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Enhanced Heat Recovery Network with Integrated Sensible Heat Storage Facilities for Energy Intensive Industry

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Energy-intensive industries contribute large amounts of greenhouse gas emissions. An effective strategy to decarbonise these industries is by applying process integration tools to enhance energy efficiency and reduce overall energy consumption. Recent studies showed that thermal energy storage offers significant benefits in energy efficiency enhancement, as it can amplify the energy recovery potential. Despite its potential, studies that applied process integration tools to address heat recovery problems with consideration of heat storage remain limited. This work develops an optimisation framework that aims to determine optimal heat storage type and size based on the total annualised cost (i.e., costs associated with storage facilities and utilities) to form a feasible heat recovery network between plants. The proposed framework is demonstrated through a case study that focuses on optimising the sensible heat storage selection for indirect heat integration between a mixed plastic waste treatment plant and a steel mill. By analysing the performance and effectiveness of the storage media studied, nitrate salt storage medium is selected due to its greatest energy and cost savings of 12.7 % and 20.7 %, when compared to direct Heat Integration. Insights from this provide information on the feasibility of implementing a storage-supported heat recovery network in the energy-intensive industry.

1. Introduction

Energy-intensive industries account for nearly 25 % of the global carbon dioxide emissions (UNECE, 2022). Among various industries, chemicals and petrochemicals, cement, and iron and steel industries contribute the most significantly to the emissions. Process Integration tools are widely applied in energy efficiency enhancement to reduce overall energy consumption by forming a heat recovery network (Varbanov, 2023). Since the development of pinch analysis by Linnhoff and Flower (1978), the heat exchanger network synthesis has been extended from a single-plant analysis to an integrated analysis of multiple plants (Tian et al., 2020). Heat recovery can be achieved through direct integration between process streams or indirect heat integration *via* an intermediate fluid (Er et al., 2022). Although direct heat integration can maximise energy recovery, practical issues (e.g., safety concerns, pipeline complexity, operational issues) are often encountered in its implementation (Liu et al., 2015). Direct heat integration often requires a more complicated design for process flowsheet, plant layout, and control (Zhang et al., 2016). Hence, indirect heat integration is usually recommended for heat recovery between plants (Chang et al., 2015).

Recently, heat storage facilities (or thermal energy storage (TES)) have emerged as a key technology in amplifying the energy recovery potential for heat integration between plants (Liew et al., 2018). The cost and energy-saving benefits of considering TES were demonstrated in studies such as the integration of a hydrogen storage system using the P-graph approach for an energy system by Ji et al. (2023) and the integration of heat storage tanks of different temperatures by Wang et al. (2020). However, they merely focused on integrating a pre-determined heat storage option without optimising through a spectrum of heat storage options. In addition, there is a lack of a comprehensive framework that optimises the storage size based on the economic feasibility

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and suitability for a given industry. Möhren et al. (2022) adopted an iterative approach to determine the storage size for a single plant by reducing a predefined maximum storage volume and studying its impact on cost. Jamaluddin et al. (2020) optimised the sizing for a thermochemical heat storage integrated into a trigeneration system. However, they did not explore the performance of other heat storage options and the feasibility of integrating them for multiple plants. This leads to limitations in achieving maximal energy recovery, as the pre-determined storage facility may not necessarily be the most suitable option for industrial applications. Thus, this work aims to develop an optimisation model that can determine optimal heat storage type and its respective sizing for the indirect heat integration based on the total annualised cost (TAC).

2. Problem Statement

Given a set P of plants, and for each plant $p \in P$ a set of hot streams HS and a set of cold streams CS with their respective heat to be released ($\mathrm{Q}_{hs}, hs \in HS$) and absorbed ($\mathrm{Q}_{cs}, cs \in CS$). The heat duties are determined based on the stream properties, including the heat capacities (CP_{hs} and CP_{cs}), supply temperatures (T_{hs}^{IN} and T_{cs}^{IN}) and target temperatures (T_{hs}^{OUT} and T_{cs}^{OUT}). With the integration of heat storage facilities, the heat transferred into storage medium $st \in ST$ is denoted by Q_{st}^{OUT}, whereas the heat transferred out from storage medium st is denoted by Q_{st}^{IN}. The determination of the hot and cold utility consumption is based on the problem table algorithm (PTA) which consists of k stages of temperature intervals with T_{hs}^{IN}, T_{cs}^{IN}, T_{hs}^{OUT}, and T_{cs}^{OUT} shifted by half the minimum approach temperature (ΔT_{min}) and arranged in descending order (Linnhoff and Flower, 1978). The start temperatures of interval $k \in \{0,1,2,\ldots,K\}$ in each plant p for charging and discharging are denoted as $T_{k,p}^{Upper,Charge}$ and $T_{k,p}^{Upper,Discharge}$. The end temperatures of interval k in each plant p for charging and discharging are denoted as $T_{k,p}^{Lower,Charge}$ and $T_{k,p}^{Lower,Discharge}$. The cascaded heat at stage of temperature interval k is denoted as d_k. This work aims to (i) evaluate the performance (i.e., TAC) of indirect heat integration compared to other heat integration scenarios; and (ii) determine the optimal storage option based on the TAC.

3. Methodology

A mixed-integer linear programming model that aims to optimise the heat storage selection and sizing is developed. The objective function is set to minimise the TAC associated with the energy and storage medium (C_{st}^{Total}), as given in Eq(1). The energy cost for each plant p includes the annualised hot utility cost and cold utility cost, which are denoted as $\mathrm{C_{HU}}$ and $\mathrm{C_{CU}}$. The storage size is represented by $V_{st}^{Storage}$, whereas the associated unit storage cost is denoted as $\mathrm{C_{st}}$.

$$Min\ C_{st}^{Total} = \mathrm{C_{HU}} \sum\nolimits_{p \in P} Q_{HU,p}^{Min} + \mathrm{C_{CU}} \sum\nolimits_{p \in P} Q_{CU,p}^{Min} + \mathrm{C_{st}} V_{st}^{Storage} \tag{1}$$

Using the PTA, the heat is cascaded down the temperature interval k in plant p. The model constraint for the energy balance equations at each temperature interval k is given in Eq(2). This minimises the utilities required for the process, as represented by Eq(3) and Eq(4). For each plant p, the cascaded heat at stage of temperature interval $k = 0$ shows the minimum hot utility required ($Q_{HU,p}^{Min}$), whereas the cascaded heat at the last stage of temperature interval ($k = K$) shows the minimum cold utility required ($Q_{CU,p}^{Min}$) for the process.

$$d_{k,p} = d_{k-1,p} + \sum\nolimits_{hs \in HS} \mathrm{Q}_{hs,k,p} + \sum\nolimits_{st \in ST} Q_{st,k,p}^{IN} - \sum\nolimits_{cs \in CS} \mathrm{Q}_{cs,k,p} - \sum\nolimits_{st \in ST} Q_{st,k,p}^{OUT}, \quad \forall k\{0,1,\ldots,K\}, p \in P \tag{2}$$

$$d_{k=0,p} = Q_{HU,p}^{Min}, \qquad \forall p \in P \tag{3}$$

$$d_{k=K,p} = Q_{CU,p}^{Min}, \qquad \forall p \in P \tag{4}$$

The total heat to be released by the hot streams ($\mathrm{Q}_{hs,k,p}$) and the total heat to be absorbed by the cold streams ($\mathrm{Q}_{cs,k,p}$) at stage of temperature interval k in plant p are given in Eq(5) and Eq(6).

$$\sum\nolimits_{hs \in HS} \mathrm{Q}_{hs,k,p} = \sum\nolimits_{hs \in HS} CP_{hs,k,p}\left(T_{k,p}^{Upper} - T_{k,p}^{Lower}\right), \qquad \forall k \in \{0,1,\ldots,K\}, p \in P \tag{5}$$

$$\sum\nolimits_{cs \in CS} \mathrm{Q}_{cs,k,p} = \sum\nolimits_{cs \in CS} CP_{cs,k,p}\left(T_{k,p}^{Upper} - T_{k,p}^{Lower}\right), \qquad \forall k \in \{0,1,\ldots,K\}, p \in P \tag{6}$$

The heat transferred into ($Q_{st,k,p}^{OUT}$) and transferred out ($Q_{st,k,p}^{IN}$) from the storage medium st at stage of temperature interval k in plant p are shown in Eq(7) and Eq(8). The heat capacity flowrate of the storage (CP_{st})

is determined by the model. The feasible temperature ranges for the charging and discharging processes are between the minimum and maximum operating temperatures of the storage st with consideration of ΔT_{min} compared to the process streams.

$$Q_{st,k,p}^{OUT} = CP_{st,p}\left(T_{k,p}^{Upper.Charge} - T_{k,p}^{Lower,Charge}\right), \quad \forall k \in \{0,1,\ldots,K\}, p \in P, st \in ST \tag{7}$$

$$Q_{st,k,p}^{IN} = CP_{st,p}\left(T_{k,p}^{Upper,Discharge} - T_{k,p}^{Lower,Discharge}\right), \quad \forall k \in \{0,1,\ldots,K\}, p \in P, st \in ST \tag{8}$$

The binary constraint is included to ensure that the storage facility is not charged and discharged simultaneously, as represented by Eq(9). $B_{st,p}^{IN}$ is the binary variable that indicates if heat is transferred out from storage medium st and $B_{st,p}^{OUT}$ is the binary variable that indicates if heat is transferred into storage medium $st.$ The constraint is activated using the big-M method in Eq(10) and Eq(11), where M is an arbitrarily large constant and m is an arbitrarily small value. When there is a heat flow into the storage medium, $B_{st,p}^{OUT}$ is forced to be “1”. When there is a heat flow out of the storage medium, $B_{st,p}^{IN}$ is forced to be “1” instead. Both $B_{st,p}^{IN}$ and $B_{st,p}^{OUT}$ will remain as “0” if otherwise.

$$B_{st,p}^{IN} + B_{st,p}^{OUT} \leq 1, \quad \forall p \in P, st \in ST \tag{9}$$

$$mB_{st,p}^{IN} \leq \sum_{\mathrm{k}=0}^{\mathrm{K}} Q_{st,k,p}^{IN} \leq MB_{st,p}^{IN}, \quad \forall p \in P, st \in ST \tag{10}$$

$$mB_{st,p}^{OUT} \leq \sum_{\mathrm{k}=0}^{\mathrm{K}} Q_{st,k,p}^{OUT} \leq MB_{st,p}^{OUT}, \quad \forall p \in P, st \in ST \tag{11}$$

$Q_{st}^{Storage}$ is taken to be the maximum $Q_{st,p}^{Storage}$ so that storage size is sufficiently large, as indicated in Eq(12). With $Q_{st}^{Storage}$, the volume of the storage required (V_{st}) can be determined using Eq(13), where $\mathrm{t_p}$ and $\mathrm{\rho_{E,st}}$ represent storage duration and energy density of the storage medium (Möhren et al., 2022).

$$Q_{st}^{Storage} = \sum\nolimits_{p \in P} \sum_{\mathrm{k}=0}^{\mathrm{K}} Q_{st,k,p}^{OUT}, \quad \forall st \in ST \tag{12}$$

$$V_{st} = \frac{Q_{st}^{Storage} \times \mathrm{t_p}}{\mathrm{\rho_{E,st}}}, \quad \forall st \in ST \tag{13}$$

4. Case Study

A case study is presented to demonstrate the proposed methodology. It comprises two plants from the energy-intensive industry: a mixed plastic waste treatment plant from Yadav et al. (2023) and steel mill from McBrien et al. (2016). The objective is to optimise the sensible heat storage selection for indirect heat integration. The model developed is used to optimise energy recovery under three scenarios. The first scenario is direct heat integration, where the heat exchange occurs between the streams in both plants. The second scenario focuses on the heat integration of each plant independently (termed as intraplant heat integration). For the third scenario, the heat storage facility is introduced as an intermediate platform that stores and transfers the heat between the participating plants (termed as indirect heat integration between plants). In this work, three commonly used sensible heat storage media are considered for the selection (see Table 1). Note that the developed model can be easily modified to incorporate other heat storage options. The operating temperature ranges are taken from Platzer and Stieglitz (2024). The energy density and cost are determined using data (i.e., cost per unit mass, density, average heat capacity, operating temperature) provided by Platzer and Stieglitz (2024). This work focuses on the storage media cost, as it is the dominant aspect of the overall system cost for TES construction.

Table 1: Data for sensible heat storage facilities.

Storage material	Operating temperature range (°C)	Energy density (kWh/m^3)	Cost (\$/(m^{3}y))
Synthetic oil	250–350	57.5	90.00
Nitrate salt	265–565	249.3	31.17
Cast iron	200–400	224.0	240.00

The lifetime of all storage options is assumed to be 30 y (Mitali et al., 2022). This work assumes a storage period of 24 h and a ΔT_{min} of 10 °C (Möhren et al., 2022). The hot utility cost is taken to be $100/kWy, and the cold utility cost is $10/kWy (Ziyatdinov et al., 2020). Table 2 summarises the data of the hot and cold streams involved in both plants. This work focuses on steady-state conditions to investigate the potential of excess heat to be stored and used by another plant.

Table 2: Stream data of mixed plastic waste treatment plant and steel mill (H: hot stream; C: cold stream).

Plants	Streams	Supply temperature (°C)	Target temperature (°C)	Heat capacity flowrate (kW/°C)
Mixed plastic waste treatment plant	H1	670	594	23.098
	H2	594	90	19.391
	H3	90	25	17.261
	H4	43	23	5.076
	H5	50	–15	3.940
	H6	–18	–37	2.598
	H7	–37	–98	0.123
	H8	50	–31	0.512
	H9	–34	–37	0.347
	H10	233	170	7.181
	H11	232	90	8.289
	H12	100	37	0.00162
	C1	–126	12	0.163
	C2	22	170	3.180
Steel mill	H1	700	20	0.334
	H2	1,100	20	0.636
	H3	1,100	20	0.021
	H4	250	20	0.523
	H5	700	20	1.333
	H6	350	20	1.036
	H7	180	20	1.726
	H8	250	20	0.239
	H9	1,500	20	0.296
	H10	1,700	20	0.117
	H11	1,700	20	0.034
	H12	1,700	1,200	0.608
	H13	1,200	700	0.608
	H14	700	20	0.676
	H15	900	20	0.590
	C1	20	1,100	0.693
	C2	60	1,100	0.081
	C3	20	1,100	0.462
	C4	20	1,300	0.109
	C5	20	1,300	0.898
	C6	20	1,300	0.869
	C7	20	1,200	0.53
	C8	20	1,200	0.132
	C9	20	1,200	1.238
	C10	20	1,180	1.717
	C11	1,500	1,700	0.952
	C12	20	1,700	0.055
	C13	20	1,700	0.106
	C14	700	1,200	0.59
	C15	20	1,200	0.792
	C16	20	1,200	0.058

5. Results and Discussion

Figure 1(a) depicts the energy required for different scenarios of heat integration. The results showed that the direct heat integration between two plants can achieve a minimal energy consumption of 15.99 MW. On the other hand, intraplant heat integration leads to 20.1 % higher energy consumption (i.e., 19.21 MW). As heat recovery is confined to the process streams within a single plant, the mixed plastic waste treatment plant requires 14.24 MW of energy, and the steel mill requires 4.96 MW of energy. Although direct heat integration provides the lowest energy consumption, it may not necessarily be suitable for actual implementation due to the practical issues in process retrofit, safety, flexibility and space. In addition, the mixed plastic waste treatment plant has excess heat that may be stored and used to fulfil the heating requirement of the steel mill. This highlights the significance of considering TES for indirect heat integration to improve heat recovery. This work also explores the effectiveness of integrating various storage options for the presented case study. Figure 1(b) illustrates the charging and discharging of the storage options and energy cost required for implementing the TES-supported heat integration. For all storage options considered, the surplus heat from the mixed plastic waste treatment can be stored and transferred to the steel mill. It can be observed that all stored heat is fully consumed in the steel mill to reduce the energy cost. While the integration of TES incurs additional storage cost, it contributes to energy savings, accounting for 4.4 % to 12.7 % lower than that of intraplant heat integration (see Figure 1(a)). This results in overall TAC reduction of between 4.9 % and 20.7 % compared to the intraplant heat integration (i.e., 632 k$/y). Based on the comparisons in Figure 1(b), nitrate salt offers superior performance in energy and cost savings, given its cost effectiveness and high energy density (see Table 2). This increases the amount of heat stored in the nitrate salt during charging and the heat available to be transferred to the steel mill during discharging. Consequently, the steel mill relies 25 % less on the external hot utility than on the intraplant direct heat integration, resulting in the lowest utility cost. By storing the excess heat, the cold utility needed by the mixed plastic waste treatment plant can also be reduced by 8.6 %. Despite having the second-largest storage volume, the storage cost of integrating nitrate salt is still the lowest (80.8 % and 77.0 % lower than that of using cast iron and synthetic oil) due to its lowest cost per unit volume (see Figure 1(c)).

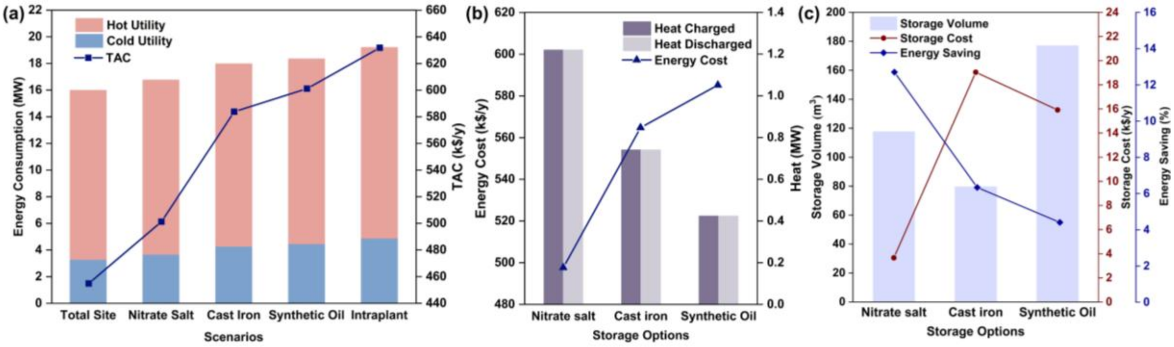

Figure 1: (a) Energy consumption and TAC of different heat integration scenarios; (b) Heat stored, heat discharged, and energy cost of integrating storage options; (c) Volume and cost of storage options integrated.

Apart from that, the operating temperature ranges of the storage facilities affect the selection. A higher maximum operating temperature of nitrate salt allows it to supply heat at higher temperature to the steel mill with target temperatures of cold streams ranging between 1,100 °C and 1,700 °C. Thus, it is more suitable for the illustrated case study, as the cold streams can be heated from 20 °C up to 555 °C given a ΔT_{min} of 10 °C. Contrarily, synthetic oil and cast iron can only heat the cold streams up to 340 °C and 390 °C. This restricts the amount of heat that can be stored and transferred to the steel mill and increases the reliance on external energy (i.e., higher utility requirement). Another key observation is that the cold utility requirement of the steel mill with integrated storage facilities is identical to the intraplant heat integration (i.e., 75.61 kW) except for the case where cast iron is used as the storage medium. This is because the heating requirement of the steel mill within the feasible operating range of cast iron (i.e., 200 °C – 400 °C) is only 608.81 kW. To return the temperature of storage to its initial temperature state for continuous periodic operation, this additional heat has to be removed by the cold utility. Hence, the cast iron is less suitable for the illustrated case study. Since the objective of this work is to minimise the TAC (i.e., energy cost and storage cost), nitrate salt is selected as the most optimal storage option to be integrated.

6. Conclusion

This work proposed an optimisation model to integrate the TES and select the optimal storage option for the indirect heat integration between plants. Among the three sensible heat storage options considered, nitrate salt is determined to be the most optimal option to be integrated for the illustrated case study. It contributes to the greatest energy and cost savings of 12.7 % and 20.7 %, compared to the indirect heat integration. The TAC required is merely 4.9 % higher than the direct heat integration case, highlighting the potential of integrating TES as a trade-off solution that can offer plausible energy recovery potential between the participating plants while addressing practicability issues associated with direct heat integration. Future work can extend the developed model to integrate TES under multi-period operations (e.g., with varied flowrate and supply temperature). Other cost factors (e.g., infrastructure development cost) and design aspects (e.g., efficiency, heat dissipation loss) can be incorporated to better reflect the actual situations.

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