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Economical heat recovery dynamic control and business model for supermarket refrigeration system coupled with district heating system

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Abstract

Large amounts of waste heat during the cooling process of supermarket refrigeration systems (SRS) would be released. A heat recovery strategy potentially contributes to reducing the supermarket’s heating costs related to buying heat from a district heating system (DHS). This paper explores the techno-economic feasibility of heat recovery for a real SRS integrated with a heat recovery unit (HRU) in terms of designing a dynamic heat recovery control (HRC) and business models. A cost-effective HRC is firstly developed for HRU to optimally manipulate the amount of heat recovered, thereby minimizing the real-time heat recovery cost. Furthermore, the business models of heat recovery under a long-term operation are proposed based on two transactional strategies between the SRS and DHS. A field test of the dynamic heat recovery for a remote SRS in Copenhagen Nordhavn area is conducted which demonstrates the proposed HRC algorithm can have a benefit of 0.49€ from a 3-h heat recovery operation. Moreover, the one-year operation of the SRS is also simulated which proves the developed two business models of heat recovery can achieve significant savings of 93% and 41% in energy costs.

1. Introduction

1.1. Background and motivation

As an increasing candidate for the refrigerant of supermarkets due to the better refrigerating performance and the natural substance of CO₂ [1], the CO₂-booster system has been increasingly installed in supermarkets as its refrigerant over the last decades. Furthermore, it also exhibits an attractive heat recovery capability in terms of a large amount of heat production and excellent recycling condition of high operating pressures [2]. The CO₂-booster based SRS becomes a promising heat prosumer that can provide additional heat for supermarkets while cooling [3,4]. Therefore, many researchers have focused on exploring the heat recovery possibility of supermarket refrigeration systems (SRS) by recycling the waste heat from the cooling process, in order to supply the heat demands of supermarkets. Some studies examine the heat supplying performance for supermarkets integrated with CO₂-booster systems, based on field measurements of supermarkets [5–7] and develop validated assessment models [8]. Besides, a techno-economic analysis of the heat recovery from SRS integrated with various heating devices and thermal storages is presented in [9], which indicates the potentially cost-competitive configuration for heat supply in a supermarket.

1.2. Literature review

Heat recovery control (HRC) strategies of SRS play a critical role to satisfy instantaneous heating and cooling demands of supermarkets, and have been increasingly investigated. The proposed HRC strategy in [10] aims at maximizing the coefficient of performance (COP) of the CO₂ refrigeration system when recovering heat which is used to provide a selected supermarket with DHW and space heating, but fewer details of HRC controller are presented. In [11], the authors present a continuous HRC for the CO₂ refrigeration system by modifying condensing pressure and gas cooler capacity to respond the variation of SRS’s heat requirements. This method saves 13% primary energy compared to using a boiler as the heat supply for supermarkets, but without reference to economic benefits from the heat recovery. In [12], five HRC strategies are evaluated for CO₂-booster based SRS by comparing their energy consumption and operation cost. These strategies are implemented via altering the mass flow and pressure level in the condenser, but without considering economic benefits from the heat recovery.
aspects for instance responding to the energy price variation, thereby hardly achieving economic heat recovery behaviors. Similarly, the authors in [13] compare several HRC strategies from the perspective of annual heat recovery and cost reduction of the annual energy usage. Nevertheless, the control process of these strategies also only focuses on adjusting refrigerant pressure in the gas cooler and condenser, without responding any economic incentive. Moreover, in order to avoid inefficient utilization of the recovered heat during the low heat demands period, a few works integrate a thermal storage system into the SRS in [2,7,14], which can effectively store the excess heat under low heat demand of supermarket. Some studies explore a combination of a geothermal storage system and a SRS, which enhances the efficiency of the CO₂ cooling system via their complementary characteristics [15], meanwhile providing a larger heating capacity and more flexibility to heat supply [16].

The available heat recovered from SRS could also play a role in distributed heat sources for the district heating system (DHS), based on a heat energy transaction. The authors study the potential of SRS integrated with a geothermal storage system on reducing the carbon footprint of a local DHS by considering the SRS’s heat recovery in [16], via evaluating techno-economic performance and environmental impact. Besides, the recovered heat from SRSs is proved to facilitate the decentralized production of DHS, thereby contributing to accelerating the decarbonization of DHS [17]. Several feasible scenarios of the SRS’s heat recovery are designed in [18,19] where they are operated as a heat source to supply DHS, and their economic performances are also evaluated. In [20], the author develops a heat supply solution for DHS by recovering heat from supermarkets aggregated with data centers, based on a practical case study in Norway. The results prove that the heat recovered can reduce the heat loss of DHS. A comprehensive techno-economic analysis of heat recovery from CO₂-booster based SRS coupled with DHS is performed in [21]. Moreover, the SRS can act as an excellent flexibility source by controlling its heat recovery to provide ancillary services for electricity networks like frequency balancing [22], and for DHS like demand-side management [23]. For instance, the author investigates a demand-side management method for space heating and cooling in a supermarket integrated with a water loop heat pump system, effectively achieving annual electricity cost savings of 4.67% [24].

1.3. Main contributions

Overall, available control strategies can effectively satisfy the instantaneous heating and cooling demand of the supermarkets by utilizing waste heat from refrigerating process, thereby reducing the gross energy consumption of supermarkets. However, there are still some limitations in current research. The first is that the current dynamic heat recovery control strategies mainly focus on presenting control principles for achieving SRS’s heat recovery via optimizing overall system efficiency [10], and comparing the impact of different control strategies on energy usage [11] and operation cost [12,13]. However, the heat recovery control process does not consider any economic incentive for instance responding to the real-time energy price. Therefore, they do not give a reference on prompting the SRS’s heat recovery in a cost-effective way considering real-time energy cost, and validating it by experiments or field tests. Furthermore, the business models of the heat recovery for SRS are hardly presented, which still need to be developed in order to evaluate their economic feasibility for SRS having a heat energy transaction between and DHS.

To overcome the abovementioned limitations, this paper presents a comprehensive study of the techno-economic feasibility of the heat recovery for a real SRS located in the Copenhagen Nordhavn area [25]. The main contributions of this paper are listed as follows:

1. Designing a cost-effective HRC for a heat recovery unit (HRU) integrated into a real SRS, based on minimizing the real-time heat recovery cost. This control algorithm prompts a maximum profit-driven heat recovery behavior of SRS, following with consideration of dynamic energy price.

2. Developing two business models of the heat recovery for SRS during a long-term operation, respectively by utilizing two transactional strategies with DHS.

3. Both a field test of SRS within the timeframe of real-time operation and simulations of one-year operation are conducted to validate the techno-economic feasibility of the proposed dynamic control algorithm and business models.
In this section, the dynamic heat recovery control for a remote SRS is investigated within a timeframe for real-time operation. Particularly, a cost-effective heat recovery control strategy is developed for the HRU device by optimally manipulating the temperature of the recovered heat to minimize the energy cost.

3.1. Design and implementation procedure

The detailed operational principle can be presented as follows based on our previous research [26]:

(1) Firstly, based on the measured data by sensors, the amount of recovered heat at time \( t \) can be obtained by

\[
QHR(t) = \rho C_p \Delta T(t) (T_{HRU}^t(t) - T_{HRU}^t(t)) = f(T_{set}, T_{amb}, T_{HRU})
\]

(1)

The calculated \( QHR \) and other measured data will be input to a heat recovery calculation module to obtain the gradients of consumed electrical power \((dPHR)\) and of the heat production \((dQHR)\) related to a unit change of \( V_{HRU} \), as well as the used electrical power \((PHR)\) for HRU controller. The mathematical model of the heat recovery calculation module can be expressed by

\[
(dQHR(t), dPHR(t), PHR(t)) = f(T_{set}, T_{HRU}, T_{HRU}, QHR(t))
\]

(2)

(2) Then, considering the electricity and heating price at time \( t \), the total energy cost during heat recovery process is

\[
\text{Cost} = \sum_{t=1}^{t=nt} (\text{Price}_{e} (t) \cdot \text{PHR}(t) - \text{Price}_{heating}(t) \cdot \text{QHR}(t))
\]

(3)

Moreover, considering the calculated gradients of consumed electrical power and heat production, the gradient of heat recovery cost \((C_{gra})\) related to \( QHR \) can be derived from Eq. (3) as follows

\[
C_{gra}(t) = \frac{\text{Price}_{e}(t) \cdot dPHR(t)}{dQHR(t)} - \text{Price}_{heating}(t)
\]

(4)

Accordingly, an additional temperature bias \( \Delta T \) will be produced, hence the ideal temperature set-point reference \((T_{set})\) of the water tank \( T_2 \) can be obtained, as expressed by

\[
\Delta T = \begin{cases} 
1 \degree C, & \text{if } C_{gra} < 0 \\
0 \degree C, & \text{if } C_{gra} = 0 \\
-1 \degree C, & \text{if } C_{gra} > 0 
\end{cases}
\]

(5)

\[
T_{set} = T_{set} - \Delta T
\]

(6)

(3) Finally, the new \( T_{set} \) will be delivered to the HRU controller (ECL 310 [28]) to produce the necessary voltage \( V_{HRU} \) thereby generating new data measured by sensors.

Therefore, the proposed HRC strategy is implemented by executing an optimization algorithm indicated from Eq. (1) to Eq. (6) running on a personal computer (PC) as a master control computer with MATLAB 2020a. The implementing procedure is illustrated in Fig. 2 in detail.

3.2. Setup of data communication

After each executing this algorithm shown in Fig. 2, a new temperature setpoint command is obtained, which must be sent to a local controller of the remote HRU-based SRS in Copenhagen Nordhavn area. Besides, the real-time operating data of SRS also need to be collected and input for the algorithm. Thus, a data flow network is necessary for delivering the relevant control command and measured data.

Fig. 3 shows the overview of data and information flow from the master control computer to the remotely local devices (HRU and SRS). The PC can access the logged data from the data management system (DMS) at the Technical University of Denmark (DTU). The DMS has no “write” access to the Danfoss controllers in order to ensure a separation of responsibility and security,
and is hence only used as a data logging system. The Danfoss controller can however be offset via the Danfoss cloud, hence the PC can send offset commands to the Danfoss cloud that then the Danfoss local controller can execute offset operations.

Through the data flow network in Fig. 3, the PC can have access to the needed input data of the proposed HRC algorithm from the DMS cloud, including the real-time operation data of HRU-based SRS, dynamic electricity and heating price. Then, the control command after executing the algorithm will be sent to the Danfoss cloud from which the local controller of the remote HRU-based SRS can receive the required control signal. Then, the new operation data of HRU will be produced and used for the next regulating event.

### 4. Business models of heat recovery

In this section, the business models of heat recovery are designed for exploring the feasible heat transaction between the SRS and DHS during a long-term operation. Two transactional strategies (TS) with DHS are presented in order to build two different business models.

Fig. 4(a) shows the heat energy flow between the SRS and DHS when adopting a transactional strategy I (TS-I). The basic idea is to use the own heat energy directly from the heat recovery of HRU for supplying the heat demand of SRS, and sell what is leftover to DHS otherwise buying the required heat for the remaining heat demands from DHS. The difference between the heat consumption of SRS and total recovered heat will determine the transactional mode during a considered interval (i.e. one month), which is either the selling heat or buying heat. The main reason for considering the monthly time horizon is that the considered heat transaction between the DHS operator and the supermarket in this paper is based on an ongoing bilateral deal framework in which a monthly heating price provided by the DHS operator is used for procuring the recovered heat from SRS. In addition, an index \( \Delta \) expressed by (7) is developed to denote the degree of self-sufficiency of the heat energy in the SRS, and enables either the buying mode or selling mode. If the \( \Delta \) is equal to the self-usage of heat for SRS, which means the heat demands are lower than the recovered heat, the transactional mode is the selling heat and SRS will have available heat to sell. Conversely, the SRS will perform a buying heat mode, when \( \Delta \) equals the total recovered heat, which implies the recovered heat is not enough to meet the heat demands.

\[
\Delta = \min \left\{ Q_{\text{rec}}(t), Q_{\text{self}}(t) \right\} \forall t \in \mathbb{R}
\]

where \( Q_{\text{rec}}(t) \) is the total recovered heat at the interval \( t \); \( Q_{\text{self}}(t) \) is the total self-usage of heat for SRS at the interval \( t \); \( \mathbb{R} \) is the one-year operation duration with the interval of one month.

When using a transactional strategy II (TS-II), according to Fig. 4(b), the basic idea is to sell all recovered heat energy to DHS then buy the needed energy back for heat demands of SRS. Consequently, the transaction between the SRS and DHS is simultaneously going for the buying heat and selling heat modes, instead determined by the \( \Delta \). This strategy is simpler than TS-I, but possibly does not have a good economy due to the higher buying price of heat than the selling price.

### 5. Case study

A field test of the remote SRS in the Nordhavn area on a certain day is firstly implemented in order to verify the proposed real-time cost-effective heat recovery control algorithm. The closed-loop control process integrated with the proposed algorithm in Fig. 2, is implemented through the presented data flow network shown in Fig. 3. In this field test, the total communication and computation latency between producing a new control command and updating the measured real-time data via the data network in Fig. 3, is almost 1–2 min. Accordingly, the time interval between two regulation events is chosen as 5 min, which means the real-time data has been updated according to the previous control commands before the next regulation event. In addition, Table 1 presents the relevant parameters including energy price and the dedicated HRU device. The other two simulation cases are also conducted for comparison. The specific setups of the three cases are described as follows:

1. **Case 1**: No heat recovery;  
2. **Case 2**: Constant temperature control with maximum temperature set-point;  
3. **Case 3**: Field test case integrated with the proposed cost-effective HRC method.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity price</td>
<td>Day-ahead electricity price in Nordpool[29]</td>
</tr>
<tr>
<td>Heating price</td>
<td>170 DKK/MWh</td>
</tr>
<tr>
<td>Technical specifications of HRU</td>
<td>Parameters of type A1 in [27]</td>
</tr>
</tbody>
</table>
Case 2 is a hypothetical case to implement essentially a constant temperature control by keeping the maximum temperature set-point, but utilizing the same input data with Case 3. As a result, the comparisons between Case 2 and Case 3 can clarify the influence of heat recovery control. Besides, Case 1 is used as the baseline to analyze the profit of heat recovery behavior by comparisons.

In addition, the one-year operation of the remote SRS is simulated for evaluating the profits of heat recovery in a long-term operation. During this long-term operation, the monthly heat price provided by the DHS system operator is utilized, which is significantly varying from different seasons (e.g., winter and summer). Such seasonal variability of heat price mainly corresponds to the seasonal variation of heat demands in the Copenhagen area. Hence, the heating prices for months belonging to the same season are almost the same, but quite different from the prices for months in other seasons. The impact of condensing pressure controls on heat recovery performance is also evaluated by conducting three comparative cases below. Furthermore, economic analysis for the presented two heating transactional strategies (TS-I and TS-II) with DHS, are carried out respectively.

(1) Case 4: Ambient temperature controlled pressure;
(2) Case 5: Constant condensing pressure at 75 bar;
(3) Case 6: Constant condensing pressure at 86 bar.

6. Results and discussion

6.1. Performance analysis under the short-term operation

6.1.1. Performance of dynamic heat recovery process

Fig. 5 depicts the heat recovery performances of HRU-based SRS from 14:00 to 17:00 on a certain day. With the proposed method (Case 3), as shown in Fig. 5(a), the cost gradient $C_{\text{gra}}$ is more than zero when the electricity price is relatively high from 14:00 to 16:00, which matches well with the relationship indicated by Eq. (4). During this period, the positive $C_{\text{gra}}$ due to high electricity price means the heat recovery cost will grow with the increasing recycled heat. As a result, according to the cost-minimization principle of heat recovery in the proposed method, as expressed by Eqs. (5) and (6), the current temperature set-point of the water tank will be automatically updated to be a new value lower than the previous one to recycle lower heat. Accordingly, the ideal $T_{\text{set}}$ calculated by the proposed method is gradually decreasing in the step of 1 °C, as shown in the bottom graph of Fig. 5(a). Furthermore, the measured temperature set-point of the remote actual water-tank device will be always following with that calculated value in PC through the data flow network, thereby performing a gradual step decreasing of 1 °C. Conversely, due to the negative $C_{\text{gra}}$ from 16:00 to 17:00 caused by relatively a lower spot price, the calculated $T_{\text{set}}$ starts increasing to recycle more excess heat from SRS, thereby reducing
Two heating recovery strategies can make profits through recycling heat. Case 1 due to no heating recovery process. Conversely, both of the related energy costs for heat recovery are equal to zero in Case 1 due to no heating recovery process. Consequently, both of the strategies make profits through recycling heat.

6.1.2. Cost analysis

Fig. 6 illustrates the results of instantaneous powers in terms of the recycled heat power and corresponding electrical power consumed. It implies that Case 3 integrated with the proposed HRC method will consume a bit more electricity but recover more heat on average than Case 2 in the 3-h short operation. Moreover, the recovered excess heat and its consumed electricity visibly vary with time in Case 3, as the \( T_{set} \) of the water tank is dynamically adjusted due to the proposed HRC method. Nevertheless, the recovered heat will be maintained at 11.36 kW (i.e., average power), but its consumed electrical power is slightly fluctuating in Case 2 due to the time-varying ambient temperature and the inlet temperature to the heat exchanger of SRS according to Eq. (2). It is thus concluded that both the recycled heat and consumed electricity in the proposed HRC method will perform in the fluctuated pattern due to the varying \( T_{set} \) however it contributes to more heat recovered, compared to the constant temperature control strategy.

The heat recovery cost. Similarly, the measured \( T_{set} \) is also increasing by following with increasing calculated \( T_{set} \). Therefore, it concludes that the proposed method can facilitate heat recovery from SRS in a cost-effective manner.

Compared with the proposed method in Case 3, Fig. 5(b) shows that the calculated \( T_{set} \) in Case 2 is always maintained at the maximum \( T_{set} \) of 85 °C where constant temperature control is implemented while extracting the excess heat as much as possible. However, the medium graph of Fig. 5(b) depicts that the \( T_{set} \) in Case 2 is positive from 14:00 to 16:00, which means the heat recovery cost will expand with the increasing recycled excess heat during this period. Consequently, the HRU should reduce the recovered heat by turning down the \( T_{set} \), but this cannot be achieved in case 2 due to using constant temperature control. Thus, the gross energy cost in case 2 will be inevitably increased to a higher level.

6.2. Performance analysis under the long-term operation

6.2.1. Heat recovered under different pressure controls

Fig. 7 depicts the recovered heat each month under the three condensing pressure controls for the compressor of HRU. Overall, the constant condensing pressure control at 86 bar in Case 6 can recover the most heat each month. This is because the higher condensing pressure brings the higher temperature level of the excess heat hence a larger part of excess heat. Besides, more heat recovered is available from June to August than other months regardless of the condensing pressure controls, because the compressors are operating at a relatively larger capacity in the summer time, and even at close maximum capacity during the warmest days.

For a business case utilizing the transactional strategy I (TS-I), the heat energy balance of SRS under different condensing pressure controls are shown in Fig. 8(a). The energy balance patterns are not quite similar among these months, depending on the heat self-consumption of SRS and the quantity of heat recovered. In Case 4 with the temperature controlled pressure controls, for instance, recovered heat (the green bar) selling to DHS is available only from May to August, owing to the low self-usage of heat (the black dotted line) and more heat recovered during these warmer days. Thus, the energy balance is obeying the selling heat pattern, where the remaining recovered heat (green bar) by subtracting the self-usage of heat from total recovered heat is sold to DHS, and the Delta (yellow bar) represents the self-usage of heat for SRS. Nevertheless, the SRE needs to buy heat from DHS (marked by blue bar) in the remaining months, due to the large heat demand of itself and less recovered heat, especially during the winter days from November to January. In this case, the Delta denotes the quantity of the total recovered heat, and the heat balance is following the buying heat pattern in which the self-usage of heat equals the sum of the total recovered heat and buying heat from DHS. In addition, the other two cases with constant pressure control also perform the two different heat balance patterns mentioned, but the energy balance is performing the selling-heat pattern in more months. For example, the SRS in Case 6 has available heat to sell in most of the months except in December and January, thus selling more heat to DHS during the one-year operation.

**Table 2**

<table>
<thead>
<tr>
<th>Energy Cost (€)</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity cost for heat recovery</td>
<td>0</td>
<td>0.28</td>
<td>0.29</td>
</tr>
<tr>
<td>Revenue of recycled heat</td>
<td>0</td>
<td>0.75</td>
<td>0.78</td>
</tr>
<tr>
<td>Total cost of heat recovery</td>
<td>0</td>
<td>-0.47</td>
<td>-0.49</td>
</tr>
</tbody>
</table>

**Fig. 6.** Energy consumption and production: (a) consumed electricity; (b) recovered heat.

**Fig. 7.** Heat recovered under different condensing pressure controls.
However, the energy balance pattern is not quite similar in a business case utilizing the transactional strategy II (TS-II), although the self-usage of heat in the SRS is the same as that in TS-I, as shown in Fig. 8(b). It indicates that the selling and buying of the recovered heat are simultaneously going on each month irrelevant to condensing pressure controls. Besides, the buying heat is equal to the self-usage of heat, while the available heat to sell equals the total recovered heat. This is because all of the recovered heat is firstly sold to DHS then buying required heat from DHS to satisfy the heat consumption of SRS, when utilizing the TS-II. Hence, the energy balance has only one pattern of simultaneous selling and buying heat, and in which the Delta is non-exist. Note that in the TS-II, the higher condensing pressure control still tend to produce more available recovered heat to sell.

6.2.2. Economic analysis of different heat transactional strategies

To evaluate the economy of heat recovery in business cases integrated with different transactional strategies with DHS, the comprehensive energy cost under two business models respectively corresponding to the TS-I and TS-II are analyzed, as summarized in Tables 3 and 4.

Table 3 gives the detailed energy cost related to heating during one-year operation, under the three condensing pressure controls in the business model with TS-I. It reveals that the three cases with different pressure controls have the same total cost of 27.53 k€ for meeting the heat consumption of SRS due to the same heat demands of SRS, when ignoring the waste heat recovery. In the scenario of heat recovery, however, the total costs are visibly different under the three cases. In the light of more available heat to sell in Case 6 with the constant pressure controls at 86 bar, it leads to more revenue from selling heat and lower cost from buying heat compared to the other two cases. In the two constant pressure controls, higher pressure of 86 bar is required in Case 6 than 75 bar in Case 5, thus increasing the compressor cost mainly regarding electricity usage and relevant electricity tax. Note that without constant pressure control in Case 4 accounts for the zero electricity cost for keeping the constant pressure. Overall, Case 6 contributes to a sharp cost reduction for heating due to the lower cost of buying heat and higher revenue of selling heat although it brings a higher compressor cost. Therefore, it leads to the largest cost savings of 25.64 k€ (i.e. about 93%) compared to the case without heat recovery.

In the business model with TS-II, the detailed energy cost in Table 4 indicates that the three cases have the same cost of buying heat which equals their total cost without heat recovery (27.53 k€). Because the heat demands of SRS in TS-II are totally supplied by buying heat from DHS, without any usage of the recovered heat. Compared to TS-I, all recovered heat can sell to DHS in TS-II, leading to more revenue from selling heat. For instance in Case 6, the revenue from selling heat in TS-II is increased to 19.76 k€ from 8.22 k€ in TS-I. Case 6 has the largest cost saving of 11.21 k€ (about 41%) compared to the other two cases due to utilizing higher condensing pressure. However, Case 5 using the constant pressure of 75 bar is lower than Case 4, because the increased revenue from heat recovered caused by the increased condensing pressure is lower than the growing compressor cost.
The comparisons between the two business models of heat recovery reveal that the TS-I can contribute to a lower overall cost of heating for the SRS than TS-II regardless of condensing pressure controls. Moreover, increasing the condensing pressure for compressor can effectively reduce the total heating cost when utilizing the TS-I, however, which can be ensured in TS-II only when the condensing pressure is increased to a large level.

7. Conclusion

This paper investigates the techno-economic feasibility of economical heat recovery for a SRS integrated with HRU, by developing a cost-effective heat recovery control and business models. Field test and simulation results have revealed that:

1. The cost-effective heat recovery control can dynamically adjust the amount of recoverable heat following with dynamic energy price, hence driving the real-time heat recovery of HRU operating under the condition of a lower recovery cost.

2. The developed two business models of heat recovery based on TS-I and TS-II, can respectively achieve significant savings in energy costs of 93% and 41%, compared to the case without heat recovery.

3. The business model based on TS-I that sells the remaining recovered heat to DHS after supplying the heat demands of SRS, has a better economic benefit than the business models with the TS-II that directly sells all recovered heat to DHS. Moreover, such an economic benefit can always be increased by using higher condensing pressure.

In addition, this paper does not much involve enabling SRS’s flexible demand response to some specific ancillary services requirements. In the next stage, therefore, the presented heat recovery setup of SRS can be further extended to explore its demand-side flexibility management for both the electric grid and DHS integrated with SRS.

CRediT authorship contribution statement

Chunjun Huang: Methodology, Investigation, Software, Validation, Writing – original draft. Yi Zong: Methodology, Resources, Supervision, Writing – review & editing. Shi You: Supervision, Writing – review & editing. Christen Throhl: Supervision, Writing acquisition, Writing – review & editing. Jan Eric Thorsen: Investigation, Funding acquisition, Writing – review & editing. Lars Finn Sloth Larsen: Investigation, Project administration, Writing – review & editing.

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.

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