Zhao *et al. Carbon Neutrality* (2023) 2:19
https://doi.org/10.1007/s43979-023-00059-3

Carbon Neutrality

ORIGINAL ARTICLE **Open Access**

Techno-economic analysis of converting low-grade heat into electricity and hydrogen

Yanan Zhao[1], Mingliang Li[1], Rui Long[1*], Zhichun Liu[1] and Wei Liu[1]

Abstract

Low-grade heat recovery has received increasing attention as an essential contributor to improving overall energy utilization efficiency and facilitating the carbon neutrality commitment. Here, we developed a techno-economic analysis model of converting low-grade heat into electricity and hydrogen via the osmotic heat engine (OHE) and power-to-gas facility to alleviate the dilemma of lacking practical application scenarios of waste heat. The contribution margin is optimized in real time by either sending the electricity generated by the OHE into the electrolyzer for hydrogen production or selling it at market price in Wuhan, China, thus to identify the economically viable OHE costs under different conditions. Results show that the allowed heat engine cost is significantly impacted by the capacity factor, lifetime and discount rate. The effect of the capacity size of power-to-gas facility on allowed heat engine cost strongly depends on the hydrogen price. The allowed OHE cost increases with the elevating waste heat temperature for each heat transfer scenario. The hybrid energy system can be economically competitive compared with current mature technologies when the waste heat temperature is higher than 68 ℃ and 105 ℃ for fluid and air as heat transfer fluid, respectively. The economically viable heat engine cost is expected to gradually decline from 50,043 ¥/kW to 18,741 ¥/kW within next 15 years. Incentive policy would boost the economic viability of converting low-grade heat into electricity and hydrogen.

Keywords Low-grade heat conversion, Electricity generation, Hydrogen production, Energy economics

1 Introduction

It is estimated that around 50% of annual primary energy consumed is wasted in form of low-grade heat [1]. The vast low-grade heat discharged into the environment not only results in the waste of limited fossil energy, but also induces severe environmental problems [2, 3]. Furthermore, governments world-wide have stepped up the introduction of policies to tighten taxes and quotas related to pollution and carbon dioxide emissions, which would increase the economic pressure on traditional industries and stimulate the development of projects for reducing environmental deterioration [4].

Nowadays, low-grade heat recovery has received more and more attention as an essential contributor to improving energy efficiency and reducing carbon emissions [5, 6]. Low-grade heat can be widely obtained from factory waste heat, solar energy, biomass energy and geothermal energy [7]. However, due to the dispersive distribution of low-grade heat and the low temperature difference with the environment, there are significant technical difficulties in recovering low-grade heat [8, 9]. Organic Rankine cycle (ORC) and Kalina cycle are recognized mature technologies for converting low-grade heat into electricity, while the applicable temperature range is usually above 100 °C and their performance under lower temperature is unsatisfactory due to the little capacity of ultralow temperature heat to conduct work from the exergetic viewpoint [10, 11].

In recent years, osmotic heat engine (OHE) as a novel heat-to-electricity technology has been proposed and

---

*Correspondence:
Rui Long
r_long@hust.edu.cn
[1] School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, People's Republic of China

extensively studied [12]. The OHE is a closed-loop system consisting of a thermal separation process for thermally separating the brackish solution into high and low concentration solutions, and a power generation process for converting the Gibbs free energy of mixing the two solutions with different concentrations into electricity [13]. It can operate under ultra-low temperature of around 40 °C, which is superior to ORC and Kalina cycle [3]. Many efforts have been made on OHE research, highlighting the configuration optimization [14], working condition effects [15] and working fluid selection [16]. Olkis et al. [17] proposed an OHE combining adsorption desalination (AD) and reverse electrodialysis (RED), the optimization of salt and material selection is conducted. Zhao et al. [18] presented two different heat recovery configurations of the AD-RED osmotic heat engine to improve the thermal separation performance. They also comprehensively invstigated the effect of working conditions such as adsorption time, switching time, working concentration and working fluid mass on an AD-RED osmotic heat engine [19]. Hu et al. [20] presented an osmotic heat engine combining multiple-effect distillation (MED) and reverse electrodialysis (RED) and investigated the effect of configuration and operation parameters on system performance. Results indicated that the increase of working concentration, operating temperature and MED effects number contributed to system performance. An energy efficiency of 1.01% can be obtained with 10 effects and working solution of 5.40 mol/kg NaCl when operated under a heat source temperature of 80 ℃. Long et al. [21] presented an OHE consisting of membrane distillation (MD) and RED, an electricity efficiency of 1.15% is achieved with 5 mol/kg NaCl solution by optimizing the relative permeate/feed solution flow rate in MD. They also conducted a high-throughput computational screening of high-performance adsorbent for the adsorption-driven osmotic heat engines [22]. Giacalone et al. [23] first constructed and tested a fully operation prototype of a RED-NH_4HCO_3 thermolytic OHE and a continuous operation of over 55 h indicated the feasibility of such system. Nevertheless, the research on OHE is still in theoretical and laboratory testing stages and the practical application of electricity generated by OHE is still a knowledge gap and severely limited by intermittent power generation caused by unstable low-grade heat sources.

One remedy to alleviate the dilemma is to divert surplus electricity generated from OHE to energy storing products, meanwhile hydrogen as a clean energy is considered a potential candidate [24]. In addition, hydrogen obtained by a Power-to-Gas (PtG) facility, where the electricity injected into water immediately decomposes water molecules into oxygen and hydrogen, is carbon free and has lower environmental effects than coal gasification and reforming as well as steam methane reforming [25]. However, such electrolytic production of hydrogen has so far been regarded as too expensive, it is estimated that the cost of hydrogen production via electrolyzers is $4.50–7.00/kg considering the cost of electricity and the efficiency of PtG system [26]. Combining OHE with PtG facility provides possibility for reducing the cost of hydrogen production due to the costless low-grade heat. While the economic feasibility is the key constraint for the practical application and marketization of this hybrid system. Extensive research on the techno-economic analysis of hydrogen production from renewable energy sources has also been carried out before [27]. Shaner et al. [28] performed a comparative techno-economic analysis of renewable hydrogen production with different solar-based energy systems, the results indicated that the fundamental limitation of the solar-based hydrogen production system is the low capacity factor and high capital cost. Glenk et al. [29] developed a techno-economic model of a real-time optimization system combining wind energy and PtG facility for hydrogen production. However, unlike the renewable energy technologies mentioned above, OHE as an emerging technology is not marketed and detailed information is not available. Therefore, defining the cost target of OHE is required for evaluating the economic feasibility of the OHE-PtG hybrid system.

In this study, we develop a techno-economic analysis model of converting low-grade heat into electricity and hydrogen via the osmotic heat engine and power-to-gas facility. The entire hybrid system consists of an osmotic heat engine for converting low-grade heat into electricity and a power-to-gas facility for electrolytic production of hydrogen. There are two strategies for managing the electricity generated by OHE at each point in time. It can either be sold at current market price denoted by $p_e(t)$ or it can be utilized to produce hydrogen through electrolysis equipment. In any given year, the OHE is theoretically available for 365 days. We then denote $m = 24 \times 365 = 8760$ h, where the time t ranges between 0 and m in the continuous time formulation. However, practical capacity is less than the available capacity due to the equipment maintenance and the intermittency of the heat source from renewable energy or plant waste heat. Therefore, the percentage of practical capacity out of the available capacity is represented as a capacity factor CF(t), which is related to the practical operation of OHE and varies with time. For simplicity and without loss of generality, several assumptions are considered: (1) We assume that the installation of OHE facility is 1 kW, i.e. $k_e = 1$ kW. (2) In this study, waste heat is assumed to be obtained from fossil fuel-fired power plant, thus the variable operating cost is considered to be negligible. (3) and the synergies between the time-variant electricity price and the intermittent power generation can be ignored [30]. (4) As the heat source is obtained from the base-load power plant, time-variant capacity factor is assumed to be satisfied the following equation $CF(t) = \begin{cases} 0 & \text{Scheduled downtime maintenance} \\ 1 & \text{Full - load operation} \end{cases}$ and the average capacity factor can be calculated as $CF = \frac{1}{m}\int_0^m CF(t)dt$.

As a novel heat engine, the acquisition cost of OHE is unknown due to lack of data, the key point of this study is to identify the cost target under an optimized electricity generation management strategy and different operating conditions. Here, the OHE-PtG hybrid system is optimized in real time by either sending the electricity generated by OHE into the electrolyzer or selling it at market price. Applying our model to low-grade heat harvested from a base-load power plant in Wuhan, China, and adopting the electricity price standards and incentive policies in Wuhan, the allowable OHE costs to ensure that the hybrid system is economically viable under different conditions can be identified.

1.1 Techno-economic analysis model development

1.1.1 Contribution Margins

To maximize the contribution margins of the integrated system with a given capacity, the key strategy is to optimize the utilization of available capacity in real time by selling the electricity generated or converting it into hydrogen. The conversion value per kilogram of hydrogen is determined by the selling price of hydrogen and the variable operating cost, and the conversion rate of the electrolyser should also be considered. Thus, the conversion value can be expressed as

$$CV_{\mathrm{h}} = \eta(p_{\mathrm{h}} - w_{\mathrm{h}}) \tag{1}$$

where η denotes the conversion rate. p_{h} and w_{h} denotes the selling price and the operating variable cost of per kg of hydrogen. When the conversion value is higher than the electricity price, the facility earns a conversion premium, which can be calculated as

$$CP_h(t) \equiv \max\{CV_{\mathrm{h}} - p_{\mathrm{e}}(t), 0\} \tag{2}$$

The contribution margin can be maximized by producing hydrogen when the conversion value is higher than the electricity price. The contribution margin at time t is given by

$$CM(t|k_{\mathrm{h}}) = p_{\mathrm{e}}(t)CF(t) + CP_{\mathrm{h}}(t)z(t|k_{\mathrm{h}}) \tag{3}$$

where $z(t|k_{\mathrm{h}})$ represents the fraction converted by PtG system from the electricity generated by osmotic heat engine, which is the minimum of the practical capacity of OHE and the peak capacity of PtG facility denoted by k_{h}, i.e.

$$z(t|k_{\mathrm{h}}) \equiv \min\{CF(t), k_{\mathrm{h}}\} \tag{4}$$

Since the above assumption ignores the synergies between the time-variant electricity price and the intermittent power generation, the average value of all $p_{\mathrm{e}}(t)CF(t)$ in the equation then can be directly expressed as $p_{\mathrm{e}}CF$ to determine the average annual contribution margin, where p_e is the average electricity selling price. To obtain the average contribution margin of the hybrid system, we define $\delta(t)$ as the deviation of the time-variant conversion premium from the average conversion premium, thus

$$\mathrm{CP_h} \times \delta(t) = \mathrm{CP_h}(t) \tag{5}$$

and the average contribution margin can be given by

$$CM(k_{\mathrm{h}}) = \frac{1}{m}\int_0^m CM(t|k_{\mathrm{h}})dt = p_{\mathrm{e}}CF + CP_{\mathrm{h}}(t)z(k_{\mathrm{h}}) \tag{6}$$

$$z(k_{\mathrm{h}}) = \frac{1}{m}\int_0^m z(t|k_{\mathrm{h}})\delta(t)dt \tag{7}$$

1.2 Levelized cost of electricity and hydrogen production

Levelized cost of electricity (LCOE) seeks to calculate all cost, including physical assets and resources required of a plant to deliver a unit of electricity output during the lifetime, which is a common method employed for comparing the cost effectiveness of different power sources [30]. To derive the expression for LCOE in present model, the operating revenue of the standalone osmotic heat engine with 1 kW installation is firstly calculated as

$$Rev_i = x^{i-1}\int_0^m p_{\mathrm{e}}(t)\cdot CF(t)dt \tag{8}$$

where $x < 1$ denotes the degradation factor representing the percentage of initial capacity that is still available in year i.

Since the variable operating cost is considered to be negligible, the pre-tax OHE operating cash flow in year i can be given by the difference between operating revenues and operating cost:

$$CFL_i^o = Rev_i(t) - F_i = x^{i-1}\int_0^m p_{\mathrm{e}}(t)\cdot CF(t)dt - F_i \tag{9}$$

The taxable income in year i is then expressed as the pre-tax OHE operating cash flow less depreciation

$$I_i = CFL_i^o - \mathrm{SP_e}\cdot d_i \tag{10}$$

Considering the current corporate income taxes and value added tax (VAT), the after-tax operating cash flow in year i is given by

$$CFL_i = CFL_i^o - \alpha I_i - \beta\left(Rev_i + x^{i-1}\mathrm{PS}\cdot\int_0^m CF(t)\mathrm{d}t\right) \tag{11}$$

where α and β are the current effective income tax rate and effective value added tax, respectively. PS denotes the subsidy for 1 kWh electricity generation. Both subsidy and operating revenue are the income subject to value added tax.

The standalone OHE system with 1 kW installation is economically viable if, and only if the present value of all after-tax operating cash flows in the future is greater than the initial capacity investment, i.e. $\sum_{i=1}^{T} CFL_i\cdot\gamma^i \geq \mathrm{SP_e}$.Combining the expressions in above equations, the inequality can be restated as

$$\sum_{i=1}^{T}\left[(1-\alpha-\beta)x^{i-1}\int_0^m p_e(t)\cdot CF(t)dt - (1-\alpha)F_i + (1-\beta)x^{i-1}\mathrm{PS}\cdot\int_0^m CF(t)\mathrm{d}t + \alpha\mathrm{SP_e}\cdot d_i\right]\gamma^i \geq \mathrm{SP_e} \tag{12}$$

As the average value of all $p_e(t)\cdot CF(t)$ in the year i can be directly expressed as $p_e CF$ in this calculation (see main text of the paper), Subsequently, the inequality in (12) holds provided

$$\begin{aligned} & m\cdot p_e\cdot CF\sum_{i=1}^{T}x^{i-1}\gamma^i \\ & \geq \frac{1-\alpha}{1-\alpha-\beta}\cdot\sum_{i=1}^{T}F_{ei}\cdot\gamma^i + \frac{1-\alpha\sum_{i=1}^{T}d_i\cdot\gamma^i}{1-\alpha-\beta}\cdot\mathrm{SP_e} - m\cdot CF\cdot\mathrm{PS}\cdot\sum_{i=1}^{T}x^{i-1}\gamma^i\cdot\frac{1-\beta}{1-\alpha-\beta} \end{aligned} \tag{13}$$

where the right hand side of inequality (13) also can be expressed as

$$\frac{1-\alpha}{1-\alpha-\beta}\cdot\sum_{i=1}^{T}F_{ei}\cdot\gamma^i + \frac{1-\alpha\sum_{i=1}^{T}d_i\cdot\gamma^i}{1-\alpha-\beta}\cdot\mathrm{SP_e} - m\cdot CF\cdot\mathrm{PS}\cdot\sum_{i=1}^{T}x^{i-1}\gamma^i\cdot\frac{1-\beta}{1-\alpha-\beta} = m\cdot LCOE \tag{14}$$

The standard definition of LCOE adopts the average capacity factor rather than hourly fluctuating capacity utilization, then the levelized capacity cost can be obtained by

$$c_e = \frac{\mathrm{SP_e}}{CF\cdot L} \tag{15}$$

where we define $L = m\sum_{i=1}^{T}x^{i-1}\gamma^i$ as the levelization factor, which represents the total discounted number of hours available during the entire lifetime. T denotes the facility's projected economic lifetime, x^{i-1} is the degradation factor representing the percentage of initial capacity that is still available in year i. To estimate the present value of cash flow, we denoted the discount rate by r and a corresponding discount factor by $\gamma = (1+r)^{-1}$. $\mathrm{SP_e}$ denotes the acquisition cost of the OHE system.

As a novel heat engine, the detailed information of OHE is not available. It is impossible to obtain the acquisition cost since this technology is not commercialized. Based on the techno-economic analysis model developed by Geffroy et al. [31], the acquisition cost of OHE system can be obtained by the heat exchanger cost plus the heat engine cost:

$$\mathrm{SP_e} = C_{hx} + C_{he} = \frac{(\varphi C_h(\varphi) + \phi C_c(\phi))}{P_{max}} + C_{he} \tag{16}$$

where C_{hx} and C_{he} are the heat exchanger cost and the heat engine cost. φ and ϕ denote the thermal conductance (W/K) of hot and cold side of the heat exchanger, which can be defined as the product of heat transfer coefficient and the area of the heat exchangers. In this study, φ and ϕ are assumed to be equal and $\varphi = \phi = 6\times10^6$ W/K. C_{hx} and C_{he} are the cost of the hot-side and cold-side heat exchanger per unit of thermal conductivity, which are dependent of their thermal conductance and typically decrease with increasing thermal conductance due to the lager heat exchanger economic scale. Thus, C_h and C_c can be regarded as the function of thermal conductivity, i.e. $C(\varphi) = a\varphi^b + c$, where a, b and c are the fitting parameters related to the material and type of heat exchanger and the working fluid in heat exchange [31]. The fitting parameters can be obtained based on the data provided by Engineering Science Data Unit (ESDU) database [32], which is a published database with comprehensive cost data on most common heat exchanger type and different heat-transfer fluid, and the selection of the combination of heat exchanger and working fluid varies with operating temperature range. In this study, we discuss two scenarios based on ESDU database, in which liquid and air are employed as heat transfer fluids (HTF) at hot side, respectively, with the heat source temperature ranging from 50 to 200 ℃ and the ambient temperature of 20 ℃. The combinations of heat exchanger and working fluid and the corresponding fitting parameters in each scenario are summarized in Table 1.

The $P_{\max}$ represents the theoretical maximum power output of the heat engine, Curzon et al. [33] developed a theoretical model to define the maximum power output of an internally reversible heat engine and $P_{\max}$ of an endoreversible engine can be calculated as

$$P_{\max} = \alpha\beta\frac{(\sqrt{T_s} - \sqrt{T_a})^2}{\alpha + \beta} \tag{17}$$

where T_s and T_a denote the temperature of waste heat source and the ambient temperature, respectively. Consequently, the acquisition cost of OHE system can be given by

$$\mathrm{SP}_e = C_{hx} + C_{he} = \frac{(\alpha C_h(\alpha) + \beta C_c(\beta))}{\alpha\beta\frac{(\sqrt{T_s}-\sqrt{T_a})^2}{\alpha+\beta}} + C_{he} \tag{18}$$

To obtained the levelized product cost, the impact of income taxes, value added tax and the depreciation tax shield on capacity cost are summarized by tax factor, which can be calculated as

$$\Delta = \frac{1 - \alpha\sum_{i=1}^{T} d_i \cdot \gamma^i}{1 - \alpha - \beta} \tag{19}$$

where α and β are the effective income tax rate and effective value added tax. The depreciation tax shield aims for tax reduction by subtraction depreciation expense from taxable income. d_i is the allowable tax depreciation rate, as the percentage of initial acquisition cost in year i. Since the tax service life of the facility is usually shorter than the estimated economic service life, it is assumed that $d_i = 0$ for the remaining year. Considering the tax preference in China, the income tax is exemptible for the first three years and half rate reduction for the next subsequent three years, and the VAT is exemptible for the first ten years [34–36].

The tax-adjusted levelized fixed operating cost incurred per kWh (including maintenance cost, management cost, insurance cost and labor cost, etc.) can be calculated by dividing the total fixed operating cost over the lifetime by the lifetime aggregated output of the OHE facility:

$$f_e = \frac{1 - \alpha}{1 - \alpha - \beta} \cdot \frac{\sum_{i=1}^{T} F_{ei} \cdot \gamma^i}{CF \times L} \tag{20}$$

where F_{ei} is the fixed operating cost of the OHE facility in year i.

Combining the aforementioned expressions of levelized fixed operating cost and levelized capacity cost, the expression of the LCOE with out price subsidy can finally be given by

Table 1 The combination of heat exchanger and working fluid for each scenario

	Heat source temperature (℃)	Waste heat fluid-recovery fluid	Hot-side heat exchanger and fitting parameters (a,b,c)	Cold-side temperature (℃)	Cold-side outlet fuild	cold-side heat exchanger and fitting parameters (a,b,c)
Scenario 1	< 100 ℃	water-water	Plate heat exchanger (517.37, -0.82, 0.03)	< 100 ℃	water	Air-cooled heat exchanger (18,023, -0.9, 0.9)
	100–175 ℃	organic liquid- organic liquid	Plate heat exchanger (348.61, -0.75, 0.13)			
	175–200 ℃	organic liquid- organic liquid	Double pipe (1255.1, -0.74, 0.35)			
Scenario 2	< 100 ℃	water–air	Shell-and-tube (56,401, -0.87, 1.53)	< 100 ℃	water	Air-cooled heat exchanger (18,023, -0.9, 0.9)
	100–200 ℃	organic liquid–air	Shell-and-tube (59,043, -0.87, 1.58)			

$$\mathrm{LCOE} = f_{\mathrm{e}} + \Delta c_{\mathrm{e}} \tag{21}$$

where the subscript e denotes electricity generation, f is the levelized fixed operating cost, Δ is the tax factor reflecting the impact of income taxes, value added tax and the depreciation tax shield, c is the capacity cost for 1 kWh.

For the PtG subsystem, we construct LFCH to characterize the levelized cost of hydrogen production, which can be given by

$$\mathrm{LFCH} = f_{\mathrm{h}} + \Delta c_{\mathrm{h}} \tag{22}$$

where the subscript h denotes hydrogen production. The levelized capacity cost and fixed operating cost of generating one kWh electricity can subsequently calculated as

$$c_{\mathrm{h}} = \frac{\mathrm{SP}_{\mathrm{h}}}{L} \tag{23}$$

$$f_{\mathrm{h}} = \frac{1-\alpha}{1-\alpha-\beta} \cdot \frac{\sum_{i=1}^{T} F_{\mathrm{h}i} \cdot \gamma^{i}}{L} \tag{24}$$

where SP_{h} denotes the acquisition cost of the PtG system and $F_{\mathrm{h}i}$ denotes and fixed operating cost of the PtG system in year i.

1.3 Net present values

In China, a subsidy to promote the development of renewable energy is provided by the government. Although the research on osmotic heat engines is in its infancy and not market-oriented, the technology for converting waste heat into electricity satisfies the subsidy conditions. The price subsidy (PS) per kWh of power generation is assumed to be based on the subsidy intensity of biomass power generation projects in Wuhan, and the duration of PS is limited to 15 years. Then the tax-adjusted levelized subsidy is given by

$$\mathrm{ps} = \mathrm{PS}\frac{\sum_{i=1}^{15} x^{i-1}\gamma^{i}}{\sum_{i=1}^{T} x^{i-1}\gamma^{i}} \cdot \frac{1-\beta}{1-\alpha-\beta} \tag{25}$$

With the subsidy taken into account in LCOE, LCOE can be then redefined as $\mathrm{LCOE} = f_{\mathrm{e}} + \Delta c_{\mathrm{e}} - \mathrm{ps}$. In order to identify the conditions under which the hybrid system has investment value, the overall Net Present Value (NPV) reflecting unit costs and revenues is employed and calculated as the present value of future cash inflows minus the present value of future cash outflows including initial capacity investment, subsequent operating cost and taxes. Thus, the NPV of the standalone OHE system can be stated as

$$\mathrm{NPV}(k_{\mathrm{e}} = 1) = (1-\alpha)L(p_{\mathrm{e}} - \mathrm{LCOE} + \mathrm{ps})CF \tag{26}$$

and the overall NPV of the hybrid system with capacity sizes of $k_{\mathrm{e}} = 1$ and k_{h} is expressed as

$$\mathrm{NPV}(k_{\mathrm{e}} = 1, k_{h}) = (1-\alpha)L[CM(k_{\mathrm{h}}) - (\mathrm{LCOE} - \mathrm{ps})CF - \mathrm{LFCH}k_{\mathrm{h}}] \tag{27}$$

It is noticed that Eq. 27 is the same as Eq. 26 when $k_{\mathrm{h}} = 0$. In summary, the standalone OHE system is economically viable when $\mathrm{NPV}(k_{\mathrm{e}} = 1) \geq 0$ and the hybrid system is economically viable when

$$\mathrm{NPV}(k_{\mathrm{e}} = 1, k_{h}) \geq \max\left\{\mathrm{NPV}(k_{\mathrm{e}} = 1), 0\right\} \tag{28}$$

1.4 Model validation

The proposed techno-economic analysis model for converting low-grade heat into electricity and hydrogen is solved via MATLAB. To validate the mathematical model, the heat exchanger costs of OHE as a function of the waste heat temperature below 200 ℃ in present calculation are compared with that in the research of Geffroy et al. [31], as depicted in Fig. 1. Here, the thermal conductance of the cold-side heat exchanger ϕ is set as 10^{6} W/K and the ambient temperature is set as 300 K.

2 Results and discussion

The techno-economic analysis model is employed to identify the economic viable heat engine cost under different situations for low-grade heat utilization. The contribution margin is optimized by sending the electricity into the electrolyzer for hydrogen production when the conversion value of hydrogen is higher than the selling price of electricity. The implementation of time-of-use electricity price policy in China leads to real-time optimization [37]. As a novel "heat to electricity" technology, the financial preferential policies on taxes and subsidies for OHE are pending. We assumed that OHEs enjoy the same financial benefits as biomass power generation which are also zero carbon technologies with commercial scale and the preference of income tax and value added tax is also applied. The main input variables for following calculation are summarized in Table 2.

2.1 Current economic viability of low-grade heat converting

For low-grade heat conversion, it is economically viable when the overall NPV satisfies inequality 17. The derived maximum allowable heat engine cost corresponds to the maximized LCOE. LCOE is decided by many factors including economic lifetime of the facility,

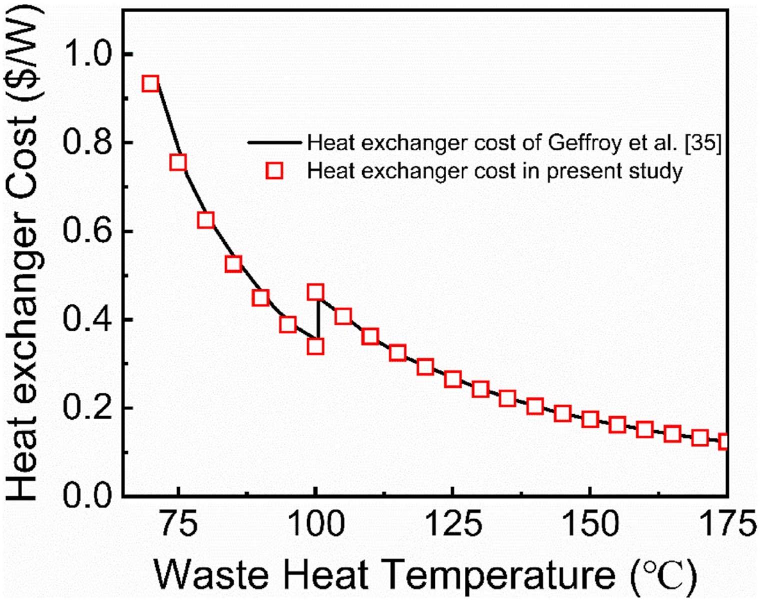

Fig. 1 Heat exchanger Cost validation curve. Comparision of the OHE heat exchanger costs as a function of the waste heat temperature of present calculation and that of Geffroy et al. [31]

Table 2 The input variables for following calculation

Input variables	Values	Sources
Economic lifetime, T	30 years	[29]
Corporate income tax rate,α	25%	[38]
value added tax rate,β	13%	[39, 40]
Degradation factor, x_i	0.8%	[29]
Discount factor, r	4%	
Depreciation rate, d_i	5% (20y linear)	
Number of hours per year, m	8760	
Price subsidy, PS	0.1788 ¥/kWh	[41]
Subsidy lifetime	15 years	
Capacity factor, CF	0.8	
Hot-side thermal conductance,φ	6×10^6 W/K	
Cold-side thermal conductance,ϕ	6×10^6 W/K	
Heat source temperature, T_s	70 ℃	
Ambient temperature, T_a	20 ℃	
PtG system price, SP_h	13,259.4 ¥/kW	[29]
Selling price of electricity,p_e	0.6255 ¥/kWh	[37]
Conversion rate of Power-to-Gas, η	0.019 kg/kWh	[29]
Selling price of hydrogen,p_h	50 ¥/kg	
Variable operating cost,w	0.528 ¥/kg	[29]

discount rate and capacity factor. According to our techno-economic analysis model, LCOE is inversely proportional to the economic lifetime, which is associated with reliability. It also depends on the discount rate, which reflects the financing cost of the technology. A higher discount rate elevates LCOE. In addition, the capacity factor also affects LCOE and higher capacity factor lowers the LCOE. Therefore, a higher heat engine cost can be tolerated with longer economic lifetime, lower discount rate and higher capacity factor. Figure 2 shows the heat engine cost target for making hybrid system economically viable as a function of capacity factor under various discount rate, lifetime of the facility and PtG capacity size. As seen in Fig. 2(a-c), liquid is employed as heat transfer fluids at the hot side. The allowed heat engine cost decreases with reduced capacity factor, reduced facility lifetime and increased discount rate. The allowed heat engine cost is strictly proportional to the capacity factor, while has a more complex relationship with lifetime and discount rate. The effect of lifetime and discount rate on the allowed cost is more significant under larger capacity factor. $k_h = 0$ indicates that the low-grade heat is only converted to electricity via a standalone power generation system. $k_h > 0$ indicates part of the generated electricity is further converted into hydrogen. The allowed heat engine cost decreases with increased k_h under lower capacity factor, while it increases with increased k_h under higher capacity factor. This can be attributed to that the contribution margin under lower capacity factor is unable to cover the cost of hydrogen production, which is proportional to k_h. However, as the contribution margin increases with the increasing capacity factor, the opposite is true. As seen in Fig. 2(d-f), gas is employed as HTF at the hot side. The allowed heat engine cost is obviously lower than that with liquid as

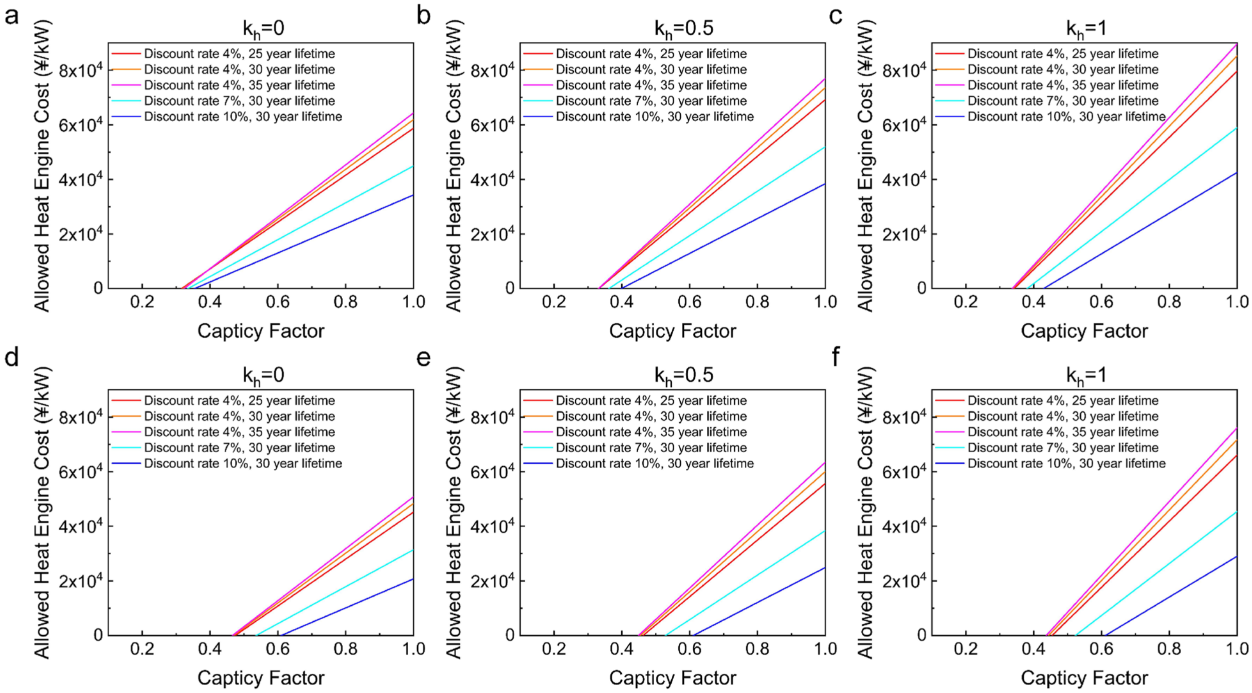

Fig. 2 Economically viable heat engine cost and capacity factor. Economically viable heat engine cost as a function of capacity factor under various discount rate, lifetime of the facility and PtG capacity size with liquid as HTF (a-c) and gas as HTF (d-f)

HTF, owing to the much lower cost of heat exchanger with liquid as HTF.

Figure 3 shows the allowed heat engine cost as a function of hydrogen price under various PtG capacity size. Since $k_h = 0$ indicates that low-grade heat is not converted into hydrogen, the allowed heat engine cost is independent of the hydrogen price. Converting low-grade heat into electricity via a standalone OHE is economically viable when the cost of heat engine is less than 43,725.3 and 30,169.4 ¥/kW with liquid and gas as HTF, respectively. There exist a critical hydrogen price of 37.5 ¥/kg, indicating that the overall conversion value of hydrogen can exactly cover the cost of hydrogen production. It is independent of k_h and heat transfer strategy. When the hydrogen price is higher than the critical price, elevating k_h increases the allowed heat engine cost. When the

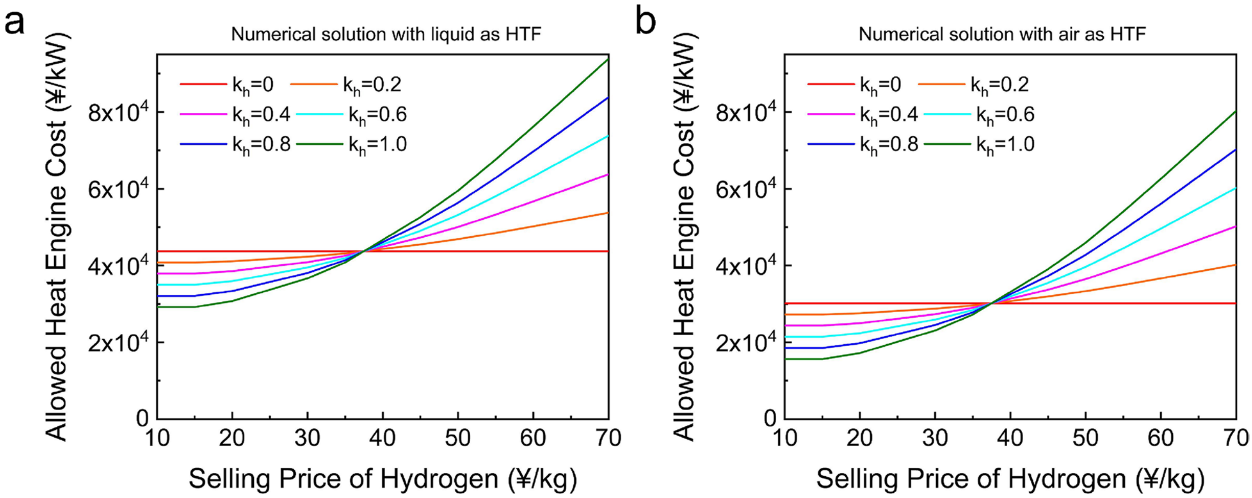

Fig. 3 Economically viable heat engine cost and hydrogen price. Allowed heat engine cost as a function of selling price of hydrogen under various PtG capacity size with liquid as HTF (a) and air as HTF (d)

hydrogen price is lower than the critical price, elevating k_h lowers the allowed heat engine cost.

When the hydrogen price is higher than 37.5 ¥/kg, the OHE-PtG hybrid system is economically viable. When the hydrogen price of is lower than 37.5 ¥/kg, converting low-grade heat into electricity is more appealing. In China, the current hydrogen price in the market is around 60 ¥/kg and the hydrogen price is gradually decreasing. The allowed heat engine cost with liquid as HTF is higher than that with gas as HTF due to the much lower heat exchanger cost with liquid as HTF.

According to Eq. 10, the allowable OHE cost is significantly impacted by heat source temperature. The heat exchanger cost per kW decreases with elevating temperature of waste heat, resulting in increasing allowed heat engine cost. Both the cost and type selection of heat exchanger are strongly dependent on temperature. Table 1 summarizes the combinations of heat-transfer fluid and heat exchanger type at different temperatures for two scenarios, where the selection of heat exchanger is based on the operation temperature and the lowest cost for each temperature range. The cost of heat exchanger as a function of waste heat temperature for both scenarios can be found in Supplementary Information. Figure 4 (a-b) depicts the impact of waste heat temperature on allowed heat engine cost under various PtG capacity size for liquid and gas as heat transfer fluid. The kinks in the figures correspond to the change of heat transfer fluid and heat exchanger type depending on different range of waste heat temperature, and the sudden decrease is the result of the increasing cost of heat exchangers and fluids at high temperatures. At a lower temperature, the allowable heat engine cost significantly increases with the increasing temperature, while a slowing growth occurs at a higher temperature. This can be attributed to that the effect of temperature on heat exchanger cost

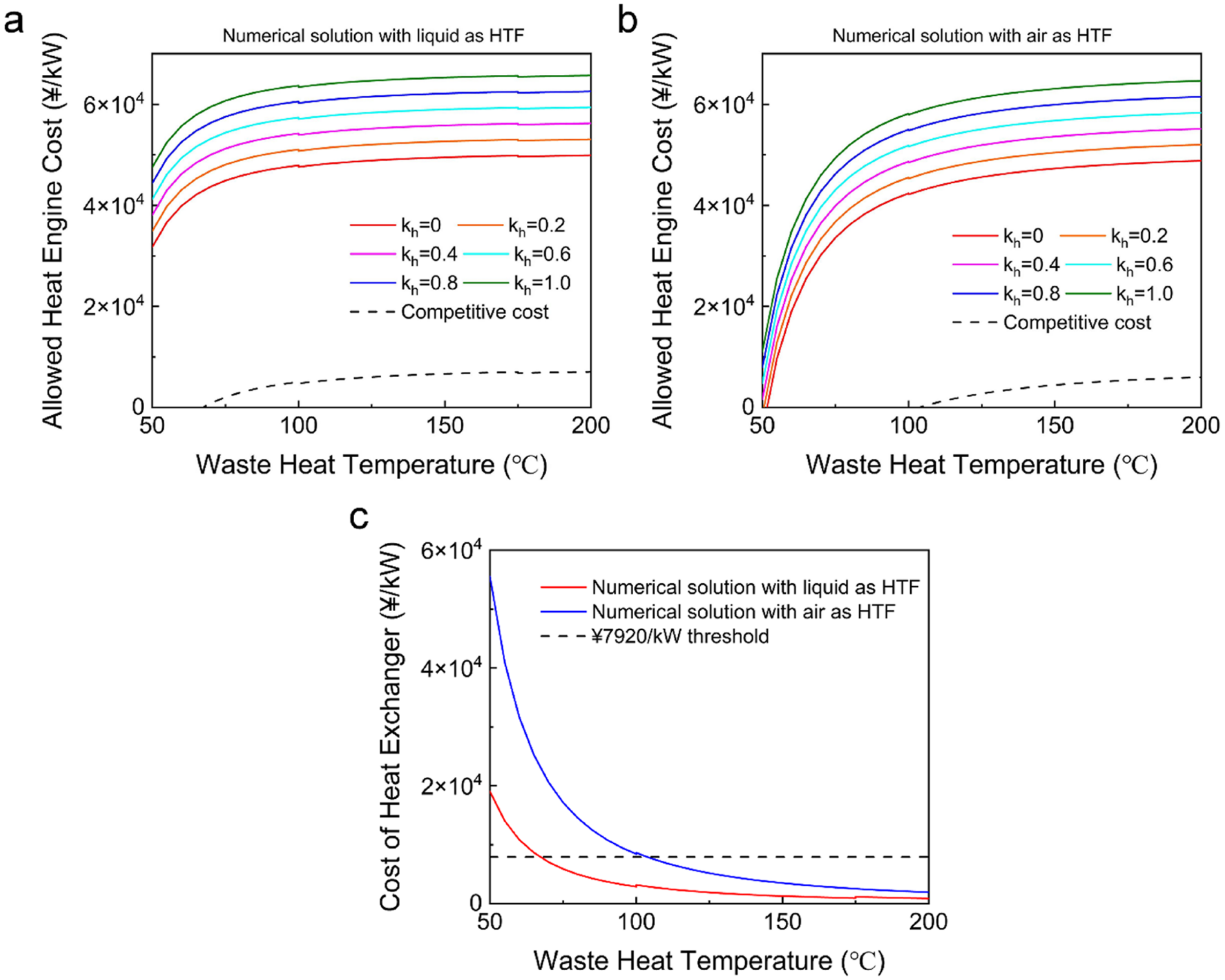

Fig. 4 Economically viable heat engine cost and waste heat temperature. Allowed heat engine cost (a-b) and heat engine cost (c) as a function of waste heat temperature under various PtG capacity size with liquid as HTFand air as HTF

is more obvious at lower temperature. The allowed heat engine cost with liquid as HTF is higher than that with gas as HTF due to the lower heat exchanger cost. The heat exchanger with gas as HTF has a low heat transfer coefficient, which requires a lager heat exchanger surface area to achieve the determined thermal conductance compared with liquid-based heat exchanger. At high temperatures, the indistinctive difference of heat exchanger cost for the two scenarios reflects the increase in working liquid cost and corresponding heat exchanger cost under higher temperature. In fact, the capital cost for different zero-carbon technologies, such as solar PV and geothermal power, are similar. To be competitive with the existing mature waste heat conversion technology, the capital cost of geothermal power plants of ¥7920/kW (Conversion to ¥ with average exchange rate of 6.6 ¥/$) is set as baseline cost target [31]. The dashed line in Fig. 4(a-b) corresponds to the competitive heat engine cost compared with current mature technologies. It is noted that, for engines working under low temperatures, the heat exchanger cost itself is already higher than the target cost as seen in Fig. 4c and the system is impossible to be economically competitive. The system can be competitive when the temperature is higher than a certain value, which is 68 ℃ for scenario 1 and 105 ℃ for scenario 2.

2.2 Prospects for low-grade heat converting

It is reported that the acquisition cost of the PtG system will continue to decline in future years. Glenk et al. [29] performed a univariate regression on a constant elastic function form to project the electrolysers prices in year i: $\mathrm{SP_h}(i) = \mathrm{SP_h}(0)\xi^{i}$. The cost decline rate of polymer electrolyte membrane (PEM) electrolyser is estimated to be $\xi = 0.9523$. The prices of electricity and hydrogen are also assumed to decline annually at a constant adjusment rate of $\lambda = 98\%$. With the gradual maturity of OHE technology, the price subsidy per kWh of power generation is expected to decrease year by year. It is assumed that PS is scheduled to decrease linearly from the initial value to zero at an annual increment of 10%.The trajectory of the allowed heat engine cost within the next decade can be obtained as seen in Fig. 5. The solid line represents the adjustment rate of $\lambda = 98\%$ for the price of electricity and hydrogen, and the shaded area surrounded by dotted lines indicates the faster and slower adjusment rate of 96.5% and 99.5%, respectively. The allowed heat engine cost continues to decline from 50,043 ¥/kW to 18,741 ¥/kW within next 15 years. The inflection point for the line of allowed heat engine cost in 2032 represent the anticipated cancellation of price subsidy for OHE to convert waste heat into electricity.

2.3 Policy implications

For novel and alternative technologies of low-grade heat utilization, incentive policies assistant non-conventional energy to get off the ground and have boosting effect on the commercialization of OHEs. We assume OHEs receive the same financial benefits as biomass power generation. A price subsidy of 0.1788 ¥/kWh for 15 years is applied and the VAT is exemptible for the first ten years. In addition, OHE technologies comply with the preferential category stipulated by the tax regulations, the income tax is exemptible for the first three years and half rate reduction for the next subsequent three years. The

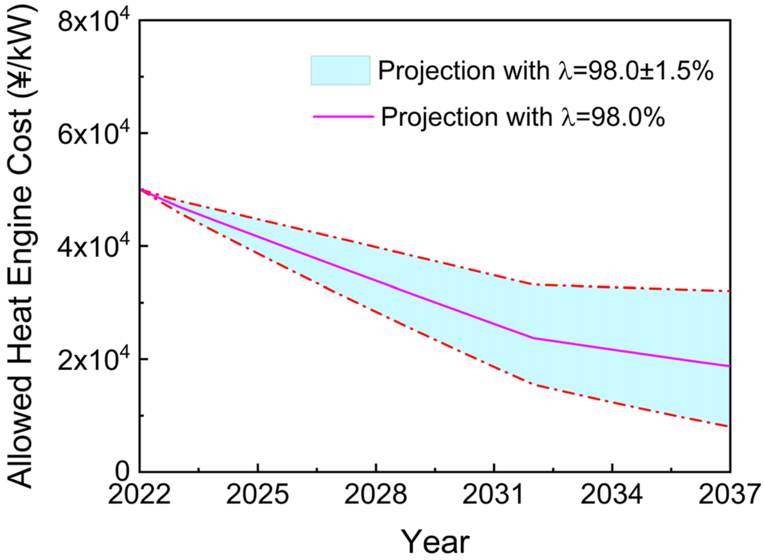

Fig. 5 Prospects for the hybrid system. Projected trajectory of the allowed heat engine cost within the next 15 years

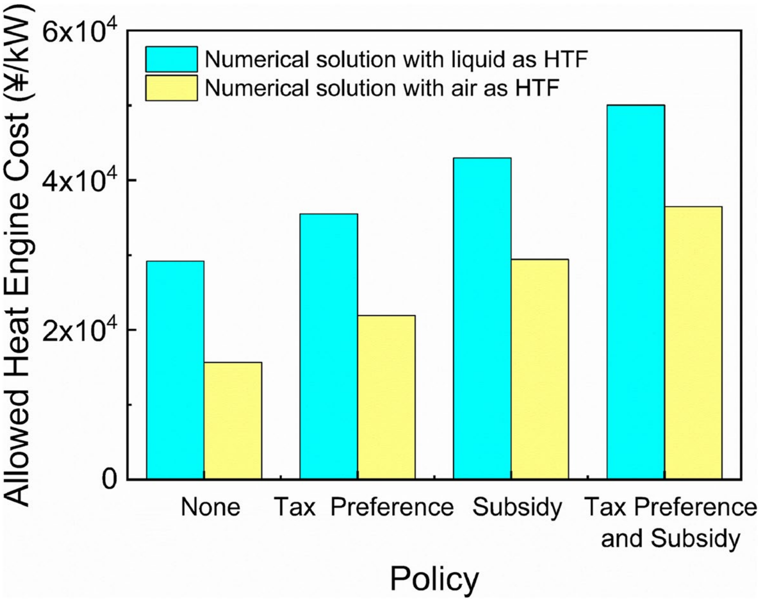

Fig. 6 Policy implications. The implications of incentive policy including tax preference and price subsidy

implications of incentive policy including income tax and VAT preference as well as price subsidy are quantified in Fig. 6. The incentive policies significantly relax the allowable heat engine cost and the impact of subsidy is greater than tax preference. Compared with no incentive policy, the allowable heat engine cost with tax preference and subsidy increased by 71.4% and 133.2% under the two scenarios of liquid and gas as HTF, respectively. Here, although the results in present calculation cannot be directly applied in other countries given the different levels of investment and policy support for clean energy technology, the economic model developed in this study is universally applicable to various regions. It is implied that incentive policy would provide critical support for the economic viability of the heat engines for converting low-grade heat into electricity and hydrogen via the OHE and PtG facilities.

3 Conclusions

In this study, we employed an osmotic heat engine for converting low-grade heat into electricity and a power-to-gas facility for electrolytic production of hydrogen. A techno-economic analysis model was developed. The contribution margin is optimized in real time by either sending the electricity generated by the OHE into the electrolyzer for hydrogen production or selling it at market price in Wuhan, China, thus to identify the economically viable OHE costs under different conditions. The results show that (1) The allowed heat engine cost is strictly proportional to the capacity factor, while has a more complex relationship with lifetime and discount rate. (2) The allowed heat engine cost increases with the elevating hydrogen price and waste heat temperature. (3) The allowed cost with liquid as heat transfer fluid is higher than that with gas as heat transfer fluid. (4) According to the present calculation, the system can be economically competitive compared with current mature technologies when the waste heat temperature is higher than 68 ℃ and 105 ℃ for fluid and air as heat transfer fluid, respectively. (5) Considering the dynamics of the electrolyser price, electricity price, hydrogen price and subsidy intensity, the allowed heat engine cost is expected to gradually decline from 50,043 ¥/kW to 18,741 ¥/kW within next 15 years. (6) Compared with no incentive policy, the allowable heat engine cost with tax preference and subsidy increased by 71.4% and 133.2% under the two scenarios of liquid and gas as heat transfer fluid, which implies that incentive policy would provide critical support for compensating the economic disadvantages of the novel technology in its early stage.

This study provides insights for the practical application of applying OHEs with PtG facilities for electricity generation and hydrogen production to alleviate the instability of low-grade heat source. Our techno-economic analysis can also be applied to various heat source and similar novel heat engines.

Abbreviations

HTF	Heat transfer fluids
LCOE	Levelized cost of electricity
MED	Multiple-effect distillation
NPV	Net Present Value
OHE	Osmotic heat engine

ORC	Organic Rankine cycle
PtG	Power-to-Gas
PS	Price subsidy
RED	Reverse electrodialysis

Acknowledgements
This work was financially supported by the National Natural Science Foundation of China (52176070).

Authors' contributions
YZ: Investigation, Visualization, Writing-original draft; ML: Investigation; RL: Conceptualization, Methodology, Supervision, Writing-review & editing, Funding acqu isition; ZL: Conceptualization; WL: Conceptualization. The authors read and approved the final manuscript.

Funding
Open access funding provided by Shanghai Jiao Tong University. National Natural Science Foundation of China (52176070).

Availability of data and materials
The original data are available from corresponding authors upon reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors have no competing interests to declare that are relevant to the content of this article.

Received: 2 December 2022 Revised: 16 June 2023 Accepted: 17 July 2023

References

1. Forman C, Muritala IK, Pardemann R, Meyer B (2016) Estimating the global waste heat potential. Renew Sustain Energy Rev 57:1568–1579
2. Huo D, Tian H, Shu G, Wang W (2022) Progress and prospects for low-grade heat recovery electrochemical technologies. Sustainable Energy Technol Assess 49:101802
3. Zhao Y, Li M, Long R, Liu Z, Liu W (2022) Review of osmotic heat engines for low-grade heat harvesting. Desalination 527:115571
4. Abrosimov K, Baccioli A, Bischi A (2020) Extensive techno-economic assessment of combined inverted Brayton – Organic Rankine cycle for high-temperature waste heat recovery. Energy 211:118406
5. Chu S, Majumdar A (2012) Opportunities and challenges for a sustainable energy future. Nature 488(7411):294–303
6. Long R, Li B, Liu Z, Liu W (2016) Performance analysis of a dual loop thermally regenerative electrochemical cycle for waste heat recovery. Energy 107:388–395
7. Lecompte S, Huisseune H, van den Broek M, Vanslambrouck B, De Paepe M (2015) Review of organic Rankine cycle (ORC) architectures for waste heat recovery. Renew Sustain Energy Rev 47:448–461
8. Li T, Zhang X, Lacey SD, Mi R, Zhao X, Jiang F et al (2019) Cellulose ionic conductors with high differential thermal voltage for low-grade heat harvesting. Nat Mater 18(6):608–613
9. Straub AP, Yip NY, Lin S, Lee J, Elimelech M (2016) Harvesting low-grade heat energy using thermo-osmotic vapour transport through nanoporous membranes. Nat Energy 1(7):16090
10. Long R, Kuang Z, Li B, Liu Z, Liu W (2019) Exergy analysis and performance optimization of Kalina cycle system 11 (KCS-11) for low grade waste heat recovery. Energy Procedia 158:1354–1359
11. Van Erdeweghe S, Van Bael J, Laenen B, D'haeseleer W (2019) Design and off-design optimization procedure for low-temperature geothermal organic Rankine cycles. Applied Energy. 242:716–31
12. Long R, Zhao Y, Luo Z, Li L, Liu Z, Liu W (2020) Alternative thermal regenerative osmotic heat engines for low-grade heat harvesting. Energy 195:117042
13. Long R, Zhao Y, Li M, Pan Y, Liu Z, Liu W (2021) Evaluations of adsorbents and salt-methanol solutions for low-grade heat driven osmotic heat engines. Energy 229:120798
14. Zhao Y, Luo Z, Long R, Liu Z, Liu W (2020) Performance evaluations of an adsorption-based power and cooling cogeneration system under different operative conditions and working fluids. Energy 204:117993
15. Kwon K, Park BH, Kim DH, Kim D (2015) Parametric study of reverse electrodialysis using ammonium bicarbonate solution for low-grade waste heat recovery. Energy Convers Manage 103:104–110
16. Micari M, Bevacqua M, Cipollina A, Tamburini A, Van Baak W, Putts T et al (2018) Effect of different aqueous solutions of pure salts and salt mixtures in reverse electrodialysis systems for closed-loop applications. J Membr Sci 551:315–325
17. Olkis C, Santori G, Brandani S (2018) An Adsorption Reverse Electrodialysis system for the generation of electricity from low-grade heat. Appl Energy 231:222–234
18. Zhao Y, Li M, Long R, Liu Z, Liu W (2021) Advanced adsorption-based osmotic heat engines with heat recovery for low grade heat recovery. Energy Rep 7:5977–5987
19. Zhao Y, Li M, Long R, Liu Z, Liu W (2021) Dynamic modeling and analysis of an advanced adsorption-based osmotic heat engines to harvest solar energy. Renewable Energy 175:638–649
20. Hu J, Xu S, Wu X, Wu D, Jin D, Wang P et al (2018) Theoretical simulation and evaluation for the performance of the hybrid multi-effect distillation—reverse electrodialysis power generation system. Desalination 443:172–183
21. Long R, Li B, Liu Z, Liu W (2017) Hybrid membrane distillation-reverse electrodialysis electricity generation system to harvest low-grade thermal energy. J Membr Sci 525:107–115
22. Long R, Xia X, Zhao Y, Li S, Liu Z, Liu W (2021) Screening metal-organic frameworks for adsorption-driven osmotic heat engines via grand canonical Monte Carlo simulations and machine learning. iScience. 24(1):101914
23. Giacalone F, Vassallo F, Scargiali F, Tamburini A, Cipollina A, Micale G (2020) The first operating thermolytic reverse electrodialysis heat engine. J Membrane Sci 595:117522
24. Gunther G, Stefan JR (2020) Synergistic Value in Vertically Integrated Power-to-Gas Energy Systems. Prod Oper Manag 29:526–546
25. Ozturk M, Dincer I (2021) A comprehensive review on power-to-gas with hydrogen options for cleaner applications. Int J Hydrogen Energy 46(62):31511–31522
26. Davis SJ, Lewis NS, Shaner M, Aggarwal S, Arent D, Azevedo IL, et al. (2018) Net-zero emissions energy systems. Science 360:eaas9793
27. Luo Z, Wang X, Wen H, Pei A (2022) Hydrogen production from offshore wind power in South China. Int J Hydrog Energy 47(58): 24558–24568
28. Shaner MR, Atwater HA, Lewis NS, McFarland EW (2016) A comparative technoeconomic analysis of renewable hydrogen production using solar energy. Energy Environ Sci 9(7):2354–2371
29. Glenk G, Reichelstein S (2019) Economics of converting renewable power to hydrogen. Nat Energy 4(3):216–222
30. Reichelstein S, Sahoo A (2015) Time of day pricing and the levelized cost of intermittent power generation. Energy Economics 48:97–108
31. Geffroy C, Lilley D, Parez PS, Prasher R (2021) Techno-economic analysis of waste-heat conversion. Joule 5(12):3080–3096
32. ESDU (1994) Selection and Costing of Heat Exchangers, Plate-Fin Type, ESDU Data Item No. 97006
33. Curzon FL, Ahlborn B (1975) Efficiency of a Carnot engine at maximum power output. Am J Phys 43(1):22–24

34. Implementation plan for improving the construction and operation of biomass power generation projects (2020) National Development and Reform Commission
35. Announcement on improving the value added tax policy for comprehensive utilization of resources (2021) State Taxation Administration
36. Regulations for the Implementation of the Enterprise Income Tax Law of the People's Republic of China (2007) State Taxation Administration
37. Notice of the Provincial Development and Reform Commission on matters related to the transmission and distribution price and sales price of Hubei Power Grid in 2020–2022 (2020) Hubei Provicial Development and Reform Commisision
38. Enterprise income tax law of the people's Republic of China (2008) Ministry of Commerce
39. Announcement on improving the value added tax policy for comprehensive utilization of resources (2021) Ministry of Finance and State Administration of Taxation
40. Implementation plan for improving the construction and operation of biomass power generation projects (2020) National Development and Reform Commission
41. Supplementary Notice on Matters Concerning "Several Opinions on Promoting the Healthy Development of Non-Water Renewable Energy Power Generation" (2020) Ministry of Finance, the National Development and Reform Commission, and the State Energy Administration

Publisher's Note