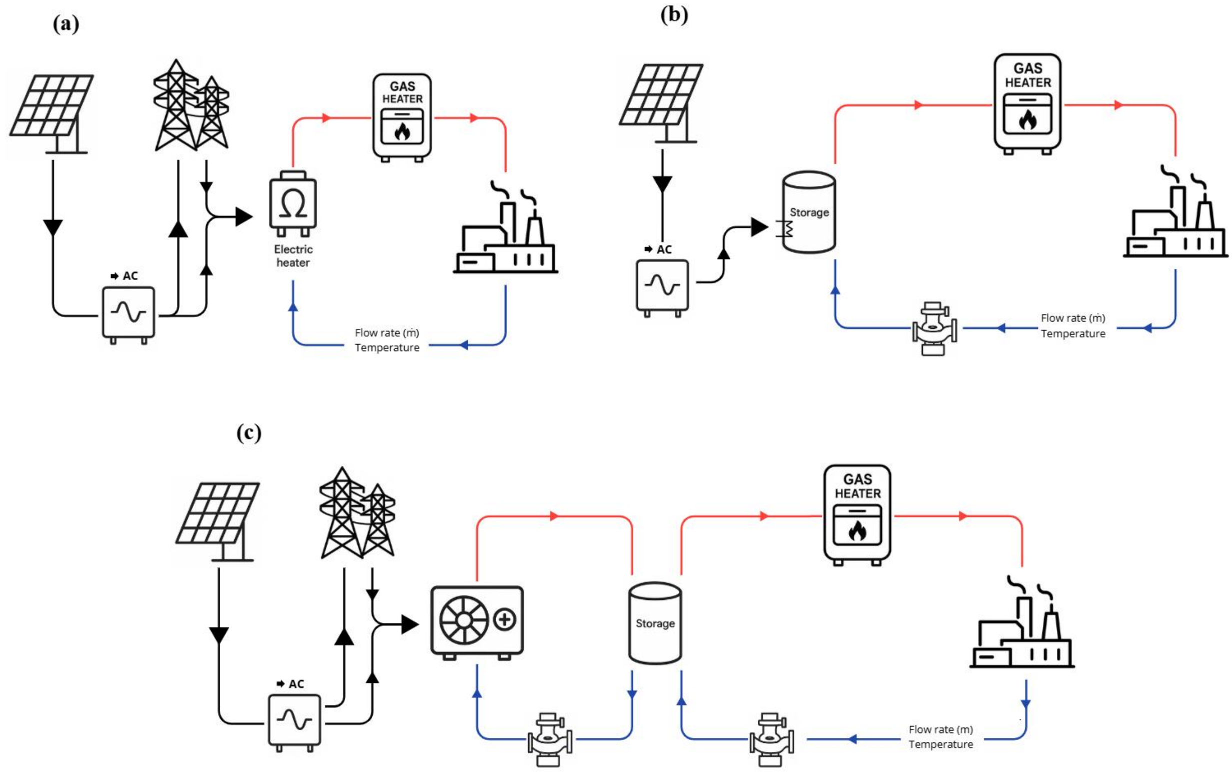

Figure 1: Basic scheme of studied systems, (a) PV system, (b) TES+PV system and (c) HTHP+TES+PV system.

Furthermore, the performances of the proposed systems are compared against the performance results of two systems reported in the literature (Lemos et al., 2024), namely, a flat plate collector system used to supply heat for industrial process (FPC-SHIP system) and the standard gas-based heater, commonly used in Brazilian industry. Therefore, this study seeks to identify the techno-economic potential of applying these solutions to typical unit operations in Brazilian industry, thereby contributing to the energy transition and the decarbonization of the sector. Thereby, the analysis is caried out by computer simulations of the proposed systems, for supplying hot water for industrial processes in Brazil, considering national market costs and pricing rules for PV-grid connections, design each system to provide a maximum life cycle saving LCS.

2. Methodology

The technical and economic assessment of high temperature heat pump combined with photovoltaic and thermal accumulation (HTHP+TES+PV) power generation systems were performed in the TRNSYS-17 simulation tool (Klein, 2018). The rationale for choosing this software is based on its modularity and open-source structure, characteristics which are presented as advantages for the development of the proposed research. These features are consistent with the objective of the present study in analyzing the HTHP+TES+PV system and comparing it against other systems.

The simulation of the heat pump in TRNSYS was performed using performance matrices as demonstrated by Starke et al., (2018). These matrices were developed using standardized information, prepared following standards related to the performance evaluation of these types of equipment. This implies that the models in TRNSYS for these components provide results with low uncertainty, since they use performance data from commercially available equipment. The hot water heat pump from Mitsubishi Electric (QAHV-N560YA-HPB) (Mitsubishi Electric, 2025) was adopted in the present study, which can supply hot water ranging from 55 to 90°C. Under normal heating conditions (the outdoor temperature of 16°C and the outlet water temperature of 65°C) this heat pump has a heating capacity of 40 kW and a power input of 10.31 kW (COP of 3.88).

The behavior of photovoltaic collectors is accounted through the model proposed by (De Soto et al., 2006), where the current-voltage curve is determined based on a semi-empirical equation, using five parameters, determined using data provided in the catalogs by the manufacturers, and two transient variables, the temperature of the photovoltaic cell and the solar radiation absorbed. The cell temperature was estimated using the same model from the System Advisor Model (SAM) (Gilman et al., 2018). For the inverter, the Sandia model was used (King et al., 2007). Other losses, such as soling, direct current losses and alternate current losses were accounted following the methodology described by (Gilman et al., 2018), considering the default losses for central inverter systems. To perform the simulation, equipment available in the Brazilian market were adopted, such as the LP182*182-M-72-MH module and the CSI-25KTL-GS-FL inverters. The capacity of PV field and inverters are designs parameters to be determined through economic assessment, as well as the size of the thermal reservoir.

It is worth mentioning that several parameters are required to estimate the performance of the PV plant, where they are all determined under standardized conditions and are reported by manufacturers in the equipment's data sheet. Regarding the modules, the following parameters need to be defined in the simulation model, the short-circuit current, open-circuit voltage at reference conditions, the module current and voltage at max power point and standard test condition, module area, number of cells and temperature model parameters. These are the parameters required for the DeSoto model (De Soto, 2004). For the inverter, the Sandia model requires four empirical parameters determined with performance tests. All these parameters were obtained from the System Advisor Model database (NREL, 2025), for the equipment's previously defined. For the sake of completeness, it is important to mention that rated performance parameters of the modules and inverter are shown in Table 1.

Regarding the other components of the system, such as storage tanks and heat exchangers, mathematical models consolidated in literature and extensively validated were adopted. It is worth mentioning that the work of (Lemos et al., 2024), also developed using TRNSYS, performed the validation of the simulation models against the work of (Quiñones et al., 2020). In addition, the heat demand profile used as basis for simulating the industrial process demand is based on the work of (Lemos et al., 2024), which assesses the technical and economic viability of using flat plate collectors for hot water production for industrial processes in the Brazilian food industry. The results obtained by (Lemos et al., 2024) will be used as a reference case in the present study.

Therefore, the presents study considers an annual hot water demand of 277.8 MWh/year, representative of thermal energy requirements in meat and dairy processing industries for hot water. It is assumed that the water returns to the system at 40 °C and must be heated to 95 °C before being supplied back to the industrial processes. Additionally, the thermal load follows a periodic mass flow pattern, operating in cycles of 12 hours on and 12 hours off, simulating the typical operational schedule of such industrial facilities. Regarding meteorological data, the study used data from a typical meteorological year for the city of Goiânia, Brazil, also used in the study of (Lemos et al., 2024). The TMY of Goiânia includes hourly information on ambient temperature, relative humidity, wind speed, global horizontal irradiation (GHI), diffuse horizontal irradiation and direct normal irradiation, as reported by (Bonini et al., 2022; Dorneles et al., 2019).

Table 1: Input and parameters for simulating the systems.

Parameter		**Value**
Location	Location	Goiânia/GO/Brazil
	Latitude, (°)	16.64 °S
	Longitude, (°)	49.22 °W
	Hourly data (TMY)	(Bonini et al., 2022; Dorneles et al., 2019).
Demand	Annual water demand	277.8 MWh/year
	Cold water temperature	40 °C

	Hot water temperature	95 °C
	Demand profile	(Lemos et al., 2024)
	Gas heater efficiency	80 %
Thermal reservoir	Tank thermal losses	33.48 kJ/(h.K) - Colle et al., (2003)
PV field	Module slope, (°)	16.64 °
	Module azimuth, (°)	0 (Facing north)
	Module area	2.56 m^2
	Module power at STC	568.16 W
	Module efficiency	22.19 %
Inverter	Inverter AC power	25000 W
	Inverter DC power	25548.1 W
	Inverter efficiency	97.6 %

2.1. Economic model

Since the goal of this article is to compare economically different types of heating systems to meet the demand of a food industry, the economic assessment was performed using a lifecycle cost approach (Duffie et al., 2020), where the life cycle savings (LCS) and levelized cost of heating (LCOH) were adopted as figure of merits to design the PV field, inverter capacity and thermal storage size. As a first step, the life-cycle cost (LCC) of a system considering a lifetime of N years can be calculated as follows,

$$LCC(x) = C_{total}(x) + PWF(N,i,d).\left(C_m + C_{gas}.E_{gas} + C_e \ \left(E_{PV,grid}f_{TUSD} + \ E_{grid}\right)\right), \quad \text{(eq. 1)}$$

where x means a specific system, such as, a standalone gas-burner, the PV system, PV with tank or the HTHP+TES+PV system. $C_{total}(x)$ is the initial investment (modules, inverters, storage tank, heat pump, installment), depending on the system for which the LCC is being calculated; C_m is the annual maintenance cost (PV array and heat pump maintenance), calculated by a fraction of the equipment cost, C_{gas} is the cost of gas fuel (USD/MWh), C_e is the electrical energy tariff (US$/MWh), and f_{TUSD} is the fraction of the electricity tariff that must be paid to the utility for the use of the grid infrastructure when injecting PV energy into the grid. E_{gas} is the annual energy delivered by the gas-burner systems, $E_{PV,grid}$ is the energy that was sent to the grid, and E_{grid} is the additional electrical energy bough from the grid. At last, PWF $(\mathrm{N,i,d})$ represents the present worth factor that accounts for the time value of money in the series of payments during the lifespan of the system. The PWF is calculated in terms of the lifetime N, inflation i and discount rate d, as defined by Duffie et al., (2020).

Equation 1 can be used to calculate the LCC of each system studied herein, including the standalone gas-based system, as shown by the following equation,

$$LCC(Gas) = C_{gas}.\frac{E_{demand}}{\eta_{gas,heater}}.PWF(N,i,d) \quad \text{(eq. 2)}$$

where E_{demand} is the annual energy demand for water heating (277.8 MWh/year) and $\eta_{gas,heater}$ is the efficiency of the gas-based auxiliary heater (Table 1), therefore, for the present case $E_{gas} = E_{demand}/\eta_{gas,heater}$. The life-cycle savings (LCS) can be calculated by the expression,

$$LCS(x) = LCC(Gas) - LCC(x). \quad \text{(eq. 3)}$$

The economic viability of each system is compared by means of the levelized cost of heating (LCOH), once it provides a comprehensive basis for comparison by consolidating all lifetime costs relative to the total heat delivered. The LCOH is calculated as shown,

$$LCOH(x) = \frac{LCC(x)}{PWF(N,d).E_{demand}}, \quad \text{(eq. 4)}$$

where, differing from eq, (1), $PWF\ (N,d)$ does not consider the inflation. Table 1 shows the equipment costs and financial considerations used in the present study, along with the technical references.

Table 2: Economic parameters and financial considerations.

	Economic parameter	Value	Unit	References
Costs	Modules	164	USD	Based on the Brazilian market
	Inverter	1114.5	USD	
	Storage tank	1415.33	USD/m^3	(Lemos et al., 2024)
	Heat pump	3151.8· $Power^{-0.435}$	USD/kW	(ARNITZ, A et al., 2019)
	C_e	172.2	USD/MWh	Equatorial energia, 2024
	f_{TUSD}	50	%	
	C_{gas}	40	USD/MWh	(Lemos et al., 2024)
Maintenance cost	$C_{m,PV}$	$0.01 \cdot C_{total}(x)$	USD	(Lemos et al., 2024)
	$C_{m,HP}$	$0.055 \cdot C_{hp}$	USD	(ARNITZ, A et al., 2019)
Financial considerations	N	25	Years	(Lemos et al., 2024)
	i	0	%	
	D	5	%	

3. Results

All three systems analyzed in this study use the annual energy demand and profile found in (Lemos et al., 2024), for a food processing industry. Each system was simulated in TRNSYS considering this load profile and solar irradiation data from Goiania-GO and then, the economic indicators were calculated. In this way, the design parameters of each system can be determined to maximize the LCS. For the PV-system, only the PV capacity must be determined, while for the TES+PV, it requires determining the PV capacity and the volume of the storage tank. For the HTHP+TES+PV there are three design parameters: the PV capacity, storage size and HP capacity. The way that these parameters were calculated was varying them and finding the optimal point where the combination of the parameters for each system reached the best LCS. Each system obtained a unique curve of LCS per PV capacity, shown in the following sections.

3.1. PV System

Figure 2 shows the LCS curve as a function of the PV capacity, where it can be seen a maximum LCS with a PV capacity of 65 kW$_p$. For larger PV arrays, the initial cost and annual costs related to the use of the grid does not compensates the amount of gas fuel saved, resulting in a decrease in the LCS.

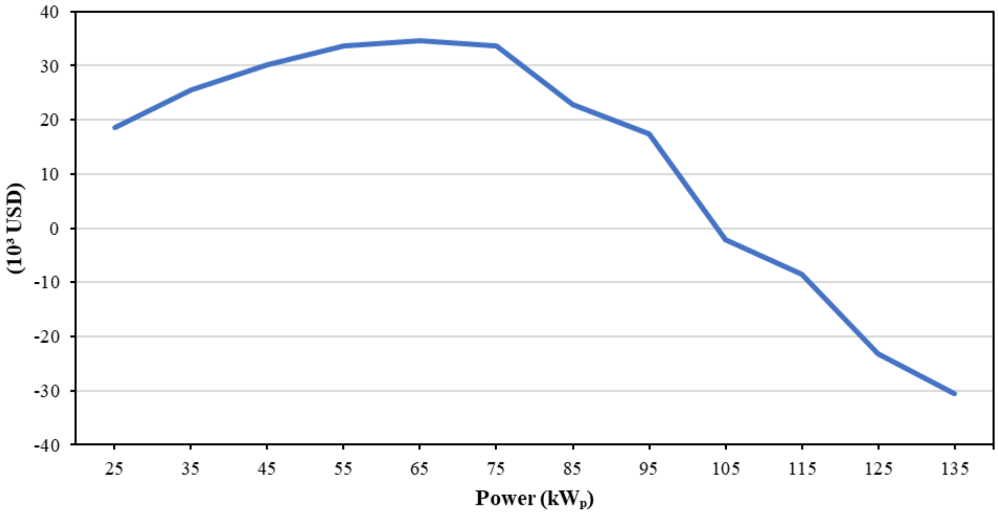

Figure 2: LCS of the PV system as a function of the PV capacity.

3.2. TES+PV System

The TES+PV system had two design parameters, tank size and PV capacity. In this case, a LCS curve was calculated for each tank size, as depicted in Figure 3. As can be seen, the maximum LCS occurs with a tank volume of 6 m^3 at a PV capacity of 125 kW_p. The motivation for using this system is to use the thermal accumulation to avoid dispatching energy to the grid and not paying for the use of the grid. Since this system is not grid connected, the setpoint parameters used to avoid superheating the tank and the heat losses of the tank are crucial in the design. Moreover, larger solar fields tend to overheat the tank and to avoid vaporization the energy must be discarded, reducing the benefit of the system. Larger tanks tend to reduce this problem, which the final design relies on the tradeoff between the advantages compensating for the costs. With the tank cost considered in the present study, increasing the tank from 6 m^3 to 9 m^3, slightly reduces the LCS.

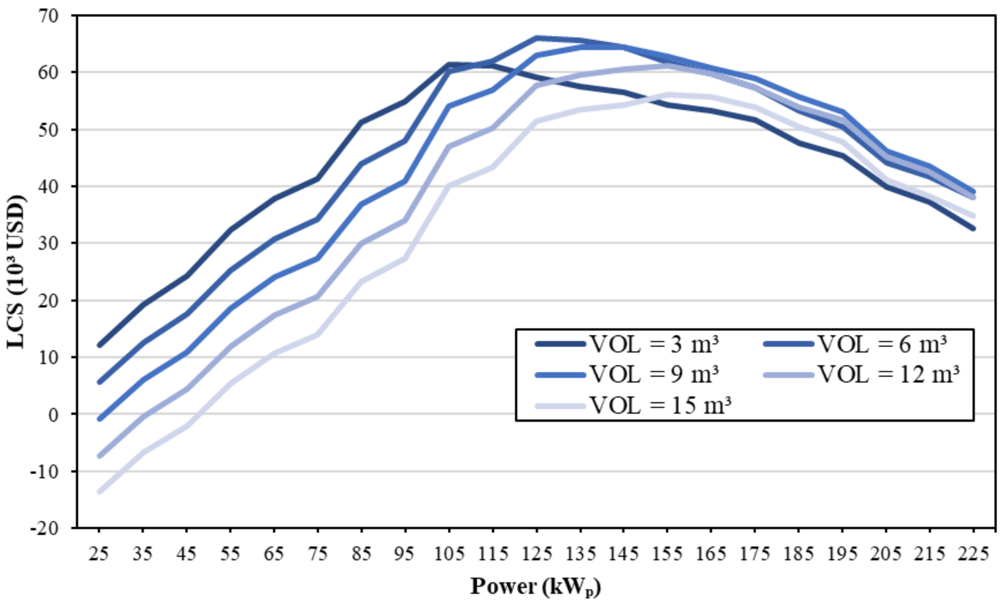

Figure 3: LCS of the TES+PV system as a function of the PV capacity and thermal reservoir size.

3.3. HTHP+TES+PV System

In the third system, the heat pump capacity is also a design parameter that must be properly defined. To do so, the heat pump capacity is varied by a rating factor, defined as the ratio between the desired heating capacity and the heating capacity at reference condition (catalog). Therefore, three rating factors were considered 0.5, 0.75 and 1.0, resulting in heating capacities of 20 kW, 30 kW, 40 kW, respectively. For each heating capacities, the LCS in terms of the PV capacity and tank's volume were calculated, as presented in Figure 4. The optimal design point can be determined by taking the maximum LCS in the figures. As can be seen in Figure 4, a rating factor of 1 result in the larger LCS between the heat pump capacities considered. Regarding the PV capacity and tank volume, it can be seen a maximum LCS with a capacity of 35 kWp and a tank size of 3 m^3, depicted in Figure 4a.

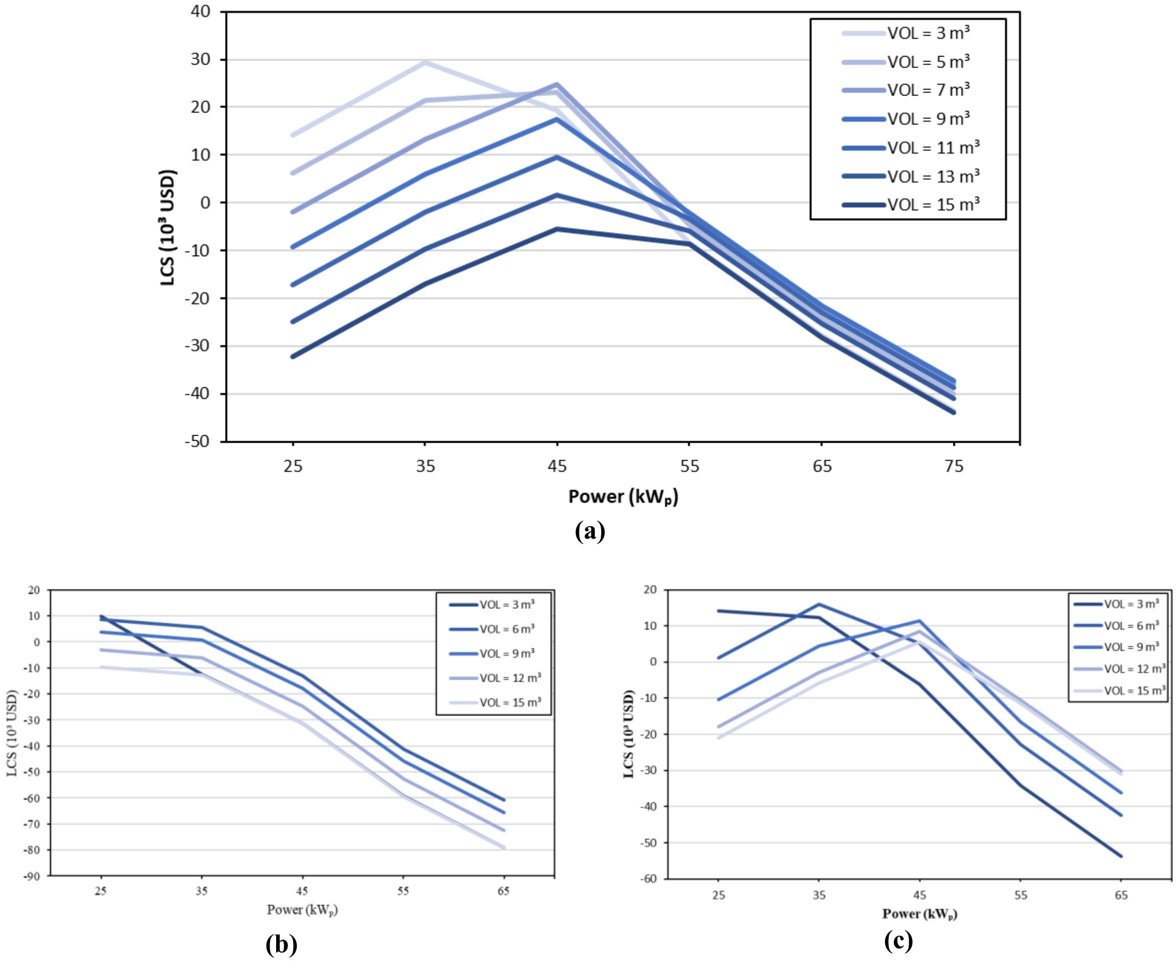

Figure 4: LCS of the HTHP+TES+PV system as a function of the PV capacity and thermal reservoir size for three HP rating factors, (a) 1.0, (b) 0.5 and (c) 0.75.

Table 3 shows a summary table of the calculated design parameters of each system. The simulation results indicated varying levels of financial viability among the designs. The TES+PV configuration demonstrated superior economic performance, proving to be the most cost-effective solution among the three PV systems evaluated. For sake of comparison, the standalone gas burner has a $LCOH_{gas} = 50\ USD/MWh$ (Lemos, et al., 2024), therefore, all three photovoltaic system can supply heat with lower cost than the gas system in Goiânia. Comparing the PV and TES+PV, it can be observed a significant reduction in the LCOH, showing that the cost of using the grid (extensively used by the PV system) has a major impact in the viability of the systems. While for the HTHP system, despite the lower electrical energy demand of the system, the higher cost of the heat pump significantly impacts the economic viability. On the other hand, none of the PV systems were economically competitive with the Flat-Plate Collector (FPC-SHIP) system (27 USD/MWh) studied by Lemos et al., (2024).

Table 3: Design parameters of each system and economic figure of merits.

	PV	TES + PV	HTHP + TES + PV
PV capacity	65 kWp	125 kWp	35 kWp
Volume	-	6 m^3	3 m^3
HP heating rate	-	-	40 kW
LCS (USD)	34603.52	65993.8	29471.68
LCOH (USD/MWh)	41.16	33.14	41.47

Finally, the LCS of the three optimal systems were plotted in terms of period of analysis to calculate the payback period for each system, as depicted in Figure 5. The PV system has the lower payback period of 8 years, while the TES+PV system has needs one more year to be paid off. In the other hand, due to the high costs of the HTHP, the payback is achieved after 12 years of operation of the system.

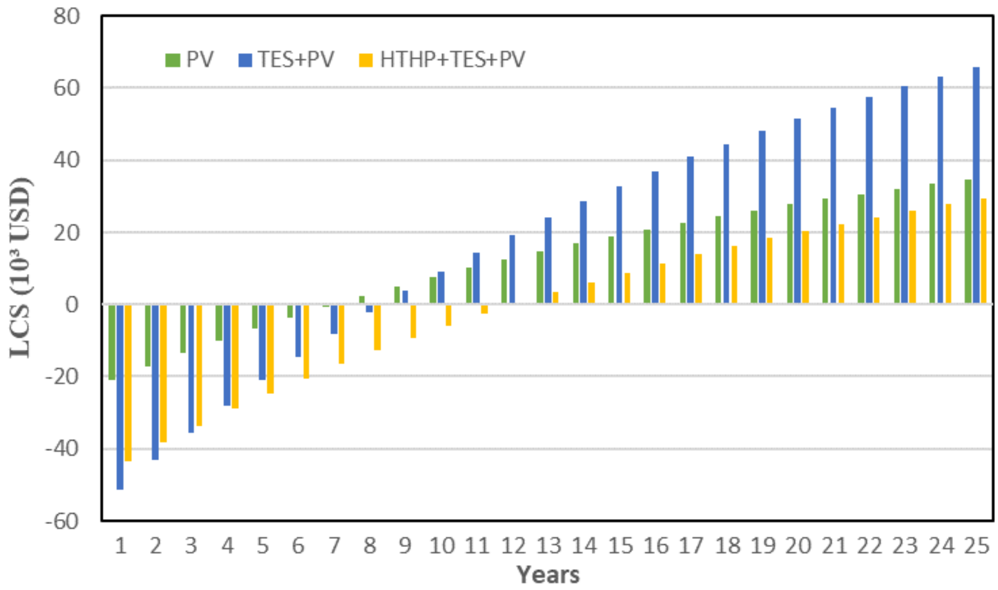

Figure 5: LCS per year for all three systems.

4. Conclusion

The present work shows a comparison of different electrification solutions for supplying hot water for industrial processes, combining a photovoltaic system with an electrical heater, a photovoltaic system with thermal accumulation, and a high temperature heap pump with thermal accumulation fed by photovoltaic energy. The study demonstrates that between all three options, TES+PV was the most attractive, followed by PV and HTHP+TES+PV. HTHP would be a good option in a scenario with lower prices.

Even though the results show that the three analyzed systems are better options compared to the current gas-based system, none of them have overcome economically the FPC-SHIP system reported by (Lemos et al., 2024), for the same city and demand. While TES+PV got the best result (33.14 USD/MWh) between the photovoltaic systems, the flat-plate stationary solar collectors coupled with thermal storage tank (FPC-SHIP system) achieved a LCOH of 27 USD/MWh, highlighting its significant economic advantage. However, if taxes and fees of the electric system are reduced along with modules and heat pump prices, the photovoltaic systems could become an alternative in the future. The case presented is limited to Goiânia/GO in Brazil, but the methodology can be extended to other locations considering local tariffs. Since Brazil has continental dimensions, a nationwide mapping of these results would provide valuable insights for policy planning.

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