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Techno-Economic Assessment of Solar Hybrid System With High-Temperature Heat Pump for Industrial Heat Generation

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Abstract. Solar thermal collectors, high-temperature heat pumps and thermal energy storage are key technologies for industrial decarbonization. The development and installation of these technologies represent a double benefit. First, by using renewable energy sources, they contribute to reducing fossil fuel consumption. Second, their integration can supply heat for industrial processes where other single renewable-based technologies, such as solar, can encounter limitations. This work presents the techno-economic assessment of a solar hybrid system using pressurized water as heat transfer fluid. The system is studied in the Greek electricity market considering prices of 2022. Dispatch strategies and system sizing are identified for optimal techno-economic performance. The main performance indicators investigated are the levelized cost of heat, the operational expenditure, and savings compared to traditional fossil-fuel solutions. The results highlight that the levelized cost of heat is as low as 98 €/MWh with operational cost savings of 23k €/y against traditional non-flexible gas boilers.

Keywords: Solar Thermal Collector, High-Temperature Heat Pump, Latent Heat Thermal Energy Storage.

1. Introduction

Nowadays, the industrial sector demands about 22% of the overall energy demand as heat emits about 30% of the whole global carbon emissions. To decarbonize the industrial sector different alternatives have been proposed [1]. Heat upgrade technologies are becoming increasingly relevant as one of the ways to meet the high energy demand required by industry. A hybrid system capable of fully decarbonize industrial heat is proposed by integrating other renewable-based technologies, such as solar thermal collectors and thermal energy storage with heat pumps. This type of system can deliver heat to numerous industries that require heat at 200-250°C.

In this work, heat is upgraded to 210°C using a high-temperature heat pump (HT-HP) and a high-temperature solar thermal collector (HT-STC). A latent heat thermal energy storage (LH-TES) is coupled to increase the flexibility of the solution. This study aims to assess the techno-economic performance of the proposed hybrid system as a renewable-based solution for industrial heat decarbonisation.

Figure 1 shows the layout of the integrated system proposed. Constant waste heat is recovered at 90°C (T_c) for an upgrade using a HT-HP. The temperature lift heats the downstream line to 210°C (T_h) and then is sent to a heat exchanger that is connected in parallel to the HT-STC. The main line connects the latter heat exchanger with the HT-STC line which can also deliver heat at 210°C (T_s) for charging the LH-TES at 210°C or for delivering heat for steam production at 175°C. The system can generate quality heat for steam production and storage by exploiting solar energy when it is abundant, or by upgrading heat using a HT-HP when electricity prices are low.

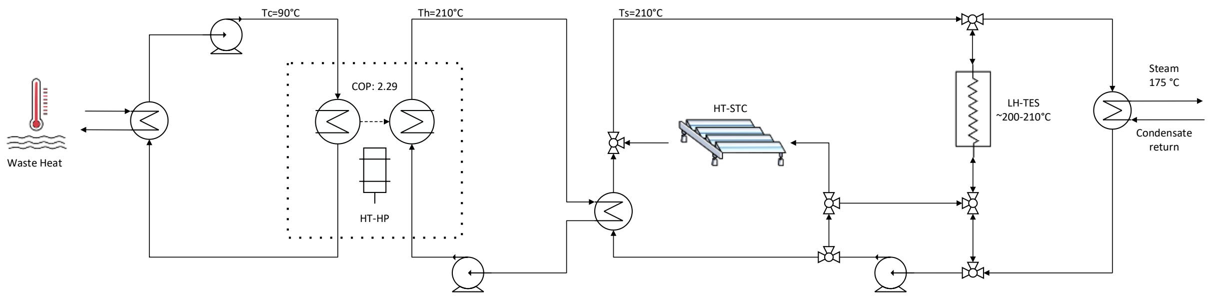

Figure 1. *Layout of the proposed system for flexible heat upgrade process*

2. Methodology

This study aims to assess the energy and economic performance of a hybrid system using industrial solar collectors and a novel high-temperature Stirling heat pump with latent heat thermal energy storage to fully decarbonize a dairy factory in Greece. The model is built via Python scripts, CoolProp for thermodynamic properties, and uses an Excel file for external input data.

In step 1, the coefficient of performance (COP) of the heat pump is calculated for the set temperatures using measured data from [2], for the given temperature lift, a COP = 2.29 is required. Then, for a given size of the heat pump, the system calculates the fluid mechanics of the pressurized water for delivering the necessary mass flow to the intermediate heat exchanger, and consequently, the water pump duty for both sizes of the heat pump (cold and hot). In parallel, the sizing and performance of the high-temperature solar collectors have been generated using SAM [3] for the given heating demand with pressurized water as heat transfer fluid (HTF).

In step 2, the operation of the system is evaluated by a dedicated dispatch optimization algorithm by the authors in [4], which considers the main technical and operational inputs of the system. Different capacities of LH-TES, heat pump sizes and solar collectors' thermal output are tested with the system constraints for the decision variables in the system optimization.

In step 3, an economic evaluation is performed to obtain the levelized cost of heat (LCoH) and average operational expenditures (OPEX) in a lifetime of 25 years compared to a conventional gas boiler. A total of 63 cases are assessed and represent the combination of three different sizes of the HP, six different sizes of the STC and three different sizes of the TES unit. Also, the case without solar thermal collectors is considered.

2.1 System boundaries and configuration

In this work, the thermal demand of a dairy factory located in Greece with a DNI of 1800kWh/m^2 is investigated. The factory has a uniform daytime demand only during the day (10h per day starting at 6:00 to 16:00 for the whole week), resulting in an annual heat load of 1510MWh/year with a weekly peak demand of 650kW$_{th}$. The factory has two gas boilers with a capacity of 600kW and 300kW respectively. Electricity and LPG prices [5] correspond to 2022, with an average electricity price of 0.28€/kWh, which is quite high for hybrid system implementation. Previous studies such as [4] and [6] have worked with average electricity values around 0.055 €/kWh to 0.15 €/kWh in different European countries.

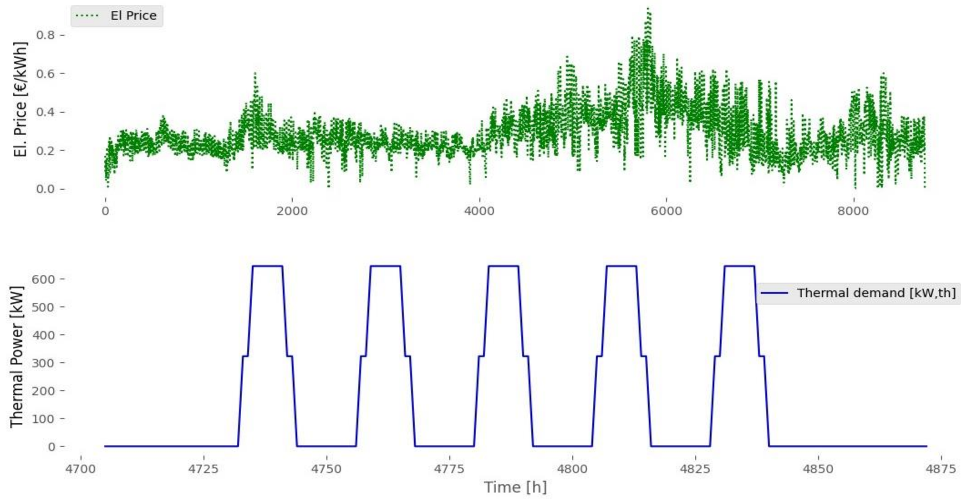

Figure 2. *a) Electricity price 2022 in Greece [5]. b) Thermal demand for week 28 [7]*

2.2 Thermodynamic model and economic evaluation

The techno-economic performance of the system is assessed focusing on capital expenditures (CAPEX), OPEX, and LCoH; benchmarking the technology against gas boilers. The sensitivity analysis considers different sizes of the solar collectors, heat pump and TES. An initial case is proposed, sizing the STC and the HP according to the peak demand (650kW$_{th}$), and then the system is evaluated by varying the ratio of STC, HP and TES between half and double the peak demand to find the best-performing configuration for the given demand. Direct solar integration would reduce electricity consumption, together with the TES integration.

The economic evaluation considers specific costs and data gathered from the literature to analyse the performance of the proposed hybrid system. The model accounts for the capital cost of the main equipment and balance of the plant units: solar field + parabolic trough system [3], the investment cost of the heat pump, the capital cost of the water pump for both circuits of the heat pump and for pumping the heat transfer fluid in the solar collector circuit, the intermediate heat exchanger between the STC and HP circuits and LH-TES size based on PCM cost material and capacity. BOP of the plant (pipes, valves and fittings) is not included since it is difficult to define the number for each one at this level of the work; it will be included in further research. For the operational costs, the electric consumption of the heat pump motor, one water pump for each HP circuit (two in total) and one water pump for the solar circuit have been considered. A lifetime of 25 years has been considered for the system.

The LCoH has been calculated as in Eq. (1):

$$LCoH = \frac{CAPEX + \sum_{t=1}^{n} \frac{OPEX}{(1+d)^n}}{\sum_{t=1}^{n} \frac{E_t}{(1+d)^n}} \tag{1}$$

Where CAPEX corresponds to the sum of the capital cost of the heat pump system, the solar thermal collectors and the thermal energy storage. The OPEX corresponds to the operational expenditure, mainly electricity consumption of the system at the giving COP over the lifetime of the project (n), which is 25 years and a discount rate (d) of 5%.

The sizing of the main components of the hybrid system has been optimized aiming to minimize the LCoH and the average OPEX throughout the lifetime of the system and compared against the current gas boilers. Configurations, where the average OPEX is higher than the gas boiler correspond to unfeasible sizes of the main components. The average OPEX of the gas boiler is 78 k€/y over 25 years of lifetime.

3. Results and discussion

In this section, the main results are presented. First, a summary of the CAPEX is explained for the HP, the STC, and LH-TES for different sizes. Second, the results of the system performance are shown for the 63 configurations, where both KPI are discussed: LCoH and OPEX of the system.

For the HP cost calculation, a specific investment cost of 600 €/kW with a safety factor (SF) of 1.1 for the thermal demand was used for three different sizes: below the peak demand (400kW), at peak demand (650kW) and twice the peak demand (1300kW). The case below the peak represents the lowest power that the system needs to be able to cover the demand by using only thermal energy storage, and without solar thermal collectors. The system operates at the set temperature source temperature of 90°C and sink temperature of 210°C. At these conditions, the high-temperature Stirling engine can achieve a COP of 2.29.

For the STC cost calculation, Table 1 shows the summary of different sizes using SAM [3] for delivering heat to the process. Financial parameters for the parabolic trough collectors were 150 €/m^2 for the solar field, 7% of contingencies and 5% of sales taxes. Land cost is not included, and neither is the heat sink. It is considered that the factory has an existing steam generator. Regarding kWth/m^2, the IEA SHC recommends a factor of 0.7kWth/m^2 [8] which are aligned with factors obtained from the simulations.

Table 1. *STC sizing summary [3].*

Thermal Power ($kW_{,th}$)	m^2	Capital Cost (€)	€/kW
400	613	190,449	476
650	996	367,378	565
900	1,380	613,913	682
1000	1,533	623,880	624
1100	1,686	633,847	576
1300	1,993	734,755	565

For the LH-TES, the power of the unit is related to the peak demand (650 kW). Simulations were tested for 3, 6 and 12 hours of storage. Giving capacities of 1,950, 3,900 and 7,800 kWh respectively. The size of the unit is calculated considering a suitable phase change material (PCM) is $NaNO_3$-KNO_3 (50-50%) with melting temperature around 210°C. For calculating the total cost of the storage, a PCM to TES ratio is 0.18 for a latent heat shell and tube system [9] is used. Figure 3 shows the share of CAPEX and OPEX of the system when HP size is 400kW, STC is 650kW and storage capacity is 1,950kWh (3 hours).

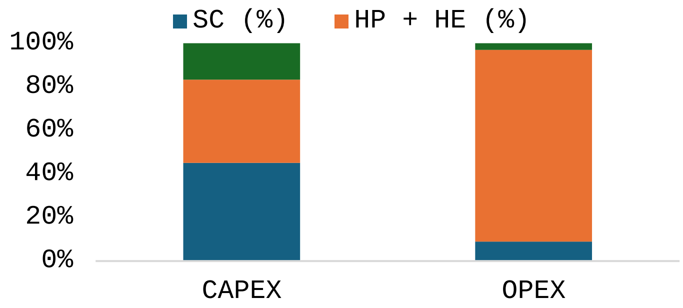

Figure 3. *CAPEX and OPEX contributions of the system*

Figure 4 shows the main dynamic results from the dispatch optimization algorithm for a characteristic week (from the 8th to the 13th of July). The considered TES capacity is 1,950kWh corresponding to 33% of the total daily demand (5,810kWh), and showing that the HP can fully charge the TES in less than 2.5h. The optimization algorithm prioritizes solar availability and cheaper electricity during the day to cover the demand and charge the TES when possible, avoiding operating the heat pump at night when the electricity price is higher.

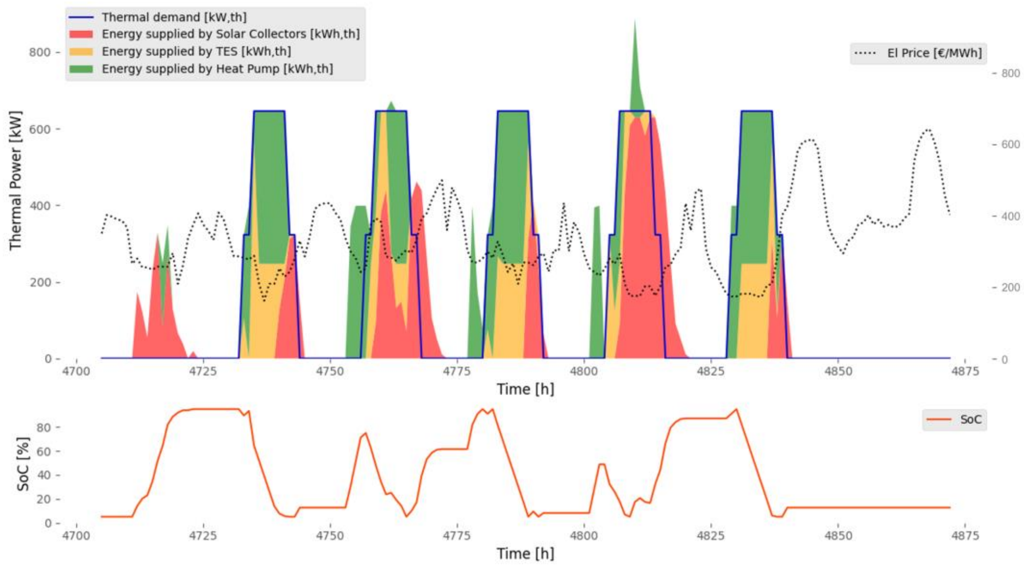

Figure 4. *Characteristic performance of the system for minimum LCoH (HP a thermal power of 400kW, STC thermal power 650kW, TES capacity: 3 hours. Week 28)*

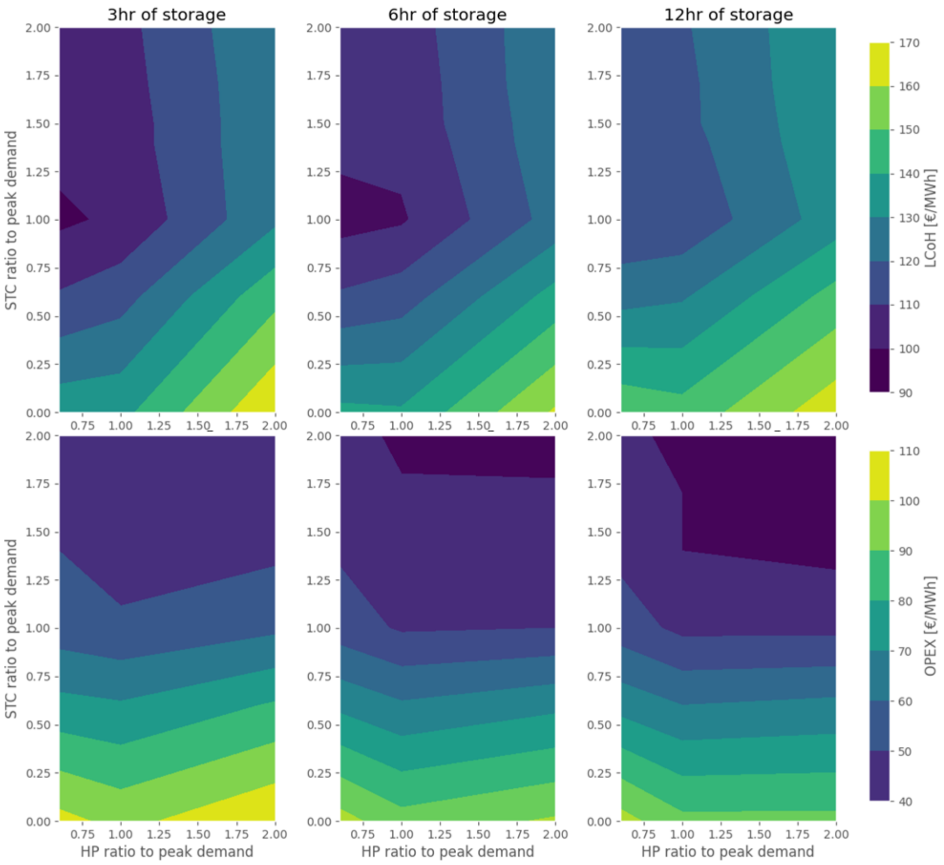

Figure 5. *System performance for different configurations. a) LCoH. b) Average OPEX*

Figure 5 a) shows the results of LCoH calculations for the 63 cases previously described. Results show that the most viable solution is when the system operates with a 400kW heat pump and a 650kW STC, similar to the results reported in [10]. Moreover, it can be seen that by oversizing the STC higher values of LCoH are obtained. However, it is identified that the best ratio of STC to peak demand is between 1.0 and 1.25. Regarding the LH-TES size, the best performances were observed within 3 and 6 hours of storage. Minimum LCoH corresponds to 98 €/MWh when HP size is 400kW, STC is 650kW and storage capacity is 1,950kWh (3 hours).

For Figure 5 b), results for average OPEX in [k€/y] are shown. It can be seen that operational expenditures are reduced when STCs are oversized and with larger TES. However, these less-expensive operations imply higher CAPEX and therefore higher LCoH values, which is not desired. Every case above the average OPEX of the gas boiler is not economically feasible, they do not generate any savings during the lifetime. OPEX of the gas boiler corresponds to 78 k€/y, which is located between 0.75 and 1.0 STC ratio, meaning that any OPEX below that threshold will not generate any savings. Additionally. there is an inflexion point of the LCoH above the range of 1.0-1.2 STC ratio, the oversizing of the system will intrinsically increase the LCoH. These two limits defined the boundaries for the STC size implementation.

4. Conclusions

This work presents the techno-economic assessment of a solar hybrid system using high-temperature heat pumps and latent heat thermal energy storage has been presented. Different size configurations have been considered using an optimization dispatch strategy. The main performance indicators considered are the levelized cost of heat, the operational expenditure, and the economic savings compared to traditional fossil-fuel gas boilers. The main conclusions are:

- A methodology to assess the techno-economic performance of a hybrid system with solar thermal collectors, heat pump, and thermal storage was successfully developed.
- The LCoH for the analyzed configurations ranges from 98 to 170 €/MWh. There is a clear trend of increasing the LCoH when oversizing the STC and the TES capacity. The reduction of the heat pump size to about half of the annual peak load results in the most viable option for minimizing the system's LCoH.
- The resulting high LCoH is mainly provoked by the oversizing of the system, and the high electricity prices of the 2022 of the Greek market when compared to other European energy markets.
- Configurations, where the STC was not considered, resulted in higher average OPEX and LCoH. The hybridization of the system grants the opportunity for better performance and flexibility.
- Feasible configurations must have a lower average OPEX throughout the lifetime of the system when compared to traditional gas boilers. External CAPEX subsidies are needed to limit the initial expenditure to facilitate the technology implementation.
- The average OPEX achieved for the lowest LCoH configuration is 55k€/y.

This study sets the ground for further power-to-heat techno-economic investigations. Future work will be focused on evaluating the solar thermal collector dimensioning and capital costs and assessing the system performance in different European energy markets.

Author contributions

Mateo Sanclemente: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Validation, Resources, Writing – original draft, Visualization.

Silvia Trevisan: Conceptualization, Methodology, Writing – review & editing. Project administration, Supervision.

Rafael Guedez: Conceptualization, Methodology, Supervision, Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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