CityU Scholars

Cost performance optimization of waste heat recovery supply chain by mobile heat storage vehicles

Yang, Jing; Chen, Jiayu; Zhang, Zhiyong; Hong, Ming; Li, Han; Li, Yilong; Yang, Mingwan

Published in:
Energy Reports

Published: 01/12/2020

Document Version:
Final Published version, also known as Publisher’s PDF, Publisher’s Final version or Version of Record

License:
CC BY-NC-ND

Publication record in CityU Scholars:
Go to record

Published version (DOI):
10.1016/j.egyr.2020.05.009

Publication details:
Yang, J., Chen, J., Zhang, Z., Hong, M., Li, H., Li, Y., & Yang, M. (2020). Cost performance optimization of waste heat recovery supply chain by mobile heat storage vehicles. *Energy Reports*, *6*(Supplement 7), 137-146. https://doi.org/10.1016/j.egyr.2020.05.009

Citing this paper
Please note that where the full-text provided on CityU Scholars is the Post-print version (also known as Accepted Author Manuscript, Peer-reviewed or Author Final version), it may differ from the Final Published version. When citing, ensure that you check and use the publisher's definitive version for pagination and other details.

General rights
Copyright for the publications made accessible via the CityU Scholars portal is retained by the author(s) and/or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights. Users may not further distribute the material or use it for any profit-making activity or commercial gain.

Publisher permission
Permission for previously published items are in accordance with publisher's copyright policies sourced from the SHERPA RoMEO database. Links to full text versions (either Published or Post-print) are only available if corresponding publishers allow open access.

Take down policy
Contact lbscholars@cityu.edu.hk if you believe that this document breaches copyright and provide us with details. We will remove access to the work immediately and investigate your claim.

Download date: 17/09/2024

Energy Reports 6 (2020) 137–146

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Cost performance optimization of waste heat recovery supply chain by mobile heat storage vehicles

Jing Yang [a], Jiayu Chen [b], Zhiyong Zhang [c], Ming Hong [c], Han Li [d], Yilong Li [d], Mingwan Yang [e,*]

[a] School of Finance and Trade, Guangdong Industry Polytechnic School of Finance and Trade, Guangzhou, 510300, China
[b] Department of Architecture and Civil Engineering, City University of Hong Kong, Kowloon, Hong Kong, China
[c] School of Economics and Commerce, South China University of Technology, Guangzhou, Guangdong, 510006, China
[d] School of Civil Engineering, University of New South Wales, Australia
[e] Guangdong University of Finance, Guangzhou, 510640, China

ARTICLE INFO

Article history:
Received 13 February 2020
Received in revised form 27 April 2020
Accepted 10 May 2020
Available online 13 May 2020

Keywords:
WHR
Mobile heat storage vehicles
Green supply chain
Cost optimization

ABSTRACT

Waste heat recovery (WHR) has been widely recognized as an effective and sustainable source of energy supply. However, conventional WHR requires a huge initial investment in equipment and infrastructures for recovered heat distribution. This study incorporates a newly emerged mobile WHR supply chain, which yields to significantly lower distribution cost and investigates the cost optimization of all participants of the supply chain. The proposed optimization model incorporates the life cycle assessment method for the complete phases of recycling, pretreatment, transportation, storage, and final utilization. After assessing the cost influencing factors of the supply chain with stochastic demands, the sensitivity analysis and case studies show that with the proposed optimizing model, the supply chain cannot only ensure the stable energy supply but also minimize the total transitional cost compared with the conventional WHR and fossil fuel heating.

1. Introduction

Energy is the essential resource to boost social development and economic growth, thus it is critical for all countries in the world to ensure sufficient energy supply. Traditional energy resources often generate pollutants that are harmful to both the environment and human beings. Therefore, renewable energy sources have been gradually studied over the past decades. However, renewable energy, such as nuclear, solar, and wind energy, is often subject to its high cost or potential risks. However, the rising cost of energy is one of the important factors associated with increasing production costs of manufacturing facilities, which encourages decision-makers to tackle this problem in different manners. Out of the safety reason and cost consideration, the generators are usually far from the end-users (densely populated areas) and the delivery cost is the major challenge of heat energy utilization. As more than 50% of the world's energy is wasted in the form of heat, recycling can significantly promote energy generation efficiency.

However, the major hurdle of the wide implementation of WHR is the cost, including the cost of transportation and the cost of transforming low-temperature heat into electrical energy (Shu et al., 2014). Ethanol can be used as an alternative transportation fuel to reduce the emissions of carbon dioxide, although its cost is higher than fossil fuels (Nguyen and Gheewala, 2008). Therefore, researchers have proposed to directly deliver heat to the end-users rather than through the electric grid. For example, utilizing the thermal dynamics between hot process flow and the cold process stream, the heat can be stored with minimum cost (Chaturvedi et al., 2015). In recent years, the mobile waste heat recovery system has emerged in the markets. Such technology significantly reduced the initial investment in the distribution network and recovery infrastructure. Also, the distribution becomes more flexible and adaptive to the dynamic needs of clients. However, there are few studies have investigated such a novel WHR supply chain. To fill in this research gap, this study developed a comprehensive optimization model for the mobile waste heat recovery supply chain to assist the decision-making of all market participants. Based on the unique characteristics of the newly developed mobile supply chain, this study intends to minimize the entire supply chain's cost while ensuring sufficient supply to satisfy the uncertain demand of end-users. The rest of this paper is summarized as follows: Section 2 summaries the major research background with a comprehensive literature review; Section 3 explains the details of the proposed

---

* Corresponding author.
E-mail address: 630705495@qq.com (M. Yang).

https://doi.org/10.1016/j.egyr.2020.05.009

Nomenclature

A_e	Unit investment cost of mobile WHR equipment
C	Cost of a centralized mobile WHR network
D_v	Distributing distance in a centralized WHR network
d_v	Travel distance of a mobile heat storage vehicle
p_s	Unit price of WHR
p_o	Unit price of the fuel
p_v	Price of a mobile heat storage vehicle
Q_D	Daily heat energy demand
Q_s	Daily heat energy production
Q_w	Loading Capacity of a mobile heat storage vehicle
r_e	Hourly cost of manual treatment of waste heat
r_v	Hourly cost of manual delivery
S_v	Residual value of a vehicle after 20 years' depreciation
t_v	Usage hours of a vehicle in a year
u_v	Utilization rate per vehicle
v_e	Release/recovery rate of WHR
v_v	Speed of mobile heat storage vehicle
w_e	Maintenance cost of WHR equipment per hour
w_v	Maintenance rate of a mobile heat storage vehicle
Y_v	Service life of a mobile heat storage vehicle
ϖ	Penalty factor of failing to meet the demand
σ	The share of interest, insurance, tax in the average cost
η_e	Hourly production rate of WHR equipment
η_v	Loading capacity of a mobile heat storage vehicle
α	Heat energy loss rate during waste heat collection, release, and delivery ($\leq$ 18%)

optimization model for the mobile WHR supply chain; Section 4 discusses the results of the validation case study for the proposed model, and Section 5 concludes this study.

2. Literature review

2.1. Use of heat storage technology

Due to the unstable appearance of light and wind in nature, photovoltaic energy, and wind power generation have problems of volatility, intermittence, and instability, which may cause serious impact on the power grid (Dincer and Rosen, 1998). For their own sake, grid companies will set a series of thresholds to refuse renewable energy. Grid enterprises are more inclined to buy cheap conventional power (Li et al., 2015). With the continuous expansion of the scale of the urban heating system, the accident rate is rising, followed by the enhancement of the demand for the reliability of the heating system. Central heating involves people's livelihood. As a result of accidents, some or all heat users in the heating system have to stop heating, which will inevitably damage the thermal environment of buildings, affect the normal life of residents and lead to incalculable social consequences. On the one hand, the researchers analyze the energy flows between sectors or regions from a macro perspective. On the other hand, they look for alternative technologies for energy from a micro perspective to improve energy efficiency (Jinyue et al., 2017). The emergence of mobile heating vehicles can effectively solve the problem of intermittent heating. It not only meets the needs of urban residents but also satisfies the needs of many heating enterprises. Mobile heating can provide stable and uninterrupted heat energy (Westin and Lagergren, 2002). The key technology of mobile heating is heat storage technology. Heat storage technology mainly uses the latent heat of heat storage materials to absorb or release heat. Temperature can remain unchanged in the process of absorption and exothermic heat, and the heat output process is relatively stable (Ahmet et al., 2008). Therefore, mobile energy storage heating equipment with energy storage technology has the advantages of stable heating, high transport efficiency, and strong transport flexibility. It can convert unstable electrical energy generated by photovoltaic energy and wind power into heat energy. Mobile heating with energy storage technology is of high energy saving and economy. Meanwhile, as a high-performance heat storage medium, mobile heat source vehicle can effectively store waste heat from power plants, steel plants, and chemical plants, improve energy utilization efficiency, reduce energy consumption and protect the environment. Also, by installing a WHR boiler can further reduce the cost of heat recovery. To reduce the energy consumption of the production process, researchers have proposed measures to implement product energy efficiency standards and to avoid high energy price periods (Shrouf et al., 2014).

Therefore, mobile energy storage heating equipment builds a bridge between industrial waste heat and dispersed heat users. It not only avoids the waste of a large amount of waste heat and low-quality heat, solves the waste problem of small heating systems, and reduces the cost of heat required by production enterprises, but also creates another energy transmission channel besides pipe network, which is a perfect combination of scientific and technological progress and business model innovation (Weilong Wang et al., 2014). Special vehicles equipped with energy storage materials are used between the heat source and heat users, which can more flexibly complete the heat transport and transfer process compared with the traditional pipeline transportation mode, providing solutions for heat users who have difficulty in pipe application (Dincer and Rosen, 1998). As for industrial waste heat, most of the literature study the technology of recycling it and seldom regard it as a product of enterprises to improve energy efficiency by utilizing supply chain management to coordinate those activities, which are related to ecology, environment, and economy, among WHR suppliers and end-users.

2.2. Waste heat recovery supply chain

The goal of supply chain management is to increase efficiency and strengthen the business advantages of its structure components (Abramovitz, 1956). Therefore, the green supply chain, as a method to promote energy conservation and environment protection, has received attention from academia and industry fields (Xi Wang et al., 2016). The green supply chain covers all ecology, environment, and economy-related activities from the supplier side to the end-user side (Nelson et al., 2014). The consumer of the final product is the original initiator of the green supply chain (Yixiong Feng et al., 2019). Starting from the sustainable development of society and enterprises, the entire supply chain of products from raw material purchase, production, and consumption to waste recycling and reuse is ecologically designed (Mehranfar et al., 2019). Through cooperation between the internal departments of various enterprises in the chain and each enterprise, The entire supply chain is coordinated in environmental management to achieve the optimization of the system environment (Xu Liu et al., 2020). Amir et al. (2020) evaluated the efficiency of the proposed new coordinated water supply and wastewater collection network model through some sensitivity analysis. In his other papers, he analyzed the factors affecting the sustainability of the green supply chain and established a bi-objective location allocation-routing model to reveal its efficiency (Amir et al., 2019a,b,c). Anita Abdi et al. (2019) solved the problem of supply chain network design under uncertainty and put forward suggestions and countermeasures on how to operate the efficiency of green products. Yi et al. (2018) assessed the greenhouse gas emissions and economic performance from the energy life cycle of the refining process from raw material supply to oil production. Wu et al. (2015) explored the life cycle energy efficiency of coal from six different stages from coal mine design to comprehensive utilization of resources. Under the circumstances of centralized decision-making, manufacturers and retailers working as whole set selling prices for retailers and green level and recovery factors of products to maximize the total revenue of the supply chain system (Ning et al., 2019) Centralized decision-making emphasizes coordination, information sharing, and win–win profit among enterprises, and its goal is to expand market demand and improve service quality to finally realize the minimization of costs. (Debabrata and Janat, 2015). Many of the above documents have studied operational efficiency from the perspective of green supply chain optimization, but few documents have included WHR in the supply chain.

WHR can be divided into three quality-levels: low temperature (<100 °C), middle temperature (100–300 °C), and high temperature (>300 °C). A series of heat recovery in the industrial processes turn most of the processed low and middle-temperature energy into waste heat and then emit it into the environment. Only 31.8 percent of industrial surplus heat of primary energy re-enters into the industrial process, and the rest 68.2 percent becomes waste heat (Kostowski et al., 2019). The transformation process loses 72 percent of primary energy in the world, 63 percent of which is the waste heat flow with a temperature lower than 100 °C (Wojciech et al., 2019). At present, there is no economical and effective solution for purchasing low-temperature waste heat, thus a large number of resources are to be developed while the low-grade cost-effectiveness of WHR is the main barrier. When WHR reaches a certain scale, whether a stable fuel supply can be guaranteed is the key issue that enterprises must consider, and at the same time, the problem of fuel supply cost will become more and more obvious. For the delivery cost, researchers have also proposed to utilize mobile WHR vehicles to reduce the capital investment of heat transfer network and they are more flexible, versatile, and free from geographical constraints (Yang et al., 2019). This study adopts these methods that use the life cycle of the WHR system to optimize the costs of the supply chain of mobile WHR to provide economical and effective solutions for developing the low-temperature industrial waste heat, which will help save energy and reduce emissions.

3. Establishment of cost operation model for the supply chain of centralized mobile WHR

3.1. Problem description

This study develops a supply chain system with a single WHR supplier, a single WHR distributor, and a single heat consumer group. In this system, the supplier is responsible for recycling industrial waste heat, and the distributor needs to deliver the recovered heat to the end consumer market and release the heat for consumers' use. To solve problems in satisfying global energy demand, waste management, and emission of greenhouse gas, this research has taken the lead to study mobile WHR energy-saving supply chain to achieve the industrial circular economy. In short, the WHR supply chain can be formed to facilitate the whole process of waste heat usage, including waste steam collection, waste hot water treatment, and heat exchange networks.

The core issue of this study is how to deliver processed low-temperature industrial waste heat to heat consumers, such as communities, schools, hospitals and other enterprises which need heat supply, and to establish a mobile WHR supply chain model to minimize supply chain costs and analyze its resources and environment. The waste heat can be collected from wastewater, waste steam, waste flue gas, and other industrial residuals. The recovered waste heat is usually regarded as clean and renewable energy as it does not require additional resources and cause no effect on the environment. Therefore, the reuse, recycling, and final disposal cost of the whole life cycle of recovery, storage, transportation, and distribution of industrial waste heat are optimized to achieve the effect of energy conservation and emission reduction from the perspective of supply chain optimization. The major workflow of processing the optimization model can be divided into three steps: (1) From the perspective of the life cycle, analyze the composition of WHR supply chain costs; (2) Establish a cost optimization model for the entire supply chain of WHR from the supply end to the customer end based on the centralized collection and transportation model; (3) Sensitivity analysis of the main factors affecting the operating costs of the WHR supply chain. The data in this study were provided by QINGDAO AO-HUAN NEW ENERGY CO., LTD [CN/CN], one of the new high-tech enterprises with new energy technology research and development, design, manufacturing, engineering general contracting and operation services in one. In 2012, we instructed the company to establish a mobile WHR distribution plant. It has created a new model of "one-stop" and "thermal energy distribution service" for waste heat utilization, achieving a revolutionary breakthrough in the traditional heating mode.

3.2. Cost structure of mobile WHR supply chain

The waste heat is usually generated during the production of energy or goods. Industrial sectors, such as thermal power plants, steel plants, and petrochemical plants can release a huge amount of waste heat in the form of steam or hot water. Although many factories adopt recovery strategies to reuse part of heat, the majority of surplus thermal energy is wasted. To assess the total cost of the mobile WHR supply chain, this study formulates the cost as a combination of four components. The quality level of the recycled waste heat and the price p of per unit heating are co-determined to maximize the system profit. C_1 is the recovery cost; C_2 is the pre-treatment cost; C_3 is the distribution cost; C_4 is the penalty cost of failing to satisfy the demand. The total cost C can be represented as

$$C = C_1 + C_2 + C_3 + C_4 \tag{1}$$

3.2.1. Purchase cost

Industrial waste heat generated from daily production will partly be recycled as industrial new energy and partly discharged. Assume the cost of per unit waste heat is c_s and the quantity of mobile WHR supply is Q_s, then the cost of purchasing recovered waste heat is

$$C_1 = c_s Q_s \tag{2}$$

3.2.2. Pre-treatment cost

Before the energy delivery, there is a pre-treatment process. The energy quality needs to be improved for efficiency and the high-temperature steam need to be compressed. The cost of pre-treatment can be expressed as the product of the pre-treatment cost c_e of per unit multiplies the quantity Q_D of daily heat demand:

$$C_2 = c_e Q_D \tag{3}$$

The pre-treatment cost c_e includes the fixed investment A_e (*yuan*/h) in pre-treatment facilities per unit time, labor costs r_e (*yuan*/h), maintenance and repair costs W_e (*yuan*/h), and the ratio of per-unit cost of fuel p_0 (*yuan*/h) to its processing capacity η_e (GJ/h).

$$c_e = \frac{A_e + r_e + W_e + p_0}{\eta_e} \tag{4}$$

From Eq. (4), it can be obtained:

$$C_2 = \frac{A_e + r_e + W_e + p_0}{\eta_e} Q_D \tag{5}$$

3.2.3. Distribution cost

The distribution cost of WHR involves various factors such as transportation distance, vehicle purchase cost, operation, and maintenance cost, which can be expressed as the product of the distribution cost c_v of per unit multiplies the quantity Q_D of waste heat distributed from the supplying place to the destination every day:

$$C_3 = c_v Q_D \tag{6}$$

Distribution cost c_v per unit can be expressed as the ratio of the total cost of round-trip distribution from the recovery site to the destination per vehicle:

$$c_v = \frac{c_T}{\eta_v} \tag{7}$$

The total costs c_T of the round-trip distribution from the recovery site to the destination of each vehicle includes fuel cost F_v traveling from the site to the destination, labor cost R_v, depreciation costs A_v of the vehicle, and other costs I_v such as interest, insurance, taxes, and maintenance cost W_v:

$$c_T = F_v + R_v + A_v + I_v + W_v \tag{8}$$

(1) Fuel cost F_v of delivery. The cost of transporting the recovered waste heat per vehicle is equal to the product of the fuel consumption L_v per vehicle for traveling once from the recovery site to the destination at the price p_o per unit fuel. The fuel consumption L_v per vehicle can be expressed as the ratio of the round-trip distance D_v between the supplying place and the destination to the ideal running distance d_v per unit fuel:

$$F_v = L_v p_o = \frac{2D_v}{d_v} p_o \tag{9}$$

(2) Labor cost R_v. The labor cost R_v of the vehicle is the product of time t multiplies the labor cost r_v per hour. The duration is related to the speed v_v per unit time.

$$R_v = t r_v = \frac{2D_v}{v_v} r_v \tag{10}$$

(3) Depreciation expense A_v. Depreciation expense is the product of depreciation expense of vehicle per unit and the time t for each vehicle to make a round trip from recovery site to the destination. The depreciation expense of vehicle per unit time is determined by the ratio of the purchase price p_v minus the residual value S_v to the total actual working time T_v of each vehicle. The total actual working time T_v of each vehicle is equal to the product of its service life Y_v, its specified service time each year t_v and the utilization rate μ_v of the vehicle.

$$A_v = \frac{p_v - S_v}{T_v} t = \frac{2D_v(p_v - S_v)}{Y_v t_v \mu_v v_v} \tag{11}$$

(4) Other costs I_v, such as interest, insurance, and tax. Usually, the recovered waste heat can receive government subsidies or tax exemption. On average, costs I_v is equal to the product of the costs i_v of interest, insurance, and tax per vehicle per unit time and the time t for each vehicle to transport waste heat from the recovery site to the destination, wherein i_v is the product of the average annual investment cost and the share σ of interest, insurance, and tax.

$$i_v = \frac{\frac{p_v - S_v}{Y_v} \frac{Y_v + 1}{2} + S_v}{t_v \mu_v} \tag{12}$$

From Eq. (12), it can be obtained:

$$I_v = i_v \sigma t = \frac{\left(\frac{p_v - S_v}{Y_v} \frac{Y_v + 1}{2} + S_v\right)\sigma}{t_v \mu_v} \frac{2D_v}{v_v} = 2\frac{(p_v - S_v)\frac{Y_v + 1}{2} + S_v Y_v}{Y_v t_v \mu_v v_v} D_v \sigma \tag{13}$$

(5) Vehicle maintenance cost W_v. The average maintenance cost per vehicle per delivery can be expressed as the product of the maintenance cost per unit time and the time t. w_v is the repair and maintenance rate (%) of the vehicle.

$$W_v = \frac{(p_v - S_v) w_v}{Y_v t_v \mu_v} t = \frac{2D_v w_v (p_v - S_v)}{Y_v t_v \mu_v v_v} \tag{14}$$

To sum up, substitute Eqs. (9)–(14) into Eq. (8) respectively, then the total cost per vehicle for transporting recovered waste heat from the supplying place to the destination is c_T.

$$\begin{aligned} c_T &= F_v + R_v + A_v + I_v + W_v \\ &= 2D_v\left[\frac{p_o}{d_v} + \frac{r_v}{v_v} + \frac{(p_v - S_v)\left(1 + \frac{Y_v + 1}{2}\sigma + w_v\right) + S_v Y_v \sigma}{Y_v t_v \mu_v v_v}\right] \end{aligned} \tag{15}$$

From Eqs. (6), (7), and (15), C_3 can be expressed as

$$\begin{aligned} C_3 &= c_v Q_D = \frac{c_T}{\eta_v} Q_D \\ &= 2\left[\frac{p_o}{d_v} + \frac{r_v}{v_v} + \frac{(p_v - S_v)\left(1 + \frac{Y_v + 1}{2}\sigma + w_v\right) + S_v Y_v \sigma}{Y_v t_v \mu_v v_v}\right] \frac{D_v Q_D}{\eta_v} \end{aligned} \tag{16}$$

3.2.4. Penalty cost

Recovered waste heat is usually subject to a high energy loss rate with the increase of distribution distance. When the supply of thermal energy fails to meet the demand of end-users, the investors may lose potential income and face additional transaction costs. This process can be expressed as the following equation:

$$C_4 = \omega \frac{(Q_s - Q_D)}{D_v} \tag{17}$$

3.2.5. Cost of mobile WHR supply chain

Substitute Eqs. (2), (5), (16), and (17) into Eq. (1), then the total cost of centralized mobile C is

$$\begin{aligned} C &= C_1 + C_2 + C_3 + C_4 \\ &= c_s Q_s + \frac{A_e + r_e + W_e + p_0}{\eta_e} Q_D \\ &\quad + 2\left[\frac{p_o}{d_v} + \frac{r_v}{v_v} + \frac{(p_v - S_v)\left(1 + \frac{Y_v + 1}{2}\sigma + w_v\right) + S_v Y_v \sigma}{Y_v t_v \mu_v v_v}\right] \\ &\quad \times \frac{D_v Q_D}{\eta_v} + \omega \frac{(Q_s - Q_D)}{D_v} \end{aligned} \tag{18}$$

3.3. Cost model of mobile WHR supply chain network

3.3.1. Model hypothesis

Without changing the nature of the problem, this study simplifies some complex conditions and makes the following assumptions about the model:

(1) Due to restrictions on professional technology and money, the WHR market is an oligopoly competitive market, in which the supplier and distributor coordinate with each other to make decisions and together set the quality level and unit price of WHR to maximize the profit.
(2) This study develops a supply chain system with a single WHR supplier, a single WHR distributor, and a single heat consumer group.
(3) In the centralized WHR model, according to limitations on current mobile WHR equipment and heat-releasing rate, the distributor in the process of recycling, mobile distributing and heat-releasing, assuming the delivery time and routes are under ideal conditions, the allowable heat consumption α is less than or equal to 18 percent ($\alpha \leq 18\%$). Set the value α equal to 17 percent ($\alpha = 17\%$).
(4) WHR is easy to lose heat. The dissipated heat increases as the delivery time and distance increase. If the heat supplied cannot meet the needs of heat consumers due to the heat loss in the process of recycling, delivering and releasing, enterprises will lose an opportunity for a deal, which brings the extra deal opportunity cost. In this study penalty cost (ω) equals \$4.23.
(5) The sum of waste heat production Q_s and final recovery amount Q_s^{π} of each day is greater than or equal to the sum of waste heat order Q_D in the market and the final distribution amount Q_D^{π} of each day.

$$Q_s - Q_D + Q_s^{\pi} - Q_D^{\pi} \geq 0 \tag{19}$$

In the centralized mobile WHR model, thermal energy loss α allowed in the process of recovery, mobile distribution, and heat release are less than or equal to 18 percent ($\alpha \leq 18\%$). The target profit π_s^m of the supply chain is greater than or equal to the product Q_s of the unit price of mobile WHR multiplies the recovery amount p_s minus the total cost of the mobile WHR network. To obtain the maximum profit for the company, the total cost of the mobile WHR network should be minimized.

$$\pi_s^m \geq p_s Q_s - C \tag{20}$$

The product of the capacity consumption rate R_s^g of per unit mobile, WHR multiplies the amount Q_s of recovery is less than or equal to the maximum available production capacity G_s^{max} of mobile WHR.

$$R_s^g Q_s \leq G_s^{max} \tag{21}$$

The product of mobile heating capacity consumption rate R_v^g per unit recovered waste heat multiplies the demand Q_D of recovered waste heat is less than or equal to the maximum available loading capacity η_v^{max}.

$$R_v^g Q_D \leq \eta_v^{max} \tag{22}$$

3.3.2. Objective function and constrains

Based on the analysis of Eq. (18), the objective function of the mobile WHR can be formulated as

$$\begin{aligned} minC = c_s Q_s + \frac{A_e + r_e + W_e + p_0}{\eta_e} Q_D & \\ + 2\left[\frac{p_o}{d_v} + \frac{r_v}{v_v} + \frac{(p_v - S_v)\left(1 + \frac{Y_v+1}{2}\sigma + w_v\right) + S_v Y_v \sigma}{Y_v t_v \mu_v v_v}\right] & \\ \times \frac{D_v Q_D}{\eta_v} + \omega \frac{(Q_s - Q_D)}{D_v} & \end{aligned} \tag{23}$$

From Eq. (23),

$$\begin{aligned} \frac{\partial C}{\partial D_v} = 2\left[\frac{p_o}{d_v} + \frac{r_v}{v_v} + \frac{(p_v - S_v)\left(1 + \frac{Y_v+1}{2}\sigma + w_v\right) + S_v Y_v \sigma}{Y_v t_v \mu_v v_v}\right] & \\ \times \frac{Q_D}{\eta_v} - \frac{\omega(Q_s - Q_D)}{D_v^2} & \end{aligned} \tag{24}$$

According to Hessian Matrix Theory,

$$\frac{\partial^2 C}{\partial D_v^2} = \frac{2D_v^2 \omega(Q_s - Q_D)}{D_v^4} > 0$$

the objective function C is the strictly convex function of heat-supply distance D_v, thus the best distance can be calculated in centralized decision making.

$$D_v^* = \sqrt{\frac{\omega(Q_s - Q_D)}{2\left[\frac{p_o}{d_v} + \frac{r_v}{v_v} + \frac{(p_v - S_v)\left(1 + \frac{Y_v+1}{2}\sigma + w_v\right) + S_v Y_v \sigma}{Y_v t_v \mu_v v_v}\right]\frac{Q_D}{\eta_v}}} \tag{25}$$

Under the constraints (19)–(22), the minimum cost C_{min}^* of mobile WHR network for the purchase cost, pre-treatment cost, and distribution cost to reach equilibrium.

$$\begin{aligned} C_{min}^* = c_s Q_s + \frac{A_e + r_e + W_e + p_0}{\eta_e} Q_D & \\ + 2\left[\frac{2}{\eta_v} Q_D \omega(Q_s - Q_D)\right]^{\frac{1}{2}} & \\ \times \left[\frac{p_o}{d_v} + \frac{r_v}{v_v} + \frac{(p_v - S_v)\left(1 + \frac{Y_v+1}{2}\sigma + w_v\right) + S_v Y_v \sigma}{Y_v t_v \mu_v v_v}\right]^{\frac{1}{2}} & \end{aligned} \tag{26}$$

From Eq. (26),

$$\frac{\partial C_{min}^*}{\partial \eta_e} = -\frac{A_e + r_e + W_e + p_0}{\eta_e^2} Q_D \tag{27}$$

According to Hessian Matrix Theory,

$$\frac{\partial^2 C_{min}^*}{\partial \eta_e^2} = \frac{2Q_D(A_e + r_e + W_e + p_0)}{\eta_e^2} > 0 \tag{28}$$

the objective function C_{min}^* is the strictly convex function of Hourly production rate of WHR equipment η_e.

$$\begin{aligned} \frac{\partial C_{min}^*}{\partial r_v} = \frac{1}{v_v}\left[\frac{2}{\eta_v} Q_D \omega(Q_s - Q_D)\right]^{\frac{1}{2}} & \\ \times \left[\frac{p_o}{d_v} + \frac{r_v}{v_v} + \frac{(p_v - S_v)\left(1 + \frac{Y_v+1}{2}\sigma + w_v\right) + S_v Y_v \sigma}{Y_v t_v \mu_v v_v}\right]^{-\frac{1}{2}} & \end{aligned}$$

According to Hessian Matrix Theory,

$$\begin{aligned} \frac{\partial^2 C_{min}^*}{\partial r_v^2} = -\frac{1}{2v_v^2}\left[\frac{2}{\eta_v} Q_D \omega(Q_s - Q_D)\right]^{\frac{1}{2}} & \\ \times \left[\frac{p_o}{d_v} + \frac{r_v}{v_v} + \frac{(p_v - S_v)\left(1 + \frac{Y_v+1}{2}\sigma + w_v\right) + S_v Y_v \sigma}{Y_v t_v \mu_v v_v}\right]^{-\frac{3}{2}} & \\ < 0 & \end{aligned} \tag{29}$$

the objective function C_{min}^* is the strictly convex function of Hourly labor cost r_v.

And

$$\frac{\partial C_{min}^*}{\partial p_o} = \frac{Q_D}{\eta_e} + \frac{\left[2\frac{Q_D}{\eta_v}\omega(Q_s - Q_D)\right]^{\frac{1}{2}}}{d_v\left[\frac{p_o}{d_v} + \frac{r_v}{v_v} + \frac{(p_v - S_v)\left(1 + \frac{Y_v+1}{2}\sigma + w_v\right) + S_v Y_v \sigma}{Y_v t_v \mu_v v_v}\right]^{\frac{1}{2}}}$$

According to Hessian Matrix Theory,

$$\frac{\partial^2 C_{min}^*}{\partial p_o^2} = -\frac{1}{2d_v^2}[2\frac{Q_D}{\eta_v}\omega(Q_s - Q_D)]^{\frac{1}{2}} \times [\frac{p_o}{d_v} + \frac{r_v}{v_v} + \frac{(p_v - S_v)\left(1 + \frac{Y_v+1}{2}\sigma + w_v\right) + S_vY_v\sigma}{Y_vt_v\mu_v v_v}]^{-\frac{3}{2}} < 0 \tag{30}$$

the objective function C_{min}^* is the strictly convex function of the unit price of the fuel p_o.

Assume that each mobile thermal vehicle has a load of Q_w and exotherms at a speed v_e for T hours, the end-user can receive the heat of $\frac{Tv_e}{Q_e}Q_w$. The minimum cost C_{min}^* of continuous heating for T hours is

$$C_{min}^* = \frac{Q_e}{Tv_eQ_w}\{c_sQ_s + \frac{A_e + r_e + W_e + p_0}{\eta_e}Q_D + 2[\frac{2}{\eta_v}Q_D\omega(Q_s - Q_D)]^{\frac{1}{2}} \times [\frac{p_o}{d_v} + \frac{r_v}{v_v} + \frac{(p_v - S_v)\left(1 + \frac{Y_v+1}{2}\sigma + w_v\right) + S_vY_v\sigma}{Y_vt_v\mu_v v_v}]^{\frac{1}{2}}\} \tag{31}$$

From Eq. (31)

$$\frac{\partial C_{min}^*}{\partial v_e} = -\frac{Q_e}{Tv_e^2Q_w}\{c_sQ_s + \frac{A_e + r_e + W_e + p_0}{\eta_e}Q_D + 2[\frac{2}{\eta_v}Q_D\omega(Q_s - Q_D)]^{\frac{1}{2}} \times [\frac{p_o}{d_v} + \frac{r_v}{v_v} + \frac{(p_v - S_v)\left(1 + \frac{Y_v+1}{2}\sigma + w_v\right) + S_vY_v\sigma}{Y_vt_v\mu_v v_v}]^{\frac{1}{2}}\} \tag{32}$$

According to Hessian Matrix Theory,

$$\frac{\partial^2 C_{min}^*}{\partial v_e^2} = \frac{Q_e}{Tv_e^4Q_w}\{c_sQ_s + \frac{A_e + r_e + W_e + p_0}{\eta_e}Q_D + 2[\frac{2}{\eta_v}Q_D\omega(Q_s - Q_D)]^{\frac{1}{2}} \times [\frac{p_o}{d_v} + \frac{r_v}{v_v} + \frac{(p_v - S_v)\left(1 + \frac{Y_v+1}{2}\sigma + w_v\right) + S_vY_v\sigma}{Y_vt_v\mu_v v_v}]^{\frac{1}{2}}\} > 0 \tag{33}$$

the objective function C_{min}^* is the strictly convex function of the rate v_e of waste heat collection and release.

The average demand $\overline{Q_D}$ of suppliers and distributors is

$$\overline{Q_D} = \frac{\sum Q_D D_v}{\sum D_v} \tag{34}$$

Average distance $\overline{D_v}$ of mobile WHR from supply site to the customer is

$$\overline{D_v} = \frac{\sum Q_D D_v}{\sum Q_D} \tag{35}$$

Then, the average cost $\overline{C}$ of mobile WHR supply chain is

$$\overline{C} = c_sQ_s + \frac{(A_e + r_e + W_e + p_0)}{\eta_e}\frac{\sum Q_D D_v}{\sum D_v} + 2[\frac{p_o}{d_v} + \frac{r_v}{v_v} + \frac{(p_v - S_v)\left(1 + \frac{Y_v+1}{2}\sigma + w_v\right) + S_vY_v\sigma}{Y_vt_v\mu_v v_v}] \times \frac{(\sum Q_D D_v)^2}{\sum D_v \sum Q_D \eta_v} + \omega\frac{(Q_s - \frac{\sum Q_D D_v}{\sum D_v})}{\overline{D_v}} \tag{36}$$

From Eq. (36)

$$\frac{\partial \overline{C}}{\partial \eta_e} = -\frac{A_e + r_e + W_e + p_0}{\eta_e^2}\frac{\sum Q_D D_v}{\sum D_v} \tag{37}$$

According to Hessian Matrix Theory,

$$\frac{\partial^2 \overline{C}}{\partial \eta_e^2} = \frac{2Q_D(A_e + r_e + W_e + p_0)}{\eta_e^2} > 0 \tag{38}$$

the objective function $\overline{C}$ is the strictly convex function of the hourly production rate of WHR equipment η_e.

If the customers have continuous demand during T hours, the average amount $\overline{Q_D^T}$ of heat required is

$$\overline{Q_D^T} = \frac{\sum Q_D^T D_v}{\sum D_v} \tag{39}$$

Continuous heating cost in T hours $\overline{C^T}$ is:

$$\overline{C^T} = c_sQ_s^T + \frac{(A_e + r_e + W_e + p_0)}{\eta_e}\frac{\sum Q_D^T D_v}{\sum D_v} + 2\left[\frac{p_o}{d_v} + \frac{r_v}{v_v} + \frac{(p_v - S_v)\left(1 + \frac{Y_v+1}{2}\sigma + w_v\right) + S_vY_v\sigma}{Y_vt_v\mu_v v_v}\right] \times \frac{\overline{D_v}\sum Q_D^T D_v}{\eta_v \sum D_v} + \omega\frac{(Q_s^T - \frac{\sum Q_D^T D_v}{\sum D_v})}{\overline{D_v}} \tag{40}$$

Assume that each mobile thermal vehicle has a load of Q_w and exotherms at a speed v_e for T hours, the end-user can receive the heat of $\frac{Tv_e}{Q_D^T}Q_w$. The average unit cost $\overline{C_{v_e}^T}$ of continuous heating for T hours is

$$\overline{C_{v_e}^T} = \frac{\overline{C^T}}{\frac{Tv_e}{Q_D^T}Q_w} = \frac{Q_D^T}{Tv_eQ_w}\{c_sQ_s^T + \frac{(A_e + r_e + W_e + p_0)}{\eta_e}\frac{\sum Q_D^T D_v}{\sum D_v} + 2\left[\frac{p_o}{d_v} + \frac{r_v}{v_v} + \frac{(p_v - S_v)\left(1 + \frac{Y_v+1}{2}\sigma + w_v\right) + S_vY_v\sigma}{Y_vt_v\mu_v v_v}\right] \times \frac{\overline{D_v}\sum Q_D^T D_v}{\eta_v \sum D_v} + \omega\frac{(Q_s^T - \frac{\sum Q_D^T D_v}{\sum D_v})}{\overline{D_v}}\} \tag{41}$$

From Eq. (41)

$$\frac{\partial \overline{C_{v_e}^T}}{\partial v_e} = -\frac{Q_D^T}{Tv_e^2Q_w}\{c_sQ_s^T + \frac{(A_e + r_e + W_e + p_0)}{\eta_e}\frac{\sum Q_D^T D_v}{\sum D_v} + 2\left[\frac{p_o}{d_v} + \frac{r_v}{v_v} + \frac{(p_v - S_v)\left(1 + \frac{Y_v+1}{2}\sigma + w_v\right) + S_vY_v\sigma}{Y_vt_v\mu_v v_v}\right] \times \frac{\overline{D_v}\sum Q_D^T D_v}{\eta_v \sum D_v} + \omega\frac{(Q_s^T - \frac{\sum Q_D^T D_v}{\sum D_v})}{\overline{D_v}}\} \tag{42}$$

According to Hessian Matrix Theory,

$$\frac{\partial^2 \overline{C_{v_e}^T}}{\partial v_e^2} = \frac{Q_D^T}{Tv_e^4Q_w}\{c_sQ_s^T + \frac{(A_e + r_e + W_e + p_0)}{\eta_e}\frac{\sum Q_D^T D_v}{\sum D_v} + 2\left[\frac{p_o}{d_v} + \frac{r_v}{v_v} + \frac{(p_v - S_v)\left(1 + \frac{Y_v+1}{2}\sigma + w_v\right) + S_vY_v\sigma}{Y_vt_v\mu_v v_v}\right] \times \frac{\overline{D_v}\sum Q_D^T D_v}{\eta_v \sum D_v} + \omega\frac{(Q_s^T - \frac{\sum Q_D^T D_v}{\sum D_v})}{\overline{D_v}}\} > 0 \tag{43}$$

the objective function $\overline{C_{v_e}^T}$ is the strictly convex function of the rate v_e of waste heat collection and release.

3.3.3. Equilibrium analysis

Lemma 1. *Cost is sensitive to changes in production capacity η_e.*

With all conditions unchanged, from Eqs. (28), and (38), we can obtain: equilibrium cost C^*_{min}, average cost $\overline{C^T_{v_e}}$ are the strictly convex functions of *production capacity* η_e.

From Eqs. (27), (28), (37), and (38), we can obtain: With the processing capacity η_e increases, the supply chain cost declines. The storage capacity of the vehicle negatively affects the cost the whole mobile WHR supply chain. During the distribution of energy, with the deletion of energy in the heat storage vehicle, the quality of heat will decline. By improving the storage capacity, the quality of heat can be ensured and the penalty cost will also be reduced.

Lemma 2. *The rate v_e of waste heat collection and release are the reciprocal to the cost C.*

With all conditions unchanged, from Eqs. (33), and (41), we can obtain: equilibrium cost C^*_{min} and average cost during time T $\overline{C}$ *and* $\overline{C^T_{v_e}}$ are the strictly convex functions of *the rate v_e of waste heat collection and release.*

From Eqs. (31), (32), (39), and (40), we can obtain: With the *rate v_e of waste heat collection and release* increases, the supply chain cost declines. Improving the heat collection and release rate can effectively reduce the loss of energy during transportation. With a higher quality of thermal energy, the profit of the mobile WHR supply chain will increase.

Lemma 3. *The labor cost r_e is proportional to the average cost $\overline{C}$ of WHR.*

With all conditions unchanged, from Eqs. (29), and (30), we can obtain: the phenomenon that should happen in production function model happens in cost function model: the objective function C is the strictly convex functions of the fuel prices p_o and labor cost prices r_v.

From Lemmas 1 and 2, the average cost of mobile WHR is sensitive to the fuel prices and labor cost prices. When hourly labor expenses rise, the average cost of mobile WHR will also increase.

Under the circumstances of perfect competition and maximization of profit, the production function in an economic system is:

$$Y = f(L, K, \ldots\ldots) \tag{44}$$

In Eq. (44), Y represents output; L represents labor input; K represents capital input and other inputs. To simplify the model, other inputs will not be discussed here. Therefore, from the following equation

$$dY = \cdot\frac{\partial f}{\partial L}dL + \frac{\partial f}{\partial K}dK \tag{45}$$

We can get Eq. (46)

$$\frac{dY}{Y} = \frac{\partial f}{\partial L}\cdot\frac{L}{f}\cdot\frac{dL}{L} + \frac{\partial f}{\partial K}\cdot\frac{K}{f}\cdot\frac{dK}{K} \tag{46}$$

In Eq. (46), $\frac{\partial f}{\partial L}\cdot\frac{L}{f}$ is Y's labor flexibility; $\frac{\partial f}{\partial K}\cdot\frac{K}{f}$ is Y's capital flexibility. So the above equation can be simplified as Eq. (47)

$$\frac{dY}{Y} = \alpha_L\cdot\frac{dL}{L} + \alpha_k\cdot\frac{dK}{K} \tag{47}$$

American economist M. Abramovitz pointed out as early as 1956.

$$\frac{dY}{Y} > \alpha_L\cdot\frac{dL}{L} + \alpha_k\cdot\frac{dK}{K}.$$

He believed that another power that the improvement of production rate contributed to the increase of output made production function move upwards. As for the WHR system, the equation is as follows:

$$\begin{aligned}&\text{production rate of WHR supply chain}\\&\quad= \frac{\text{system total output } Y}{\text{total inputCof production factors (including labor cost and fuel cost)}}.\end{aligned}$$

That production function in a production system moves upwards shows the advancement of technology, and this movement helps the production system to get the same output as previous with less input or to obtain more output with the same input as previously. Therefore,

$$\begin{aligned}&\textit{production capacity of WHR}\\&\quad= \textit{technology} \times (\textit{laborer} + \textit{the means of labor} + \textit{subject of labor}).\end{aligned}$$

The increase in production capacity depends mainly on technology. Whatever the capital input and labor input are in a production system, the higher the technology efficiency is, the larger its output is, and the lower unit cost is.

Therefore, to mitigate the impacts of growing average cost, the centralized mobile WHR network should improve its production capacity η_e, the heat release rate v_e, and other relevant technologies. From Lemmas 1 and 2, the average cost of mobile WHR is sensitive to the fuel prices and labor cost prices. When hourly labor expenses rise, the average cost of mobile WHR will also increase.

4. Case study of validation

4.1. Basic information

To assess the effectiveness of the proposed model, this section selected a typical mobile WHR supply chain to conduct a cost–benefit analysis. As the market condition varies over time, this study randomly selected 10 typical scenarios of an industrial heat generating company as a case study. From Eqs. (34) and (35), the relevant parameters of the scenarios are shown in Table 1. These data were provided by QINGDAO AOHUAN NEW ENERGY CO., LTD in 2018 [CN/CN]

In the model, the cost of the supply chain is jointly affected by suppliers and distributors. The price p of per unit heating is determined by them who can maximize the total supply chain profit for both parties. For all scenarios, industrial waste heat is used to heat 25 °C tap water to 65 °C to store thermal energy. Assume the waste heat distributor uses a 9 M container, which can transport 19×10^6 kJ(130 t) waste heat (equivalent to $\eta_v = 19$ GJ per car). If it assumes the capital investment for the WHR treatment facility is $p_v = \$71011.63$ and the life cycle is 20 years, the equivalent unit investment cost is $A_e = \$0.41/\text{h}$. The maintenance cost of the facility is $w_e = \$0.20/\text{h}$. Assume a mobile heat storage vehicle travels 9 h a day, and then it travels $t_v = 3285$ h per year. Thermal energy loss α allowed by distributors in the process of recovery, mobile distribution, and heat release is usually less than 18%. Other parameters are listed in Table 2 for reference. Data from qdaohuan (2018).[1]

4.2. Sensitivity analysis of related factors under different conditions

The sensitivity analysis was conducted to assess the impact of external factors on the optimization results.

---

[1] The Detail Introduction of the Company can be seen on the web page: http://www.qdaohuan.com.

Table 1
Thermal energy demand scenarios.

	S1	*S2*	*S3*	*S4*	*S5*	*S6*	*S7*	*S8*	*S9*	*S10*
Q_D (GJ)	162.5	165.4	168.5	169.2	186.9	188.5	189.1	191.0	193.3	198.6
D_v (GJ)	13.54	15.3	15.31	16.84	17.9	18.95	19.08	19.32	19.66	19.76
$\overline{Q_D}$ (GJ)	182.78									
$\overline{D_v}$ (GJ)	17.71									
α	0.15	0.15	0.16	0.16	0.17	0.17	0.17	0.18	0.18	0.18
Q_s (GJ)	191.1	194.6	200.7	201.5	225.1	227.1	227.8	232.9	235.7	242.2
No. of vehicles	9	9	9	9	10	10	10	11	11	11

Table 2
Supply chain system parameters of the case study.

Parameter	Value
η_e	25 GJ/hol
v_v	100 km/h
μ_v	90%
ω	$4.23
p_o	$1.07/l
η_v	19 GJ per car
w_v	90%
σ	10%
S_v	0

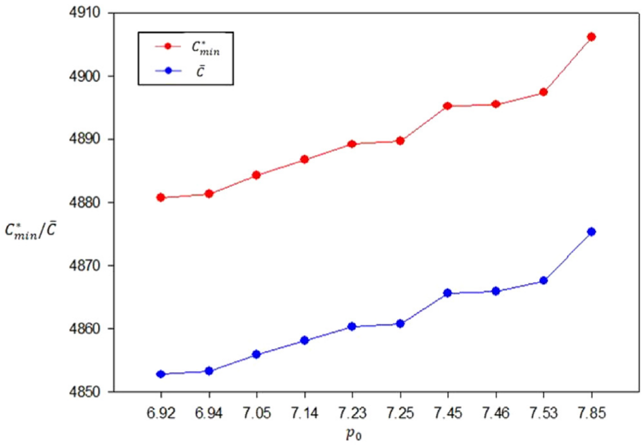

Fig. 1. Fuel price and average cost.

(1) **Fuel price.** In the centralized mobile WHR network, fuel contributes to the major cost of energy production and distribution. Fluctuations in fuel prices can inevitably lead to changes in cost. As it can be seen in Fig. 1, when the fuel price rises from $0.98/day to $1.11/day, the average cost will increase from $693.17/day to $696.78/day. The average cost and the minimal cost will rise with the increase in fuel price, and $\overline{C} > C^*_{min}$.

(2) **Labor cost.** Figs. 2, 3 shows 10 samples with hourly labor cost for heat recovery r_e and distribution hourly labor cost r_v. $\overline{C}$ and C^*_{min} are related to both r_v *and* r_e. When r_e increases from $2.89/h to $7.04/h and r_v increases from $1.52/h to $5.66/h, the optimized cost rises from $706.48/day to $750.98/day. The average cost and the minimal cost increase with the increase in labor cost, and $\overline{C} > C^*_{min}$.

(3) **Production capacity.** As are shown in Eqs. (26), and (36), with the increase of the heat recovery capacity η_e, the costs decrease. In Fig. 4, when η_e increases from 26.79 GJ/h to 39.48 GJ/h, the average cost will decrease from $693.91/day to $687.12/day.

(4) **Heat release rate.** As is shown in Table 3, the average cost decreases with the increase in heat release rate. It shows that the higher the heat release rate, the lower the loss due to the energy quality depreciation.

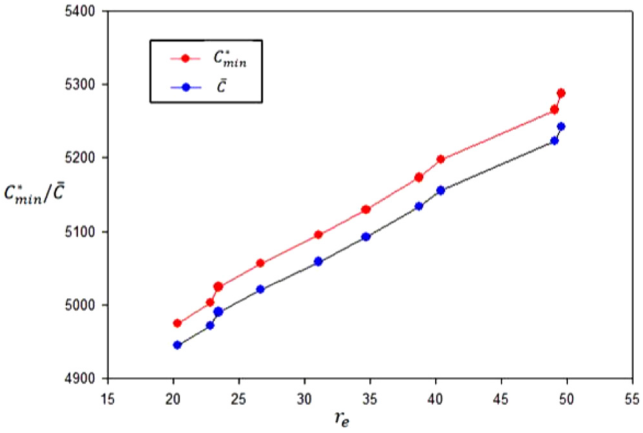

Fig. 2. Labor costs r_e and costs.

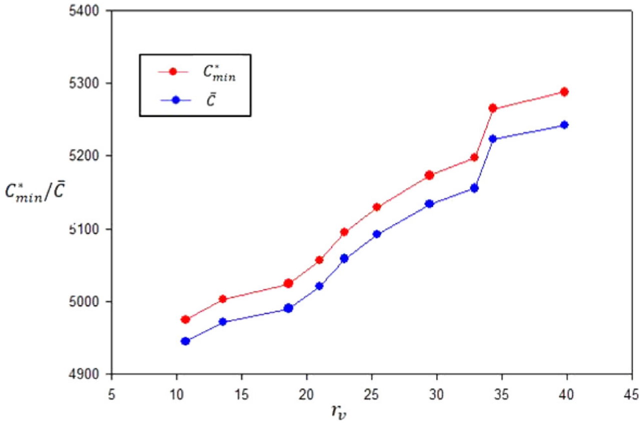

Fig. 3. Labor costs and costs r_v.

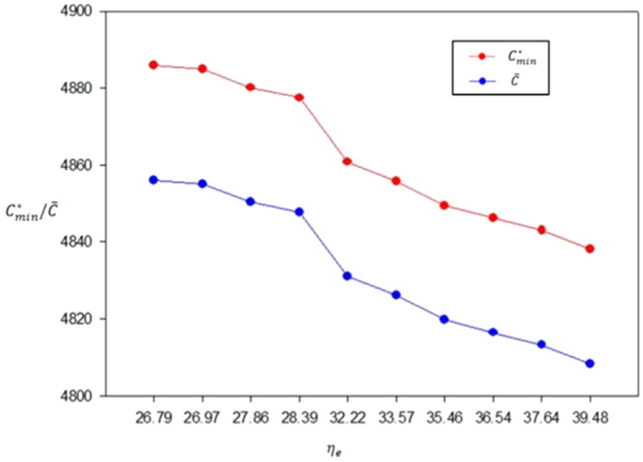

Fig. 4. Production capacity η_e and costs.

Table 3
Heat release rate and average cost.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Heat release rate (t/h)	45	50	55	60
Q_D (GJ/day)	171	190	210	228
Minimum cost ($/GJ)	5.08	4.57	4.13	3.80
Average cost ($/GJ)	5.08	4.58	4.15	3.74

4.3. Model solving

Incorporate the related inputs into the mobile WHR supply chain network and assume the WHR and release rate is $v_e = 50t/\text{h}$. If the heat energy loss rate is and daily energy production is $Q_s = 225.10$ GJ/day. When the fuel price is $1.07/GJ liter, and then $r_e = r_v = \$1.42(10\ \text{yuan})/\text{h}$. In this sample case, the average demand of thermal energy is 182.78 GJ and average distance of distributing waste heat is 17.71 km.

Based on Eq. (36), the average cost of the centralized mobile WHR network $\overline{C} = \$872.70/\text{day}$. With Eq. (40), the cost of delivery cost $\overline{C}^{T} = \$3.14/\text{GJ}$. Based on Eq. (25), the optimal distance $D_v^* = 15$ km for the purchase cost, pre-treatment cost, the distribution cost, and the penalty cost to reach equilibrium can be obtained. Similarly, from Eq. (31), the minimum cost of mobile WHR network from the supply site to the end-users is $C^*_{\text{min}} = \$867.86/\text{day} < \overline{C} = \$872.70/\text{day}$. Suppose the price for the recovered heat is $5.68/GJ, then the profit π_D is

$$\pi_D = (p_D - p_s)Q_D - \overline{C} = (100 - 40) \times 182.78 - 6144.74$$
$$= \$684.84/\text{day}$$

In the centralized mobile WHR supply chain network, the target profit π_s^m of the distributor is

$$\pi_s^m = p_s Q_s - C_s Q_s = (40 - 20) \times 220.22 = \$625.53/\text{day}$$

To obtain the maximum profit, the total cost C should be minimized with

$$\pi_D^* = (p_D - p_s)Q_D - c^* = (100 - 40) \times 182.78 - 6110.72$$
$$= \$689.68/\text{day}$$

Accordingly, the cost of WHR for the entire supply chain from recovery to delivery is $C^{T*}_{min} = \$3.12/\text{GJ}$. Assume the daily demand of the company for waste heat is 182.78 GJ. The energy needed for using recovered waste heat to heat room temperature water from 25 °C to 65 °C is equivalent to that of 6.26 t of standard coal. If they use recovered waste heat to replace regular electricity from the grid, it can save $8650.88 per day.

5. Conclusion

This study analyzes the cost structure of the mobile WHR supply chain network and proposes an optimization model based on the centralized mobile WHR supply chain. A sensitive analysis concludes the main factors that affect the cost of energy distribution. Based on the propositions, this study suggested three major conclusions. First, improving mobile WHR production capacity and waste heat collection/release rate can not only satisfy the users' demand but also improve the total profits. Fluctuations in the market fuel price and labor price can result in variation in the average cost. By improving the storage capacity, the quality of heat can be ensured and the penalty cost will also be reduced. Through improving the heat quality can ensure the profitability of the mobile WHR network when labor wages increase. Second, in the supply chain, both the supplier and distributor jointly determine the quality of the market price of the heat recovery system. Recovering surplus heat from the generation site can create additional income for suppliers and foster a market to use thermal energy at a lower price. Also, the recovered heat is clean and sustainable. Using recovered waste heat to heat room temperature water from 25 °C to 65 °C, it can save 6.26 t of standard coal. Third, compared with conventional coal-fired, electric, and natural gas boilers, mobile heat storage vehicles are more cost-effective. Due to unstable industrial waste heat quality and scattered recovery and discharge destinations, building an energy pipeline is rather expensive. Therefore, when the distance is shorter than 20 km, the mobile heating vehicle is the best choice for investment.

Based on the above conclusions, this study would provide two recommendations: (1) Improving heat recovery efficiency of the green supply chain, discharge temperature, and heat preservation can effectively reduce the minimum cost of $867.86/day. (2) The selection of green supply chain distribution routes also should be optimized to ensure the thermal energy supply within the effective distribution distance.

CRediT authorship contribution statement

Jing Yang: Conceptualization, Writing - original draft, Methodology. **Jiayu Chen:** Writing - review & editing, Validation. **Zhiyong Zhang:** Supervision. **Ming Hong:** Visualization, Data curation. **Han Li:** Investigation. **Yilong Li:** Software, Investigation. **Mingwan Yang:** Methodology, Formal analysis.

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.

Acknowledgments

This work is supported by Guangzhou the 13th Five-Year Plan for the Development of Philosophy and Social Science Program (2019GZYB71), by Guangzhou Science and Technology Innovation and Development Special Fund Project (201904010403), and by Guangdong Industry Polytechnic Program (JG201820) (KJ2019-017).

References

Abramovitz, M., 1956. Resources and Output Trends in the United States Since 1870, American Economic Review. In: Papers and Proceedings of the Sixty-eighth Annual Meeting of the American Economic Association, vol. 5, pp. 5–23. http://dx.doi.org/10.1080/00346765700000016.

Ahmet, K., Oztopb, H.F., Tansel, K., 2008. Energy and exergy analysis of a latent heat storage system with phase change material for a solar collector. Renew. Energy 33, 567–574. http://dx.doi.org/10.1016/j.renene.2007.03.012.

Amir, Mohammad Fathollahi-Fard, Guangdong, Tian, zhiwu, Li, Hua, Ke, 2019a. A multi-objective supplier selection and order allocation through incremental discount in a fuzzy environment. J. Intell. Fuzzy Systems http://dx.doi.org/10.33233/JIFS-182843.

Amir, Mohammad Fathollahi-Fard, Kannan, Govindan, Mostafa, Hajiaghaei-Keshteli, Abbas, Ahmadi, 2019b. A green home health care supply chain: New modified simulated annealing algorithms. J. Cleaner Prod. 240, 118200. http://dx.doi.org/10.1016/j.jclepro.2019.118200.

Amir, Mohammad Fathollahi-Fard, Mehdi, Ranjbar-Bourani, Naoufel, Cheikhrouhou, Mostafa, Hajiaghaei-Keshteli, 2019c. Novel modifications of social engineering optimizer to solve a truck scheduling problem in a cross-docking system. Comput. Ind. Eng. 137, 106103. http://dx.doi.org/10.1016/j.cie.2019.106103.

Amir, Mohammad Fathollahi-Fard, Mostafa, Hajiaghaei-Keshteli, Guangdong, Tian, Zhiwu, Li, 2020. An adaptive Lagrangian relaxation-based algorithm for a coordinated water supply and wastewater collection network design problem. Inform. Sci. 512, 1335–1359. http://dx.doi.org/10.1016/j.ins.2019.10.062.

Anita Abdi, Andisheh, Abdi, Amir Mohammad, Fathollahi-Fard, Mostafa, Hajiaghaei-Keshteli, 2019. A set of calibrated metaheuristics to address a closed-loop supply chain network design problem under uncertainty. Int. J. Syst. Sci.: Oper. Logist. 1–18. http://dx.doi.org/10.1080/23302674.2019.1610197.

Chaturvedi, Nitin Dutt, Manan, Zainuddin Abdul Wan, Alwi, Sharifah Rafidah, Bandyopadhyay, Santanu, 2015. Maximising heat recovery in batch processes via product streams storage and shifting. J. Cleaner Prod. 112, 2802–2812. http://dx.doi.org/10.1016/j.jclepro.2015.10.076.

Debabrata, Ghosh, Janat, Shah, 2015. Supply chain analysis under green sensitive consumer demand and cost sharing contract. Int. J. Prod. Econ. 164, 319–329. http://dx.doi.org/10.1016/j.ijpe.2014.11.005.

Dincer, I., Rosen, M.A., 1998. A worldwide perspective on energy, environment and sustainable development. Int. J. Energy Res. 22 (15), 1305–1321, http://refhub.Elsevier.com/S1359-4311(18)30124-8/h0020.

Jinyue, Y., Bin, C., Wennersten, Ronald, Pietro, C., Jin, Y., 2017. Cleaner energy for transition of cleaner city. Appl. Energy 196, 97–99. http://dx.doi.org/10.1016/j.apenergy.2017.04.015.

Kostowski, W., Pajączek, K., Pociecha, A., Kalina, J., Niedzielski, P., Przybył, A., 2019. Methods of waste heat recovery – A compressor station case study. Energy Convers. Manage. 197, 111837. http://dx.doi.org/10.1016/j.enconman.2019.111837.

Li, C.B., Shi, H.Q., Cao, Y.J., Kuang, Y.H., Zhang, Y.G., Gao, D., Sun, L., 2015. Modeling and optimal operation of carbon capture from the air driven by intermittent and volatile wind power. Energy 87, 201–211. http://dx.doi.org/10.1016/j.energy.2015.04.098.

Mehranfar, N., Hajiaghaei-Keshteli, M., Fathollahi-fard, A.M., 2019. A novel hybrid whale optimization algorithm to solve a production-distribution network problem considering carbon emissions. Int. J. Eng. 32 (12), 1781–1789. http://dx.doi.org/10.5829/ije.2019.32.12c.11.

Nelson, Oliveira Stefanelli, Charbel, José Chiappetta Jabbour, Ana Beatriz Lopes, de Sousa Jabbour, 2014. Green supply chain management and environmental performance of firms in the bioenergy sector in Brazil: An exploratory survey. Energy Policy 75, http://dx.doi.org/10.1016/j.enpol.2014.06.019, 312-315.

Nguyen, T.L.T., Gheewala, S.H., 2008. Fossil energy, environmental and cost performance of ethanol in Thailand. J. Cleaner Prod. 16, 1814–1821. http://dx.doi.org/10.1016/j.jclepro.2007.12.009.

Ning, W., Ruifang, S., Zongguo, W., Djavan De, C., 2019. Life cycle energy efficiency evaluation for coal development and utilization. Energy 179, 1–11. http://dx.doi.org/10.1016/j.energy.2019.04.111.

Shrouf, F., Ordieres-Meré, J., García-Sánchez, A., Miguel, O., 2014. Optimizing the production scheduling of a single machine to minimize total energy consumption costs. J. Cleaner Prod. 67, 197–207. http://dx.doi.org/10.1016/j.jclepro.2013.12.024.

Shu, G., Liu, L., Tian, H., Haiqiao, Wei, Guopeng, Yu, 2014. Parametric and working fluid analysis of a dual-loop organic Rankine cycle (DORC) used in engine waste heat recovery. Appl. Energy 113, 1188–1198. http://dx.doi.org/10.1016/j.apenergy.2013.08.027.

Weilong Wang, Shaopeng, Guo, Hailong, Li, Jinyue, Yan, Jun, Zhao, Xun, Li, Jing, Ding, 2014. Experimental study on the direct_indirect contact energy storage container in mobilized thermal energy system (M-TES). Appl. Energy 116, 181–189. http://dx.doi.org/10.1016/j.apenergy.2013.12.058.

Westin, P., Lagergren, F., 2002. Re-regulating district heating in Sweden. Energy Policy. Energy Policy 30, 583–596. http://dx.doi.org/10.1016/s0301-4215(01)00126-4.

Wojciech, Kostowski, Krzysztof, Pajączek, Agnieszka, Pociecha, Jacek, Kalina, Piotr, Niedzielski, Adam, Przybył, 2019. Methods of waste heat recovery – A compressor station case study. Energy Convers. Manage. 197, 111837. http://dx.doi.org/10.1016/j.enconman.2019.111837.

Wu, J.Z., W.S., Lin, Wang, L.H., 2015. Application of fuel supply cost optimization model by stalk-burning power plants. Logist. Technol. 3, 257–261. http://dx.doi.org/10.3969/j.issn.1005-152X.2015.02.078.

Xi Wang, Hua, Cai, Keith Florig, H., 2016. Energy-saving implications from supply chain improvement: An exploratory study on China's consumer goods retail system. Energy Policy 2016 (95), 411–420. http://dx.doi.org/10.1016/j.enpol.2016.04.044.

Xu Liu, Guangdong, Tian, Amir Mohammad, Fathollahi-Fard, Mohammad, Mojtahedi, 2020. Evaluation of ship's green degree using a novel hybrid approach combining group fuzzy entropy and cloud technique for the order of preference by similarity to the ideal solution theory. Clean Technol. Environ. Policy 22, 493–512. http://dx.doi.org/10.1007/s10098-019-01798-7.

Yang, J., Zhiyong, Z., Mingyan, Y., Jiayu, C., 2019. Optimal operation strategy of green supply chain based on waste heat recovery quality. Energy 183, 599–605. http://dx.doi.org/10.1016/j.energy.2019.06.105.

Yi, H., Qun, Y., Guoqiang, W., Jingxian, K., Wenying, L., Jie, F., Kechang, X., 2018. Energy use, greenhouse gases emission and cost effectiveness of an integrated high– and low–temperature Fisher–Tropsch synthesis plant from a lifecycle viewpoint. Appl. Energy 228, 1008–1019. http://dx.doi.org/10.1016/j.apenergy.2018.07.007.

Yixiong Feng, zhifeng, Zhang, Guangdong, Tian, Amir Mohammad, Fathollahi-Fard, Nannan, Hao, Zhiwu, Li, Wenjie, Wang, Jianrong, Tan, 2019. A novel hybrid fuzzy grey TOPSIS method: Supplier evaluation of a collaborative manufacturing enterprise. Appl. Sci. 9 (18), 3770. http://dx.doi.org/10.3390/app9183770.