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Optimization of a distributed energy system with multiple waste heat sources and heat storage of different temperatures based on the energy quality

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HIGHLIGHTS

- Optimization model with energy quality distinction is developed.
- The optimized results are feasible and convenient to employ in practice.
- The model can deal with multiple heat sources of different temperatures.
- The model can distinguish energy quality of heat storage.

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ABSTRACT

Distributed energy systems (DESs) have garnered significant attention because of their flexibility and high efficiency. Owing to the diversity of user demand and the complex composition of the DES, the optimization of operation and planning for the entire system is complex. A mixed integer linear programming (MILP) model can be used to solve the optimization problem effectively. Different nonlinear factors should be considered and linearized in the model such that it is more accurate and practical for application. It is important to match waste heat recovery technologies (WHRTs) with various heat sources of different temperatures based on energy quality, which can improve efficiency of the entire system. Consequently, a new method is proposed herein to match multiple heat sources with various WHRTs and heat storage of different temperatures in the MILP optimization model. The optimization model can select the most suitable WHRTs, including their capacity for the DES, according to energy quality and user demand. Additionally, a one-year operating schedule of all the technologies can be optimized. The practicability of the method in real applications is validated by the dynamic simulation of waste heat distribution to different WHRTs. Hence, two cases are studied. One case indicates that the model can match the WHRTs with multiple heat sources of different temperatures with a short time needed to solve the optimization (22 s with a gap of 0.001%). The other case proves that the model can distinguish the energy qualities of low- and high-temperature heat storage, and that a 1189 kWh output cooling during a typical day is increased by high-temperature heat storage.

1. Introduction

The pressure to reduce the use of carbon-based fuels for energy production has motivated engineers to improve the efficiency of energy systems. Distributed energy systems (DES), which are located near the end user, have garnered significant attention [1] because they can avoid energy transmission losses and enable the flexible use of many types of advanced energy generation technologies [2]. Furthermore, they can fully utilize waste heat of different energy qualities by a variety of waste heat recovery technologies (WHRTs) [3], thereby increasing the efficiency of the entire system [4]. Owing to the diversity of user demand and complex composition of the DES, which incorporates technologies such as internal combustion engines (ICEs), gas turbines, solar photovoltaics (PV), wind turbines, energy storage, microgrids, and different types of WHRTs, the optimization of planning and operation of the DES is complex and critical [5–6]. The suitable

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Nomenclature

C	Cost (dollar)
CP	Capacity (kW)
D	Demand (kW)
H	Heating (kW)
P	Electrical power (kW)
Q	Absorption heat (kW)
QC	Cooling (kW)
Qht	Heat from heat tank (kW)
Z	Binary variable for energy quality
η	Efficiency
X	Binary variable for energy installation

Subscript

con	Condensing
d	Day
exh	Exhaust
ele	Electricity
hs	Heat source
h	Hour
ind	Industry
Inv	Investment
jw	Jacket water
m	Month
Mtn	Maintain
op	Operation
pur	Purchase
sto	Store
sal	Sale
tech	Technology

Abbreviation

ARS	Absorption refrigeration system
COP	Coefficient of performance
DES	Distributed energy system
DARS	Double-effect absorption refrigeration
DH	Direct heating
EC	Electrical chiller
EB	Electrical boiler
HT	High temperature
HP	Heat pump
JW	Jacket water
LT	Low temperature
ORC	Organic Rankine cycle
PM	Prime mover
RC	Rankine cycle
VCHP	Vapor compression heat pump
WHRT	Waste heat recovery technology

selection and operation of these technologies are crucial for improving the energy efficiency of the entire system. Therefore, it has been an area of recent research focus [1–6].

The DES is highly nonlinear because of its complexity, as mentioned above. To reduce the computation task for nonlinear problems, many researchers have focused on converting the problem into approximated mixed integer linear programming (MILP) [7–12]. The results by Ommen et al. [7] indicated that using the linearization method to approximate a nonlinear model, MILP was the most appropriate from the viewpoint of accuracy and run time among linear programming, nonlinear programming, and MILP methods. To render the MILP model more accurate and practical for applications, different factors must be considered, such as off-design efficiency, start–stop, and natural gas networks. Additionally, the model of these factors must be linearized. For example, Alvarado et al. [9] divided the load of technologies into several levels such that the part-load efficiency was discrete in several values. Using this method, the part-load performance can be included in the MILP model. Misaghian et al. [10] used a quadratic equation to represent the cost of start–stop in their trilevel optimization MILP model, and the piecewise linear form of a quadratic equation was adopted. Li et al. [11] integrated a natural gas system model with security constraints into the MILP optimization model. To linearize the natural gas pipeline flow constraints, they derived the gas shift factor matrix for natural gas networks to quantify the effects of supply and demand at each node on the gas flow path.

In addition to the factors mentioned above, the WHRT is a vital part of the DES, and it is critical to match waste heat sources of different energy qualities with suitable WHRTs in the MILP model. Typically, different types of waste heat with different energy qualities are characterized by their temperatures. For example, the waste heat temperature of exhaust and jacket water from ICEs, which are widely applied in DES as the prime mover [13], is approximately 400–700 °C and 70–90 °C, respectively [14]. Waste heat from industry has a large temperature range from less than 100 °C to more than 300 °C [15]. The waste condensing heat of a power plant is approximately 30 °C [16]. It has been proven that by the appropriate matching of WHRTs with waste heat energy quality, the operation cost of the DES can be reduced significantly compared with using traditional central energy systems [17–19], otherwise the cost may be more expensive.

Wu et al. [20] proposed the concept of energy cascade utilization according to energy quality and described it in detail based on the basic law of energy transformation. The authors concluded with the famous principle of “temperature matching and cascade utilization.” Based on this principle, many studies have been performed that matched WHRTs with energy quality. For example, Sui et al. [21] proposed a combined system to recover the exhaust heat of ICEs for simultaneously producing power and cooling because of its high temperature (HT), while low-temperature (LT) jacket water heat was recovered by an absorption heat transformer system to produce low-pressure steam. Yang et al. [22] proposed a novel highly efficient double-effect absorption refrigeration system to recover ICE waste heat. The ICE jacket water and exhaust were the heat sources of a low-pressure and high-pressure generator, respectively. Han et al. [23] developed a novel DES combining the Kalina cycle with energy storage for recovering low-temperature heat.

However, most of the above-mentioned studies focused only on proposing new energy systems that could match the energy quality to improve the efficiency. Only a few studies have considered the waste heat energy quality in the MILP optimization model to decide the most suitable WHRTs and their operation schedule. Gao et al. [24] developed a method of energy matching and optimization for the DES operation. However, it was for a specific DES and provided an optimal operation zone according to energy levels only for the given system, instead of a detailed operation schedule. Li et al. [25] proposed a novel DES considering the energy quality of waste heat, and optimized the design and operation of the system. A heat pump was used to recover the low-temperature condensing heat from the absorption chiller that recovered the high-temperature exhaust heat. However, it also was designed for a specific DES. In [26], a MILP model of cascade energy optimization for the DES based on energy quality was developed. A case study indicated that the energy cost could be reduced by 5% compared with the traditional optimization model. However, the model and linearization method are complex, and it typically requires several hours of calculation time to obtain a solution. Therefore, it is not possible to add more heat sources of different temperatures or to distinguish between HT and LT heat storage. Additionally, it is difficult to control the amount of utilized heat by each WHRT according to the optimal results in practice. These will be described later in detail.

In this study, a new method to match multiple heat sources of different energy qualities with various WHRTs and LT and HT heat storage is proposed in the MILP optimization model for DES planning and operation. Compared to the former researches, the contribution of this work is that the model can deal with multiple heat sources and heat storage according to energy qualities in a short computation time, and the optimization results can be applied conveniently in practice. The remainder of the paper is organized as follows. Section 2 discusses the principle of waste heat utilization based on energy quality and the method of distributing waste heat to different WHRTs. Section 3 describes the MILP mathematical model of the optimization problem. Section 4 demonstrates the results of two case studies to test the functions of the model. Finally, conclusions are presented in Section 5.

2. Waste heat utilization according to energy quality

As mentioned earlier, waste heat recovery is a critical aspect of the DES. To improve the efficiency of the entire DES, each WHRT should match the energy quality. Fig. 1 illustrates an energy flow tower that displays the energy quality levels of various waste heat sources and the corresponding matched technologies. The energy efficiency for each technology is cited from [26]. The technologies in the figure, ranked from high-quality to low-quality energy levels, are the Rankine cycle (RC), organic Rankine cycle (ORC), single-effect and double-effect absorption refrigeration system (ARS and DARS), first- and second-type absorption heat pumps (1AHP/2AHP), vapor compression heat pump (VCHP), and direct heating (DH). There are numerous ORC working fluids, and some of them are suitable for HT heat source, while others are suitable for LT heat source. Therefore, ORCs are classified as LTORC for LT heat source and HTORC for HT heat source with higher efficiency. The heat storage tanks are divided into HT and LT tanks to distinguish the energy quality. The HT tank is used for storing HT heat to drive technologies requiring high-quality energy that exhibit high efficiencies, such as the RC and HTORC. By contrast, an LT heat tank is used for LT heat and low-quality energy technologies. According to the second law of thermodynamics, an HT heat source can drive low-quality energy WHRTs with exergy loss if required, but not vice versa. For example, the HT exhaust heat from ICEs or gas turbines can drive the RC, HTORC, DARS, ARS, and DH, while the LT jacket water can only drive technologies at low-quality energy levels, such as DH and ARS. However, if HT heat is used to drive low-quality energy technologies, the energy quality loss will be high, resulting in a decrease in the energy efficiency of the entire DES. For example, the high-temperature exhaust can drive the DARS with a coefficient of performance (COP) of ~ 1.2, while if it drives the ARS, the COP is only ~ 0.7. Therefore, it is critical to consider the energy quality. Meanwhile, considering user demand and economic problems such as energy price and the cost of technologies, using energy only according to its equality may not always be optimal. Therefore, the planning and operation of WHRTs must be optimized using various criteria.

In [26], a MILP optimization model with the aim of matching WHRTs based on energy quality was proposed. In that model, to obtain an optimal performance, the waste heat source is utilized by different WHRTs sequentially based on energy quality, especially for heat sources with a large temperature drop during recovery such as ICE exhaust. For example, Fig. 2 (left) depicts the cascade utilization of exhaust heat by serial arrangement of ORC and ARS equipment. However, it is not easy to control the amount of heat utilized by each WHRT in practice according to the optimal results. In other words, it is hard to exactly control the values of T_1', $T_2'\dots T_n'$ shown in Fig. 2, because these temperatures influence each other. In addition, the optimization model is complex because of linear processing, resulting in a long calculation time (usually several hours or more to get the results with a gap of less than 0.1%). Due to the difficulty in obtaining a solution, it is not possible to add additional waste heat sources of different temperatures or HT and LT heat storage in the model. Therefore, in order to make the optimal results more practical for application and able to contain more heat sources of different energy quality, all heat sources should be utilized by different WHRTs in parallel, as shown in Fig. 2 (right).

Because in the series arrangement various technologies may utilize different amounts of heat at different time steps, the outlet temperatures of the heat sources (T_1', $T_2'\dots T_n'$) vary continually. Therefore, it is necessary to ascertain whether every part of the heat source still has a high enough temperature to drive each technology at every time step, which makes the optimization model complex. By contrast, in the parallel arrangement, because every part of the heat input has the same

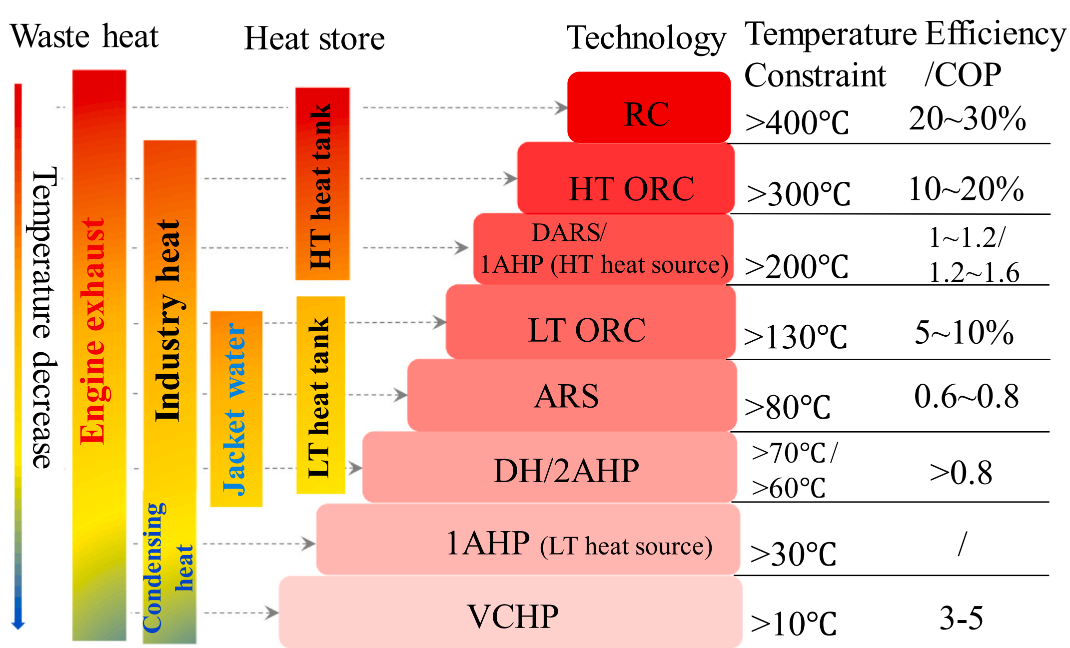

Fig. 1. Temperatures of typical waste heat sources and the matched recovery technologies.

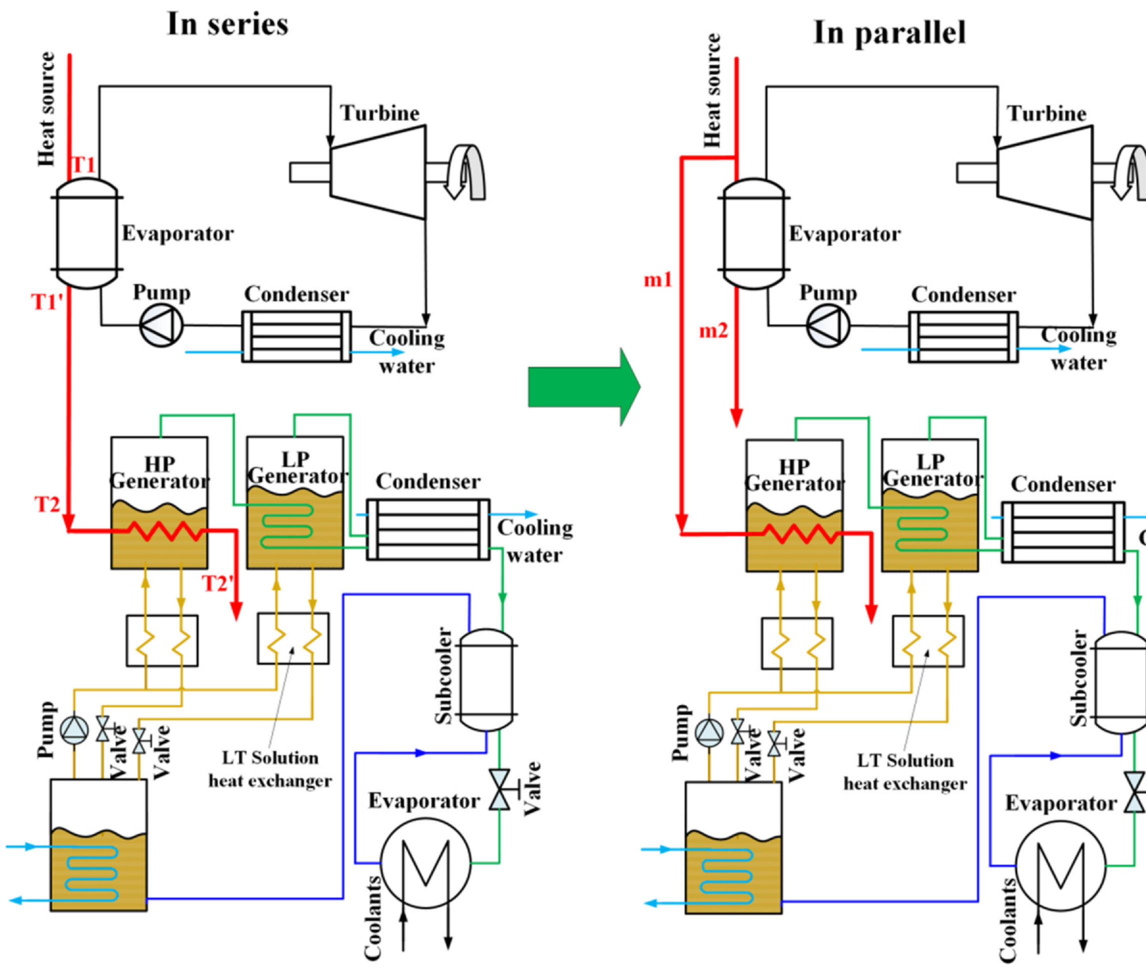

Fig. 2. Utilization of waste heat in series and parallel.

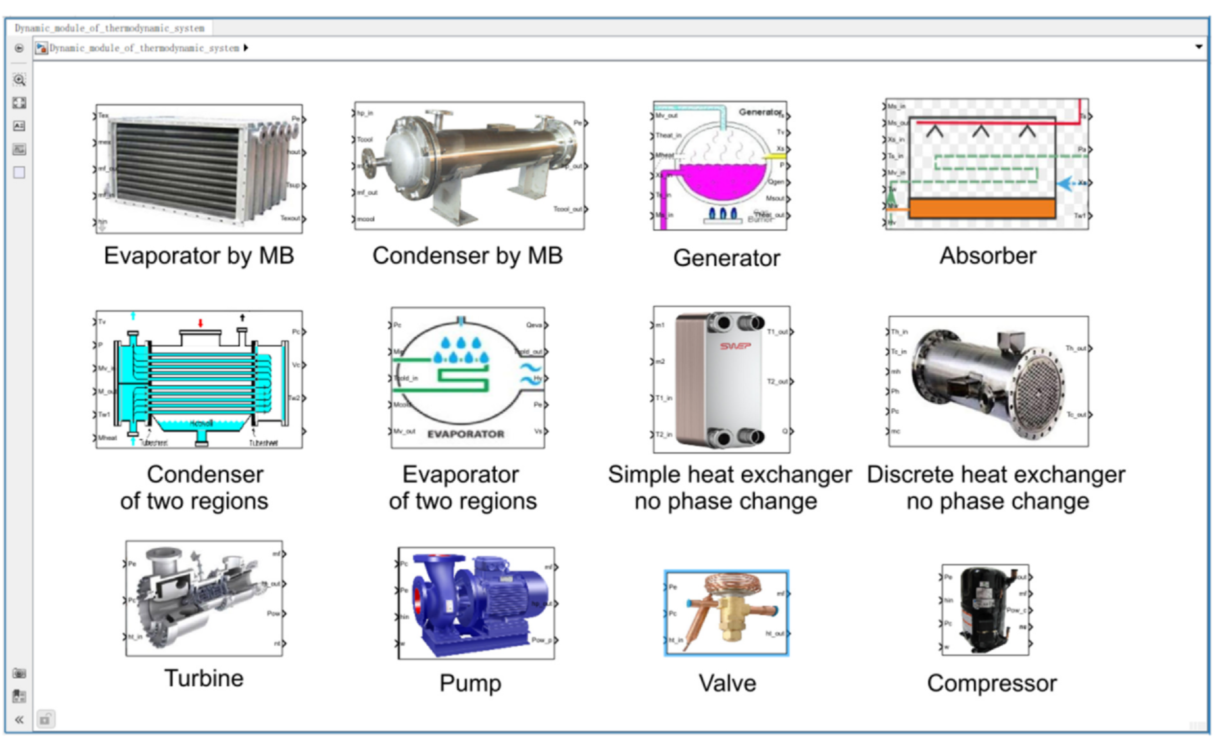

Fig. 3. Module library of common components in thermodynamic systems [27]

temperature, it is not necessary to check the input temperature at every time interval. The candidate technologies only need to be filtered once according to the temperature limit at the beginning of optimization. The detailed model will be introduced in the below part of the mathematic model. In addition, it is quite convenient to control the absorbed heat of each piece of equipment by adjusting the mass flow rate of the heat source. In order to verify whether the parallel utilization model is feasible in practical application, a simulated model of distributing ICE exhaust heat to different WHRTs is created using our dynamic model library as shown in Fig. 3 [27]. Our dynamic model library is developed by SIMULINK and contains the most common components in thermodynamic systems, such as different kinds of heat exchangers, expanders, pumps and other components. When establishing a dynamic model of certain thermodynamic system, it needs to select the component models from the library and connect them with each other according to their interrelationship. Therefore, it is possible to create dynamic models of different WHRTs.

The dynamic model can calculate the entire varying process of the system state. Fig. 4 shows the change of exhaust outlet temperature when the mass flow is split between HTORC and DARS in different ratios. According to the data shown in this figure, the absorbed heat can be calculated by the enthalpy drop of the exhaust. It can be seen that if the split ratio of the exhaust mass flow is the same as the distribution ratio of waste heat to the different equipment, the actual absorbed heat is different from the desired value, because the outlet temperature of the exhaust varies continuously. For example, in Fig. 4 the exhaust temperature is 532 °C and the final temperature after heat recovery by different technologies under the design conditions is 160 °C. When the HTORC or DARS requires 90% of the exhaust heat, and 90% of the exhaust mass flow is distributed to it, it actually absorbs more than 90% of the heat, because the outlet exhaust temperature is lower than 160 °C. In Table 1, it can be seen that as the mass split ratio decreases, the error between the actual absorbed heat and the desired value becomes increasingly obvious. However, the error value remains small overall, and results in better use of waste heat, so it can be neglected. If the absorbed heat needs to be controlled accurately, the distributed mass flow should be reduced slightly. In contrast, if the exhaust temperature becomes lower than the acid dew point, which may lead to corrosion in the heat exchanger [28], a part of the mass flow can be fed back to the inlet, and the outlet temperature of the exhaust will then rise as shown in Fig. 5. In summary, the parallel utilization model of waste heat is feasible and convenient for controlling the amount of absorbed heat by different technologies in practical applications.

3. Mathematical model

3.1. Optimal problem state

The optimization process for planning and operation of DES involves obtaining the most suitable technologies from many candidates and deciding their capacities and running schedules to satisfy the demands of heating, cooling, and electricity, as shown in Fig. 6. The model in this study involves all the technologies shown in Fig. 6, while it primarily focuses on matching various WHRTs with multiple waste heat sources of different temperatures and distinguishing the energy quality of HT and LT heat storage when optimizing. In addition, the optimal solution can be solved in a short timeframe. The ICE is the most commonly used prime mover in the DES between 1 and 10 MW [29], and is employed in this model. Consequently, waste heat sources comprise ICE exhaust and jacket water. Additionally, the model contains the industry waste heat (~70–80 °C) and condensing heat of a power plant (~30 °C). The optimization problem is formulated as a MILP model and solved using Gurobi. Except the variables of Z_{tech_hs} and X_{tech_hs} are binary, the other variables appeared in this paper are continuous. The operating schedule of the DES for one year in the future is considered, and a one-hour time step is adopted. The load for the entire year is represented by 12 months and two representative days (weekday and weekend) every month, and therefore 576 (12*2*24) time steps are involved. The optimization model is introduced below by the objective function and constraints.

3.2. Objective function

The aim of this optimization model is to minimize the annual operating and maintenance cost of the entire DES, including the overall annualized investment cost as described in equation (1).

$$\min C_{\cos t} = C_{inv} + C_{op} + C_{mtn} + C_{pur}^{grid} + C_{pur}^{heat} - C_{sal}^{grid} \tag{1}$$

where C_{inv}, C_{op}, and C_{mtn} are the investment, operation, and maintenance costs, respectively. In this model, the DES can purchase and sell electricity. The industry waste heat and condensing heat can be purchased at different low prices. Therefore, in Equation (1), $C_{pur}^{grid}$and C_{sal}^{grid} are the purchase cost and sale price for electricity, respectively; $C_{pur}^{heat}$is the purchase cost of industry waste heat and condensing heat. The detailed calculation of every item is conventional in many literatures and has been described in detail in our previous study [30]; therefore, it is omitted here.

3.3. Constraints

1. WHRTs according to energy quality

As shown in Fig. 1, at higher temperatures, higher-efficiency WHRTs can be used. Additionally, every technology has its minimum limit temperature, below which the technology cannot be driven. To avoid an inappropriate selection of technology, the candidate technologies should first be segregated according to the temperature limit. Consequently, the binary variable Z_{tech} is adopted to remove unmatched technologies. Before organizing all the constraints, the value of Z_{tech_hs} for every technology and heat source is first determined by inequation (2). The subscript hs indicates the heat source.

$$\text{If } T_{hs} < T_{tech\_limit},\ Z_{tech\_hs} = 0$$

Subsequently, the capacity is limited by inequation (3), which shows that if Z is 0, then the capacity of the technology for this heat source will also be 0. Using this method, the WHRTs are initially segregated based on energy quality.

$$CP_{tech\_hs} < Z_{tech\_hs} \cdot \max CP_{tech\_hs} \tag{3}$$

2. Energy balance

The load demands of electricity, heating, and cooling must be satisfied by different technologies, including different WHRTs driven by various waste heat sources. Because the energy qualities of electricity

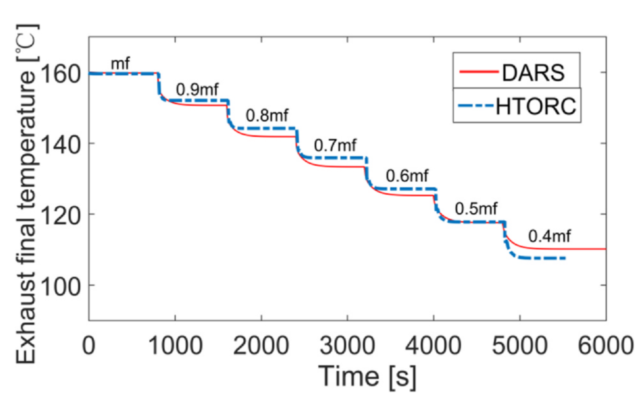

Fig. 4. Temperature of exhaust at the outlet of DARS and HTORC when the exhaust mass flow rate is split.

Table 1
The comparison of objective and actual absorbed heat by DARS and HTORC.

Mass split ratio	Objective /kW	Real (HTORC)/kW	Error	Real (DARS)/kW	Error
1	697	697	0	697	0
0.9	627.3	643.0	0.025	645.1	0.028
0.8	557.6	584.5	0.048	586.2	0.051
0.7	487.9	522.6	0.071	523.7	0.073
0.6	418.2	456.9	0.093	457.3	0.093
0.5	348.5	388.1	0.114	388.0	0.114
0.4	278.8	316.1	0.134	315.4	0.131

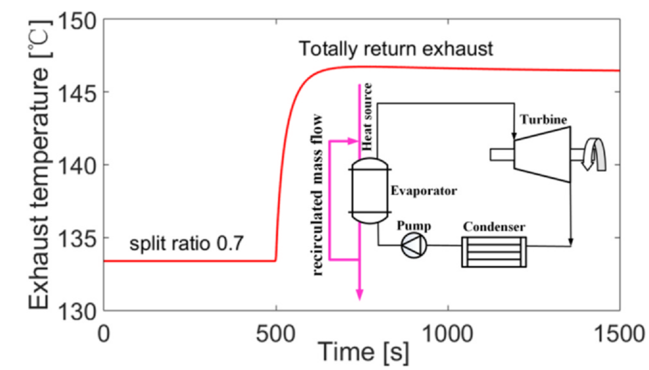

Fig. 5. Effect of recirculated mass flow on the exhaust temperature.

are the same, and those for living cooling loads are similar, their energy balances are separately represented by Equations (4–5).

Electricity balance:

$$D^{ele\_only}_{m,d,h} + P^{grid\_sal}_{m,d,h} + P^{EC}_{m,d,h} + P^{EB}_{m,d,h} + P^{HP}_{m,d,h} + P^{EST\_sto}_{m,d,h} = P^{grid\_pur}_{m,d,h} + P^{PV}_{m,d,h} + \sum^{hs} P^{RC\_hs}_{m,d,h} + \sum^{hs} P^{HTORC\_hs}_{m,d,h} + \sum^{hs} P^{LTORC\_hs}_{m,d,h} + P^{PM}_{m,d,h} + P^{EST\_from}_{m,d,h} \quad (4)$$

Cooling balance:

$$D^{cooling}_{m,d,h} + QC^{CST\_sto}_{m,d,h} = QC^{NGC}_{m,d,h} + QC^{EC}_{m,d,h} + QC^{HP}_{m,d,h} + \sum^{hs} QC^{DARS\_hs}_{m,d,h} + \sum^{hs} QC^{ARS\_hs}_{m,d,h} + QC^{CST\_from}_{m,d,h} \quad (5)$$

Heating for living involves low temperatures, and is expressed as Equation (6):

$$D^{heat}_{m,d,h} + H^{LTHST\_sto}_{m,d,h} = H^{NGB}_{m,d,h} + H^{EB}_{m,d,h} + H^{HP}_{m,d,h} + \sum^{hs} H^{1AHP\_hs}_{m,d,h} + \sum^{hs} H^{DH\_hs}_{m,d,h} + H^{LTHST\_from}_{m,d,h} \quad (6)$$

The heat for driving different WHRTs exhibits different energy qualities, and therefore their energy balance constraints should be separated. Because the industry waste heat and condensing heat of a power plant are purchased according to demand, the heat balance is represented as Equations (7–8). It should be noted that all constraint equations are used for single time step, and the subscripts (*m*, *d*, *h*) are omitted.

Industry waste heat:

$$Q_{ind} = \sum^{tech} Q_{tech\_ind} \quad (7)$$

Condensing heat of power plant:

$$Q_{con} = \sum^{tech} Q_{tech\_con} \quad (8)$$

The waste heat amount of exhaust and jacket water is determined by the ICE power. Occasionally, a part of the waste heat may be discharged because of less load demand, and no equipment can utilize the abundant waste heat. Consequently, their heat balance is represented as inequations (9–10).

Exhaust:

$$Q_{exh} \geqslant \sum^{tech} Q_{tech\_exh} \quad (9)$$

Jacket water:

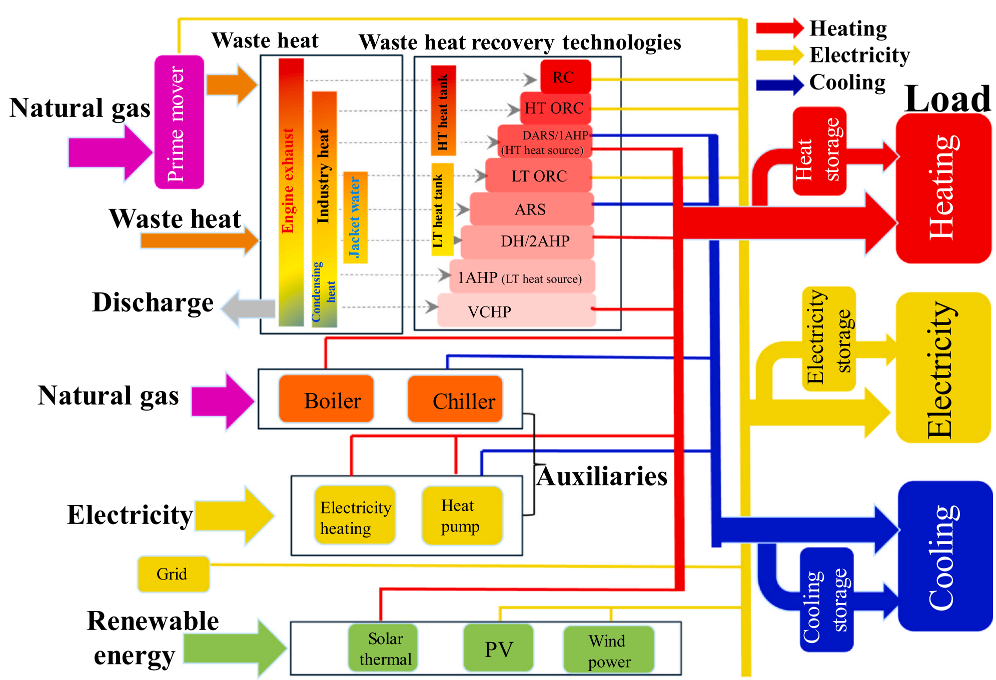

Fig. 6. Composition of the DES.

$$Q_{JW} \geqslant \sum^{tech} Q_{tech\_JW} \tag{10}$$

3. Constraints for technologies

This section primarily focuses on the constraints of the WHRT and heat storage. Other technologies, such as natural gas boilers, PV, and EC, have the same constraints as those in our previous study [30], and are therefore omitted here. To match the suitable WHRT with the energy quality, many candidate technologies are added in the optimization model, as shown in Fig. 1. These technologies require heat sources of different temperatures to drive them, and also have different efficiencies. The efficiency of WHRT is directly proportional to the energy quality. The RC, as well as HT and LT ORC, are used for producing electricity with different efficiencies, of approximately 20–30%, 10–20%, and 5–10%, respectively [31]. Their constraints for every hour can be represented by Equations (11–12), where Q_{tech_hs} represents the absorbed heat from a certain heat source. Equation (13) is the constraint for installation. X_{tech_hs} is a binary variable to determine whether this technology is installed.

$$P_{tech\_hs} = Q_{tech\_hs} \cdot \eta_{tech} \tag{11}$$

$$P_{tech\_hs} < CP_{tech\_hs} \tag{12}$$

$$X_{tech\_hs} \cdot \min CP_{tech\_hs} < CP_{tech\_hs} < X_{tech\_hs} \cdot \max CP_{tech\_hs} \tag{13}$$

To supply heating, 1AHP, 2AHP, VCHP, and DH are used. Their COP or efficiency are approximately 1.2–1.6 [32], 0.6 [33], 3–5 [34], and 0.9 [35], respectively.

$$H_{tech\_hs} = Q_{tech\_hs} \cdot COP_{tech}/\eta_{tech} \tag{14}$$

$$H_{tech\_hs} < CP_{tech\_hs} \tag{15}$$

If 1AHP is used, then Q_{1AHP_hs} means that the HT absorbed heat. Furthermore, 1AHP must absorb LT heat such as the condensing heat of a power plant, and it must satisfy Equation (16).

$$Q_{1AHP\_LThs} = Q_{1AHP\_hs} \cdot (COP_{1AHP} - 1) \tag{16}$$

If the VCHP is used, Q_{tech_hs} means that the LT absorbed heat. This type of heat pump requires electricity to drive instead of HT heat. Its consumption power can be calculated from Equation (17):

$$P_{VCHP\_hs} = Q_{VCHP\_hs}/COP_{VCHP} \tag{17}$$

The DARS and ARS are used to produce cooling and their COPs are 1–1.2 and 0.6–0.8, respectively [32].

$$QC_{tech\_hs} = Q_{tech\_hs} \cdot COP_{tech} \tag{18}$$

$$QC_{tech\_hs} < CP_{tech\_hs} \tag{19}$$

The heat storage tanks are divided into LT and HT to distinguish the energy quality. An HT heat tank is used to store HT heat, and the heat is released at another time to drive WHRTs of high energy quality, such as the RC and DARS. Therefore, the heat stored in the tank is an HT heat source and must satisfy constraint (20). Therein, α is the ratio of high-quality energy for a heat source with a large temperature drop that must be calculated at the beginning of optimization. For example, if the exhaust temperature is 520 °C with 90 °C discharged temperature, and the lowest temperature that can be stored in the heat tank is 300 °C, then α can be derived as ((520–300) / (520–90) = 0.512).

$$H_{HTsto\_hs} \leqslant \alpha \cdot Q_{hs} \tag{20}$$

$$H_{HTsto} = \sum^{hs} H_{HTsto\_hs} \tag{21}$$

The heat from the HT heat tank is used to drive WHRTs of high energy quality, and they are considered to be the additional heat source of the HTORC and DARS that are driven by exhaust in the model; this is defined in Equation (22). The additional heat amount should also be considered for optimizing the capacity of these two technologies, as shown in Equations (23–24).

$$H_{HTsto\_from} = Qht_{HTORC\_exh} + Qht_{DARS\_exh} \tag{22}$$

$$Q_{HTORC\_exh} \cdot \eta_{HTORC} + Qht_{HTORC\_exh} \cdot \eta_{HTORC} \leqslant CP_{HTORC\_exh} \tag{23}$$

$$Q_{DARS\_exh} \cdot COP_{DARS} + Qht_{DARS\_exh} \cdot COP_{DARS} \leqslant CP_{DARS\_exh} \tag{24}$$

The heat stored in the LT heat tank is generally LT heat, which can be either from 1AHP, DH, or other sources. Therefore, the constraints of stored and released heat are represented by Equation (6). Many other constraints exist for the LT and HT heat tanks, and the detailed description is available in our previous study [30].

4. Case study

In this section, two cases are investigated to test the optimization model for the planning and operation of the DES. Case A aims to test the function of optimizing with multiple waste heat sources of different temperatures in a short time. Case B aims to test the function of distinguishing the energy quality of HT and LT heat storage. The candidate technologies for both cases are shown in Fig. 1. The load profile, operative cost assumptions and technologies, and parameters of the two cases are also the same. The difference between them is that the cost of both LT and HT heat tanks is considerably lower in Case B, because it needs to include HT and LT heat tanks in the optimized results to test the function of distinguishing the energy quality of the two heat tanks. In addition, the waste heat sources in these two cases are different. The main operating cost assumptions are listed in Table 2, which refer to literature [26]. The performance parameters of all the technologies are described in the Appendix. As mentioned above, a one-year load is represented by 12 months and two representative days (weekday and weekend) each month. The demand profile used in the model comprising 576 (12*2*24) time steps is shown in Fig. 7 [26]. To analyze the operation of different technologies, two typical days are selected in the two cases. Typical Day 1 represents the heating season (winter) and typical Day 2 represents the cooling season (summer).

4.1. Case 1 (multiple heat sources)

This case aims to test the function of optimizing with multiple waste heat sources of different temperatures. Four heat sources are used in this case: exhaust heat (532 °C) and jacket water (75–85 °C) of ICE, LT industry heat (~70–90 °C), and condensing heat of power plant

Table 2
Main operating cost parameters.

Price	Value ($/kWh)					
Natural gas	0.03					
Industry heat purchase	0.012					
Condensing heat purchase	0.001					
Time interval	1st–5th	6th–8th	9th–11th	12th–18th	19th–21st	22nd–24th
Electricity purchase	0.064	0.134	0.207	0.134	0.207	0.064
Electricity sale	0.054	0.114	0.176	0.114	0.176	0.054

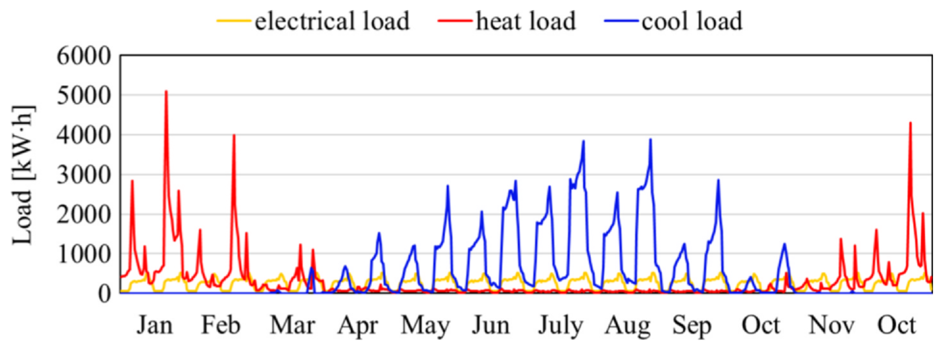

Fig. 7. Load profiles in the two cases [26]

(~30 °C). Industry heat needs to be purchased, as does the condensing heat of the power plant, but their prices are quite cheap owing to the low temperature. The abundant waste heat of the ICE is not allowed to be sold in this case. The model can obtain a solution in 22 s with a gap of 0.001%. Additionally, the model can distinguish the energy quality effectively, which will be discussed in detail later.

The optimization results of technology selection and capacity are shown in Table 3. Because the exhaust waste heat is of high energy quality, it is recovered by the RC, 1AHP, and DARS with a high efficiency level. In the heating season, when the electricity price is low, it is more economical to use exhaust heat to provide heating than electricity, while it is the opposite when the electricity price is high. Therefore, both the 1AHP and RC are selected. In the cooling season, the exhaust heat is primarily used to generate cooling by the DARS. The temperature of the jacket water waste heat is low and only matches with DH and the ARS. It is therefore primarily recovered to generate heating by DH in the heating season and cooling by the ARS in the cooling season. The LT industry heat only matches with the ARS and DH, and can therefore be purchased at a low price to offer cooling and heating when the ICE waste heat is insufficient. The temperature of the condensing heat is low and can only be utilized as the LT heat source of 1AHP. When the electricity price is low in the cooling season, using EC for cooling is the most economical. The optimization results therefore involve using EC for generating cooling when the capacity of all the other cooling equipment is insufficient.

4.1.1. Typical Day 1

Figs. 8–9 depict the detailed operation of every WHRT as well as the other technologies for a typical Day 1. During hours 1–5 and 22–24, the grid electricity price ($0.064/kWh) is lower than the power generation cost of the ICE ($0.075/kWh); however, the waste heat of the ICE can satisfy part of the heating load, thereby avoiding the purchase of industry heat ($0.015/kWh). Consequently, it is more economical to use ICE cogeneration during these time periods. However, if the ICE power is larger than the electricity load, then additional power must be sold at a lower price ($0.054/kWh), which renders the cogeneration no longer the most economical. Therefore, the ICE power is only equal to the electricity load during these hours, as shown in Fig. 8, and the remaining heating load is satisfied by purchasing industry heat.

During hours 6–21, owing to the high purchase and sale price of electricity grids, electricity is generated by the ICE and a significant amount of electricity is sold to grids. Jacket water heat is typically used to generate heating by DH. The exhaust heat is used prior to electricity generation by the RC when the grid price is the highest (hours 9–11 and 19–21). Furthermore, if the exhaust heat is abundant, then it is recovered by 1AHP to produce heating. By contrast, when the grid price decreases during hours 6–8 and 12–18, the exhaust heat is used prior to heating by 1AHP. Industry heat is purchased when the waste heat of the ICE is insufficient to supply heating. To demonstrate the utilization of different heat sources, they are illustrated in Fig. 10. As shown, every waste heat source is recovered by the matched technologies according to the energy quality. It is more economical for the exhaust to be recovered by 1AHP than RC, which requires high energy quality. Consequently, its heat is distributed to the two technologies. The temperature of condensing heat from a power plant is low and can only be used as the LT heat source of 1AHP. If 1AHP shuts down during certain hours, then the condensing heat cannot be utilized. The jacket water and industry heat have similar temperatures, and therefore are both utilized in DH.

4.1.2. Typical Day 2

Figs. 11–13 show the electricity, heating, and cooling balance of a typical day in the cooling season. Because the grid price is the lowest during hours 1–5 and 22–24, most of the electricity load is supplied by the grid, while the ICE is only used to generate a small amount of waste heat for heating and a small amount of electricity, as shown in Fig. 11. By contrast, when the grid price increases during hour 6–21, the ICE generates electricity in large amounts, which is then sold to the grid at a high price.

During hours 6–21, according to the optimization results in Figs. 11–13, it is more economical to produce cooling or electricity than heating by ICE waste heat. Therefore, the heating load is only supplied using purchased industry heat, as shown in Fig. 12. In this period, the jacket water can only drive the ARS to produce cooling, while the exhaust can produce electricity or cooling by the RC or DARS. The ARS driven by jacket water heat and industry heat is used prior to supplying cooling, in order to save more HT exhaust heat to produce electricity by the RC. If the cooling capacity of the ARS driven by LT heat is insufficient to satisfy the cooling load, then the exhaust heat is used prior to generating cooling by the DARS to avoid using electricity for cooling. For example, during hour 6–7, because the cooling load is small and the waste heat of the exhaust and jacket water can generate enough cooling by the DARS and ARS, a significant amount of exhaust heat is recovered by the RC to produce electricity, as shown in Figs. 11 and 13. During hour 20–21, the electricity sale price is the highest and the cooling load is small and can be satisfied with the ARS driven by jacket water and industry heat. All the exhaust heat is therefore recovered by the RC to generate electricity. During the other hours, owing to the large cooling load, all the waste heat of the ICE, purchased industry heat, and EC at

Table 3
Optimization of technology selection and capacity in Case 1.

Technology	Capacity (kW)
ICE	1400
RC	117
1AHP	1081
DARS	828
JWDH (for jacket water)	620
JWARS (for jacket water)	482
LTARS (for industry heat)	362
Electrical chiller (EC)	2198
PV	3920 (m^2)

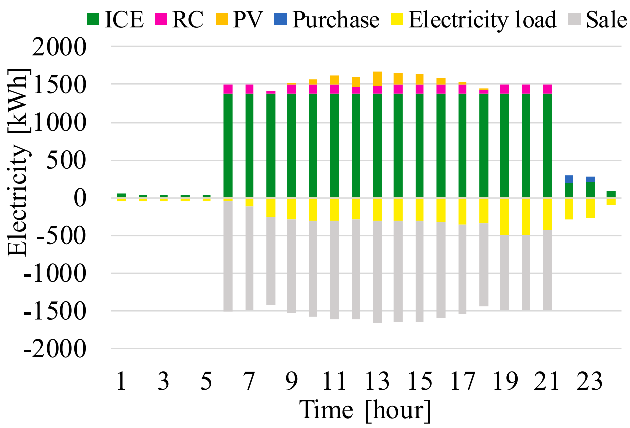

Fig. 8. Electricity balance during the typical Day 1 of Case 1.

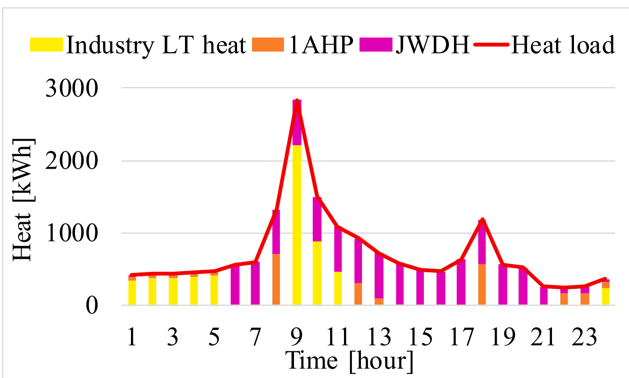

Fig. 9. Heat balance during the typical Day 1 of Case 1.

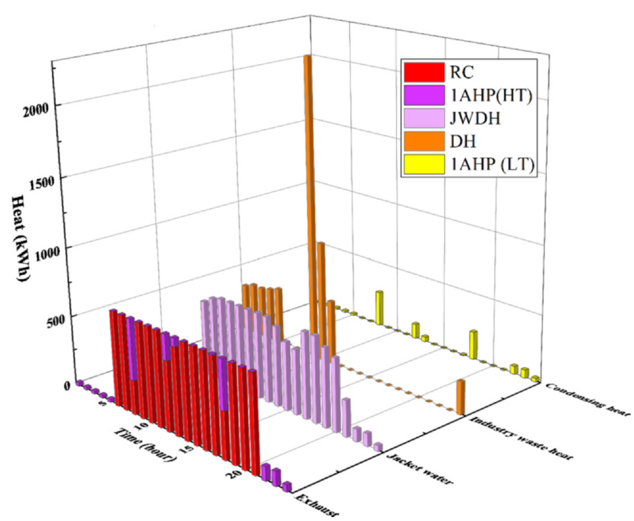

Fig. 10. Utilization of different heat sources during typical Day 1 of Case 1.

peak times should be used to generate cooling, as shown in Fig. 13.

Fig. 14 depicts the detailed hourly utilization of different waste heat sources. Similar to Fig. 10, every waste heat source with different temperatures is recovered by the matched technologies based on the energy quality. The exhaust heat is primarily matched with the RC and DARS, and the distribution of waste heat to the two technologies depended on the variation in the load and grid price, as mentioned above. The jacket water heat is primarily matched with the ARS for cooling. Part of the industry waste heat is used for heating demand, and the other for driving the ARS to supply cooling. The condensing heat from the power plant can only be used as an LT heat source for 1AHP owing to its low temperature.

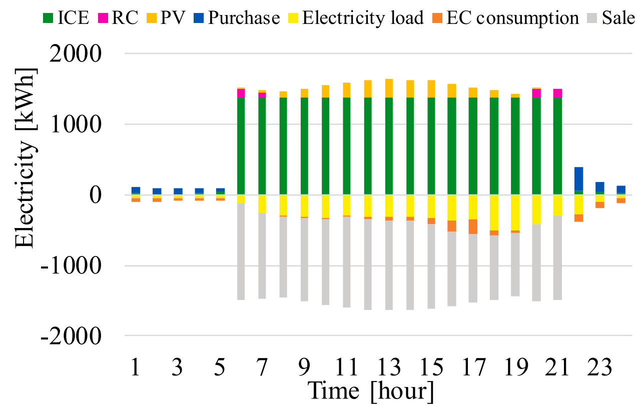

Fig. 11. Electricity balance during the typical Day 2 of Case 1.

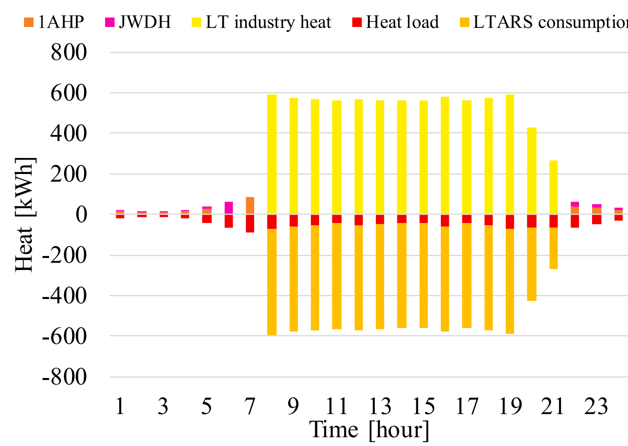

Fig. 12. Heat balance during the typical Day 2 of Case 1.

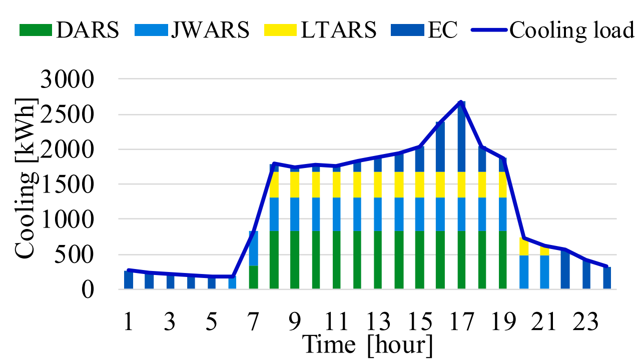

Fig. 13. Cooling balance during the typical Day 2 of Case 1.

4.2. Case 2 (HT and LT heat storage)

In this case, no industry heat exists, and to test the function of distinguishing the energy quality of HT and LT heat tanks, their costs are assumed to be low so that they can appear in the optimization results. The equipment cost, and operation cost of the HT heat tank are more expensive than those of the LT heat tank. Table 4 shows the optimization results of technology selection and capacity. Because no cheap industry heat is available for heating, all the ICE waste heat of the exhaust and jacket water is used for heating by 1AHP and DH to avoid using expensive natural gas or electricity boilers. Meanwhile, the ICE waste heat is abundant at times, and can be stored and released at other times when the waste heat is insufficient for heating. Fig. 16

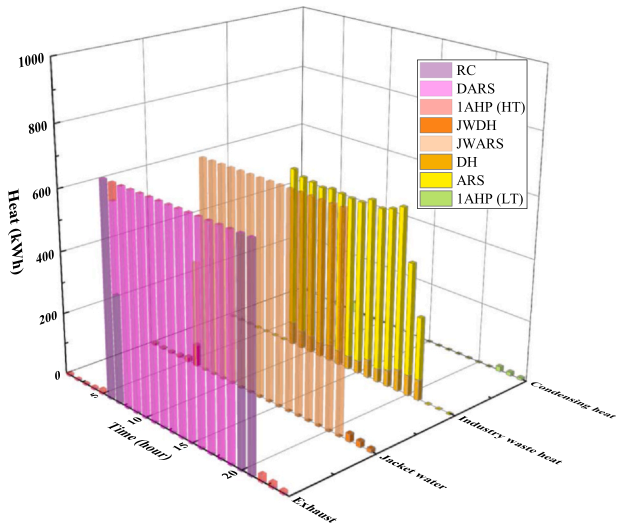

Fig. 14. Utilization of different heat sources during typical Day 2 of Case 1.

Table 4
Optimization of technology selection and capacity in Case 2.

Technology	Capacity (kW)
ICE	4000
1AHP	966
DARS	1963
JWDH	719
JWARS	559
LT heat tank	16,293
HT heat tank	6680
PV	3920 (m^2)
EC	1348

indicates that the cheap LT heat tank which can store both high-energy-quality exhaust heat and low-energy-quality jacket water heat is sufficient for supplying the remaining heating load without using other equipment. Consequently, it is used during the heating season instead of expensive HT heat tanks that are only for storing high-quality energy to drive 1AHP. The DARS and ARS are primarily used for recovering the waste heat of exhaust and jacket water in the cooling season. Similarly, the ICE waste heat is abundant at certain times for generating cooling, and can therefore be stored. To produce more cooling from the DARS than from ARS, the HT heat tank is used to store high-quality exhaust energy to drive the DARS. When the load is larger than the cooling supplied by waste heat, the other cooling load at the peak time is supplemented by EC.

4.2.1. Typical Day 1

In the heating season, during hours 6–21, electricity is provided by ICE and the excess is sold to the grid due to the high grid price, as shown in Fig. 15. All the waste heat of the exhaust and jacket water is used to supply heating by 1AHP and DH to avoid using expensive natural gas or electricity boilers. Fig. 16 indicates that the waste heat is abundant at times, while it is insufficient at other times. Therefore, redundant waste heat is stored when the heating load is small, and it is released to supply heating when the heating load is large, as shown in Fig. 16. During hours 1–5 and 22–24, because the price of the grid is the cheapest and LT heat in the LT heat tank is sufficient, the electricity load is provided by the grid, and the heating load is supplied by the stored waste heat, as shown in Figs. 15 and 16.

4.2.2. Typical Day 2 (cooling season)

The electricity balance shown in Fig. 17 is almost the same as that of typical Day 1. The only difference is that the electricity consumption by the chiller is not included in the electricity load. The heating load in cooling season is small. The LT heat stored in the LT heat tank at hour 6 when the cooling load is small is almost sufficient for satisfying all the heating loads for the other hours, as shown in Fig. 18. Fig. 19 indicates that during hours 1–5 and 22–24, because the electricity purchase price is the lowest, all the cooling is supplied by EC. During hour 6–21 when the grid price increases, all the waste heat of the exhaust and jacket water is recovered by the DARS and ARS to supply cooling. Occasionally, there is excess waste heat over that required for cooling; therefore, the jacket water heat is prior to generate cooling, and subsequently, a maximum amount of high-energy-quality exhaust heat can be retained to store in the HT heat tank. When the waste heat is insufficient for generating cooling at other times, the stored HT heat is released to drive the DARS with a high COP, generating more cooling than the ARS. Fig. 18 depicts the LT heat balance, where no HT heat is stored in the HT heat tank. Fig. 20 shows the HT heat stored in the HT heat tank over 24 h. All the heat shown in Fig. 20 is from the exhaust because only its energy quality satisfies the requirement of the HT heat tank. In total, 1287 kWh of HT heat is stored in the heat tank during the entire day and 1189 kWh of cooling is output. Figs. 18–19 show that LT heat is stored in the LT heat tank, while HT heat is stored in the HT heat tank, indicating that our model can distinguish the energy quality of LT and HT heat tanks.

5. Conclusion

In this study, a new MILP optimization model for the planning and optimization of the DES is proposed to match various WHRTs with multiple heat sources and heat storage tanks of different temperatures according to energy quality. The practicability of the main method in practice is validated by dynamic simulations of waste heat distribution to different WHRTs. Subsequently, two optimization cases were investigated to validate the model functions. One is to test the matching of WHRTs with multiple waste heat sources of different temperatures based on energy quality. The other is to test the energy quality differentiation of LT and HT heat storage tanks. The results show that:

1. The parallel utilization form of waste heat is feasible and convenient in practical applications to control the distributed heat amount to different technologies according to the optimal results.
2. The model can achieve the matching of WHRTs with multiple waste heat sources of different temperatures based on energy quality to improve the efficiency of the entire DES. Additionally, the optimal solution can be obtained rapidly. Case A indicates that the model can obtain the solution in 22 s with a gap of 0.001%. Therefore, the model can handle many types of waste heat sources at the same time.

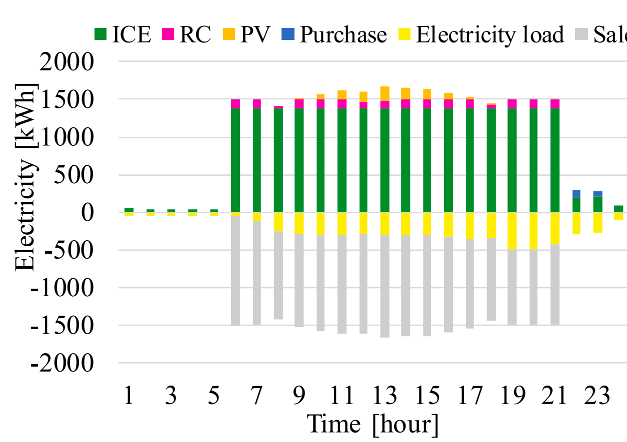

Fig. 15. Electricity balance during typical Day 1 of Case 2.

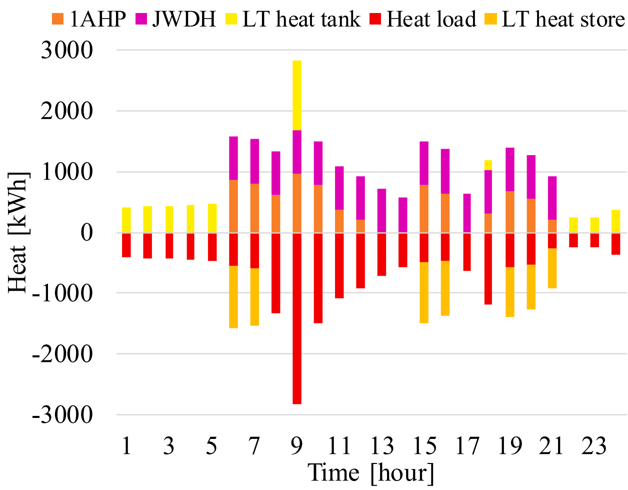

Fig. 16. Heat balance during typical Day 1 of Case 2.

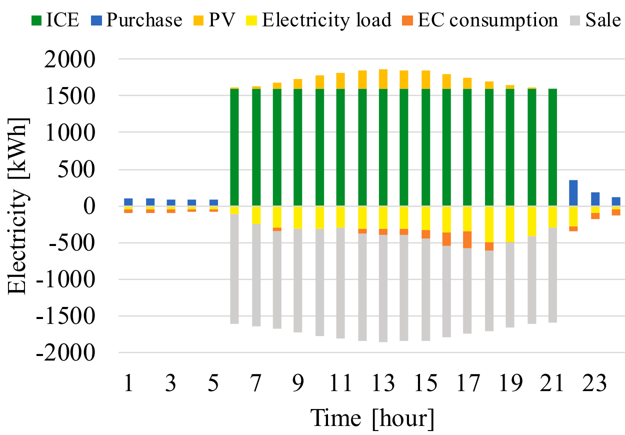

Fig. 17. Electricity balance during typical Day 2 of Case 2.

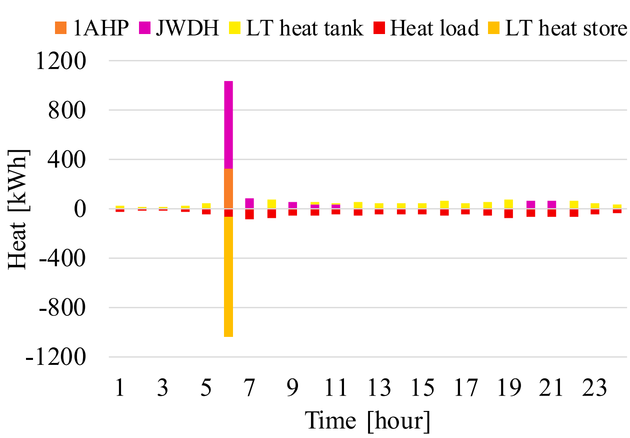

Fig. 18. Heat balance during typical Day 2 of Case 2.

3. The model can distinguish the energy quality of LT and HT heat storage tanks. Therefore, it can optimize the storage of HT heat and release it at other times to drive WHRTs of high-quality energy with high efficiencies, instead of only storing it in an LT heat tank with a loss in energy quality. Case B indicates that 1189 kWh of output cooling can be increased by the HT heat tank.

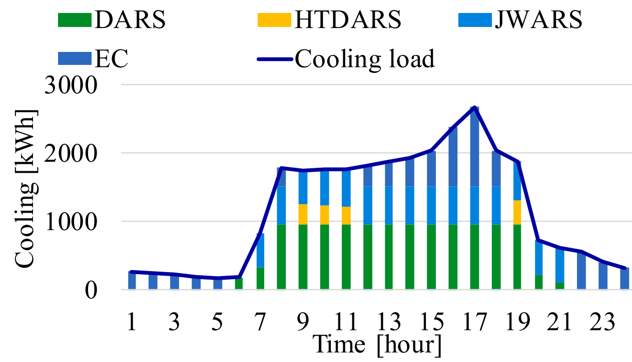

Fig. 19. Cooling balance during typical Day 2 of Case 2.

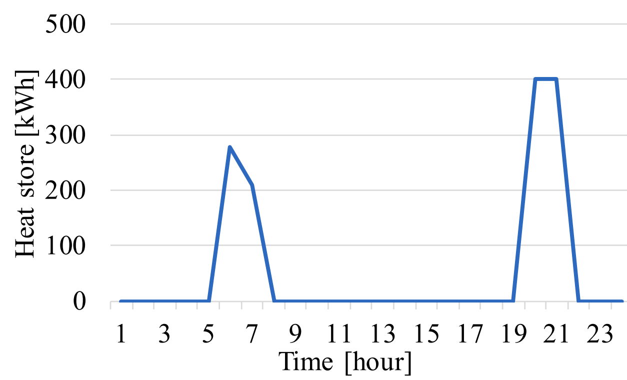

Fig. 20. Heat stored in HT heat tank during typical Day 2 of Case 2.

In summary, the model can distinguish the energy quality and select the optimal WHRTs including heat storage based on energy quality as well as their operation schedule. Furthermore, the optimal results are practical in real application. Consequently, meaningful guidance can be provided to the builders and operators of DESs.

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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Appendix

The main performance parameters of technologies

Technology	Parameter value	
Photovoltaics	Solar efficiency: 0.15	Unit out ratio: 0.15
Solar thermal	Solar efficiency: 0.69	Unit out ratio: 0.1
Internal combustion engine	Thermal efficiency: 0.4	
Natural gas boiler	Efficiency: 0.9	
Electric boiler	Efficiency: 0.9	
Natural gas chiller	COP: 1.2	
Electric chiller	COP: 4.8	
Heat pump	COP (heating): 3	COP (cooling): 5
Rankine cycle	Thermal efficiency: 0.17	
HT Organic Rankine Cycle	Thermal efficiency: 0.15	
LT Organic Rankine Cycle	Thermal efficiency: 0.08	
Double effect absorption refrigerator	COP: 1.2	
Absorption heat pump	COP: 1.6	
Single effect absorption refrigerator	COP: 0.7	
Direct heating	Efficiency: 0.9	
Electric battery	Charging efficiency: 0.9 Max charge rate: 0.25 Min SOC: 0.1	Discharging efficiency: 0.9 Max discharge rate: 0.25
Heat storage tank	Charging efficiency: 0.9 Max charge rate: 0.25 Min SOC: 0.15	Discharging efficiency: 0.8 Max discharge rate: 0.25
Cooling storage tank	Charging efficiency: 0.9 Max charge rate: 0.25 Min SOC: 0	Discharging efficiency: 0.9 Max discharge rate: 0.25

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