Environmental impact investigation of ceramic kiln's Kalina cycle under different operating strategies based on life cycle assessment

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Abstract. Recovering waste heat from ceramic kiln is an efficient approach to mitigate environmental pollution and energy crisis. In order to evaluate the environmental performance of Kalina cycle (KC) driven by flue gas of the ceramic kiln, the environmental model based on life cycle assessment are established, and the environmental performances of main component, each phase and the system under environmental and economic operation strategies are discussed and compared. The results indicate that under both operating strategies, the pump and evaporator units are the main components affecting 7 different environmental impact categories, the operation phase and manufacturing phase are the key factors contributing the most to environmental impact. In addition, the soot and dust potential and the solid waste potential have the greatest impacts on environmental impact load of the system.

Keywords: Ceramic kiln, waste heat utilization, Kalina cycle, life cycle assessment, environmental performance

1. Introduction

The firing process of ceramic kiln is the main energy consuming stage in tile production. More than 25% of the input fuel energy in ceramic kiln is discharged into the environment in the form of waste heat by flue gas [1]. Therefore, recovering waste heat resource from ceramic kiln's flue gas is beneficial for improving energy utilization efficiency and reducing pollutant emission.

Kalina cycle (KC) is a trustworthy technology for converting the waste heat to power, which has attracted the attention of many scholars. Sohrabi et al. [2] conducted thermodynamic, economic, and environmental comparisons for two KC and identified the more suitable configuration for diesel engine's waste heat recovery. Fallah et al. [3] applied advanced exergy analysis to KC driven by diesel engine, and distinguished that the crucial exergy loss sourced from internal irreversibility. Zheng et al. [4] conducted a detailed off-design performance investigation on geothermal KC based on the thermodynamic analysis and pointed out the condenser had the largest room for performance improvement. Zhang et al. [5] used KCs with single-screw expander as the bottom cycle in geothermal power generation, the thermal efficiency of the system can reach 11.44%-10.85%. In terms of energy, exergy, economy, and exergoeconomy, Kojur et al. [6] conducted the optimization and parametric investigation for a solar KC. Singh et al. [7] performed a thermodynamics and economic comparison on the conventional and coated PTC- KC in the field of solar energy utilization, and concluded the coated PTC- KC exhibited better thermodynamic and economic performance, with the thermal efficiency of 58.5% and payback period of 6.42 years. Fan et al. [8] conducted a dynamic performance of KC using ocean thermal energy and evaluated the step response behavior of output power to the flow rate of working fluid, warm seawater and cold seawater. Özahi et al. [9] carried out thermodynamic and thermoeconomic analysis on the KC using the solid waste power plant heat source, and the results showed that the system can generate 954.6 kW of power with exergy efficiency of 24.15%. From the generated power and investment cost viewpoint, Horta et al. [10] conducted a comparative research of KC1 and KC34 for cement industry's waste heat recovery, and the results showed that KC1 had more attractive in investment cost, while KC34 had more advantage in power generation.

From the above analysis, it can be seen that the KC has been widely used in various fields of thermal energy utilization, such as geothermal energy, solar energy, ocean thermal energy, and waste heat energy. However, there is few research on the application of KC for flue gas's waste heat recovery from ceramic kiln. In addition, the performance evaluation of KC usually focuses on thermodynamic and/or economic performance, and rare

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literature evaluate environmental performance based on life cycle assessment (LCA), especially under different operational strategies. Therefore, this article proposes a modified KC for waste heat utilization from the ceramic kiln's flue gas, establishes an environmental model based on LCA, carries out optimization under environment and economy scenarios, and analyzes the environmental performances of main component, each process and the system under two different strategies.

2. System Description

The KC adopted for waste heat recovery from ceramic kiln's flue gas is shown in Fig. 1. The system mainly consists of an evaporator unit (a preheater, an evaporator and a superheater), a turbine, a condenser, a pump, a high-temperature regenerator, a low-temperature regenerator, a separator, a throttle valve and a mixer. Different from the traditional KC, this modified system places the superheater after the separator to increase the vapor temperature and thus enhance the system's work capacity. Taking a typical ceramic factory as a case, the mass flow of flue gas is 3.19kg/s, and the temperature is 540K [11].

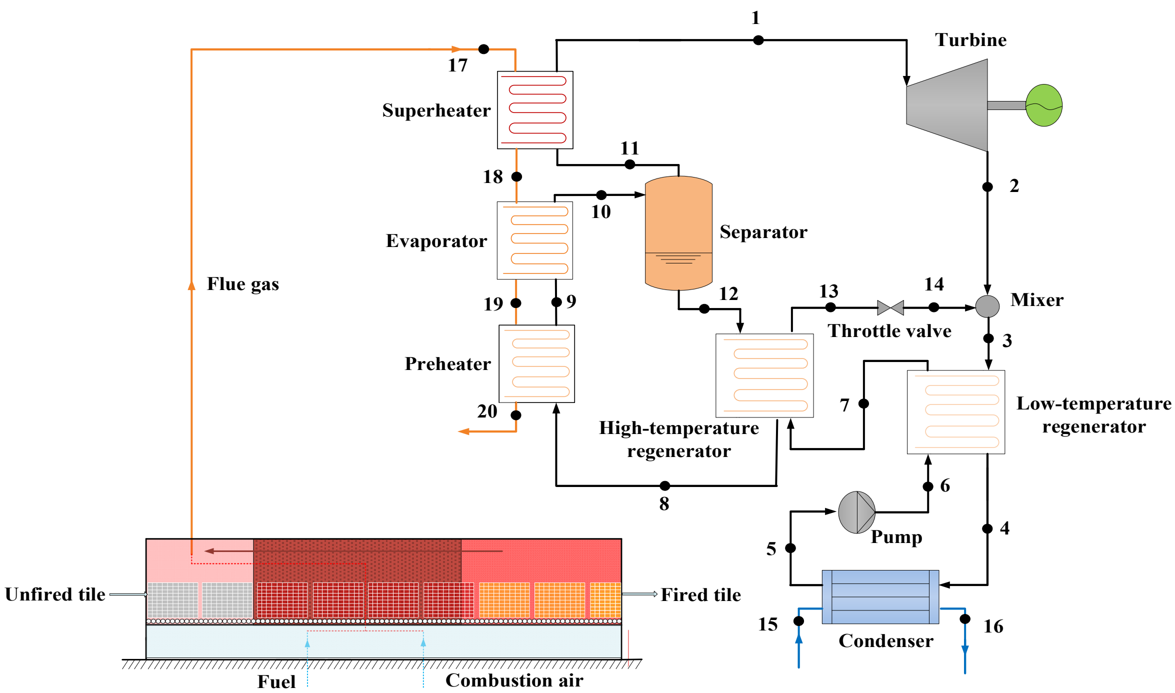

Figure 1. Schematic diagram of KC system for waste heat recovery of ceramic kiln.

3. Model Establishment

3.1 Environmental Model

Based on the LCA, this study evaluates the environmental impact of the ceramic kiln KC system during the manufacturing, operation and decommissioning phases. The environmental performance of LCA is carried out as follows:

(1) Determination of purpose and scope

The environmental impact analysis boundary of KC system for waste heat recovery of ceramic kiln is shown in Fig. 2. In this study, stainless steel is considered for the raw material of the system's main components, and pipe and other fitting are ignored. Compared to the whole operation process of the system, the factors related to civil engineering such as factory building could also be ignored. In addition, it should be noted that the functional unit of the system is defined as 1kWh.

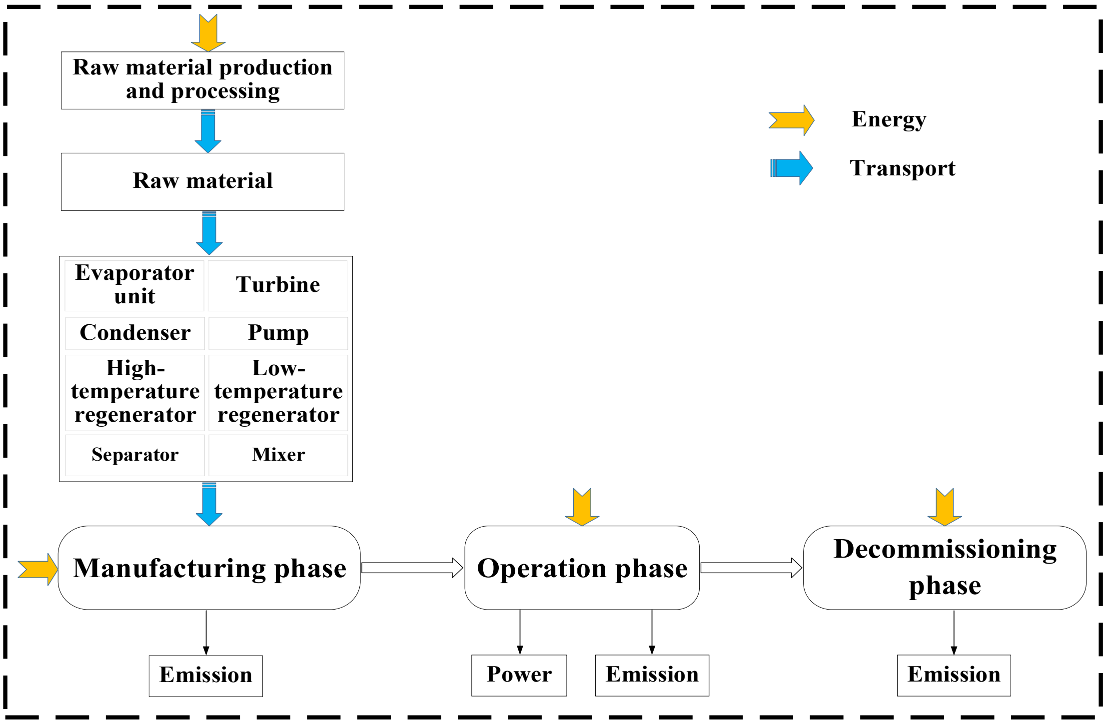

Figure 2. Environmental impact analysis boundary of KC system for waste heat recovery of ceramic kiln.

(2) Inventory analysis

It is assumed that the raw materials adopted are all carried by truck, and the average distance is set at 186.72km [12]. According to reference [13], the emissions of per tn·km truck transportation are: CO_2 23.77g, NO_x 0.76g, CO 2.76g, HC 0.34g, SO_2 0.18g; the emissions of per kWh of power generation are: CO_2 1141.2g, NO_x 5.22g, CO 2.77g, SO_2 10.31g, SW 45.80g, SA 9.55g; the emissions of the per kg of steel production are: CO_2 410g, CH_4 0.9g, NO_x 0.8g, CO 5.5g, HC 0.095g, SO_2 2.55g, H_2S 0.00435g, HCl 0.0437g, SW 243g, SA 15g.

(3) Impact assessment

In this study, the main emissions involve CO_2, NO_x, CO, NH_4, SO_2, H_2S, HC, HCl, solid waste, and soot and dust. The environmental impact types relate to global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), human toxicity potential (HTP), photochemical ozone creation potential (POCP), solid waste potential (SWP), and soot and dust potential (SAP).

The environmental impact assessment model is established according to the following steps:

Environmental impact potential (EP) refers to the sum of environmental emission impacts for a system, and it can be calculated as follows:

$$EP\ (j) = \sum\ [Q\ (j)_i \times EF\ (j)_i] \tag{1}$$

where $Q\ (j)_i$ refers to the emission amount of pollutant i; $EF\ (j)_i$ refers to the equivalent factor of pollutant i on the environment impact potential j. The equivalent factors for the environmental impact category can be obtained in reference [13].

The data standardization (NEP) is expressed as:

$$NEP\ (j) = EP\ (j)/ER\ (j)_{90} \tag{2}$$

Where $ER\ (j)_{90}$ represents the total environmental impact of j for region in 1990.

The environmental impact weighted assessment (WP) is calculated as follows:

$$WP\ (j) = NEP\ (j)\ WF(j) \tag{3}$$

$$WF(j) = ER\ (j)_{90}/ER\ (j)_{2000} \tag{4}$$

Where $ER\ (j)_{2000}$ represents the total environmental impact of j for region in 2000.

The environmental impact load (EIL) is calculated as follows:

$$EIL = \sum WP\ (j) \tag{5}$$

3.2 Economic Model

To evaluate the economic cost of a system, it is necessary to firstly determine the investment cost of each component, and it can be calculated as follows [14]:

$$C_{bm} = C_p F_{bm} \tag{6}$$

$$\lg C_p = K_1 + K_2 \lg X + K_3 (\lg X)^2 \tag{7}$$

$$F_{bm} = B_1 + B_2 F_M F_P \tag{8}$$

$$\lg F_p = C_1 + C_2 \lg P + C_3 (\lg P)^2 \tag{9}$$

where P is the working pressure, and X is the capacity parameter of each component. The component coefficient of K_1, K_2, K_3, C_1, C_2, C_3, B_1, B_2, F_M, and F_{bm} can be acquired in reference [15].

Therefore, the total investment of a system in 2022 (Cost2022) is calculated as follows:

$$Cost2001 = \sum C_{bm} \tag{10}$$

$$Cost2022 = Cost2001 \cdot CEPCI2022/CEPCI2001 \tag{11}$$

where CEPCI2001 and CEPCI2022 are the chemical indices for 2001 and 2022, with values of 397 and 816, respectively.

The electricity production cost (EPC) is expressed as:

$$EPC = \frac{Cost\ 2022 \cdot (i \cdot (1+i)^T/((1+i)^T - 1)) + f_k \cdot Cost\ 2022}{W_{net} \cdot h} \tag{12}$$

Where i is the interest rate of 5%, T is the system lifespan of 16 years, f_k is the operation and maintenance cost coefficient of 1.65%, h is the annual operating time of 7500h.

3.3 Optimization Strategy

Minimizing environmental impact load (EIL_{min}) and minimizing electricity production cost (EPC_{min}) are selected as objective functions, and superheat (ΔT_{sup}), evaporator's narrow point temperature difference (ΔT_{919}), condenser's narrow point temperature difference (ΔT_{515}), high-temperature regenerator's temperature difference (ΔT_{1213}), turbine's inlet temperature (T_{turb}), turbine's inlet pressure (P_{turb}), and ammonia water mass flow (m) are defined as optimization variables. The optimization model can be expressed as:

$$\begin{cases} EIL_{min} \text{ or } EPC_{min} \\ \text{Subjectto:} \\ 10 \le \Delta T_{sup}\ (K) \le 18 \\ 3 \le \Delta T_{919}\ (K) \le 11 \\ 3 \le \Delta T_{515} (K) \le 11 \\ 30 \le \Delta T_{1213} (K) \le 50 \\ 392 \le T_{turb} (K) \le 416 \\ 4500 \le P_{turb} (kpa) \le 5000 \\ 3 \le m(kg/s) \le 14 \end{cases} \quad (13)$$

4. Results and Discussion

4.1 System optimization results

In this study, it considers two optimization strategies: environmental strategy (EIL_{min}) and economic strategy (EPC_{min}). Genetic algorithm is adopted for optimization, and the iteration number, population size, crossover factor and mutation factor are set to 300, 200, 0.8 and 0.2, respectively. The optimization results under the two optimization strategies are shown in Table 1. It can be concluded that, at the EIL_{min} strategy, the system has more attractive environmental performance, with the EIL of 2.61mPEChina, 90/kWh; at the EPC_{min} strategy, its EIL is 6.24mPEChina,90/kWh. Meanwhile, lower values of ΔT_{sup} and ΔT_{515}, and higher values of ΔT_{919} are beneficial to achieve lower EIL.

Table 1. The optimization results of ceramic kiln's KC system under different strategies.

Optimization strategy	EIL_{min}	EPC_{min}
EIL [$mPE_{China,90}$/kWh]	2.61	6.24
EPC [\$/kWh]	0.99	0.27
ΔT_{sup} [K]	10.01	10.00
ΔT_{919} [K]	10.99	11.00
ΔT_{515} [K]	3.11	3.00
ΔT_{1213} [K]	32.71	50.00
T_{turb} [K]	403.12	392.00
P_{turb} [kpa]	4993.93	4527.39
m [kg/s]	4.25	3.00

4.2 Environment performance comparison of KC under the different optimization strategies

Based on the optimization results under the two strategies, LCA is employed for environment performance analysis, and the emission inventory of the system can be determined, which is shown in Table 2. It can be seen that, at EIL_{min} strategy, the emissions of the pollutant are all lower than those at EPC_{min} strategy. In both strategies, CO_2 has the highest emissions, then followed by SO_2, CO, NO_x, HC, CH_4, SA, SW, HCl, and H_2S.

Table 2. The emission inventory of ceramic kiln's KC system under different optimization strategies.

Pollutant's emission (kg)	EIL_{min}	EPC_{min}
CO_2	12.40	23.53
CH_4	6.77×10^{-3}	2.23×10^{-2}
NO_x	5.05×10^{-2}	8.70×10^{-2}
CO	7.16×10^{-2}	1.94×10^{-1}
HC	8.46×10^{-3}	2.79×10^{-2}
SO_2	1.03×10^{-1}	1.84×10^{-1}
H_2S	3.27×10^{-5}	1.08×10^{-4}
HCl	3.29×10^{-4}	1.08×10^{-3}
SW	5.43×10^{-3}	1.62×10^{-2}
SA	6.45×10^{-3}	1.63×10^{-2}

The weighted environmental impact potential of the main components is shown in Table 3. At both EIL_{min} and EPC_{min} strategies, for GWP, the pump has the greatest contribution, with the values of 2.18×10^{-2} $mPE_{China,90}$/kWh and 3.09×10^{-2} $mPE_{China,90}$/kWh, respectively. It could be the fact that the pump continuously consume power during the life span, thereby emitting a large amount of CO_2. The evaporator unit is another key factor leading to GWP. This is because the evaporator unit has the largest heat transfer area and causes the most steel consumption, which generates a lot of greenhouse gases during the production and transportation process. The mixer and separator have the minimum impacts on GWP, while the condenser, turbine, low-temperature regenerator, and high-temperature regenerator have the moderate impacts. For AP, the pump and evaporator unit are also the decisive components. At EIL_{min} strategy, the AP values of the pump and evaporator unit are $2.30\times10^{-2}$$mPE_{China,90}$/kW and $4.95\times10^{-3}$$mPE_{China,90}$/kW, respectively; at EPC_{min} strategy, the AP values of the pump and evaporator unit are $3.26\times10^{-2}$$mPE_{China,90}$/kW and $1.66 \times 10^{-2}$$mPE_{China,90}$/kW, respectively. The mixer and separator contribute the least to the AP. For EP, at EIL_{min} strategy, the maximum contribution is the pump, with the value of 6.72×10^{-3} $mPE_{China,90}$/kW; at EPC_{min} strategy, the evaporation unit is the leading component, with the EP value of 1.28×10^{-2} $mPE_{China,90}$/kW. It could be the fact that at EIL_{min} strategy, the power consumption of pump is 18.40 kW, which is 6.82 kW higher than that at EPC_{min} strategy, hence resulting in a higher emission; at EIL_{min} strategy, the heat transfer area of the evaporator unit is 126 m^2, which is 76 m^2 less than that at EPC_{min} strategy. The steel consumption is less, and the corresponding emissions are also lower. For HTP, at both strategies, the pump has the highest impact, followed by the evaporator unit and condenser. For POCP, at the two strategies, the evaporator unit has the greatest contribution, with the values of 2.60 × 10^{-2} $mPE_{China,90}$/kW and 8.73 × 10^{-2} $mPE_{China,90}$/kW, respectively. The POCP is mainly affected by the emissions of HC, which sources from the steel production and transportation process. The complex structure of the evaporator unit causes the maximum steel consumption, thus leading to greatest impact on POCP. The pump has the secondary contribution, and the separator and mixer devote to the minimal effect. For SWP and SAP, at both strategies, the evaporator unit is still the key contribution, followed by the pump and condenser, while the separator and mixer have the least impact.

Table 3. The weighted environmental impact potential of the component of ceramic kiln's KC system under different optimization strategies.

Optimization strategy	Category ($mPE_{China,90}$/kWh)	Evaporator unit	Turbine	Condenser	Pump	High-temperature regenerator	Low-temperature regenerator	Separator	Mixer
EIL_{min}	GWP	5.45×10^{-3}	1.40×10^{-4}	2.07×10^{-4}	2.18×10^{-2}	3.50×10^{-5}	3.87×10^{-5}	1.25×10^{-8}	2.34×10^{-8}
	AP	4.95×10^{-3}	1.95×10^{-5}	1.88×10^{-4}	2.30×10^{-2}	3.18×10^{-5}	3.51×10^{-5}	1.13×10^{-8}	2.13×10^{-8}
	EP	3.83×10^{-3}	1.51×10^{-5}	1.45×10^{-4}	6.72×10^{-3}	2.46×10^{-5}	2.72×10^{-5}	8.77×10^{-9}	1.65×10^{-8}
	HTP	8.58×10^{-3}	3.38×10^{-5}	3.26×10^{-4}	3.96×10^{-2}	5.52×10^{-5}	6.09×10^{-5}	1.97×10^{-8}	3.69×10^{-8}
	POCP	2.60×10^{-2}	1.02×10^{-4}	9.89×10^{-4}	9.17×10^{-3}	1.67×10^{-4}	1.85×10^{-4}	5.96×10^{-8}	1.12×10^{-7}
	SWP	4.28×10^{-2}	1.68×10^{-4}	1.63×10^{-3}	9.18×10^{-3}	2.75×10^{-4}	3.04×10^{-4}	9.80×10^{-8}	1.84×10^{-7}
	SAP	3.62×10^{-2}	1.43×10^{-4}	1.38×10^{-3}	2.62×10^{-2}	2.33×10^{-4}	2.57×10^{-4}	8.30×10^{-8}	1.56×10^{-7}
EPC_{min}	GWP	1.83×10^{-2}	1.43×10^{-4}	4.69×10^{-4}	3.09×10^{-2}	1.34×10^{-4}	4.60×10^{-5}	2.91×10^{-8}	1.02×10^{-7}
	AP	1.66×10^{-2}	1.99×10^{-5}	4.25×10^{-4}	3.26×10^{-2}	1.22×10^{-4}	4.18×10^{-5}	2.64×10^{-8}	9.25×10^{-8}
	EP	1.28×10^{-2}	1.54×10^{-5}	3.29×10^{-4}	9.55×10^{-3}	9.43×10^{-5}	3.23×10^{-5}	2.04×10^{-8}	7.15×10^{-8}
	HTP	2.88×10^{-2}	3.46×10^{-5}	7.38×10^{-4}	5.62×10^{-2}	2.11×10^{-4}	7.25×10^{-5}	4.58×10^{-8}	1.60×10^{-7}
	POCP	8.73×10^{-2}	1.05×10^{-4}	2.24×10^{-3}	1.30×10^{-2}	6.41×10^{-4}	2.20×10^{-4}	1.39×10^{-7}	4.86×10^{-7}
	SWP	1.44×10^{-1}	1.72×10^{-4}	3.68×10^{-3}	1.30×10^{-2}	1.05×10^{-3}	3.61×10^{-4}	2.28×10^{-7}	7.99×10^{-7}
	SAP	1.22×10^{-1}	1.46×10^{-4}	3.11×10^{-3}	3.73×10^{-2}	8.93×10^{-4}	3.06×10^{-4}	1.93×10^{-7}	6.77×10^{-7}

The weighted environmental impact potential of each phase is shown in Table 4. For GWP, the operating phase is critical in the life span at both EIL_{min} and EPC_{min} strategies, with the values of 2.18×$10^{-2}$$mPE_{China,\ 90}$/kWh and 3.09×$10^{-2}$$mPE_{China,\ 90}$/kWh, respectively. This is due to the pump generates a large amount of CO_2, CH_4, and other greenhouse gases during operation phase. The manufacturing phase is another important factor. Because the manufacturing and transportation of steel also contribute to a lot of greenhouse gases. The decommissioning phase has the least impact on GWP. For AP, the conclusion similar to GWP can also be drawn that the order by the value of AP is operation phase, manufacturing phase and decommissioning phase at two strategies. For EP, at EIL_{min} strategy, the operation phase has the leading contribution of 6.72 × $10^{-3}$$mPE_{China,90}$/kWh, followed by the manufacturing phase and decommissioning phase; at EPC_{min} strategy, the manufacturing phase has the highest value of 1.28×10^{-2} $mPE_{China,90}$/kWh, followed by the operation phase and decommissioning phase. This is due to CH_4 and NO_X emitted from pump is dominate during operation phase at EIL_{min} strategy, while eutrophication gas is preponderant during manufacturing phase at EPC_{min} strategy. For HTP, at both strategies, the HTP values of declining order are operation phase, manufacturing phase and decommissioning phase. The operation phase has the highest HTP at both strategies, corresponding to 3.96× 10^{-2} $mPE_{China,\ 90}$/kWh and 5.62×10^{-2} $mPE_{China,\ 90}$/kWh, respectively. For POCP, at both strategies, the main contributions belong to the manufacturing phase and decommissioning phase. It is noted that the operation phase has no effect on POCP. For SWP and SAP, the key contributions involve manufacturing phase and operation phase at the two strategies. The decommissioning phase is not considered due to that no solid waste and dust are generated during the transportation.

Table 4. The weighted environmental impact potential of the process of ceramic kiln's KC system under different optimization strategies.

Optimization strategy	Category ($mPE_{China,90}$/ kWh)	Manufacturing phase	Operation phase	Decommissioning phase
EIL_{min}	GWP	5.39×10^{-3}	2.18×10^{-2}	3.67×10^{-4}
	AP	5.02×10^{-3}	2.30×10^{-2}	2.04×10^{-4}
	EP	3.87×10^{-3}	6.72×10^{-3}	1.71×10^{-4}
	HTP	8.71×10^{-3}	3.96×10^{-2}	3.53×10^{-4}
	POCP	1.49×10^{-2}	0	1.26×10^{-2}
	SWP	4.52×10^{-2}	9.17×10^{-3}	0
	SAP	3.82×10^{-2}	2.62×10^{-2}	0
EPC_{min}	GWP	1.78×10^{-2}	3.09×10^{-2}	1.21×10^{-3}
	AP	1.65×10^{-2}	3.26×10^{-2}	6.73×10^{-4}
	EP	1.28×10^{-2}	9.55×10^{-3}	5.62×10^{-4}
	HTP	2.87×10^{-2}	5.62×10^{-2}	1.16×10^{-3}
	POCP	4.91×10^{-2}	0	4.14×10^{-2}
	SWP	1.49×10^{-1}	1.30×10^{-2}	0
	SAP	1.26×10^{-1}	3.73×10^{-2}	0

The EIL of the ceramic kiln's KC at EIL_{min} and EPC_{min} strategies are shown in Fig. 3. As shown, the EIL values at the two strategies are $2.61\times10^{-1}mPE_{China,90}$/kWh and $6.24\times10^{-1}mPE_{China,90}$/kWh, indicating that the system has better environmental performance at EIL_{min} strategy. Therefore, from the environmental perspective, the EIL_{min} operating strategy is the preferred choice. In addition, at EIL_{min} strategy, SAP has the most serious environmental impact, accounting for 24.67%; then followed by SWP, occupying 20.79%; the rest are HTP, AP, GWP, POCP, and EP in that order. At EPC_{min} strategy, SWP has the highest EIL, accounting for 27.23%; next ranked by SAP, corresponding to 26.54%; the rest are POCP, HTP, GWP, AP, and EP in that order. At two strategies, SAP and SWP are both the key factors causing EIL, accounting for up to 50% of the total EIL. Since the dust and solid waste causing SAP and SWP mainly sourced from steel production during the manufacturing phase and the power consumption of pump during operation phase. Therefore, regarding ceramic kiln's KC system, reducing heat exchanger area and optimizing pump performance have significant room for environment performance improvement.

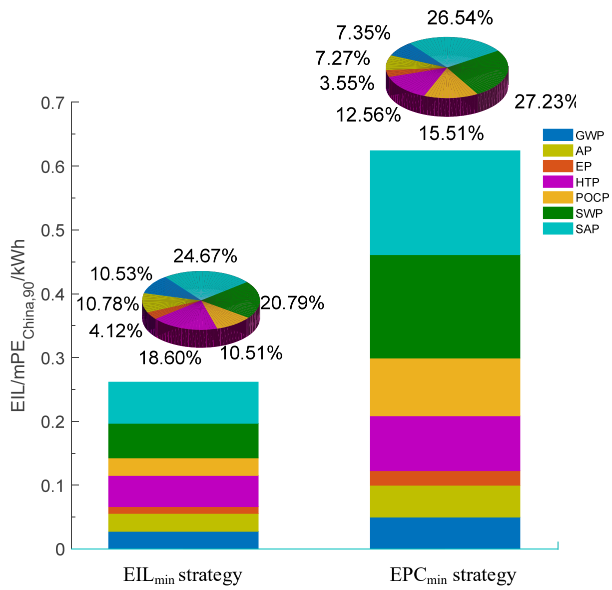

Figure 3. The EIL of ceramic kiln's KC system under different optimization strategies.

5. Conclusion

(1) For the KC system of ceramic kiln, at both EIL_{min} and EPC_{min} strategies, the pump and evaporator unit are key components contributing to the GWP, AP, EP, HTP, POCP, SWP and SAP; the operation phase and manufacturing phase are the main factors affecting the GWP, AP, EP, HTP, POCP, SWP and SAP.

(2) The KC system of ceramic kiln has better environmental performance at EIL_{min} strategy, with the EIL value of $2.61\times10^{-1}mPE_{China,90}$/kWh. At both optimization strategies, SAP and SWP are the dominant factors affecting the environmental impact load.

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