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Optimizing Heat Storage Integration for Solar Thermal Systems in Industrial Process Heat Networks

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ABSTRACT

European industry accounts for approximately 20% of total European CO_2 emissions, with heat demand representing one of the largest energy consumers. Solar thermal collectors offer an efficient renewable alternative to fossil fuels to cover the heat demand. However, due to the temporal mismatch between the solar thermal generation and process heat generation a thermal storage is needed to maximize the renewable utilization. This article presents a novel optimization framework for integrating an ideal heat storage with solar thermal systems in multiperiod heat exchanger network synthesis. We derive an analytical approach to optimize the heat storage by using physical insights from Pinch Analysis: heat can only charge the storage below the lowest pinch point in a given period and discharge above the highest pinch point. We show both how to do it for a storage of infinite size and of finite size, and that the infinite size storage is much more efficient to solve. The approach is validated using real industrial data from a lubricant plant and optimizing the implementation of solar thermal at the plant. By increasing the size of the storage more of the solar thermal heat is utilized, however, the increase in utilization becomes smaller as the storage becomes larger. While 100% solar thermal heat utilisation requires a storage size of 1040 kWh, 90% utilisation can be reached with a storage of 250 kWh, compared to only 70% without a storage.

Keywords: Heat Exchanger Network, Energy Storage, Renewable and Sustainable Energy, Solar Thermal

INTRODUCTION

European industry accounts for approximately 20% of total European CO_2 emissions, with heat demand representing one of the largest energy consumers. Currently, this demand is predominantly met through fossil fuel combustion [1]. Decarbonising industrial heat production is therefore critical to achieving European climate targets, and increasing the penetration of renewable heat sources offers a promising pathway forward.

Solar thermal (ST) collectors can efficiently convert solar radiation into low- to medium-temperature heat suitable for many industrial applications [2]. However, a fundamental challenge arises from the temporal mismatch between the availability of solar thermal energy and industrial heat demand. Solar radiation follows predictable daily and seasonal patterns, whereas industrial processes often exhibit different temporal profiles or require heat during periods of low solar availability. This mismatch can significantly limit the fraction of renewable heat that can be directly utilised, potentially undermining the economic viability of solar thermal installations.

Beyond solar thermal integration, industrial processes themselves exhibit fluctuations in heat demand and in the availability of hot process streams over time. These variations create opportunities to capture and store surplus process heat during periods of excess and to recover it during periods of heat deficit. Thermal energy storage systems can address both challenges simultaneously: storing excess solar thermal energy when production exceeds demand and capturing surplus process heat for later use when additional heat is needed.

Efficiently integrating heat sources, storage systems, and process demands in an industrial site requires sophisticated process integration methods. Heat exchanger network synthesis (HENS) provides a systematic framework for designing optimal heat exchanger layouts that minimise utility consumption while meeting all process heating and cooling requirements. When dealing with time-varying conditions—whether from fluctuating solar production, variable process schedules, or both—multiperiod HENS becomes necessary to capture the full complexity of the system and optimise across all operational scenarios.

Previous work has explored the integration of thermal energy storage into HENS problems. Walmsley et al. [3] investigated the integration of industrial solar and gaseous waste heat into heat recovery loops using both constant and variable temperature storage. Oliveira et al. [4] addressed process integration in a multiperiod sugarcane biorefinery, demonstrating the importance of capturing temporal variations in process conditions. Olsen et al. [5] developed a methodology for thermal energy storage integration based on pinch analysis principles. However, efficient optimisation methods that can simultaneously determine optimal storage parameters—temperature, size, and initial charge—within multiperiod HENS frameworks remain an active area of research.

This work presents a novel analytical optimisation framework for integrating ideal heat storage systems within multiperiod HENS. By using physical insights from pinch analysis principles, we derive closed-form expressions and efficient solution procedures for determining optimal storage temperature and initial charge. We distinguish between infinite-size and finite-size storage cases, showing that the infinite-size formulation offers significant computational advantages and can serve as a screening tool before considering size constraints. The methodology is implemented within COMPHENS [5], an open-source HENS optimisation framework, enabling its application to industrial-scale problems.

We validate the approach using real operational data from a lubricant manufacturing plant in the Mediterranean region, considering solar thermal collector integration. The results quantify the relationship between storage size and solar thermal utilisation, revealing diminishing returns as storage capacity increases and identifying the minimum storage size required for complete renewable heat utilisation.

MODELLING

Heat exchanger network synthesis

The HENS modelling framework utilised in this work is the COMPHENS framework [6], which builds upon the seqHENS framework [7], [8]. This splits the problem into four subproblems: first, the minimum utilities required are determined; second, the minimum number of heat exchangers is determined; third, the optimal heat-load distributions are determined; and finally, the network generation and optimisation are performed. In this work, we focus primarily on the first subproblem, implementing heat storage as a preprocessing step to minimise utility costs. To be able to store and use the heat this also means that we will consider multiperiod HENS problems, where the heat storage links these periods together.

Heat storage

To derive an analytical approach to the heat storage implementation we consider an ideal heat storage, i.e. no losses and constant temperature. In addition, we assume that we have a cyclic process so the heat storage needs to start and end with the same charge level. In practice this means that there is no accumulation or depletion of heat over the cycle and that the heat storage is sized perfectly. It also means that the plant operates at consistent repeating cycles, e.g. over a day or a week.

Storage temperature

To determine the optimal temperature of the heat storage we use Pinch Analysis. A priori we know that it is only useful to charge the storage below the lowest pinch in each period and it is only useful to discharge it above the largest pinch in each period, otherwise we would need to increase the usage of hot or cold utilities in the period, either to directly charge the storage or to cover the extra heat or cold not available at the correct temperature somewhere else in the process. This already limits the storage temperature to be below the maximum pinch and above the minimum pinch of the overall problem. Furthermore, the optimal use of the heat storage is to charge and discharge it as much as possible over the periods to minimize the utility consumption. To determine the maximum chargeable or dischargeable heat in a single period at a given temperature, we use the Grand Composite Curve (GCC). The maximum chargeable heat is the heat that can be consumed to heat an extra cold stream at that temperature and create an extra pinch point at or below the given temperature (shifted up by $\Delta T_{min}/2$). Similarly, the maximum heat that can be discharged would be the maximum heat that could be delivered from an extra hot stream and create a single pinch point at or above the given temperature (shifted down by $\Delta T_{min}/2$).

By evaluating the maximum chargeable and dischargeable heat as functions of temperature for each period, we can identify the temperature at which these quantities are balanced across all periods. This balance point minimises utility consumption by maximising storage utilisation. For an infinite-size storage, this optimal temperature, $T_{storage}$, is found by solving:

$$T_{storage} = \underset{T}{\text{root}} \sum_p Q_p(T), \tag{1}$$

where T is the storage temperature, p denotes the period and Q_p the heat transferred to or from the storage in period p subject to the constraints outlined above, with charging of the storage having a positive sign and discharging having a negative sign. This equation finds the temperature where the net heat transferred to/from storage over all periods equals zero, ensuring cyclic operation while maximizing the absolute heat transfer.

To derive Equation (1) we have assumed that the heat storage has infinite size and heat capacity, so it is always able to store the heat provided and deliver the heat requested in each period. The infinite storage assumption simplifies the problem significantly, as we only need to find where net heat transfer equals zero. However, for a finite storage, the optimization becomes more complex. In each period, charging is limited by the available capacity (maximum charge minus current charge), and discharging is limited by the current stored energy. This transforms the problem from finding a root to maximizing the total heat transferred subject to the cyclic constraint:

$$T_{storage} = \underset{T}{\operatorname{argmax}} \sum_p |Q_p(T)| \;\; s.t. \sum_p Q_p(T) = 0. \tag{2}$$

Initial storage charge and storage size

Similarly to the storage temperature the optimal initial charge is the one which maximizes the amount of heat that is transferred between the different periods, and therefore that is charged and discharged from the storage, while making sure that the start and end charge of the storage are the same and no extra utilities are used in any period. If the storage starts at a charge that is large enough such that it never reaches 0,

$$\min_p Q_p > 0, \tag{3}$$

then increasing the initial storage charge by a would just lift the charge in all periods by a. Doing this for a second initial charge b which also respects Equation (3) one can easily to find the initial charge, Q_i, where the storage just reaches 0 charge once at the end of a single period by linear extrapolation. Ensuring Equation (3) is respected can also easily be done by making sure a and b are larger than the maximum of the total cold and hot utilities when no heat storage is present. Equivalently, one could find the minimum initial charge where the storage is never fully emptied, but has an infinitesimal charge left at the minimum:

$$Q_i = \min_{q_i} q_i \;\; s.t. \min_p Q_p(q_i) > 0. \tag{4}$$

This represents the critical initial charge: any lower and the storage becomes fully depleted in at least one period (limiting heat transfer), any higher and the storage simply operates at an elevated baseline without transferring additional heat, essentially moving away from optimum. From the optimal initial charge, we can also find the optimal size of the storage, $Q_{storage}$, which just equals the maximum stored after any period:

$$Q_{storage} = \max_p Q_p. \tag{5}$$

If we again limit the storage to a finite size we end up with an optimization problem, this time finding the initial charge, Q_i, that maximizes the heat transferred:

$$Q_i = \underset{q_i}{\operatorname{argmax}} \sum_p |Q_p(q_i)| \;\; s.t. \sum_p Q_p(q_i) = 0. \tag{6}$$

However, if the size of the storage is greater than the optimal size from Equation (5) we can instead use Equation (4) to find the initial charge. As these two equations can be solved simultaneously with only two evaluations, they are much faster than the optimization problem in Equation (6) and it will typically be worth checking them first even for a finite storage. In addition, if the storage temperature is not specified Equation (1) must be solved together with Equation (4) for an infinite storage, which is much faster than solving Equation (2) together with Equation (6) for a finite storage, increasing the speed advantage of checking the infinite storage first.

HENS integration

To add the heat storage to the HENS framework, we need to find both the storage temperature and the initial charge, given either an infinite or a finite storage. These depend on one another and can be solved simultaneously or sequentially. As finding the initial storage charge is very easy for the infinite-size storage, we do not want to redo this, so the storage temperature is solved each time for a given initial storage charge, both for the infinite and finite storage size.

With the heat storage temperature and initial charge we can find the heat transferred in each period. Based on the heat transferred we add a stream to each period of the HENS problem, with a hot stream being added when the storage is discharging heat and a cold stream being added when the storage is charging, with their heat capacity flow rate being dependent on the heat and duration of the period.

CASE

The case considers a chemical plant producing lubricants, located in the mediterranean region. The plant operates for 16 hours, five days a week. The heat demand consists of heating base oils and additives before they are pumped from storage tanks to mixing tanks, heating the mixing tanks, heating for an intermediate drum storage, and space heating. These heat demands are all relatively low temperature, and with little cooling demand, no internal heat exchange is currently in place. Currently, the heat demand of the plant is covered by a hot oil loop which is heated centrally by a gas boiler and then delivers the heat through several separate loops. The plant is looking into building solar thermal collectors to cover some of the heat demand and reduce the usage of the natural gas boiler.

To get an accurate picture of the time dependency of the heat demand a month-long measurement campaign was performed and combined with operational data from the plant. The heat produced from the solar thermal collectors were modelled on an hourly basis and averaged into a morning, midday and afternoon production giving three periods of different heat production which was assumed to be the same each day. As the plant is not operational on weekends the solar thermal collectors were assumed to be defocused at this time and the heat storage could therefore not be charged on the weekends. This lead to a total heat production of 18.9 MWh from the solar thermal collectors over the period investigated.

The heat demand of the site and the heat production of the solar thermal collectors were used to optimize the solar thermal heat usage, and due to the large numbers of consumers with intermittent heat demand it was decided that the solar thermal heat would be connected to the existing hot oil loop alongside the gas boiler. To best utilise the solar thermal energy a heat storage is also required with the required heat storage capacity for this plant being investigated.

RESULTS

To investigate the impact of the heat storage on the amount of solar thermal energy used, the heat storage was optimised for varying sizes using the method described in the Methodology section. The resulting fraction of solar thermal heat utilised is shown in Figure 1. As expected, we see that by introducing the storage, we increase the fraction of the solar thermal heat that can be utilised. This increase is also nonlinear, with the gain in heat usage largest for small storages and flattening out for larger storages. For instance, the increase is greater from no storage to 50 kWh than from 50 kWh to 100 kWh, and this increase is again larger than the increase from 500 kWh to 750 kWh. This is because, for a small storage, increasing the size slightly allows it to store and discharge additional heat over multiple periods, whereas increasing the size of an already large storage only allows some additional heat to be transferred between a few periods. At the extreme is when all the solar thermal is utilised, as we see for a storage size of 1040 kWh, where increasing the size further would not increase the heat utilisation since there is no more heat to transfer between periods.

While a storage size of 1040 kWh achieves 100% solar thermal utilisation, the economic optimum may lie at a smaller capacity. The relationship between storage size and utilisation suggests strong diminishing returns: a 250 kWh storage (24% of the maximum size) captures over 90% of available solar thermal energy, whereas a 500 kWh storage (48% of the maximum size) captures approximately 95%. From a techno-economic perspective, the marginal benefit of the last 10% of utilisation must be weighed against the capital and operating costs of doubling storage capacity from 500 to 1000+ kWh. Additionally, the ratio of storage capacity to total heat production (1040 kWh / 18, 900 kWh ≈ 5.5%) indicates relatively efficient storage sizing, though this ratio would vary with different operational patterns and solar resource availability.

However, determining the optimal plant size would require a techno-economic analysis to evaluate the trade-off between increased heat utilisation and increased storage costs as size increases, which is outside the scope of this study.

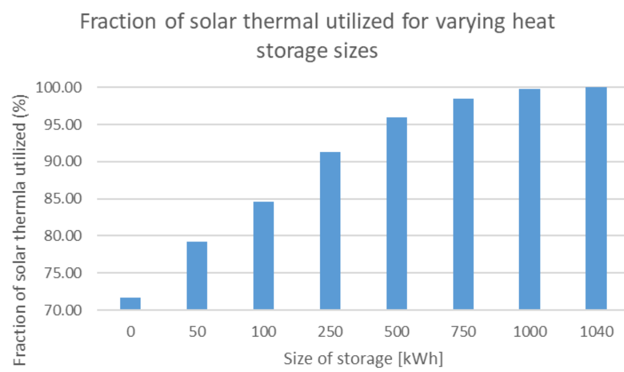

Figure 1. Fraction of solar thermal heat utilized as a function of the size of the heat storage.

CONCLUSION

A model for an ideal heat storage suitable for implementation in multiperiod HENS frameworks has been developed in this work. Based on pinch analysis principles, we have shown efficient methods for optimising both the temperature and initial charge of the storage, with particular emphasis on the infinite-size case, which requires only solving a root-finding problem and performing linear extrapolation, compared to two optimisation problems for finite-size storage. This computational advantage makes the infinite-size approach valuable as a screening tool to establish upper bounds on storage benefits.

Applying this methodology to optimise solar thermal integration at a lubricant manufacturing plant demonstrates that heat storage significantly enhances renewable energy utilisation, with diminishing returns as storage size increases. A relatively modest storage of 250 kWh achieves over 90% solar thermal utilisation, while complete utilisation requires 1040 kWh—representing only 5.5% of the total heat production over the analysed period. This efficient storage-to-production ratio suggests that well-designed thermal storage can enable high solar thermal penetration in industrial applications with manageable storage requirements.

Future work should extend this methodology to non-ideal storage systems that account for heat losses and temperature variations, and conduct comprehensive techno-economic analyses to identify the economically optimal storage sizing, considering both capital costs and renewable energy benefits.

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