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Thermodynamic and economic investigation of a thermochemical heat transformer integrated with solar collectors for industrial process heat

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Abstract:

The present paper investigates two alternative configurations in terms of thermodynamics and economics designed to cover an industrial process heat demand of 5 MW through a thermochemical heat transformer (THT). In the first configuration, solar thermal energy from a parabolic trough collector (PTC) field and industrial waste heat are combined to drive the THT. In the second configuration, the PTC field and a waste heat-driven THT operate in parallel. In both systems, auxiliary electrical heaters are employed to meet the remaining heat demand. The thermodynamic results indicate that, under default operating conditions, the mixed heat source configuration achieves weekly and annual energy efficiencies of 56.25% and 58.76%, respectively, whereas the parallel configuration exhibits higher efficiencies of 61.88% on a weekly basis and 63.30% annually. Electrical heaters primarily contribute during nighttime operation, while increasing the solar aperture area and thermal storage capacity enhances the solar contribution. Furthermore, higher nominal THT capacity leads to reduced electricity consumption. The economic analysis reveals that the levelized cost of heat (LCOH) is minimized at an optimal number of PTC modules, depending on electricity and waste heat costs. The minimum LCOH varies from 0.0620 €/kWh to 0.1028 €/kWh for the first configuration, while lower values between 0.0438 €/kWh and 0.0809 €/kWh are achieved in the parallel arrangement, identifying it as the most economically viable solution.

Keywords:

Thermochemical heat transformer; Heat upgrade; PTC; Solar energy; Industry.

1. Introduction

The industrial sector is one of the largest energy consumers worldwide, with a significant share of input energy being dissipated as low- and medium-temperature waste heat. Recovering and upgrading this waste heat represents a major opportunity to improve overall energy efficiency and reduce greenhouse gas emissions. In this context, the integration of renewable energy sources and waste heat recovery systems has emerged as a promising pathway toward more sustainable industrial processes. In addition, advanced heat upgrade technologies enable the valorization of wasted thermal streams to meet process heat requirements. The synergistic coupling of waste heat recovery, renewable energy integration, and heat upgrade systems can significantly enhance industrial energy flexibility, decarbonization, and resilience [1].

Among emerging heat upgrade technologies, the thermochemical heat transformer (THT) has gained increasing attention as a highly promising solution for industrial applications. By exploiting reversible chemical reactions, such as solid-gas reactions, these kinds of systems are capable of exploiting alternative heat sources, such as renewables or waste heat, to deliver upgraded heat to industrial processes. They offer high conversion efficiency, high energy storage density, and minimal electrical input. Another key advantage of this technology is its ability to achieve large temperature lifts, often exceeding 50 K, making it suitable for various industrial processes [2].

There are many publications in the literature focusing on THTs. First, Wu et al. [3] investigated a THT in terms of thermodynamics, where $MnCl_2/NH_3$-$SrCl_2/NH_3$ were used as working pairs. The maximum value of the coefficient of amplification was 1.74, while the energy storage density reached the value of 444.1 kJ/kg, when the heat source temperature ranged from 120°C to 150°C, and the heat output temperature was 50°C. In addition, the study of Zeng et al. [4] concentrated on a THT assisted by a mechanical booster pump. The configuration was fed with heat coming from solar thermal collectors and was supposed to be installed in a building. Three different reactive salts ($SrBr_2$, LiOH, and $CaCl_2$) were examined to investigate the system performance. According to the results, the heat output temperature achieved values up to about 130°C, and the highest temperature lifts were computed in the case of using $CaCl_2$, ranging from 23 to 26°C. When a two-stage mechanical booster pump was integrated, the heat output temperature was enhanced by up to 16°C, while the overall coefficient of performance (COP), the electrical COP, and the exergy efficiency were decreased by 6.6%, 84.4%, and 9.0%, respectively, in comparison with a THT assisted by a single-stage mechanical booster pump. Furthermore, Yan et al. [5] studied a solid-gas THT under three operating modes, implementing $NiCl_2$-$SrCl_2$/NH_3. The three operating modes were: i) direct thermal energy storage and release mode, ii) heat upgrade mode, and iii) combined cooling and heating production mode. The highest values of the heat output temperature, heat storage efficiency, and heat storage density were determined at 187°C, 0.978, and 2646.92 kJ/kg, respectively. Moreover, Stengler et al. [6] investigated experimentally and numerically a prototype THT, with a capacity of 1 kW, fed with waste heat, where $SrBr_2$/H_2O was utilized as the working pair. The process heat temperature reached the value of 280°C, and the maximum value of specific thermal power was 250 W/kg.

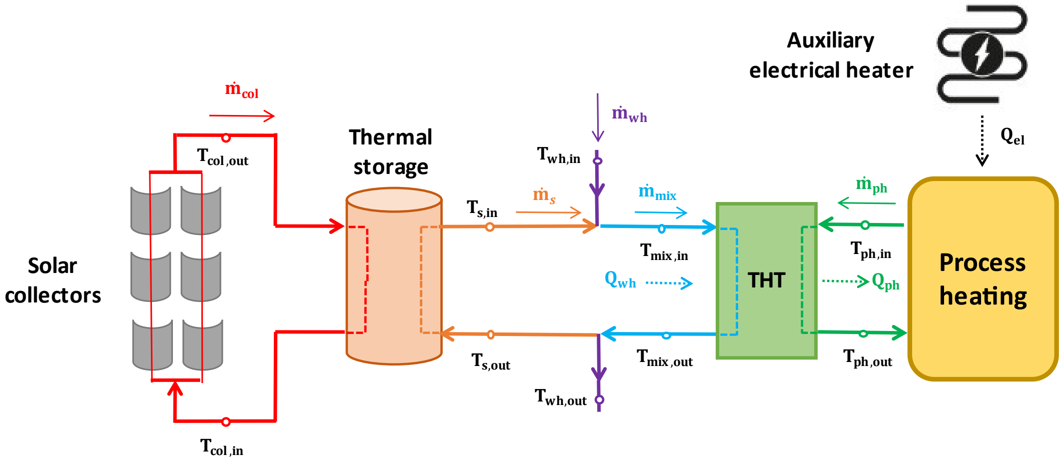
According to the existing literature, most studies analyze THT installations driven by a single heat source, particularly focusing on the investigation of the thermodynamic performance. The purpose of the present work is the analysis of a THT based on $SrBr_2$/H_2O, where both waste heat and heat coming from a solar thermal collectors' field are used. The configuration is studied parametrically in terms of thermodynamics under transient operating conditions, while its economic feasibility is also examined through an economic analysis. Thus, the novelty of the current paper lies in the integration of two heat sources in two different modes, i.e., mixing of the two heat streams, and parallel arrangement, whereas the techno-economic evaluation of the proposed system is an innovative research element, too. The simulation procedure is carried out through a detailed dynamic model using the Matlab software tool [7].

2. Material and methods

2.1. Examined configurations

Two different configurations based on a THT based on $SrBr_2$/H_2O aiming to provide industrially useful heat are examined in the current work. In each configuration, the two heat sources, i.e., the industrial waste heat and the solar heat, are arranged differently. In the first case, the available heat streams are mixed, and then the combined stream provides heat to the THT. On the other hand, the second case is based on the parallel arrangement of the two heat sources. The THT is driven by waste heat, producing useful heat, and runs in parallel with the solar field. In both cases, any remaining heat demand is met by auxiliary electrical heaters. The investigated layouts are shown in Figure 1. Notably, the process heat demand that should be covered is about 5 MW in both configurations. The available industrial waste heat stream is at a temperature level of 200°C, the nominal mass flow rate of the waste heat stream is 103.4 kg/s, and the inlet temperature of the process heat stream is assumed at 230°C. The waste heat stream feeds the dehydrator of the THT, while the hydrator of the THT provides useful heat to the process. Regarding the solar field, parabolic trough collectors (PTCs) along with a thermal energy storage tank are used. Furthermore, thermal oil is used as a heat transfer fluid in the solar field, the waste heat stream, and the process heat stream, as well as a storage medium in the storage tank.

(a)



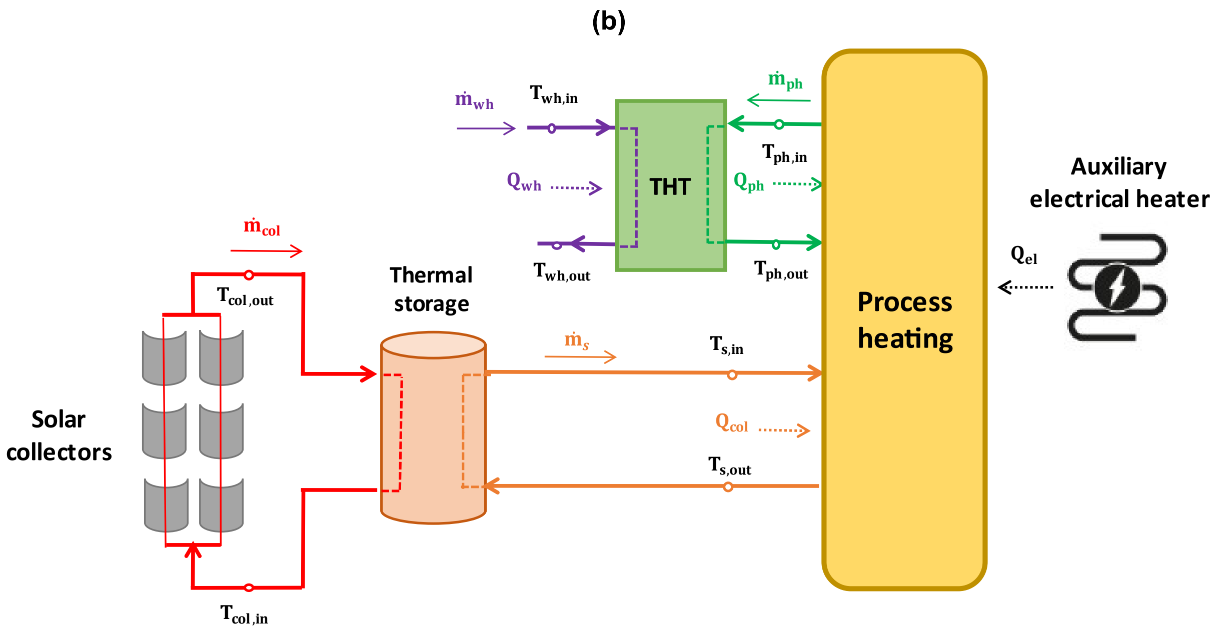


Figure. 1. *a) Mixing of waste and solar heat to feed a THT, and b) waste heat-driven THT in parallel with a solar field to provide process heat.*

2.2. Thermodynamic modeling

Regarding the PTC field, the EuroTrough module is used, with a module aperture area (A_{col}) of 69.6 m². The PTC thermal efficiency is expressed by the polynomial equation below [8]:

$$\eta_{th,col} = 0.7408 \cdot K(\theta) - 0.0432 \cdot \frac{T_{col,in}-T_{am}}{G_{bn}} - 0.000503 \cdot \frac{(T_{col,in}-T_{am})^2}{G_{bn}} \quad (1)$$

The incident angle modifier ($K(\theta)$) is defined by the following expression [8]:

$$K(\theta) = cos(\theta) - 5.25 \cdot 10^{-4} \cdot \theta - 2.86 \cdot 10^{-5} \cdot \theta^2 \quad (2)$$

The thermal efficiency of the collectors is defined as the ratio of the useful heat production (Q_u) to the available solar irradiation rate (Q_{sol}):

$$\eta_{th,col} = \frac{Q_u}{Q_{sol}} \quad (3)$$

The useful heat production is given by the following equation:

$$Q_u = \dot{m}_{col} \cdot c_{p,col} \cdot (T_{col,out} - T_{col,in}) \quad (4)$$

The available solar irradiation rate can be defined as:

$$Q_{sol} = A_{col} \cdot G_{bn} \quad (5)$$

Furthermore, the thermal energy storage tank is modeled using the mixing zone model. The energy balance of the tank is expressed as follows:

$$Q_{st} = Q_u - Q_{ph,sol} - Q_{loss} \quad (6)$$

Where ($Q_{ph,sol}$) is the process heat production by the solar unit. The stored thermal energy (Q_{st}) in the tank is written as below:

$$Q_{st} = \rho \cdot c_p \cdot V \cdot \frac{dT_{st}}{dt} \quad (7)$$

The efficiency of the auxiliary electrical heaters is defined as the ratio of the heat production load to the electricity consumption load:

$$\eta_{heaters} = \frac{Q_{heaters}}{P_{el,heaters}} \quad (8)$$

An efficiency of 98% [9] is assumed for the auxiliary electrical heaters. Moreover, regarding the THT, a detailed modeling approach can be found in the study of Rahbari and Arabkoohsar [10]. The COP of the THT is calculated by the following equation [10]:

$$COP_{THT} = \frac{Q_{hyd}}{Q_{deh}+Q_{evap}} \tag{9}$$

The temperature lift of the THT is determined by the following expression, knowing the hydration temperature (T_{hyd}) and the dehydration temperature (T_{deh}) [10]:

$$T_{lift,THT} = T_{hyd} - T_{deh} \tag{10}$$

At the design point of the THT, the hydration temperature (T_{hyd}) is equal to 260°C, the dehydration temperature (T_{deh}) is 175°C, the process heat outlet temperature is 250°C, and the waste heat inlet temperature is 200°C [10]. The overall energy efficiency is defined as the ratio of the total process heat production to the total energy inputs, which include solar energy, waste heat, and electricity:

$$\eta_{en} = \frac{E_{ph}}{E_{sol}+E_{wh}+E_{el}} \tag{11}$$

2.3. Economic analysis

For the economic assessment of the proposed installations, the levelized cost of heat (*LCOH*) is determined as follows:

$$LCOH = \frac{CC + \sum_{i=1}^{N} \frac{C_{O\&M}}{(1+r)^i}}{\sum_{i=1}^{N} \frac{E_{ph}}{(1+r)^i}} \tag{12}$$

The total capital cost (*CC*) includes the capital costs of all the integrated components, i.e., solar collectors, storage tank, and THT, considering the cost of the electrical heaters as negligible:

$$CC = K_{col} \cdot A + K_{tank} \cdot V + K_{THT} \cdot Q_{nom,THT} \tag{13}$$

Regarding the operation and maintenance cost, it is assumed to be a fraction of the capital cost ($f_{O\&M}$), while the expenses due to electricity and waste heat consumption are also included. So, the annual operation and maintenance cost ($C_{O\&M}$) is calculated as below:

$$C_{O\&M} = f_{O\&M} \cdot CC + K_{el} \cdot E_{el} + K_{wh} \cdot E_{wh} \tag{14}$$

The economic parameters can be found in Table 1.

Table 1. *Economic parameters.*

Parameters	Values
Specific cost of the solar collectors (K_{col})	250 €/m^2 [11]
Specific cost of the storage tank (K_{tank})	1000 €/m^3 [12]
Specific cost of THT (K_{THT})	600 €/kW [10]
Electricity cost (K_{el})	0.10-0.25 €/kWh
Waste heat cost (K_{wh})	0-0.03 €/kWh
Project lifetime (N)	20 years
Discount factor (r)	5% [13]
Operation and maintenance cost fraction ($f_{O\&M}$)	5% of the capital cost

2.4. Simulation strategy

The proposed configurations are simulated via a dynamic model in Matlab [7]. It is highlighted that, regarding the available waste heat stream, a typical industrial load profile, as depicted in Figure 2a, is used, which has been defined by the same research team, taking into account various industrial data [14]. Moreover, climate data for Athens, Greece, coming from the Photovoltaic Geographical Information System (PVGIS) [15] are utilized. The variation in ambient temperature and direct normal irradiation during a summer week is shown in Figure 2b.

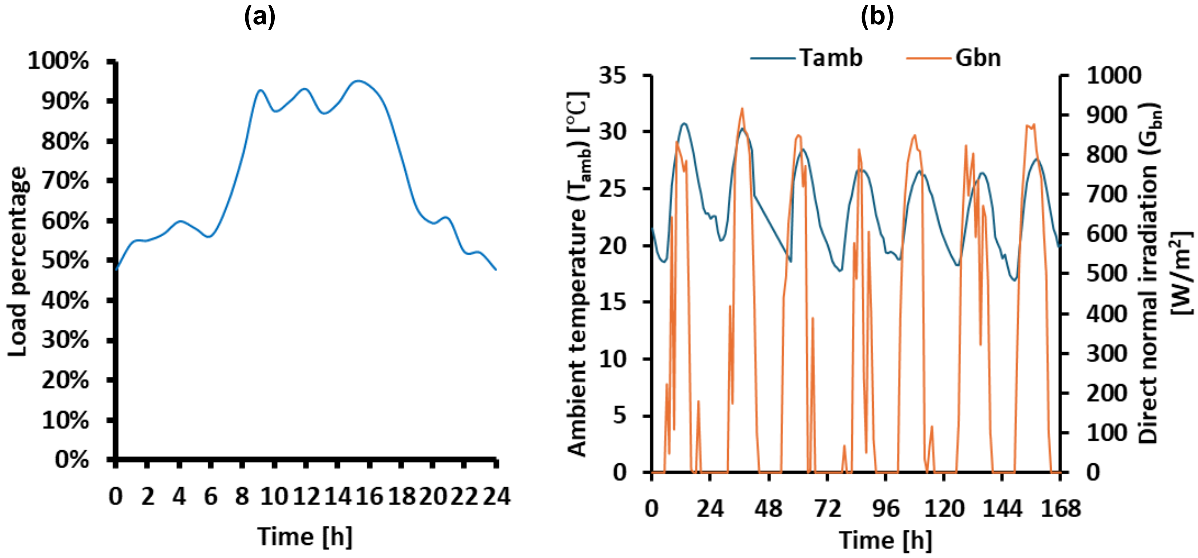


Figure. 2. *a) Typical industrial load profile, and b) ambient temperature and direct normal irradiation variation during a summer week in Athens, Greece.*

First, the thermodynamic results during the summer week for the default scenario of both configurations are presented. In the case of mixing the two heat sources, a number of 200 collectors, a collector aperture area to tank volume ratio of 20 m^2/m^3, and a THT nominal capacity of 4 MW are considered at the default scenario. On the other hand, in the case of parallel arrangement, a number of 200 collectors, a collector aperture area to tank volume ratio of 20 m^2/m^3 [16], and a THT nominal capacity of 2.2 MW are considered at the default scenario. The THT nominal capacity is lower in the case of the parallel arrangement because the THT is driven only by the waste heat stream. When the solar heat and the waste heat streams are mixed to feed the THT, the THT must handle a higher heat input, a fact that leads to a higher required nominal capacity. Subsequently, the two configurations are studied parametrically in terms of thermodynamics, and the outcomes during the summer week are shown. The number of collectors lies in the range of 0-500, and the collector aperture area to tank volume ratio varies from 20 to 100 m^2/m^3. Notably, for the configuration based on the mixing of the two heat sources to feed the THT, the THT nominal capacity is studied parametrically in the range of 3-5 MW. Furthermore, the configurations are investigated economically, determining the LCOH for various solar aperture areas, as well as different values of electricity and waste heat costs. More specifically, the PTC modules range from 0 to 1000 with a step of 20, the electricity cost (K_{el}) varies from 0.1 €/kWh to 0.25 €/kWh with a step of 0.05 €/kWh, while the waste heat cost (K_{wh}) lies in the range of 0-0.03 €/kWh with a step of 0.005 €/kWh. In the case of heat sources' mixing, various THT nominal capacities are assumed, while in the case of the parallel arrangement, the economic performance is determined with and without the integration of the waste heat-driven THT. For the economic analysis, the systems are simulated on a yearly basis, assuming a collector aperture area to tank volume ratio of 20 m^2/m^3. In addition, a sensitivity analysis regarding the cost of the THT and the solar collectors is carried out, taking into account that the THT cost ranges from 250 to 500 €/m^2, whereas the PTC cost lies in the range of 400-800 €/kW. Finally, it is important to mention that the number of tank thermal zones is 10, and the simulation time step is 10 min, after performing a sensitivity analysis.

3. Results and discussion

3.1. Weekly thermodynamic results for the default scenarios

In this section, the thermodynamic results during the summer week for the default scenario of both cases are presented. First, the weekly thermodynamic results for the case of mixing solar and waste heat to feed the THT are shown in Figure 3. More specifically, Figure 3a depicts waste heat and solar heat input to the THT, while the process heat production by the THT and the electrical heaters' consumption are illustrated in Figure 3b. Notably, the waste heat input follows the industrial heat load profile, and the solar heat input achieves its peak values during noon hours. Moreover, the solar field can provide considerable heat input loads after sunset, due to the implementation of the storage tank. Additionally, the THT produces higher process heat loads during the daylight hours, as the available waste heat loads and the solar irradiation rates are higher. In contrast, the share of the electrical heaters in the process heat demand coverage increases during the night hours. According to the results, the weekly waste heat input to the THT is 469.8 MWh, the weekly solar heat input to the THT is 383.2 MWh, the weekly THT process heat production is 517.4 MWh, and the weekly electricity consumption of the auxiliary heaters is 329.1 MWh. It is essential to mention that the weekly energy efficiency is computed at 56.25%, while the yearly energy efficiency is found at 58.76%.

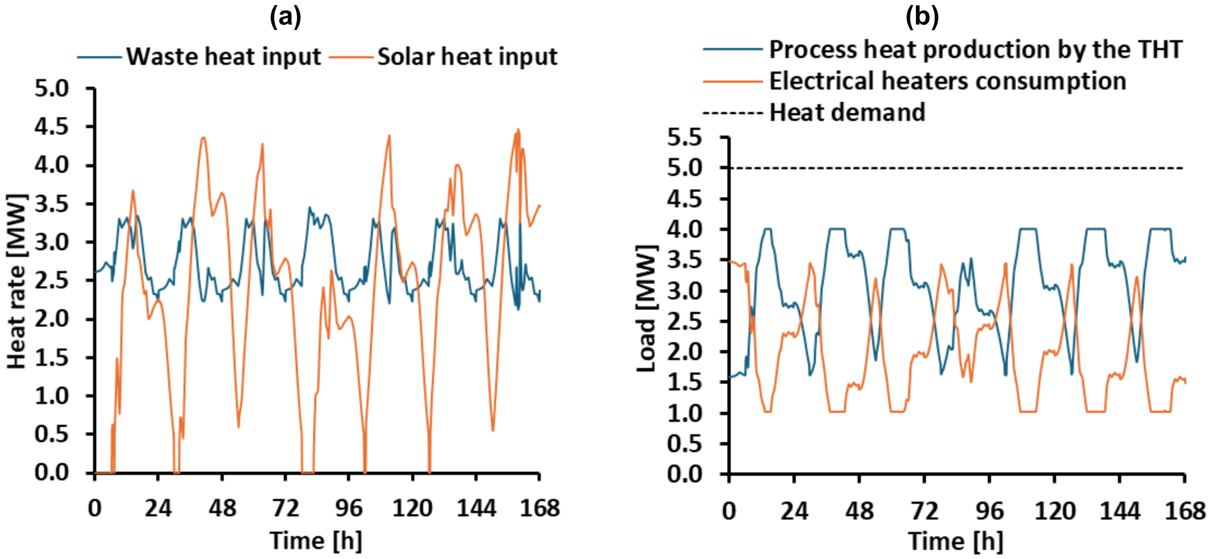


Figure. 3. *a) Waste heat and solar heat input to the THT, and b) process heat production by the THT, and electrical heaters consumption during the summer week for the case of mixing of the two heat sources.*

Furthermore, Figure 4 presents the thermodynamic outcomes during the summer week for the case of the parallel arrangement of the solar field and the waste heat-powered THT. To be more specific, the contribution of the solar collectors to the process heat production is significant during daylight hours, while electrical heaters supplement them at night. It is underlined that the THT contributes continuously during the day according to the industrial load profile. The waste heat input to the THT, the THT process heat production, the process heat production by the solar field, and the electricity consumption of the heaters are equal to 503.1 MWh, 305.2 MWh, 377.9 MWh, and 160.1 MWh during the summer week, respectively. Finally, the weekly energy efficiency is equal to 61.88%, and the annual energy efficiency is computed at 63.30%.

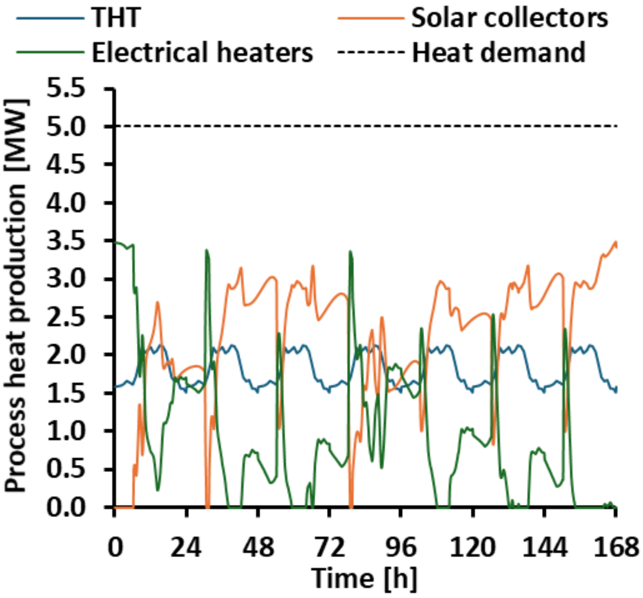


Figure. 4. *Process heat production by the THT, the solar collectors, and the electrical heaters during the summer week for the case of parallel arrangement of the two heat sources.*

3.2. Thermodynamic parametric analysis

The results of the thermodynamic parametric analysis for both configurations during the summer week are provided in this section. First, regarding the case of mixing the two heat sources, Figure 5a shows the results of the auxiliary electrical load consumed by the electrical heaters for various numbers of solar collectors and for the baseline case, which does not include any collectors. The electrical load decreases when the number of solar collectors increases, and the solar heat contribution is enhanced. Notably, the weekly electricity consumption is equal to 329.1 MWh and 199.4 MWh, in the case of using 200 and 500 PTC modules, respectively.

Assuming a solar field of 200 collectors, the outcomes of the electrical load for different values of the ratio of the aperture area to storage tank volume are depicted in Figure 5b. When this ratio increases, the storage tank volume decreases, and the heat amount stored in the tank decreases. As a result, the solar share decreases, and the auxiliary electricity consumption is enhanced. In the case of using a ratio of 100, the weekly electricity consumption is 373.4 MWh, which is greater compared to the value of 329.1 MWh determined for the default operating conditions. The electrical load is higher than 1 MW, as the THT nominal process heat load is equal to 4 MW, and the process heat demand load is equal to 5 MW. Finally, Figure 5c illustrates the distribution of the electrical load of the heaters for different THT nominal capacities. The electricity consumption is reduced as the THT nominal capacity increases, calculating the values of 375.2 MWh and 327.5 MWh, for a THT nominal capacity of 3 MW and 5 MW, respectively.

Regarding the installation based on the parallel arrangement of the two heat sources, the results of the auxiliary electrical load for different numbers of solar collectors during the summer week are shown in Figure 6a. The weekly electricity consumption is equal to 25.8 MWh when the solar field includes 500 modules, which is significantly smaller compared to that defined for the default scenario. At the default value of 200 modules, the electricity consumption is defined at 160.1 MWh during the same week. Furthermore, Figure 6b indicates that the increment of the aperture area to storage tank volume ratio leads to lower storage tank volumes and higher electricity consumption levels. When this ratio is equal to 100, the weekly electricity consumption is computed at 252.8 MWh.

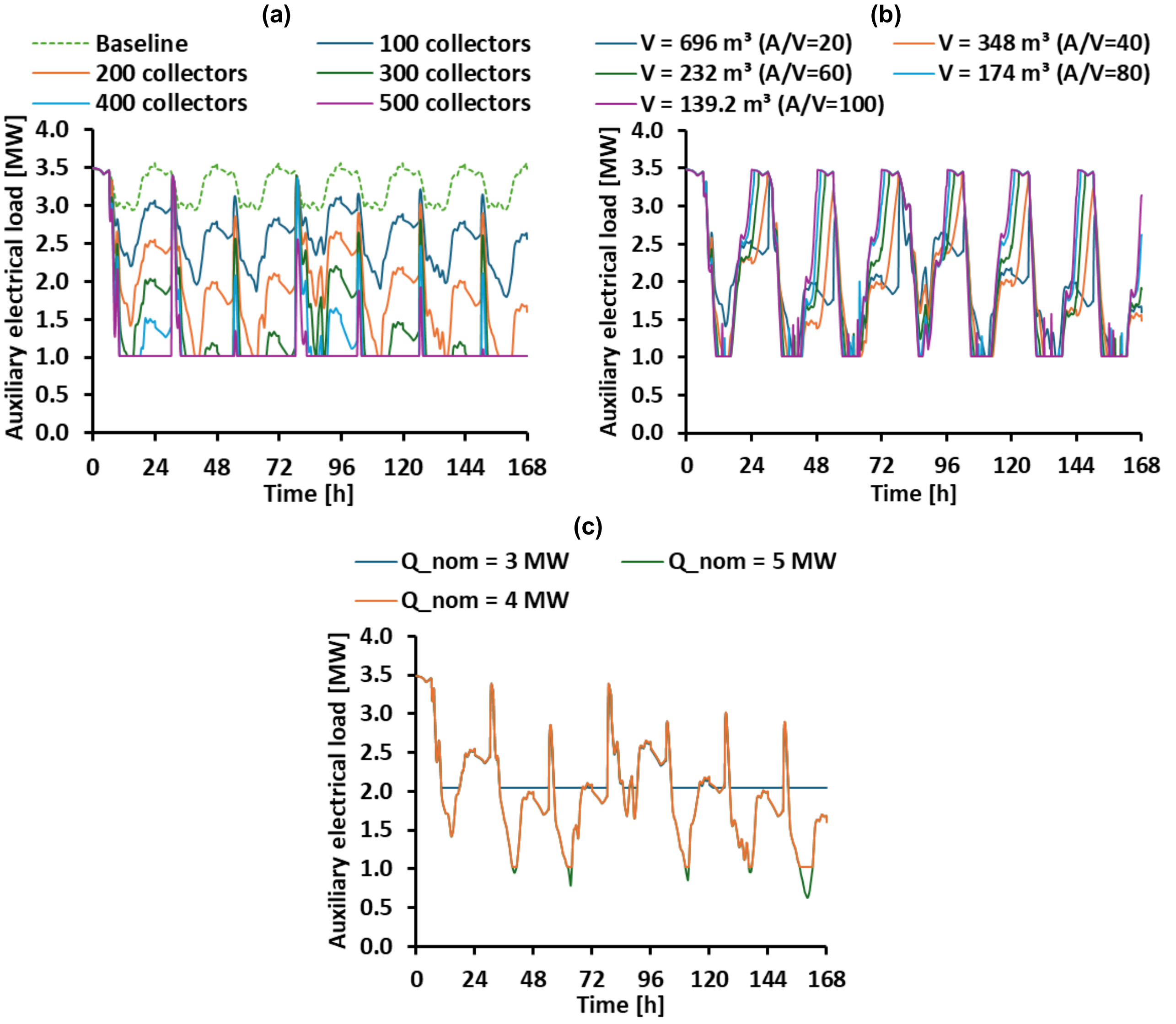


Figure. 5. *Auxiliary electrical load consumption during the summer week for the case of mixing of the two heat sources for different values of a) the number of solar collectors, b) the storage tank area to volume ratio, and c) the THT nominal capacity.*

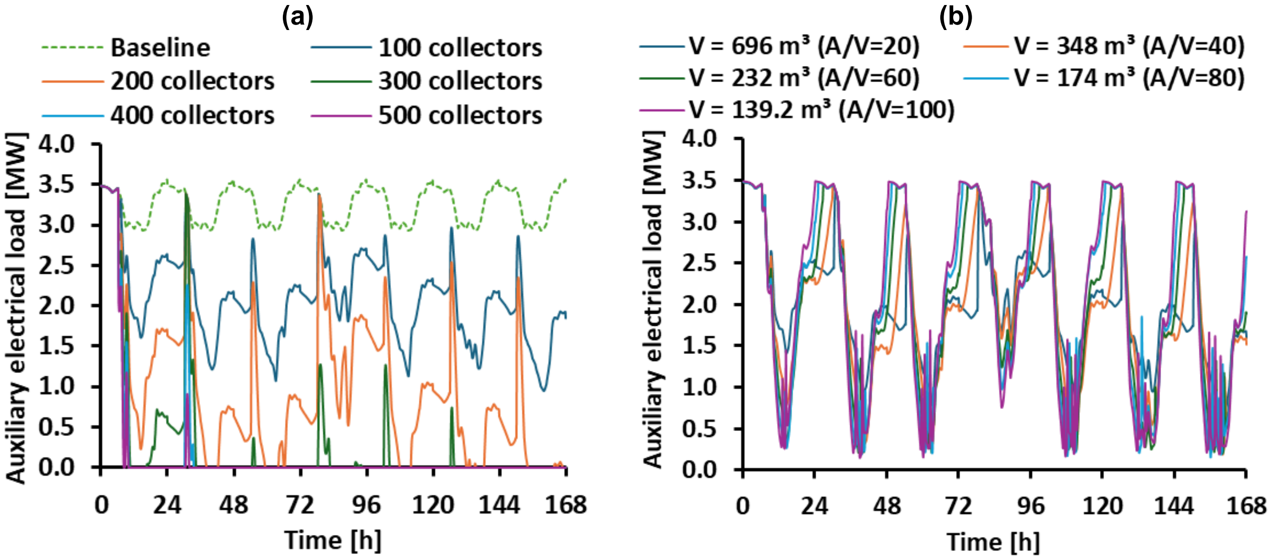


Figure. 6. *Auxiliary electrical load consumption during the summer week for the case of parallel arrangement of the two heat sources for different values of a) the number of solar collectors, and b) the storage tank area to volume ratio.*

3.3. Economic analysis

First, the outcomes of the economic evaluation of the configuration that is based on the mixing of solar and waste heat to feed the THT can be found in this section. Figure 7a illustrates the LCOH variation of various values of the electricity cost and PTC modules, assuming that the waste heat cost is equal to 0.01 €/kWh. It is obvious that the LCOH is minimized for a specific number of PTC modules when the electricity cost varies. The minimum values of LCOH are determined at 0.0668 €/kWh, 0.0795 €/kWh, 0.0895 €/kWh, and 0.0982 €/kWh for electricity cost values that are equal to 0.10 €/kWh, 0.15 €/kWh, 0.20 €/kWh, and 0.25 €/kWh, respectively. The number of PTC modules that achieve the minimum LCOH is defined at 400, 620, 720, and 840, respectively. Additionally, the LCOH variation of different values of the waste heat cost and PTC modules, assuming that the electricity cost is equal to 0.15 €/kWh, is depicted in Figure 7b. For waste heat cost values that are equal to zero, 0.02 €/kWh, and 0.03 €/kWh, the minimum LCOH is calculated at 0.0760 €/kWh, 0.0829 €/kWh, and 0.0859 €/kWh, respectively. The aforementioned values are determined when the solar field includes 580, 660, and 680 modules, respectively. It is highlighted that for all the results presented above, a THT nominal capacity of 5 MW has been taken into account. Higher values of LCOH have been computed for lower THT nominal capacities. The economic outcomes shown in Figure 7 indicate that variations in electricity and waste heat costs lead to different optimal numbers of PTC modules, each corresponding to a distinct minimum LCOH value. An illustrative map of minimum LCOH values achieved for different electricity and waste heat costs, considering a THT nominal capacity of 5 MW, is depicted in Figure 8. According to the minimum LCOH lies in the range of 0.0620-0.1028 €/kWh.

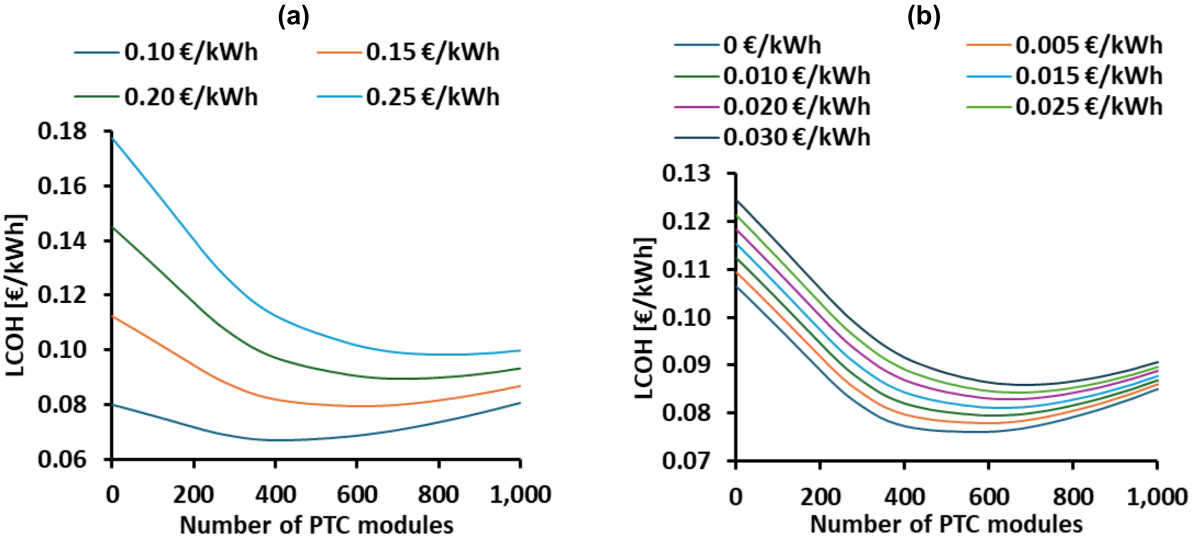


Figure. 7. *LCOH for the case of mixing of the two heat sources, considering a THT capacity of 5 MW for different values of the number of solar collectors and various values of a) electricity cost, and b) waste heat cost.*

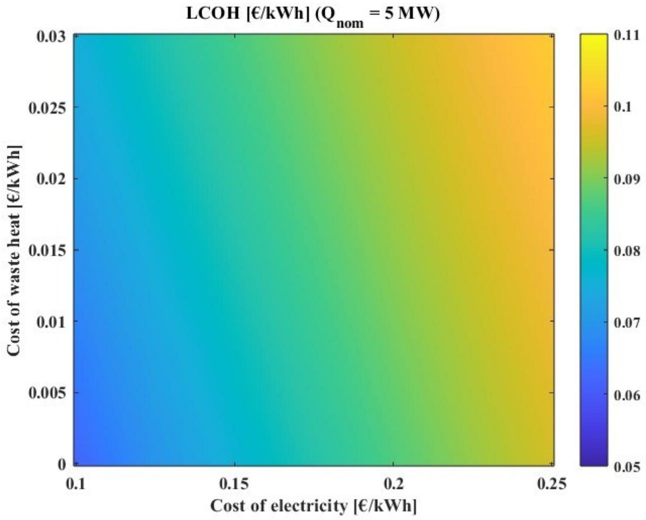


Figure. 8. *Minimum LCOH values for the case of mixing of the two heat sources, considering a THT capacity of 5 MW for different values of waste heat and electricity costs.*

The outcomes of the previous economic analysis for the case of mixing the two heat streams indicate that the electricity cost has a greater effect on the LCOH in comparison with the cost of waste heat. Regarding the results of the sensitivity analysis, when the PTC cost is equal to 400 €/m^2, the minimum LCOH values range from 0.0774 €/kWh to 0.1201 €/kWh, as the electricity cost varies from 0.10 €/kWh to 0.25 €/kWh. The respective LCOH values lie in the range of 0.0799-0.1320 €/kWh, assuming that the PTC cost is equal to 500 €/m^2. Moreover, the minimum LCOH values fall in the range of 0.0639-0.0952 €/kWh and 0.0698-0.1012 €/kWh, when the THT cost is considered to be 400 €/kW and 800 €/kW, respectively. It is underlined that the cost of the solar field strongly affects the overall capital cost and LCOH, while the variation of the THT cost is less influential.

Moreover, the results of the economic analysis of the configuration that is based on the parallel arrangement of the solar field and waste heat-fed THT are presented. Similarly to the other installation, the LCOH is minimized at a different number of PTC modules as the electricity and the waste heat costs vary. The LCOH variation for various values of the electricity cost and PTC modules, assuming that the waste heat cost is equal to 0.01 €/kWh, is shown in Figure 9a. Taking into account a waste heat cost of 0.01 €/kWh, the minimum LCOH is computed to be 0.0498 €/kWh, 0.0577 €/kWh, 0.0638€/kWh, and 0.0690€/kWh when the electricity cost is equal to 0.10 €/kWh, 0.15 €/kWh, 0.20 €/kWh, and 0.25 €/kWh, respectively. The optimal number of solar collectors is 360, 440, 520, and 580, respectively. Figure 9b illustrates the LCOH distribution for different values of the waste heat cost and PTC modules, assuming that the electricity cost is equal to 0.15 €/kWh. The minimum LCOH is calculated at 0.0517 €/kWh, 0.0637 €/kWh, and 0.0697 €/kWh when the cost of waste heat is equal to zero, 0.02 €/kWh, and 0.03 €/kWh, respectively. The aforementioned values are determined when the solar field includes 440 modules, regardless of the waste heat cost level. Finally, Figure 10 depicts the LCOH map, where the minimum LCOH values range from 0.0438 €/kWh to 0.0809 €/kWh, considering various values of electricity and waste heat costs.

The performed sensitivity analysis investigating the impact of the specific capital costs on the overall economic performance reveals that when the PTC cost is equal to 400 €/m^2, the minimum LCOH values vary from 0.0591 €/kWh to 0.0848 €/kWh for electricity costs that vary from 0.10 €/kWh to 0.25 €/kWh. The respective LCOH values fall in the range of 0.0643-0.0940 €/kWh, assuming that the PTC cost is equal to 500 €/m^2. Moreover, the minimum LCOH values lie in the range of 0.0485-0.0677 €/kWh and 0.0511-0.0703 €/kWh when the THT cost is considered to be 400 €/kW and 800 €/kW, respectively. This case also indicates that the cost of the solar field has a significant effect on the overall capital cost and LCOH. According to the economic analysis, along with the sensitivity one, that is carried out for the parallel arrangement of the THT and the PTC field, the determined LCOH values are lower compared with the case of mixing solar and waste heat to drive the THT.

Furthermore, the economic results of the configuration that is based only on the solar collectors and the auxiliary heaters to cover the process heat demand are illustrated in Figure 11. For electricity cost of 0.10 €/kWh, 0.15 €/kWh, 0.20 €/kWh, and 0.25 €/kWh, the minimum LCOH is determined at 0.0586€/kWh, 0.0701€/kWh, 0.0790 €/kWh and 0.0864€/kWh, respectively. These values are calculated for a solar field of 560, 700, 820, and 940 modules, respectively. It is important to mention that when the waste heat-driven THT is not used, larger solar aperture areas are required, resulting in higher LCOH values.

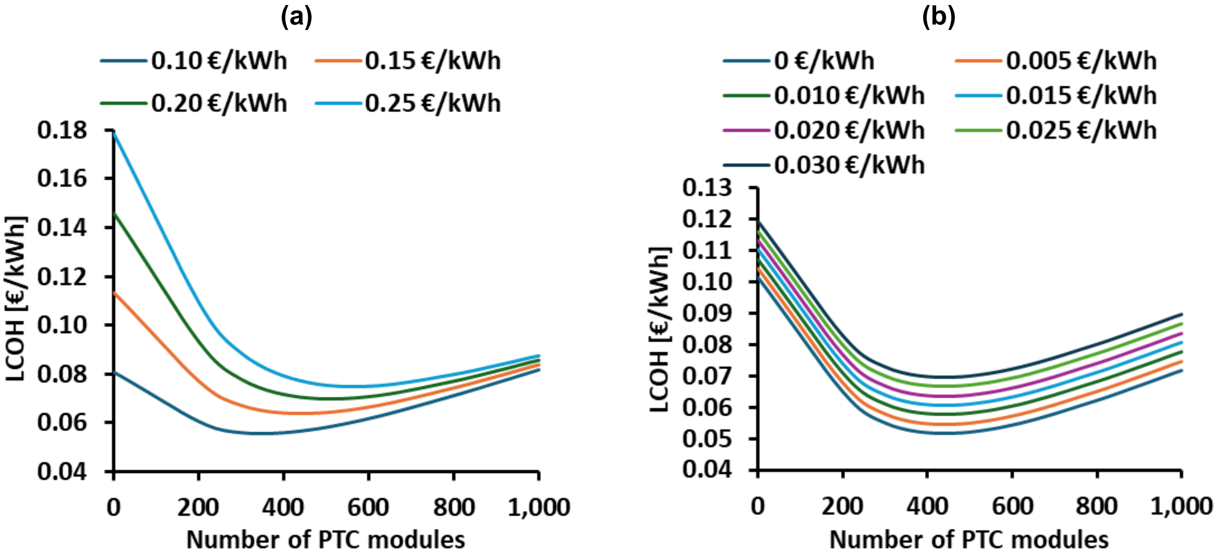


Figure. 9. *LCOH for the case of parallel arrangement of the two heat sources, considering a THT capacity of 2.2 MW for different values of the number of solar collectors and various values of a) electricity cost, and b) waste heat cost.*

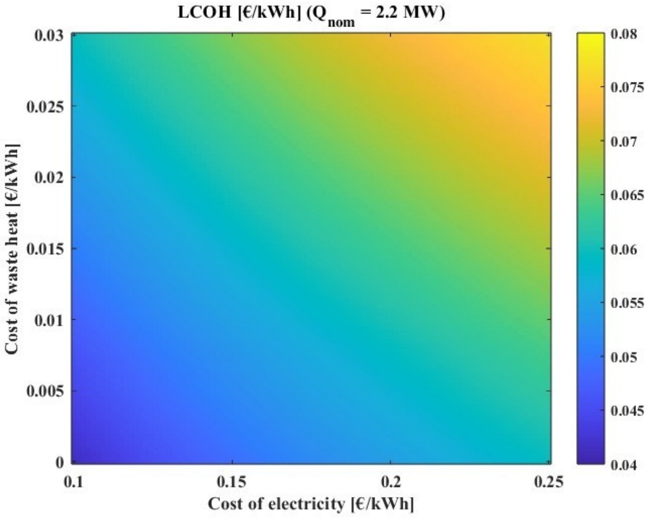


Figure. 10. *Minimum LCOH values for the case of parallel arrangement of the two heat sources, considering a THT capacity of 2.2 MW for different values of waste heat and electricity costs.*

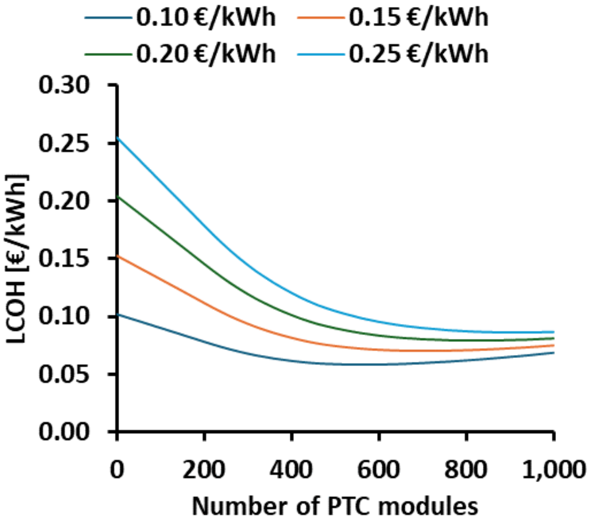


Figure. 11. *LCOH for the case of using only solar collectors and electrical heaters for different values of the number of solar collectors and various values of electricity cost.*

Based on the sensitivity analysis conducted for the case of using only PTC and electrical heaters, it is noteworthy that higher LCOH values are determined when the PTC cost increases. Assuming a PTC cost that is equal to 400 €/m^2, the minimum LCOH values range from 0.0740 €/kWh to 0.1119 €/kWh when the electricity cost varies from 0.10 €/kWh to 0.25 €/kWh. The respective LCOH values fall in the range of 0.0826-0.1262 €/kWh, considering a PTC cost of 500 €/m^2. Finally, it is concluded that the parallel arrangement of the waste heat-powered THT and the PTC field seems to be the most economically viable configuration option to meet the desired process heat demand.

4. Conclusions

The current study concentrates on the thermodynamic and economic investigation of two configurations aiming to meet an industrial process heat demand of 5 MW through a THT. The two heat sources, i.e., the solar heat and waste heat, are mixed to drive the THT in the first case, while in the second case, the PTC field and the THT, driven by waste heat, work in parallel. In both cases, any unmet heat demand is covered by auxiliary electrical heaters. The main conclusions are summarized below:

- In default scenarios, the configuration based on the mixing of the two heat sources achieves a weekly energy efficiency of 56.25%, and a yearly energy efficiency of 58.76%, while in the case of the parallel arrangement, the corresponding values are equal to 61.88%, and 63.30%.
- The electrical heaters particularly contribute during the night hours, while the increment of the solar aperture area and storage tank volume increases the solar share.
- The electricity consumption decreases when the THT nominal capacity increases.
- The LCOH is minimized at a specific number of PTC modules, for different values of electricity and waste heat costs.
- The minimum LCOH values range from 0.0620 €/kWh to 0.1028 €/kWh when the THT is fed with mixed heat sources.
- The minimum LCOH lies in the range of 0.0438-0.0809 €/kWh for the second configuration, concluding that the parallel arrangement is the most economically feasible installation.
- In the case of using only PTCs and electrical heaters to meet the heat demand, the economic performance is poorer.

Future work may include the dynamic optimization and environmental evaluation of the proposed systems, as well as the utilization of multi-objective optimization techniques and the implementation of control strategies. Finally, case studies in various industrial sectors should be carried out.

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Nomenclature

A	Aperture area, m²
CC	Capital cost, €
$C_{O\&M}$	Operation and maintenance cost, €
COP	Coefficient of performance, -
c_p	Specific heat capacity, kJ/kgK
E	Energy, kWh
$f_{O\&M}$	Operation and maintenance cost fraction, -
G_{bn}	Direct normal irradiation, W/m²
K	Specific cost, €/m², €/m³, €/kW or €/kWh
$K(\theta)$	Incident angle modifier, -
$LCOH$	Levelized cost of heat, €/kWh
$\dot{m}$	Mass flow rate, kg/s
N	Project lifetime, years
P_{el}	Electrical load, kW
Q	Heat rate, kW

Subscripts and superscripts

am	Ambient
col	Collector
deh	Dehydrator
el	Electrical
en	Energetic
evap	Evaporator
heaters	Heaters
hyd	Hydrator
in	Inlet
lift	Lift
nom	Nominal
out	Outlet
ph	Process heat
sol	Solar

r	Discount factor, %
T	Temperature, °C
V	Tank volume, m^3

Greek symbols

η	Efficiency, -
θ	Incident angle, °
ρ	Density, kg/m^3

st	Stored in the tank
tank	Storage tank
th	Thermal
THT	Thermochemical heat transformer
u	Useful
wh	Waste heat

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