Chinese Journal of Chemical Engineering 58 (2023) 341–354

Contents lists available at ScienceDirect

Chinese Journal of Chemical Engineering

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

Full Length Article

Energy, exergy, economic and environmental comprehensive analysis and multi-objective optimization of a sustainable zero liquid discharge integrated process for fixed-bed coal gasification wastewater

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ARTICLE INFO

Article history:
Received 22 July 2022
Received in revised form 30 September 2022
Accepted 20 October 2022
Available online 11 November 2022

Keywords:
Waste water
Case study
Energy
Exergy
Economy
Environment

ABSTRACT

For a long time, China's regional water resource imbalance has restricted the development of coal chemical industry, and it is imperative to achieve zero liquid discharge (ZLD). Therefore, the game relationship between technical indicators, costs and emissions in ZLD process of fixed-bed coal gasification wastewater treatment process should be explored in detail. According to the accurate model, the simulation for ZLD of fixed-bed coal gasification wastewater treatment process is established, and this process is assessed from the perspective of thermodynamics, economy, and environment. The total energy consumption of ZLD process before optimization is 4.032×10^8 W. The results of exergy analysis show exergy destruction of ZLD process is 94.55%. For economic and environmental results, the total annual cost is 1.892×10^7 USD·a^{-1} and the total environmental impact is 4.782×10^{-8}. The total energy consumption of the optimal six-step ZLD process based on multi-objective optimization is 4.028×10^8 W. The CO_2 content in the treated wastewater is 0.1%. This study will have an important role in promoting the establishment of the ZLD process for coal chemistry industry.

1. Introduction

Since the 1970s, the increasingly serious water pollution problem has gradually aroused attention due to the acceleration of China's industrialization process [1]. The Chinese government has issued a series of policies to solve this problem, such as the Water Pollution Prevention Action Plan [2]. Although, the volume of IV-V and inferior V water quality dropped by 1.5% and 1.6% respectively in 2017 [3] and the preliminary control measures have begun to solve environmental problems, water pollution problems still exist and could not be ignored [4]. The source of water pollution in China is mainly enterprises [5], and it is industrial wastewater discharged without proper treatment. Therefore, the research based on the actual situation is of great significance.

Coal-to-natural gas projects are booming in China and most projects are located in the northwestern of China [6,7]. These areas are rich in coal resources, but they also face the question of serious water shortage and lack of water containing wastewater [8]. Therefore, the core issue of coal chemical industry development is the restriction of industrial environment on water resources. The coal-to-gas production is accompanied by water consumption of about 1×10^4 kg water per 1×10^6 m^3 of natural gas and amounts of generated wastewater. It is the main problems for human to face high water consumption [9] and wastewater discharge in modern coal chemical industry [10]. Therefore, water shortage and water pollution have restricted the development of the coal chemical projects in China [11]. Zero liquid discharge (ZLD) is a necessary measure to ensure the sustainable development of coal chemical industry.

The Chinese government introduced the ZLD policy, which requires that the new coal chemical plants must reach ZLD [12]. The current related research mainly focuses on the analysis and optimization of single processing unit. With the continuous deepening of research on a single processing unit, it is very difficult to optimize a single operating unit to achieve efficient and low-cost ZLD processing through the development of new technologies [13,14]. Therefore, it is an effective way to reduce costs through global optimization of system engineering [15]. Otherwise,

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https://doi.org/10.1016/j.cjche.2022.10.012
1004-9541/

clarifying the game relationship between technology, economic and environment in the process of fixed-bed coal gasification wastewater (FBCGW) treatment will play a vital role in promoting the synthesis for ZLD of coal gasification wastewater (CGW) [16].

Exergy is a thermodynamic concept, which represents the maximum useful work got from system, and it is reversibly balanced with the environment [17]. Exergy analysis can quantify the thermodynamic inefficiencies of system and it can identify the source and extent of damage in the given process, thereby helping to maximize the use of resources [18]. Pan *et al.* [19] solved the relationship between materials, energy and water to achieve process and industrial network-level optimization. However, in industrial networks, the optimization of exergy flow is almost the same as the energy flow, and more research is still demanded [20]. In addition, the exergy-based method applied to a single unit is conducive to technical optimization. Many works focus on various facilities in high energy consumption industries, such as blast furnace [21], waste heat refrigeration system [22]. However, there is little research on exergy analysis of the FBCGW treatment processes currently.

When optimizing the ZLD process system of FBCGW, economic factors should also be considered. Najafi *et al.* [23] conducted the thermal economic evaluation of the hybrid solar power supply in a ZLD plant, the results show that the average weather conditions design has no economic advantages over traditional designs. In response to environmental emissions, life cycle assessment (LCA) is used to reflect the environmental performance of industrial process [24,25]. Due to LCA represents cumulative environmental impact of each stage in life cycle of production [26], compared with single-emission analysis, comprehensive thermodynamic, economic and environmental analysis are more convincing [27].

In recent years, multi-objective problem discovery schemes have attracted widespread attention [28]. For the cascaded absorption refrigeration system, Cui *et al.* [29] obtained a solution targeting the total cost and exergy through multi-objective optimization. Compared with a single-target solution, its total cost and exergy have more comprehensive advantages. Clarifying the game relationship between technology, economy, and environment [30] in the ZLD treatment of FBCGW, and realizing multi-objective optimization, will play an important role in promoting the establishment of the integration of the zero-discharge process of coal gasification wastewater.

In this study, considering energy, exergy, economy and environment (4E analysis), a comprehensive modeling and analysis of ZLD process of FBCGW is carried out. Firstly, a complete thermodynamic model of a FBCGW wastewater treatment ZLD system is established, so that the energy efficiency of the water plant could be evaluated. Secondly, an economic model of the total plant cost rate including capital and operating costs is established. Thirdly, the environmental emissions are determined by LCA for assessing the environmental impact. ZLD process is just getting started from a global perspective, and this work would indicate the direction for the improvement of ZLD process in coal chemistry industry.

2. Framework

The framework is shown in Fig. 1.

Unit modeling is the first part, which identifies basic unit of the ZLD process. Generally, the ZLD process of FBCGW is complicated, but it is mainly composed of six basic units: pre-treatment (PT), phenol and ammonia recovery (PAR), biochemical treatment (BT), advanced treatment (AT), water reuse unit (WR), and multi-effect evaporation and crystallization (MEEC), as shown in Fig. 1. The above six units and modeling methods would be introduced later in this work.

Process synthesis is the second part which uses mass flow to connect those units from the first module to integrate the process. The optimal structure of the process is determined by using different methods. Basing on the first law and second law of thermodynamics, synthesizing process needs to follow the mass, energy and exergy balance. In addition, process synthesis must meet basic chemical engineering requirements.

The third part is process analysis. This block involves many analytical techniques. Generally, they can be divided into three categories: technical and economic analysis, thermodynamic analysis, and LCA, as shown in Fig. 1. These technologies will be introduced in detail later.

The fourth part is process evaluation. In order to getting the best process with the best performance in terms of technology, economic and environment, comprehensive 4E analysis show the influence on ZLD process.

2.1. Case study

According to our previous research of Cui *et al.* [15], the basic case of the ZLD process of FBCGW is shown in Fig. 2.

During the coal gasification process, the light components in the coal are converted into tar, medium oils and other substances simultaneously with the coal gas and becomes liquid entering the CGW finally. The PT of PAR is dedusting and deoiling. If the effect of treatment is not up to the standard, it will have a greater impact on the PAR, which may easily cause fouling of the equipment, affect the extraction effect of the extraction column, and increase the consumption of extractant. Unqualified effluent indicators directly affect subsequent BT. In the construction of the basic case, we selected oil separation technology for the PT. To ensure the separation efficiency of insoluble oils, the flotation is used after the gravitational sedimentation [31]. The most prominent feature of oil separation is that the equipment is simple, easy to operate, and can effectively remove the floating oil in the wastewater.

The PAR unit is specific to FBCGW process which phenolic substances is 40%–60% of chemical oxygen demand (COD) [32]. A large number of phenolic substances which cannot be directly biochemically processed have a certain recycling value. In the basic case, a single column with deacidification, deamination and extraction process is selected, and methyl isobutyl ketone (MIBK) is used as the extractant [33].

The BT unit is mainly suitable for eliminating ammonia nitrogen and COD in wastewater [34]. The BT unit includes aerobic treatment and anaerobic treatment. Since the types and contents of organic refractory substances in FBCGW are too much to biodegrade, AT is needed to further eliminate organics. In this study, the specific anaerobic or aerobic process is not specifically studied. The BT of basic case includes anaerobic and aerobic parts. For AT, we select the coagulation sedimentation and biological aerated filter (BAF) commonly used in industry.

The WR unit is the main unit to achieve ZLD of CGW. In this unit, the treated wastewater undergoes desalination to produce recycled water that can be recycled. This wastewater is characterized by high concentrations of suspended solids (SS) and total dissolved solids (TDS), and low concentrations of ammonia nitrogen and COD. After the WR unit, most of wastewater is reused as product water in the process, and a small amount of concentrated water enters the MEEC for further treatment. Ultrafiltration (UF) and reverse osmosis (RO) membrane system is currently unanimously accepted by industry [35,36]. As the pretreatment of RO, UF is used to remove SS, colloid and organics in the wastewater [37,38]. After RO treatment, the wastewater is concentrated 3 to 10 times, and the recovery rate of reused water reaches 60%. The basic case established in this study selects UF + RO as the treat-

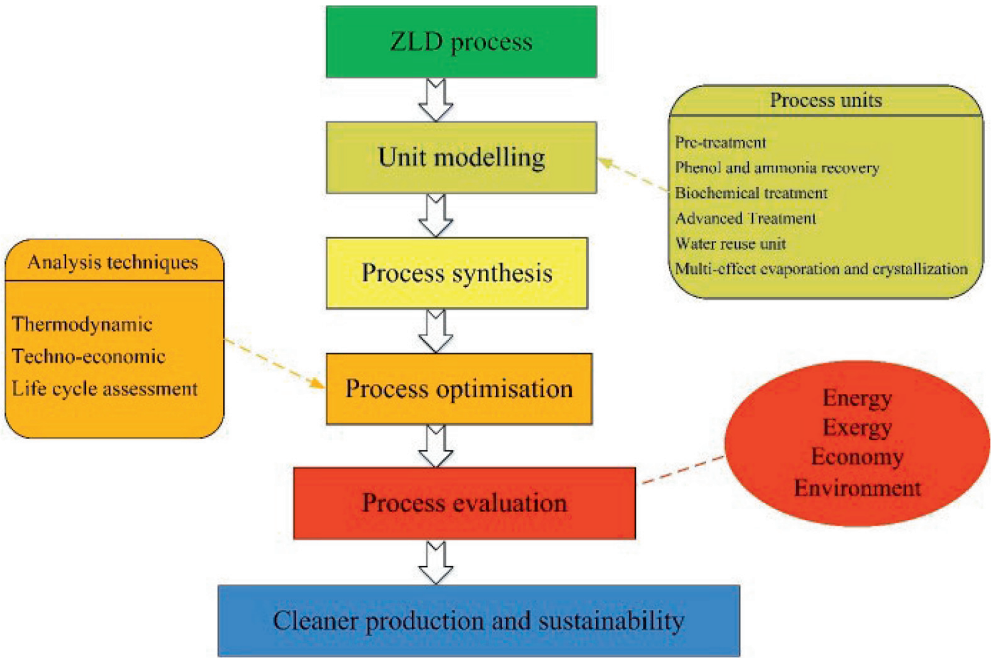

Fig. 1. The framework of proposed work.

ment process of saline wastewater, and the concentrated brine treatment process selects the high-efficiency reverse osmosis (HERO) process.

MEEC is the unit that ultimately achieves ZLD of CGW. In this unit, the concentrated water produced by WR unit undergoes evaporation and solidification into crystalline salts, and the condensed water is used for reusing. In the basic case, multi-effect evaporation is selected as the technical route of the MEEC.

2.2. Model validation and case study

In this work, Aspen Plus 8.4 is used to simulate the PT, PAR, MEEC of ZLD process, and GPS-X is used to simulate the BT and AT of ZLD process. For WR, a black box model is built. In actual industry, the composition of high-concentration organic wastewater from FBCGW is too complicated to input each component into the simulation software. In addition, the main purpose of this process is to simulate the calculation of phenolic substances [39,40]. Therefore, in the simulation, the composition of the wastewater is simplified, and phenol is used to replace the monophenols in the wastewater, and hydroquinone is used to replace the polyphenols in the wastewater. Other organic matter such as heterocyclic compounds, fatty acids, aromatic hydrocarbons. Whether it is not considered in the simplified wastewater composition [41]. Ammonia exists in two forms, free ammonia and fixed ammonia [42,43]. The physical property method is electrolyte non-random two liquid (ELENRTL) and the binary interaction parameters are shown in Tables S1 and S2 (in Supplementary Material). The feed composition of wastewater comes from the actual industrial process of FBCGW treatment plant. The detailed information of the simulation is listed in Tables 1 and 2. and Table S3.

2.3. Theoretical analysis

To further study the property of the ZLD treatment system, it is necessary to establish a mathematical model that conforms to conservation of mass-balance equations and energy-balance equations. The analysis in this article is based on the following assumptions [22]:

(1) The system is in a stable working state.

(2) The potential energy and kinetic energy in system is ignored.

(3) The pressure drops of pipes and equipment and heat loss of system to surrounding environment are ignored.

(4) The temperature in the reference state is T_0 = 298 K, and the pressure is P_0 = 1.01 $\times$ 10^5 Pa.

(5) The fluid at the outlet of the condenser, the bottom of the distillation column, and the bottom of the reboiler is a saturated liquid.

(6) The fluid at the inlet of the top of distillation column and the outlet of evaporator is saturated vapor.

2.3.1. Energy analysis

Basing on the mass-balance equations and energy-balance equations, energy analysis of ZLD process is calculated by Eqs. (1) and (2), the energy analysis of system is shown in Tables 1 and 2.

Mass-balance equation:

$$\sum \dot{m} = 0 \tag{1}$$

Energy-balance equation:

$$\sum \dot{Q} + \dot{W} + \dot{m}h = 0 \tag{2}$$

where $\dot{m}$ is mass flow rate, $\dot{Q}$ is heat transfer rate, $\dot{W}$ is power, h is specific enthalpy.

For energy evaluation, the total energy consumption (TEC) is defined as Eq. (3):

$$\mathrm{TEC} = Q_{st} + Q_{cw} + W_{ele} \tag{3}$$

where Q_{st} is steam heat transfer rate, Q_{cw} is cooling water heat transfer rate, W_{ele} is the power of electricity.

The energy analysis results for each unit component of ZLD process are listed in Table 3.

2.3.2. Exergy analysis

Based on the second law of thermodynamics, exergy analysis helps to analyze the irreversibility of system. It can be used not only to evaluate the degree of utilization of available energy, but also to reveal the shortcomings of the system, and to give the

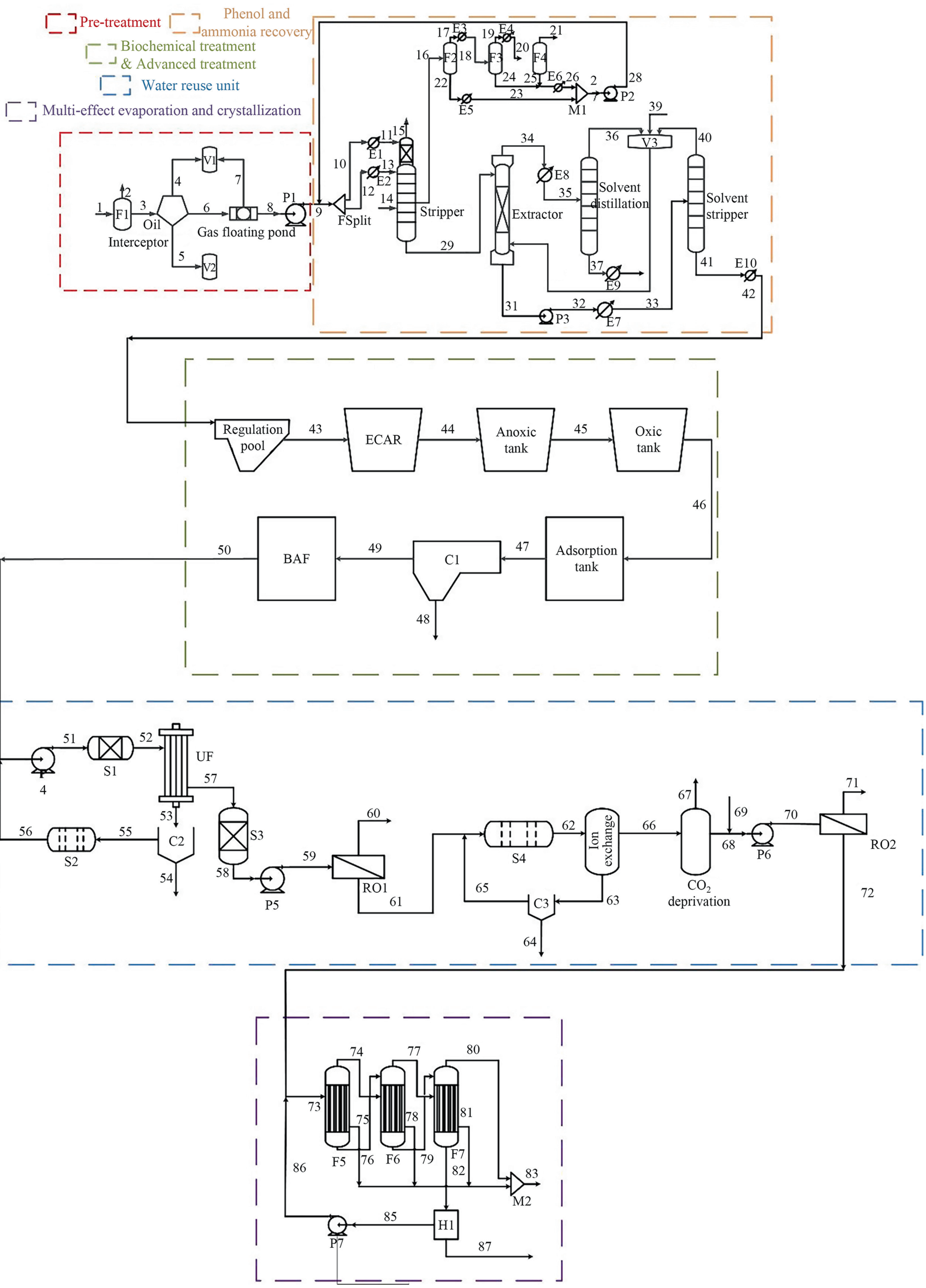

Fig. 2. The flowsheet of ZLD process.

Table 1
Input information of the ZLD process

Process	Block	Specification
PT	Flash tank (F1)	Duty: 0, Pressure: 1×10^5 Pa
	Pump (P1)	Pressure: 1.6×10^6 Pa, Efficiencies isentropic: 0.8
PAR	Heat exchanger (E1)	Outlet temperature of hot stream: 308.15 K
	Heat exchanger (E2)	Outlet temperature of cold stream: 413.15 K
	Stripper column (Stripper)	Number of stages: 56, Pressure: 5.5×10^5 Pa
	Flash tank (F2)	Duty: 0, Pressure: 4×10^5 Pa
	Flash tank (F3)	Duty: 0, Pressure: 2.5×10^5 Pa
	Flash tank (F4)	Duty: 0, Pressure: 1.5×10^5 Pa
	Heat exchanger (E3)	Outlet temperature of hot stream: 368.15 K
	Heat exchanger (E4)	Outlet temperature of hot stream: 313.15 K
	Heat exchanger (E5)	Outlet temperature of hot stream: 323.15 K
	Heat exchanger (E6)	Outlet temperature of hot stream: 323.15 K
	Pump (P2)	Pressure: 1.6×10^6 Pa, Efficiencies isentropic: 0.8
	Extractor column (Extractor)	Number of stages: 4, Pressure: 1×10^5 Pa
	Pump (P3)	Pressure: 2×10^5 Pa, Efficiencies isentropic: 0.8
	Heat exchanger (E7)	Outlet temperature of cold stream: 373.15 K
	Heat exchanger (E8)	Outlet temperature of cold stream: 363.15 K
	Heat exchanger (E9)	Outlet temperature of hot stream: 323.15 K
	Solvent distillation column	Number of stages: 40, Pressure: 1×10^5 Pa, Distillate rate: 3.171 $kg \cdot s^{-1}$, Reflux ratio: 0.15
	Solvent stripper column	Number of stages: 22, Pressure: 1×10^5 Pa, Distillate rate: 4.049 $kg \cdot s^{-1}$, Reflux ratio: 0.43
	Heat exchanger (E10)	Outlet temperature of hot stream: 333.15 K
BT&AT	Anoxic tank	Volume: 12000 m^3
	Oxic tank	Volume: 12000 m^3
	Sedimentation tank (C1)	Volume: 12000 m^3
	BAF	Volume: 12000 m^3
WR	UF	Polyvinylidene fluoride (PVDF), area: 21600 m^2
	RO1	Hollow fine fiber, area: 1000 m^2
	RO2	Hollow fine fiber, area: 1000 m^2
MEEC	Flash tank (F5)	Duty: 0, Pressure: 1×10^5 Pa
	Flash tank (F6)	Duty: 0, Pressure: 3×10^4 Pa,
	Flash tank (F7)	Duty: 0, Pressure: 1×10^4 Pa
	Crystallizer (H1)	Pressure: 1×10^5 Pa
	Pump (P7)	Pressure: 1×10^5 Pa, Efficiencies isentropic: 0.8

direction of system performance improvement. The steady flow without considering the chemical reaction is calculated by Eq. (4) [44]:

$$\dot{E} = \dot{m}[(h - h_0) - T_0(s - s_0)] \tag{4}$$

where $\dot{E}$ is energy, T_0 is standard temperature, s_0 is standard entropy.

The exergy destruction ($\dot{E}_D$) rate is calculated by Eq. (5) [44]:

$$\dot{E}_D = \sum \dot{E}_{in} - \sum \dot{E}_{out} + \sum \dot{Q}\left(1 - \frac{T_0}{T}\right) + \sum \dot{W} \tag{5}$$

The exergy analysis results of ZLD process are listed in Table 4.

2.3.3. Economic analysis

Economic factors must be considered in decision-making process, it is also conducive to the design of operating conditions [45]. Besides, economic factors should also be considered as a deciding factor, whether it is meaningful to implement the plan. The related cost equation is divided into two parts: capital and maintenance cost ($\sum Z$), operating cost (C_{op}). For this study, the integrated ZLD process is analyzed from an economic perspective, the equation is as follows:

$$C_t = \sum Z + C_{op} \tag{6}$$

where C_t is total annual cost.

The basic situation which contains basic cost, basic size and cost exponent of entire system is shown in Table S4. Under different operating conditions, the material and size of the equipment need to be adjusted which will also lead to changes in costs. The changed maintenance and capital costs is calculated by Eq. (7) [46]. The correction coefficients are shown in Table S4.

$$\sum Z = \phi \alpha Z_E f_M f_P f_T \tag{7}$$

Z_E is equipment investment cost, where f_M is the construction material correction factor, f_P is design pressure correction factor f_T is design temperature correction factor, ϕ is maintenance cost factor, set as 1.06 [44], and α is capital recovery factor, which is calculated by the Eq. (8):

$$\alpha = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{8}$$

where N is the service lifetime year and the value is 10, i is annual interest rate and the value is 15%.

Eq. (7) uses the basic equipment cost data reported in 2015 [47]. To convert the equipment cost in 2015 to the equipment cost in 2020, using the chemical economic plant cost index (CEPCI) to modify parameters basing on Eq. (9). The CEPCI was 556.8 in 2015 and 607.5 in 2020 [48].

$$Z_{E,2020} = Z_{E,2015}\frac{CEPCI_{2020}}{CEPCI_{2015}} \tag{9}$$

The equipment investment cost (Z_E) is calculated by Eq. (10).

$$Z_E = Z_B\left(\frac{S_E}{S_B}\right)^M \tag{10}$$

where Z_B is basic capital cost of equipment, S_E and S_B are current size and benchmark size. And M is cost exponent which is shown in Table S4 [44,45].

Table 2
The information for streams in the simulation results of the ZLD process

Process	Stream number	Temperature/K	Pressure $\times 10^{-6}$/Pa	Mass flows/kg·s^{-1}
PT	1	323.15	0.1	291.667
	2	323.15	0.1	1.222
	3	323.15	0.1	29.056
	8	323.15	0.1	277.778
PAR	9	323.15	1.6	277.778
	10	323.15	1.6	46.139
	11	308.15	1.6	46.139
	12	323.15	1.6	261.389
	13	413.15	1.6	261.389
	14	303.15	1.6	0.553
	15	323.15	0.55	1.306
	16	424.15	0.57	32.000
	17	399.55	0.4	8.481
	18	368.15	0.4	8.481
	19	356.55	0.25	3.089
	20	313.15	0.25	3.089
	21	303.05	0.15	2.255
	22	399.55	0.4	23.506
	23	323.15	0.4	23.506
	24	356.55	0.25	5.391
	25	303.05	0.15	0.834
	26	323.15	0.15	6.225
	27	323.35	0.15	29.722
	28	323.95	1.6	29.722
	29	432.15	0.6	274.778
	30	323.15	0.5	35.806
	31	323.75	0.1	277.417
	32	323.65	0.2	277.417
	33	373.15	0.2	277.417
	34	321.35	0.1	33.139
	35	363.15	1.2	33.139
	36	363.75	0.1	31.722
	37	473.15	0.12	1.433
	38	323.15	0.12	1.433
	39	323.15	0.5	0.043
	40	358.25	0.1	4.050
	41	378.25	0.12	273.389
	42	333.15	0.12	273.389
BT&AT	50	303.15	0.1	272.306
WR	59	303.15	0.1	272.306
	60	303.15	0.1	204.222
	61	303.15	0.1	68.083
	71	303.15	0.1	49.556
	72	303.15	0.1	18.519
MEEC	73	425.55	0.51	6.639
	83	318.95	0.1	23.894
	87	303.15	0.1	0.690

The operating cost C_{op} of the ZLD process includes electricity, cooling water and steam, as shown in Eq. (11):

$$C_{op} = t_{op}\left[\frac{c_{ele}}{3600} \times (e_{T1} + e_{T2} + e_{T3} + e_{T4} + e_{T5} + e_{T6}) + c_{cw} \times Q_{cw} + c_{st} \times Q_{st}\right] \quad (11)$$

where c_{ele} is the electricity price, the value is 1.68×10^{-5} USD·J^{-1}, c_{cw} is the cooling water price, the value is 3.50×10^{-7} USD·J^{-1}, c_{st} is steam price, the value is 1.328×10^{-5} USD·J^{-1} (5×10^5 Pa, 433.15 K) [49], t_{op} is annual operation time, and the value is 2.88×10^7 s, e_{Ti} is the electricity consumption of each unit.

2.3.4. Environmental analysis

The environmental impact of the ZLD process is assessed by process life cycle assessment (PLCA) and the system boundary is shown in Fig. 3. 1 ton wastewater input was used as the functional unit of LCA. According to the system boundary, the global parameters from the GaBi 9.2.1.68 database are used to simulate the process.1.3.

The environmental impacts can be characterized using CMLBaseline 2001 method. The five environmental impact categories of Global warming potential (GWP), Eutrophication potential (EP), Acidification potential (AP), Photochemical ozone creation potential (POCP) and Abiotic depletion potential (ADP) are selected for this study [32]. The external normalization method is used to normalize the environmental impact. For the regional and local impacts, the normalized reference is calculated based on Chinese data. The normalization factor is derived from studies [50] (Table 5) and it is calculated by Eq. (12).

$$\mathrm{NEI} = \frac{\mathrm{CEI}}{\mathrm{NF}} \quad (12)$$

where NEI represents the normalized environmental impacts, CEI represents the characterized environmental impacts, and NF is normalization factor.

Total environmental impact (TEI) can be obtained by Eq. (13). The weighting factors of five environmental impact categories are based on reference, as shown in Table 6.

$$\mathrm{TEI} = \sum_i w_i \times \mathrm{NEI}_i \quad (13)$$

where w_i is a weighting factor for category i.

Table 3
Mass/Energy equations for each component of ZLD process

Unit	Component	Mass/Energy equations
PR	F1	$\dot{m}_1 = \dot{m}_2 + \dot{m}_3$, $\dot{Q}_{F1} = \dot{m}_2 h_2 + \dot{m}_3 h_3 - \dot{m}_1 h_1$
	Oil interceptor	$\dot{m}_3 = \dot{m}_4 + \dot{m}_5 + \dot{m}_6$, $\dot{m}_4 h_4 + \dot{m}_5 h_5 + \dot{m}_6 h_6 = \dot{m}_3 h_3$
	Gas floating pond	$\dot{m}_6 = \dot{m}_7 + \dot{m}_8$, $\dot{m}_7 h_7 + \dot{m}_8 h_8 = \dot{m}_6 h_6$
	P1	$\dot{W}_{P1} = \dot{m}_9 h_9 - \dot{m}_8 h_8$
PAR	FSplit	$\dot{m}_{28} + \dot{m}_9 = \dot{m}_{10} + \dot{m}_{12}$, $\dot{m}_{10} h_{10} + \dot{m}_{12} h_{12} = \dot{m}_{28} h_{28} + \dot{m}_9 h_9$
	E1	$\dot{Q}_{E1} = \dot{m}_{11} h_{11} - \dot{m}_{10} h_{10}$
	E2	$\dot{Q}_{E2} = \dot{m}_{13} h_{13} - \dot{m}_{12} h_{12}$
	Stripper	$\dot{m}_{11} + \dot{m}_{13} + \dot{m}_{14} = \dot{m}_{15} + \dot{m}_{16} + \dot{m}_{29}$, $\dot{Q}_{Stripper} = \dot{m}_{15} h_{15} + \dot{m}_{16} h_{16} + \dot{m}_{29} h_{29} - \dot{m}_{11} h_{11} - \dot{m}_{13} h_{13} - \dot{m}_{14} h_{14}$
	F2	$\dot{m}_{16} = \dot{m}_{17} + \dot{m}_{22}$, $\dot{Q}_{F2} = \dot{m}_{17} h_{17} + \dot{m}_{22} h_{22} - \dot{m}_{16} h_{16}$
	E3	$\dot{Q}_{E3} = \dot{m}_{18} h_{18} - \dot{m}_{17} h_{17}$
	F3	$\dot{m}_{18} = \dot{m}_{19} + \dot{m}_{24}$, $\dot{Q}_{F3} = \dot{m}_{19} h_{19} + \dot{m}_{24} h_{24} - \dot{m}_{18} h_{18}$
	E4	$\dot{Q}_{E4} = \dot{m}_{20} h_{20} - \dot{m}_{19} h_{19}$
	F4	$\dot{m}_{20} = \dot{m}_{21} + \dot{m}_{25}$, $\dot{Q}_{F4} = \dot{m}_{21} h_{21} + \dot{m}_{25} h_{25} - \dot{m}_{20} h_{20}$
	E5	$\dot{Q}_{E5} = \dot{m}_{23} h_{23} - \dot{m}_{22} h_{22}$
	E6	$\dot{m}_{24} + \dot{m}_{25} = \dot{m}_{26}$, $\dot{Q}_{E6} = \dot{m}_{26} h_{26} - \dot{m}_{24} h_{24} - \dot{m}_{25} h_{25}$
	M1	$\dot{m}_{23} + \dot{m}_{26} = \dot{m}_{27}$, $\dot{m}_{27} h_{27} = \dot{m}_{23} h_{23} + \dot{m}_{26} h_{26}$
	P2	$\dot{W}_{P2} = \dot{m}_{28} h_{28} - \dot{m}_{27} h_{27}$
	Extractor	$\dot{m}_{29} + \dot{m}_{30} = \dot{m}_{31} + \dot{m}_{34}$, $\dot{Q}_{Extractor} = \dot{m}_{31} h_{31} + \dot{m}_{34} h_{34} - \dot{m}_{29} h_{29} - \dot{m}_{30} h_{30}$
	P3	$\dot{W}_{P3} = \dot{m}_{32} h_{32} - \dot{m}_{31} h_{31}$
	E7	$\dot{Q}_{E7} = \dot{m}_{33} h_{33} - \dot{m}_{32} h_{32}$
	E8	$\dot{Q}_{E8} = \dot{m}_{35} h_{35} - \dot{m}_{34} h_{34}$
	E9	$\dot{Q}_{E9} = \dot{m}_{38} h_{38} - \dot{m}_{37} h_{37}$
	Solvent distillation	$\dot{m}_{35} = \dot{m}_{36} + \dot{m}_{37}$, $\dot{Q}_{D-Solvent} = \dot{m}_{36} h_{36} + \dot{m}_{37} h_{37} - \dot{m}_{35} h_{35}$
	V3	$\dot{m}_{36} + \dot{m}_{39} + \dot{m}_{40} = \dot{m}_{30}$, $\dot{m}_{30} h_{30} = \dot{m}_{36} h_{36} + \dot{m}_{39} h_{39} + \dot{m}_{40} h_{40}$
	Solvent stripper	$\dot{m}_{33} = \dot{m}_{40} + \dot{m}_{41}$, $\dot{Q}_{S-Solvent} = \dot{m}_{36} h_{36} + \dot{m}_{37} h_{37} - \dot{m}_{31} h_{31}$
	E10	$\dot{Q}_{E10} = \dot{m}_{42} h_{42} - \dot{m}_{41} h_{41}$
BT&AT	Regulation pool	$\dot{W}_{P-Regulation} = \dot{m}_{43} h_{43} - \dot{m}_{42} h_{42}$
	ECAR	$\dot{W}_{ECAR} = \dot{m}_{44} h_{44} - \dot{m}_{43} h_{43}$
	Anoxic tank	$\dot{W}_{T-Anoxic} = \dot{m}_{45} h_{45} - \dot{m}_{44} h_{44}$
	Oxic tank	$\dot{W}_{T-Oxic} = \dot{m}_{46} h_{46} - \dot{m}_{45} h_{45}$
	Adsorption tank	$\dot{W}_{T-Adsorption} = \dot{m}_{47} h_{47} - \dot{m}_{46} h_{46}$
	C1	$\dot{m}_{47} = \dot{m}_{48} + \dot{m}_{49}$, $\dot{W}_{C1} = \dot{m}_{48} h_{48} + \dot{m}_{49} h_{49} - \dot{m}_{47} h_{47}$
	BAF	$\dot{W}_{BAF} = \dot{m}_{50} h_{50} - \dot{m}_{49} h_{49}$
WR	P4	$\dot{m}_{50} + \dot{m}_{56} = \dot{m}_{51}$, $\dot{W}_{P4} = \dot{m}_{51} h_{51} - \dot{m}_{50} h_{50} - \dot{m}_{56} h_{56}$
	S1	$\dot{W}_{S1} = \dot{m}_{52} h_{52} - \dot{m}_{51} h_{51}$
	UF	$\dot{m}_{52} = \dot{m}_{53} + \dot{m}_{57}$, $\dot{W}_{UF} = \dot{m}_{53} h_{53} + \dot{m}_{57} h_{57} - \dot{m}_{52} h_{52}$
	C2	$\dot{m}_{53} = \dot{m}_{54} + \dot{m}_{55}$, $\dot{W}_{C2} = \dot{m}_{54} h_{54} + \dot{m}_{55} h_{55} - \dot{m}_{53} h_{53}$
	S2	$\dot{W}_{S2} = \dot{m}_{56} h_{56} - \dot{m}_{55} h_{55}$
	S3	$\dot{W}_{S3} = \dot{m}_{58} h_{58} - \dot{m}_{57} h_{57}$
	P5	$W_{P5} = \dot{m}_{59} h_{59} - \dot{m}_{58} h_{58}$
	RO1	$\dot{m}_{59} = \dot{m}_{60} + \dot{m}_{61}$, $\dot{W}_{RO1} = \dot{m}_{60} h_{60} + \dot{m}_{61} h_{61} - \dot{m}_{59} h_{59}$
	S4	$\dot{m}_{61} + \dot{m}_{65} = \dot{m}_{62}$, $\dot{W}_{S4} = \dot{m}_{62} h_{62} - \dot{m}_{61} h_{61} - \dot{m}_{65} h_{65}$
	Ion exchange	$\dot{m}_{62} = \dot{m}_{63} + \dot{m}_{66}$, $\dot{W}_{Ion-Exchange} = \dot{m}_{63} h_{63} + \dot{m}_{66} h_{66} - \dot{m}_{62} h_{62}$
	C3	$\dot{m}_{63} = \dot{m}_{64} + \dot{m}_{65}$, $\dot{W}_{C3} = \dot{m}_{64} h_{64} + \dot{m}_{65} h_{65} - \dot{m}_{63} h_{63}$
	CO_2 deprivation	$\dot{m}_{66} = \dot{m}_{67} + \dot{m}_{68}$, $\dot{Q}_{D-CO_2} = \dot{m}_{67} h_{67} + \dot{m}_{68} h_{68} - \dot{m}_{66} h_{66}$
	P6	$\dot{m}_{68} + \dot{m}_{69} = \dot{m}_{70}$, $\dot{W}_{P4} = \dot{m}_{70} h_{70} - \dot{m}_{68} h_{68} - \dot{m}_{69} h_{69}$
	RO2	$\dot{m}_{70} = \dot{m}_{71} + \dot{m}_{72}$, $\dot{W}_{RO2} = \dot{m}_{71} h_{71} + \dot{m}_{72} h_{72} - \dot{m}_{70} h_{70}$
MEEC	F5	$\dot{m}_{72} + \dot{m}_{73} + \dot{m}_{86} = \dot{m}_{74} + \dot{m}_{75} + \dot{m}_{76}$, $\dot{Q}_{F5} = \dot{m}_{74} h_{74} + \dot{m}_{75} h_{75} + \dot{m}_{76} h_{76} - \dot{m}_{72} h_{72} - \dot{m}_{73} h_{73} - \dot{m}_{86} h_{86}$
	F6	$\dot{m}_{74} + \dot{m}_{76} = \dot{m}_{77} + \dot{m}_{78} + \dot{m}_{79}$, $\dot{Q}_{F6} = \dot{m}_{77} h_{77} + \dot{m}_{78} h_{78} + \dot{m}_{79} h_{79} - \dot{m}_{74} h_{74} - \dot{m}_{76} h_{76}$
	F7	$\dot{m}_{77} + \dot{m}_{79} = \dot{m}_{80} + \dot{m}_{81} + \dot{m}_{82}$, $\dot{Q}_{F7} = \dot{m}_{80} h_{80} + \dot{m}_{81} h_{81} + \dot{m}_{82} h_{82} - \dot{m}_{77} h_{77} - \dot{m}_{79} h_{79}$
	M2	$\dot{m}_{75} + \dot{m}_{78} + \dot{m}_{80} + \dot{m}_{81} = \dot{m}_{83}$, $\dot{m}_{83} h_{83} = \dot{m}_{75} h_{75} + \dot{m}_{78} h_{78} + \dot{m}_{80} h_{80} + \dot{m}_{81} h_{81}$
	H1	$\dot{m}_{82} = \dot{m}_{85} + \dot{m}_{87}$, $\dot{Q}_{H1} = \dot{m}_{85} h_{85} + \dot{m}_{87} h_{87} - \dot{m}_{82} h_{82}$
	P7	$\dot{W}_{P7} = \dot{m}_{86} h_{86} - \dot{m}_{85} h_{85}$

2.3.5. Multi-objective optimization

Multi-objective optimization is an effective method to solve the problem of objective conflicts [29,30]. This method can simultaneously consider multiple conflicting targets under multiple constraints, thereby optimizing the process. A single solution cannot meet the goals of multiple conflicts. Therefore, there is no single optimal solution for multi-objective problems. The solution to this problem is to obtain a solution set, where each solution corresponds to a different requirement. The decision maker finally chooses the best solution for the process according to a specific design Objective function, decision variables and constraints are three important factors in the process of multi-objective optimization. Based on these two functions, an environmental optimization plan, an economic optimization plan and a multi-objective opti-

Table 4
Exergy equations for each component of ZLD process

Unit	Component	Exergy equations
PR	F1	$\dot{E}_{D,F1}=\dot{E}_1-\dot{E}_2-\dot{E}_3+\dot{Q}_{F1}\left(1-\frac{T_0}{T_{F1}}\right)$
	Oil interceptor	$\dot{E}_{D,I-oil}=\dot{E}_3-\dot{E}_4-\dot{E}_5-\dot{E}_6$
	Gas floating pond	$\dot{E}_{D,P-gas}=\dot{E}_6-\dot{E}_7-\dot{E}_8$
	P1	$\dot{E}_{D,P1}=\dot{E}_8-\dot{E}_9+\dot{W}_{P1}$
PAR	FSplit	$\dot{E}_{D,FSplit}=\dot{E}_9+\dot{E}_{28}-\dot{E}_{10}-\dot{E}_{12}$
	E1	$\dot{E}_{D,E1}=\dot{E}_{10}-\dot{E}_{11}+\dot{Q}_{E1}\left(1-\frac{T_0}{T_{E1}}\right)$
	E2	$\dot{E}_{D,E2}=\dot{E}_{12}-\dot{E}_{13}+\dot{Q}_{E2}\left(1-\frac{T_0}{T_{E2}}\right)$
	Stripper	$\dot{E}_{D,\text{Stripper}}=\dot{E}_{11}+\dot{E}_{13}+\dot{E}_{14}-\dot{E}_{15}-\dot{E}_{16}-\dot{E}_{29}+\dot{Q}_{Stripper}\left(1-\frac{T_0}{T_{Stripper}}\right)$
	F2	$\dot{E}_{D,F2}=\dot{E}_{16}-\dot{E}_{17}-\dot{E}_{22}+\dot{Q}_{F2}\left(1-\frac{T_0}{T_{F2}}\right)$
	E3	$\dot{E}_{D,E3}=\dot{E}_{17}-\dot{E}_{18}+\dot{Q}_{E3}\left(1-\frac{T_0}{T_{E3}}\right)$
	F3	$\dot{E}_{D,F3}=\dot{E}_{18}-\dot{E}_{19}-\dot{E}_{24}+\dot{Q}_{F3}\left(1-\frac{T_0}{T_{F3}}\right)$
	E4	$\dot{E}_{D,E4}=\dot{E}_{19}-\dot{E}_{20}+\dot{Q}_{E4}\left(1-\frac{T_0}{T_{E4}}\right)$
	F4	$\dot{E}_{D,F4}=\dot{E}_{20}-\dot{E}_{21}-\dot{E}_{25}+\dot{Q}_{F4}\left(1-\frac{T_0}{T_{F4}}\right)$
	E5	$\dot{E}_{D,E5}=\dot{E}_{22}-\dot{E}_{23}+\dot{Q}_{E5}\left(1-\frac{T_0}{T_{E5}}\right)$
	E6	$\dot{E}_{D,E6}=\dot{E}_{24}+\dot{E}_{25}-\dot{E}_{26}+\dot{Q}_{E6}\left(1-\frac{T_0}{T_{E6}}\right)$
	M1	$\dot{E}_{D,M1}=\dot{E}_{23}+\dot{E}_{26}-\dot{E}_{27}$
	P2	$\dot{E}_{D,P2}=\dot{E}_{27}-\dot{E}_{28}+\dot{W}_{P2}$
	Extractor	$\dot{E}_{D,Extractor}=\dot{E}_{29}+\dot{E}_{30}-\dot{E}_{31}-\dot{E}_{34}+\dot{Q}_{Extractor}\left(1-\frac{T_0}{T_{Extractor}}\right)$
	P3	$\dot{E}_{D,P3}=\dot{E}_{31}-\dot{E}_{32}+\dot{W}_{P3}$
	E7	$\dot{E}_{D,E7}=\dot{E}_{32}-\dot{E}_{33}+\dot{Q}_{E7}\left(1-\frac{T_0}{T_{E7}}\right)$
	E8	$\dot{E}_{D,E8}=\dot{E}_{34}-\dot{E}_{35}+\dot{Q}_{E8}\left(1-\frac{T_0}{T_{E8}}\right)$
	Solvent distillation	$\dot{E}_{D,D-Solvent}=\dot{E}_{35}-\dot{E}_{36}-\dot{E}_{37}+\dot{Q}_{D-Solvent}\left(1-\frac{T_0}{T_{D-Solvent}}\right)$
	E9	$\dot{E}_{D,E9}=\dot{E}_{37}-\dot{E}_{38}+\dot{Q}_{E9}\left(1-\frac{T_0}{T_{E9}}\right)$
	V3	$\dot{E}_{D,V3}=\dot{E}_{36}+\dot{E}_{39}+\dot{E}_{40}-\dot{E}_{30}$
	Solvent stripper	$\dot{E}_{D,S-Solvent}=\dot{E}_{33}-\dot{E}_{40}-\dot{E}_{41}+\dot{Q}_{S-Solvent}\left(1-\frac{T_0}{T_{S-Solvent}}\right)$
	E10	$\dot{E}_{D,E10}=\dot{E}_{41}-\dot{E}_{42}+\dot{Q}_{E10}\left(1-\frac{T_0}{T_{E10}}\right)$
BT&AT	Regulation pool	$\dot{E}_{D,P-Regulation}=\dot{E}_{42}-\dot{E}_{43}+\dot{W}_{P-Regulation}$
	ECAR	$\dot{E}_{D,ECAR}=\dot{E}_{43}-\dot{E}_{44}+\dot{W}_{ECAR}$
	Anoxic tank	$\dot{E}_{D,T-Anoxic}=\dot{E}_{44}-\dot{E}_{45}+\dot{W}_{T-Anoxic}$
	Oxic tank	$\dot{E}_{D,T-Oxic}=\dot{E}_{45}-\dot{E}_{46}+\dot{W}_{T-Oxic}$
	Adsorption tank	$\dot{E}_{D,T-Adsorption}=\dot{E}_{46}-\dot{E}_{47}+\dot{W}_{T-Adsorption}$
	C1	$\dot{E}_{D,C1}=\dot{E}_{47}-\dot{E}_{48}-\dot{E}_{49}+\dot{W}_{C1}$
	BAF	$\dot{E}_{D,BAF}=\dot{E}_{49}-\dot{E}_{50}+\dot{W}_{BAF}$
WR	P4	$\dot{E}_{D,P4}=\dot{E}_{50}+\dot{E}_{56}-\dot{E}_{51}+\dot{W}_{P4}$
	S1	$\dot{E}_{D,S1}=\dot{E}_{51}-\dot{E}_{52}+\dot{W}_{S1}$
	UF	$\dot{E}_{D,UF}=\dot{E}_{52}-\dot{E}_{53}-\dot{E}_{57}+\dot{W}_{UF}$
	C2	$\dot{E}_{D,C2}=\dot{E}_{53}-\dot{E}_{54}-\dot{E}_{55}+\dot{W}_{C2}$
	S2	$\dot{E}_{D,S2}=\dot{E}_{55}-\dot{E}_{56}+\dot{W}_{S2}$
	S3	$\dot{E}_{D,S3}=\dot{E}_{57}-\dot{E}_{58}+\dot{W}_{S3}$
	P5	$\dot{E}_{D,P5}=\dot{E}_{58}-\dot{E}_{59}+\dot{W}_{P5}$
	RO1	$\dot{E}_{D,RO1}=\dot{E}_{59}-\dot{E}_{60}-\dot{E}_{61}+\dot{W}_{RO1}$
	S4	$\dot{E}_{D,S4}=\dot{E}_{61}+\dot{E}_{65}-\dot{E}_{62}+\dot{W}_{S4}$
	Ion exchange	$\dot{E}_{D,Ion-Exchange}=\dot{E}_{62}-\dot{E}_{63}-\dot{E}_{66}+\dot{W}_{Ion-Exchange}$
	C3	$\dot{E}_{D,C3}=\dot{E}_{63}-\dot{E}_{64}-\dot{E}_{65}+\dot{W}_{C3}$
	CO_2 deprivation	$\dot{E}_{D,D-CO_2}=\dot{E}_{66}-\dot{E}_{67}-\dot{E}_{68}+\dot{W}_{D-CO_2}$
	P6	$\dot{E}_{D,P6}=\dot{E}_{68}+\dot{E}_{69}-\dot{E}_{70}+\dot{W}_{P6}$
	RO2	$\dot{E}_{D,RO2}=\dot{E}_{70}-\dot{E}_{71}-\dot{E}_{72}+\dot{W}_{RO2}$

(*continued on next page*)

Table 4 (*continued*)

Unit	Component	Exergy equations
MEEC	F5	$\dot{E}_{D,F5} = \dot{E}_{72} + \dot{E}_{73} + \dot{E}_{86} - \dot{E}_{74} - \dot{E}_{75} - \dot{E}_{76} + \dot{Q}_{F5}\left(1 - \frac{T_0}{T_{F5}}\right)$
	F6	$\dot{E}_{D,F6} = \dot{E}_{74} + \dot{E}_{76} - \dot{E}_{77} - \dot{E}_{78} - \dot{E}_{79} + \dot{Q}_{F6}\left(1 - \frac{T_0}{T_{F6}}\right)$
	F7	$\dot{E}_{D,F7} = \dot{E}_{77} + \dot{E}_{79} - \dot{E}_{80} - \dot{E}_{81} - \dot{E}_{82} + \dot{Q}_{F7}\left(1 - \frac{T_0}{T_{F7}}\right)$
	M2	$\dot{E}_{D,M2} = \dot{E}_{75} + \dot{E}_{78} + \dot{E}_{80} + \dot{E}_{81} - \dot{E}_{83}$
	H1	$\dot{E}_{D,H1} = \dot{E}_{82} - \dot{E}_{85} - \dot{E}_{87} + \dot{W}_{H1}$
	P7	$\dot{E}_{D,P7} = \dot{E}_{85} - \dot{E}_{86} + \dot{W}_{P7}$

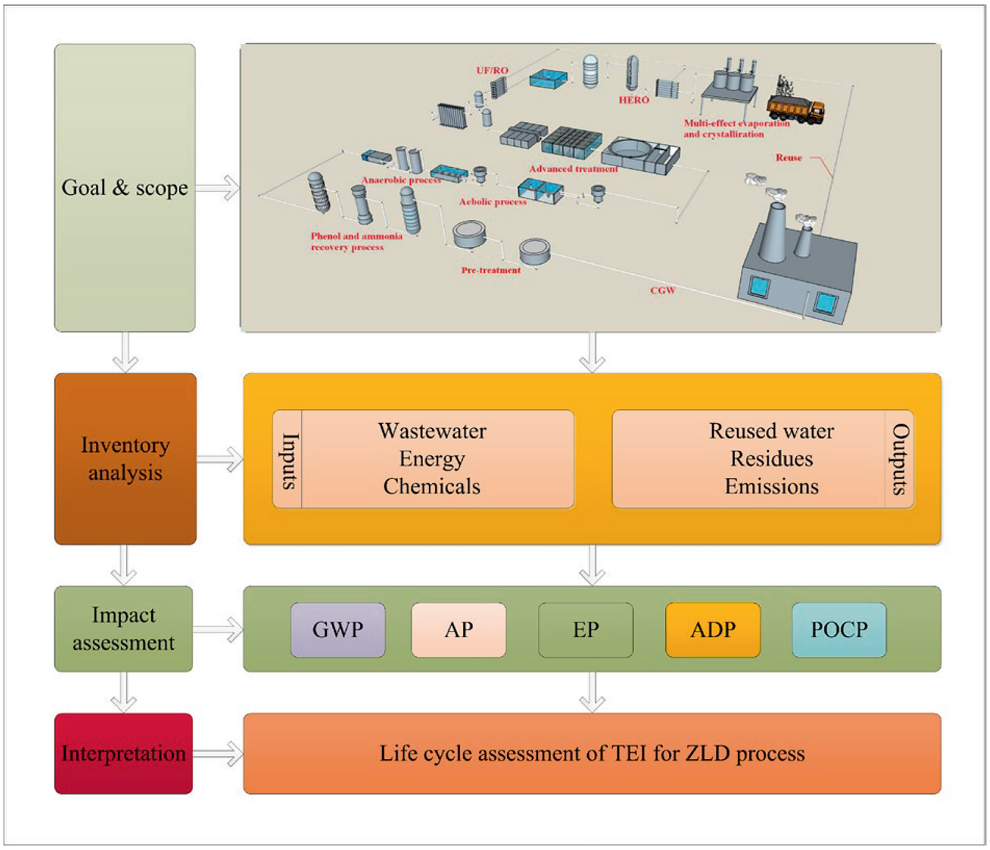

Fig. 3. Life cycle boundary of ZLD process.

Table 5
Normalization indicators

Impact category	Unit	Amount
GWP	$kg{\cdot}a^{-1}$ (based on CO_2)	1.130×10^{13}
AP	$kg{\cdot}a^{-1}$ (based on SO_2)	4.500×10^{10}
EP	$kg{\cdot}a^{-1}$ (based on PO_3^-)	5.170×10^{9}
ADP	$kg{\cdot}a^{-1}$ (based on Sb)	1.820×10^{12}
POCP	$kg{\cdot}a^{-1}$ (based on C_2H_4)	7.370×10^{13}

Table 6
Weighting factor of environmental impact categories

Environmental impact categories	Weighting factor
GWP	0.644
AP	0.124
EP	0.149
ADP	0.044
POCP	0.039

mization plan are determined. The objective function is minimized by changing the decision variables. Information about the decision variables is listed in Table 7.

Using the pseudo code of the NSGA-II program, this article establishes a multi-objective optimization program in Matlab software. The tuning parameters of NSGA-II are shown in Table 8.

3. Results and Discussion

The established model is used to study the entire ZLD process from energy, exergy, and economic and environmental perspective, and the process simulation results are discussed in this section.

Table 7
Decision variables for ZLD process and their ranges

Decision variable	Variable range
Stripper pressure	1×10^5 Pa < $P_{Stripper}$ < 8×10^5 Pa
Extraction from sideline of stripper	5% < $F_{Stripper}$ < 15%

Table 8
Tuning parameters in the process of NSGA-II technology

Tuning parameter	Numerical value
Population size	100
Maximum number of calculations	400
Mutation probability	0.01
Crossover probability	0.90

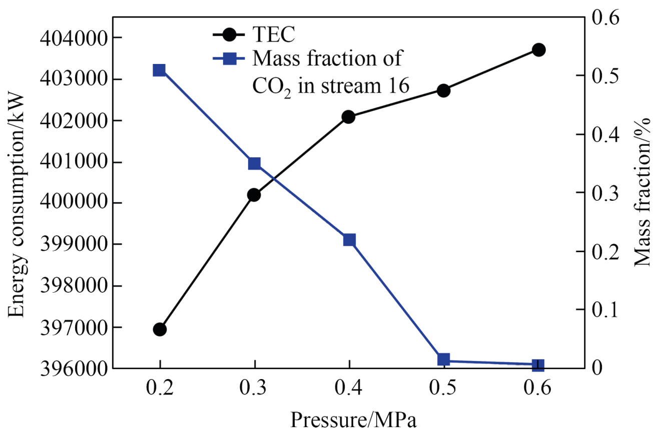

Fig. 4. The influence of stripper pressure on TEC.

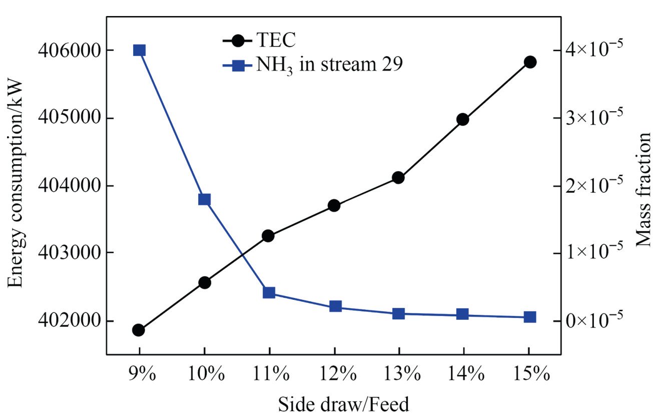

Fig. 5. The influence of stripper side draw on TEC.

3.1. Energy analysis of ZLD process

According to Eqs. (1)–(3), the TEC of the ZLD process is 4.032×10^8 W. Most of the energy consumption comes from the consumption of utilities such as steam and cooling water, and a small part is due to the power consumption of equipment and pumps. Therefore, energy consumption is mainly concentrated in the PAR unit. For the PAR unit, the stripper occupies a large part of the influence. Fig. 4 and Fig. 5 show the influence of pressure and side draw on TEC. The result shows when the pressure of stripper rises from 2×10^5 Pa to 6×10^5 Pa, the TEC increases from 3.970×10^8 W to 4.037×10^8 W. At this time, in order to satisfy the residual rate of CO_2 less than 0.01%, the optimal pressure is 5.5×10^5 Pa. As the side draw increased from 9% to 15%, TEC increases from 4.019×10^8 W to 4.058×10^8 W. In order to ensure the removal rate of NH_3, the optimal side draw is 3.197 $kg{\cdot}s^{-1}$.

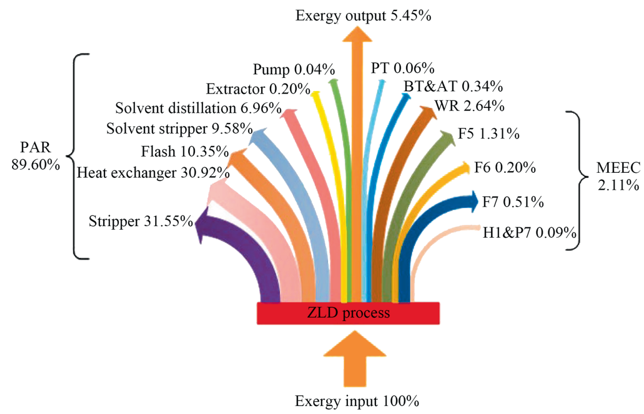

Fig. 6. The exergy destruction for each component in ZLD process.

3.2. Exergy analysis of the ZLD process

The exergy input and output data for each component is shown in Table 9. In the BT, AT and WR units, the basic parameters of streams, such as temperature and pressure, remain unchanged. Therefore, the exergy of these streams is basically unchanged, and the exergy destruction are mainly made up of the power consumption of equipment. Among them, the average power consumption of A/O process is 1.116×10^9 $J{\cdot}m^{-3}$ [51], BAF is 9.360×10^5 $J{\cdot}m^{-3}$ [52], UF-RO is 1.800×10^7 $J{\cdot}m^{-3}$ [53], HERO is 1.440×10^7 [54]. Therefore, the exergy destruction of BT&AT, RO1 and RO2 are 5.700×10^5 W, 3.683×10^6 W and 7.100×10^5 W, respectively. According to Eqs. (4) and (5), the exergy destruction for each component is better illustrated in Fig. 6 and they are 0.06%, 89.60%, 0.34% (BT & AT), 2.64% and 2.61%, respectively. The result shows that 89.60% of exergy destruction is from PAR. And components of higher exergy destruction in PAR unit are stripper and heat exchanger which are 31.55% and 30.92%, respectively. Using of steam and cooling water would cause higher exergy destruction. Besides, exergy destruction of flash, solvent stripper and solvent distillation has the same reason. Otherwise, the destruction could also come from during process. The losses of exergy destruction in other units are caused by heat transfer, power consumption and so on. In particular, the exergy output which is only 5.45% shows that the system wastes a lot of energy.

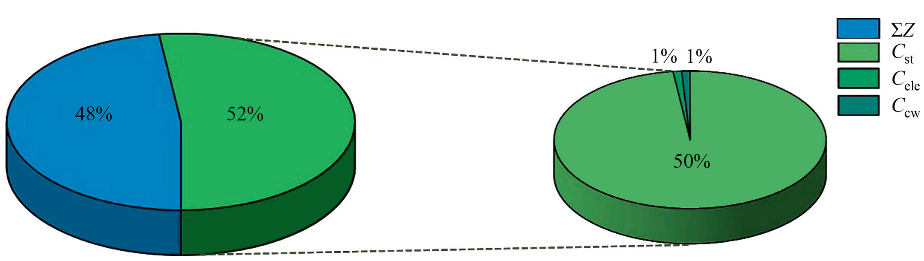

Fig. 7. The economic costs analysis results of ZLD process.

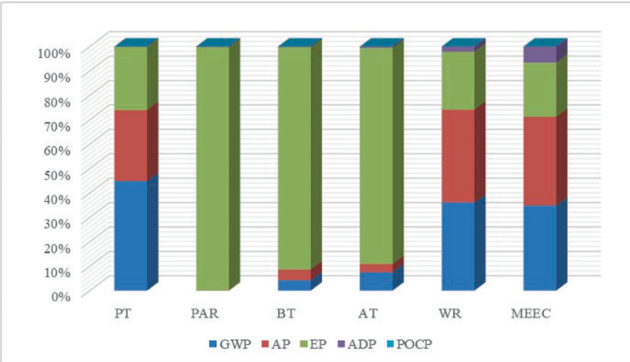

Fig. 8. The NEI for each unit of ZLD process.

For reducing the exergy destruction of ZLD process, energy integration of the system should be given priority.

3.3. Economic analysis of ZLD process

Different units of ZLD process on the economic performance are discussed in this section. The economic costs analysis of ZLD process is shown in Fig. 7 and the total cost is 1.892×10^7 USD·a^{-1}. The wastewater treatment costs of each unit are calculated as 9.070×10^5 USD·a^{-1} for PT, 1.028×10^7 USD·a^{-1} for PAR, 3.216×10^6 USD·a^{-1} for BT & AT, 3.541×10^6 USD·a^{-1} for WR, 0.984×10^6 USD·a^{-1} for MEEC.

3.4. Environmental analysis of the ZLD process

The CEI of the seven units for ZLD process based on GaBi are shown in Table 10, respectively. The results show that PAR, BT and MEEC provide most of the environmental impact for ZLD process, which is account for 67% taking GWP as an example. The main reason is the heavy use of energy and chemicals, such as the use of a large amount of extractant, steam, condensate water in the PAR unit and a lot of electricity consumed in the MEEC unit.

According to the CEI, Fig. 8 shows NEI of ZLD process which is normalized based on Eq. (12). The EP value of ZLD process is greatest. The high EP value of ZLD process is due to the emissions from WWTPs. The high GWP value is due to the greenhouse gas emissions (*i.e.* CO_2) though processes to environment [55]. High energy consumption is the reason why ZLD process causes more CO_2 emissions. AP shows environmental impact of substances which can cause acid rain and it is mainly caused by the consumption of electricity. There is less influence on ADP and POCP for ZLD process, so these two indicators are not discussed in detail.

Table 9
The exergy input and output data for each component in ZLD process

Unit	Component	Exergy input × 10^3/W			Exergy output × 10^3/W	Exergy destruction × 10^3/W
PT	P1	95.170①	$5.268 \times 10^2$④		524.960①	97.030
PAR	E1	76.130①	$3.244 \times 10^2$③		36.760①	363.740
	E2	431.400①	$3.333 \times 10^4$②		$1.595 \times 10^4$①	1.782×10^4
	Stripper	$1.599 \times 10^4$①	$4.107 \times 10^4$②	$1.757 \times 10^4$④	$2.211 \times 10^4$①	5.252×10^4
	F2	$2.060 \times 10^4$①			$3.975 \times 10^3$①	1.662×10^4
	E3	$2.848 \times 10^3$①	$3.220 \times 10^3$③		449.660①	5.618×10^3
	F3	449.660①			90.890①	358.770
	E4	246.470①	277.130③		276.850①	246.750
	F4	276.850①			12.210①	264.640
	E5	$1.128 \times 10^3$①	$1.181 \times 10^3$③		66.740①	2.243×10^3
	E6	−161.020①	101.210③		−69.280①	9.470
	P2	−49.960①	105.030④		−8.810①	63.880
	Extractor	$1.311 \times 10^3$①			980.090①	331.070
	P3	$1.007 \times 10^3$①	34.690④		$1.040 \times 10^3$①	1.830
	E7	$1.040 \times 10^3$①	$1.534 \times 10^4$②		$9.417 \times 10^3$①	6.964×10^3
	E8	−27.290①	834.250②		424.020①	382.940
	E9	99.640①	70.130③		−4.350①	174.120
	Solvent distillation	424.020①	$7.409 \times 10^3$②	$4.251 \times 10^3$③	481.980①	1.160×10^4
	Solvent stripper	$9.417 \times 10^3$①	$1.514 \times 10^4$②	$1.990 \times 10^3$③	$1.058 \times 10^4$①	1.596×10^4
	E10	$1.054 \times 10^4$①	$9.306 \times 10^3$③		$2.150 \times 10^3$①	1.770×10^4
BT&AT		$2.150 \times 10^3$①	570.000④		$2.150 \times 10^3$①	570.000
WR	RO1	$2.150 \times 10^3$①	$3.683 \times 10^3$④		$2.150 \times 10^3$①	3.683×10^3
	RO2	537.620①	709.760④		537.62①	709.760
MEEC	F5	$4.862 \times 10^3$①			$2.677 \times 10^3$①	2.185×10^3
	F6	$2.672 \times 10^3$①			$2.164 \times 10^3$①	328.550
	F7	$1.972 \times 10^3$①			$1.120 \times 10^3$①	852.590
	H1	67.030①	18.950④		72.370①	13.640
	P7	145.51①	0.120④		4.160①	141.470

①The stream exergy; ②The heat energy exergy; ③The cool energy exergy; ④The electric energy exergy.

Table 10
Environmental impacts of the process

Impact categories	PT	PAR	BT	AT	WR	MEEC	ZLD
GWP (kg $CO_{2\text{-eq}}$)	2.008×10^3	1.817×10^3	3.153×10^3	1.151×10^3	174.410	1.645×10^3	9.948×10^3
AP (kg $SO_{2\text{-eq}}$)	5.180	6.290	13.010	2.080	0.730	6.830	34.120
EP (kg PO_4^{3-}−eq)	0.530	1.597×10^3	30.940	6.240	0.052	0.480	1.635×10^3
ADP × 10^{-5} (kg $Sb_{\text{-eq}}$)	1.000	1.333×10^3	27.200	14.400	1.670	50.000	1.444×10^3
POCP (kg $Ethene_{\text{-eq}}$)	0.320	0.540	1.230	0.220	0.078	0.660	3.050

Table 11
The TEI of ZLD process

Impact category	GWP	AP	EP	ADP	POCP	TEI
Value × 10^{-10}	5.67	0.94	471.28	0.35	0.16 × 10^{-4}	478.24

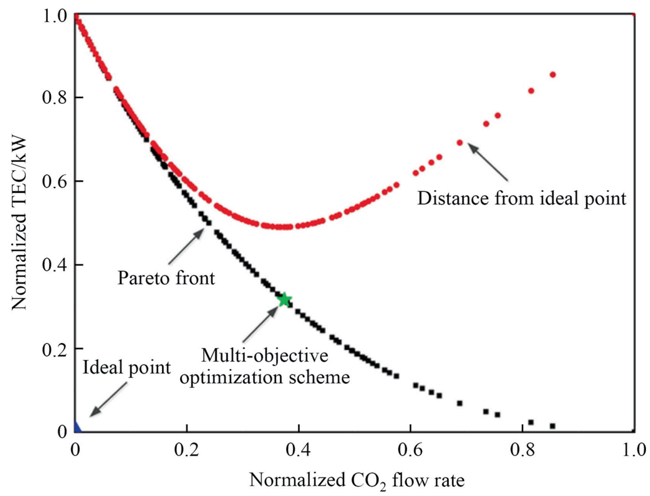

Fig. 9. Pareto frontier of multi-objective optimization of ZLD process based on CO_2 content.

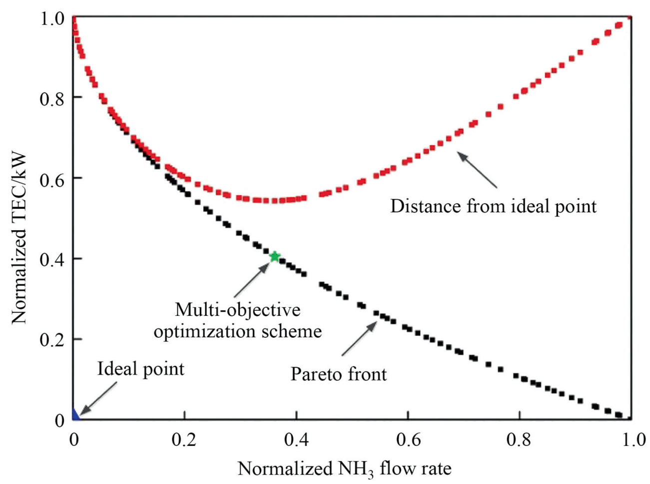

Fig. 10. Pareto frontier of multi-objective optimization of ZLD process based on NH_3 content.

Table 11 shows the TEI of ZLD process is 478.24 × 10^{-10}. As described in Section 2.3.4, the value shows the gap with China's corresponding total annual emissions.

3.5. Multi-objective optimization scheme design of the ZLD process

Based on the technique for order preference by similarity to ideal solution (TOPSIS) method, the point closest to the ideal point (0, 0) is selected as the optimal solution at the Pareto frontier. Figs. 9–10 show the Pareto frontier of the multi-objective optimization process. The red lines in Figs. 9–10 indicate the distance from the Pareto frontier to the ideal point. The coordinates of the minimum distance point are (0.374, 0.316) and (0.362, 0.404) respectively, which are the optimal solutions. The optimal solution for multi-objective optimization results in a TEC of 4.027 × 10^8 kW and a CO2 content of 0.1%.

4. Conclusions

In this study, energy, exergy, and economic and environmental analysis are combined to provide an innovative opinion for ameliorating the production capacity and environmental performance of ZLD process, which is reduced environmental impact and improved energy utilization. The results are as follows:

(1) For the entire ZLD process, the TEC is 4.032 × 10^8 W. The TEC is the smallest when the pressure of Stripper in the PAR unit is 5.500 × 10^7 Pa, the side draw is 3.197 kg·s^{-1}.

(2) The results of thermodynamic analysis show that the exergy output of the ZLD process is only 5.45%. The exergy destruction of PAR unit is the largest, which is 89.60%. Therefore, the optimization of the PAR unit can reduce exergy destruction and maximize energy utilization.

(3) Economic analysis shows the same results as the exergy analysis, that is, while the PAR unit occupies the largest part of the exergy destruction, it also costs the most in ZLD process. And for the entire ZLD process, $\sum Z$ and C_{op} are basically equal and C_{st} occupies most of C_{op}, which accounts for 50%.

(4) The LCA results of the ZLD process show that PAR, BT and MEEC units have the serious impact on the environment. The results after external normalization method show EP is one of the most important indexes and the TEI of the ZLD process is 4.780 × 10^{-8}.

(5) The total energy consumption of the multi-objective optimized low stripper pressure process is 4.0284 × 10^8 W, and the CO_2 content in the treated wastewater is 0.1%, which is 0.4% lower than the original process.

In this work, the comprehensive study and analysis of ZLD process is proposed by combining energy, exergy, economic and environmental analysis. Research results show that PAR is the key unit. This is of great significance to clarify the key links of the ZLD process, improve its production efficiency, and achieve clean, low energy consumption production through comprehensively considering various factors. Multi-objective optimization and heat-water network optimization would also the direction to related researchers for the optimization of the ZLD process of FBCGW. Otherwise, this work provides an insight choice for researchers to choose renewable energy and other clean process like organic Rankine cycle for integrated process design, in response to local conditions in the future.

Data Availability

No data was used for the research described in the article.

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.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (22078166, 22178188).

Supplementary Material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cjche.2022.10.012.

Nomenclature

C	cost
$\dot{E}$	exergy
h	specific enthalpy
I	interest rate
$\dot{m}$	mass flow rate
N	service lifetime
$\dot{Q}$	heat transfer rate
S	equipment size
s	entropy
T	temperature
$\dot{W}$	power
w	weighting factor
Z	capital cost
α	capital recovery factor
ϕ	maintenance cost factor

Subscripts

B	base capital
cw	cooling water
ele	electricity
D	destruction
E	equipment
i	category
in	input state
op	operational
out	output state
st	steam
t	total annual
T1…T6	process unit
0	standard state

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