Sustainability and ecological efficiency of low-carbon power system: A concentrating solar power plant in China

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Abstract

Low-carbon power generation has been proposed as the key to address climate change. However, the sustainability and ecological efficiency of the generating plants have not been fully understood. This study applies emergy analysis and systems accounting to a pilot solar power tower plant in China for the first time to elaborate its sustainable and ecological performances. Emergy analysis covers virtually all aspects of sustainability and ecological efficiency by considering different forms of materials inputs, environmental support and human labor on the same unit of "solar joule". The input–output analysis based systems accounting is applied to trace the complete emergy embodied in the supply chain for all product materials of the given plant against the back ground of complex economic network, which improved the accuracy of accounting. This analysis illustrated unexpectedly low sustainability and ecological efficiency of this particular plant compared with the emergy analysis based on the primary materials (steel, iron, cement, etc.). Purchased emergy responses more than 95% of the total and emergy input in the construction phase is more than twice as much as that in the operation phase. Comparisons with other kinds of clean energy technologies indicate previous studies may have overestimated the sustainability and ecological benefits of low-carbon power plants. Thus, it is necessary to establish this kind of unified accounting framework. In addition, sensitivity analysis suggests that strictly controlling monetary costs of purchased inputs, extending service lifetime and improving power generation efficiency can promote higher sustainability and ecological efficiency for solar power tower plants. This study provides a more comprehensive framework for quantitative emergy-based evaluation of the sustainability and ecological efficiency for low-carbon power systems.

Keywords: Concentrating solar power plant; Sustainability; Ecological efficiency; Emergy method; Systems accounting

1. Introduction

Due to the current global oil market, geopolitical tensions, the pursuit of carbon emissions reduction and sustainable development goals, clean energy technology has attracted widespread attention and has been deployed rapidly worldwide. Solar power technology, including solar

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photovoltaic (PV) and concentrating solar power (CSP) technology, is widely considered as one of the most competitive alternatives thanks to the features of low cost and being environmental friendly [1, 2]. CSP system uses a large array of mirrors to collect solar heat, then provides high temperature steam through a heat exchanger, and finally achieves the purpose of electricity generation by combining the technology of traditional turbo generator. The CSP system can be integrated with thermal energy storage technologies and generate electricity uninterruptedly during periods without efficient sunshine. Thus, ability to providing a dispatchable source of electricity makes it a very promising way to generate electricity [3, 4]. Solar power tower (SPT) is one of the dominant types of CSP systems. Although the development of SPT technology is relatively slow compared with PV technology, it has received extensive attention, and its technical feasibility has been verified in the United States, Spain, South Africa and other countries [5-8]. As for China, construction of the first experimental SPT station in the megawatt class began at Beijing in 2007. The first nine SPT demonstration projects were launched in 2016, with a total of four completed and put into operation in 2018 and 2019. The total installed capacity of these four SPTs is more than 250 MW which has been greatly changing the energy structure of northwest China [9].

In this era, the concepts of sustainable development and ecological efficiency cannot be avoided in any discussion of construction and production, including that of the SPT systems. In fact, many scholars have emphasized that the renewable power systems (referring to solar power plants, etc.) need the support of many non-renewable energy sources (referring to fossil fuels, etc.), especially in the process of infrastructure construction, and thus have questioned the sustainability and ecological efficiency of the renewable power systems qualitatively or quantitatively [10-12]. For example, Yang and Chen [10] pointed out that the non-renewable energy consumed in corn-based ethanol production is conservatively estimated to be 1.70 times the energy produced (ethanol) through a process-based energy analysis. Fan et al. [12] concluded after conducting a unified accounting of the pilot power station based on the cosmic exergy perspective that a SPT plant is of low renewability and sustainability due to huge non-renewable investment. The latest work assesses the impact of wind farms on soil organic carbon and shows that the renewable energy investments should be comprehensively reevaluated in accordance with long-term environmental costs, capability of strategic environmental assessment processes and environmental impact assessment, etc. [13].

By considering different forms of materials, environmental support, human and economic services on the same basis, various aspects of sustainability and ecological efficiency would be more adequately covered. The use of emergy helps to meet this criterion [14]. Such research is crucial for developing mitigation and adaptation policies to balance the bottom line of society, ecology and economy. Emergy analysis, first proposed by Odum, transforms all goods, services, information, and environmental investments (including sunlight, wind, rain, soil, etc.) into a common unit of solar emjoule (seJ) of available energy [15, 16]. In recent years, emergy method has been widely applied to the evaluation of some ecological and economic systems, including architectural systems [17, 18], agricultural systems [19], and some mixed systems, such as sewage treatment industry [20], at different scales, like regional [21], national [22, 23] and global scale [15, 24]. Emergy based indicators have also been used in the evaluation and comparison of the sustainability and ecological efficiency of various power generation systems [25-32]. In 2002, emergy accounting techniques were used to evaluate the environmental efficiencies of six power systems [33, 34]. Subsequently, some scholars evaluated the economic and environmental performance of eight Japanese power generation systems by improving new indicators based on emergy analysis [35]. Shortly thereafter, an emergy evaluation of a dry steam storm power system in Italy was conducted and the extent to which the system became harmless was determined [25]. Recently, Ren et al. found that the sustainability of hydropower systems was the best, while the sustainability of wind and solar power plants were lower after comparing ten power generation systems by emergy evaluation [36].

In emergy evaluation of power generation systems, one concept which is particularly important is the conversion factor (i.e. emergy intensity). It refers to emergy required to produce per unit product or provide per unit service. A higher conversion factor means that more emergy needs to be invested in the creation of goods, resources or services. Many scholars have made great efforts to calculate conversion factors based on emergy algebra [15, 37-39]. In the early assessments, the amount of input was often multiplied by a single conversion factor, which led to misleading accounting results [40]. Later, some researchers tried to trace the historical representation of each product through process analysis. But it turned out to be very time consuming and labor intensive. In addition, they must be truncated after some steps, which resulted in the truncation errors [41]. The input-output method allows completing modeling of the entire economy network by organizing matrices of intermediate inputs [42]. Chen and his colleagues [43] presented the embodiment analysis of resources use of Chinese economy 2007 based on ecological input-output modeling and the sectoral embodiment intensities of resources in terms of emergy, which has laid a very good foundation for environmental accounting of resources using at different levels.

It is also important to note that the conversion factors based on the system input-output method vary with the study area and/or time. A case study by Zhang et al. [44] of accounting for a SPT plant with emergy analysis has attracted our attention. This report provides some information of great significance. However, the selection of conversion factors in Zhang's research was doubted by Campbell E. [45], including the faulty choice of a solar emergy baseline and conversion factors that has not been adjusted by research region or time. On the other hand, the conversion factor database that it used by Zhang et al., cannot track the utilization of renewable and non-renewable resources in a comprehensive way. In fact, every commodity and social service consumes both renewable and nonrenewable resources through its supply chain except for some essentially natural resources [46]. Failure to explicitly track its renewable and nonrenewable resources will affect the accuracy of sustainability and ecological efficiency assessments.

Systems accounting combines conversion factors based on input-output method and process analysis. As a bottom-up approach, process analysis provides detailed process information for product or technology inputs. In 1976, Bullard et al. [47] pointed out that the direct and indirect energy required to produce different types of goods or services could be calculated by combining process analysis with the energy intensity coefficient based on energy input-output analysis. Originating from this hybrid method and the thought of systems ecology raised by Odum [48], Chen and his colleagues further extended the energy input-output analysis to the systems input-output analysis and generalized the systems accounting for the quantification of embodying ecological elements [49]. Existing study estimated the total fossil energy cost and greenhouse gas emissions of a SPT system through a systems accounting associated with energy-use and carbon-emission intensity databases obtained from the input-output analysis [50]. Based on the specific systems accounting, Wu et al. comprehensively analyzed the industrial water use in each stage and found that the industrial water use caused by the SPT plant infrastructure was surprisingly high [51]. Such kind of research shows certain advantages, but is still extremely rare at present.

This study attempts to conduct sustainability and ecological efficiency assessment for the aforementioned SPT system studied by Zhang et al., based on the detailed inventory of input items, systems accounting, and the emergy analysis method. Different from previous studies, in which only primary materials of each input were considered, the renewable and non-renewable resources of all inputs in the supply chain has been specifically tracked in this study by using conversion factors based on input-output analysis under the background of complex economic network. The conversion factor database of this study is also in line with the national economy of China in 2007, the year in which construction of the plant began. The accuracy of emergy accounting could be improved combining this conversion factor database and the most detailed first-hand data of this project. Moreover, studying the components of emergy based inputs and the emergy utilization at all stages helps to comprehensively measure the social benefits and environmental impacts of SPT plants, which will facilitate their long-term planning and management in turn. Finally, this research complements some policy recommendations to improve the sustainability performance of SPT plants according to the sensitivity analysis.

Therefore, the main objectives of this study are: (1) to combine the systems accounting with the emergy method and apply it to the sustainability and ecological effeciency assessment of a SPT plant for the first time; (2) to comprehensive track and analysis the emergy composition of the case plant; (3) to explore possible ways to improve the plant's sustainability and ecological effeciency, in an attempt to provide advice or supports for policy making in this low-carbon power generation industry.

2. Method and materials

2.1. Data sources

The case plant is the first megawatt-class CSP plant in China and Asia. The construction of it began in 2007 and was officially put into operation in 2012. A layout diagram of the case (Figure 1) is drawn according to the detailed first-hand information for readers' better understanding of the system. The plant primarily includes solar collectors' field, heat exchange system, energy storage system, turbo-generator system and test base; and it has an installed capacity of 1.5MW and an annual generating capacity of 2.7 GWh according to the Feasibility Report of Dahan Solar Tower Project [52] jointly developed by China Huadian Engineering Group and the Institute of Electrotechnics, Chinese Academy of Sciences. All the first-hand data about the inputs also comes from this Feasibility Report. More details can be found in Zhang et al. [44].

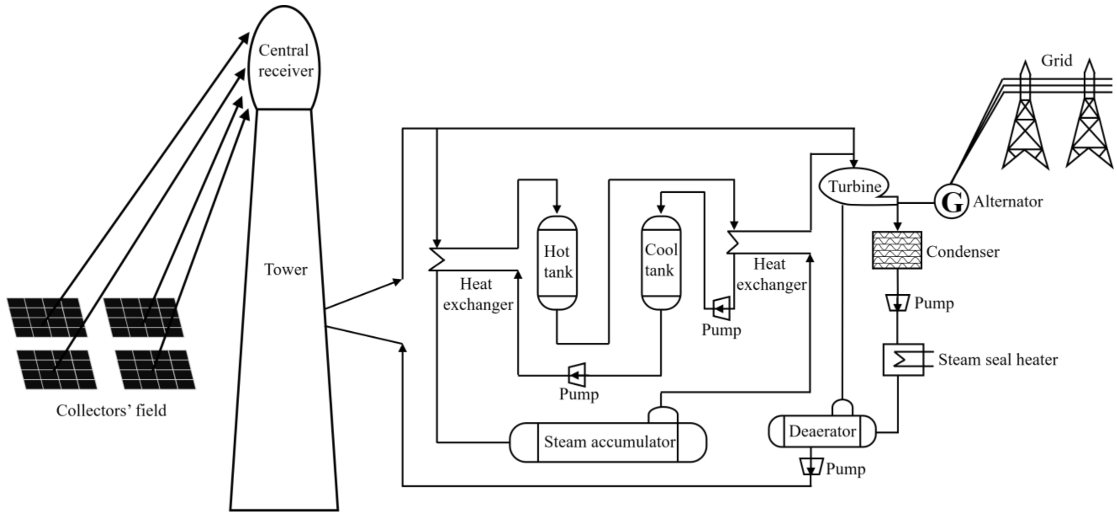

Fig. 1 Layout diagram of the SPT plant

2.2. Assessment procedures

Combined with emergy methods, conversion factors based on input-output analysis, and sensitivity analysis, the sustainability and ecological efficiency assessment procedure is as follows:

I、Draw an emergy diagram (Figure 2) according to the layout diagram and previous descriptions of the system [12], determine the boundary of the system and manage the relationships of the main components. This emergy diagram is obtained based on the emergy circuit symbols developed by Odum (1983) [48].

II、List the detailed input inventory. All investments include environmental inputs and purchased ones (include goods and social services). The amounts of environmental inputs are measured in joules and for purchased inputs in currency. Due to the fact that the costs of the dismantling phase are only a small part of the total [12], as well as the current lack of original data, the costs of this phase are not taken into account in this study.

III、Select the appropriate conversion factor database and calculate the corresponding emergy value for each input respectively. Total emergy is obtained by summing up all input emergies [53].

$$\text{Total Emergy} = \sum_{i=1}^{n}(Qi * CFi), i = 1, \ldots, n \quad ①$$

in which, Qi is the i-th quantity (i.e. input flow) of energy or matter, CFi is the conversion factor of the *i-th* flow.

The conversion factors for environmental inputs are relatively constant based on a classic database of Odum's contributions. The selections of conversion factors for purchased inputs must meet the following conditions. Firstly, conversion factors should be synchronized with the country or territory of the target system. Secondly, conversion factors should be synchronized with the year in which the target system is constructed and with the corresponding economy communities. The construction of this SPT plant started in 2007. In addition, the input-output table of 135 sectors in 2007 provides the most detailed classification of sectors for Chinese economy. Therefore, the emergy conversion factor database established by Chen et al. [43] with reference to the Chinese economic input-output table of 2007 is chosen in this study.

IV、The composition of inputs is then analyzed, including the proportion of natural (environmental) and purchased inputs, the proportion of construction and operation stage, and emergy corresponding to each economic sector, so as to have a better understanding of the system.

V、A series of emergy-based indexes [53] are calculated according to the emergy fluxes, which include:

⑴ Transformity (Tr), in order to make a more intuitive comparison with Zhang's results, the Tr here is also defined as the amount of emergy it would take when produce one unit of output. The greater the Tr is, the lower ecological efficiency of the system is over the whole process.

$$\mathrm{Tr} = \mathrm{I} / \mathrm{Y} \quad ②$$

in which, I represents total inputs (including all purchased and natural renewable and nonrenewable inputs) and Y means total yield in emergy.

⑵ Emergy Yield Ratio (EYR), comes from the total yield divided by purchased inputs. It could be used to measure the return on purchased investment. The greater the EYR is, the more outputs produced by unit of purchased input.

$$\mathrm{EYR} = \mathrm{Y} / \mathrm{Ieco} \quad ③$$

in which, Ieco is renewable and non-renewable inputs from economic purchasing activities.

⑶ Environmental Loading Ratio (ELR), is the ratio of total nonrenewable inputs divided by total renewable inputs. The greater the ELR is, the heavier load of the system is to the environment.

$$\mathrm{ELR} = \mathrm{In} / \mathrm{Ir} \quad ④$$

in which, In means total nonrenewable inputs (including all purchased and natural nonrenewable inputs) and Ir is total renewable inputs (including all purchased and natural renewable inputs).

⑷ Environmental Sustainability Index (ESI), indicates the sustainability of the system in the long run. The greater the ESI is, the better the system performs in terms of sustainability.

$$\mathrm{ESI} = \mathrm{EYR} / \mathrm{ELR} \quad ⑤$$

VI、Compare various emergy based indexes of different power generation systems.

VII、A set of scenarios were proposed to explore future optimization directions for reducing the environmental pressure and improving the sustainability and ecological efficiency of the SPT plant.

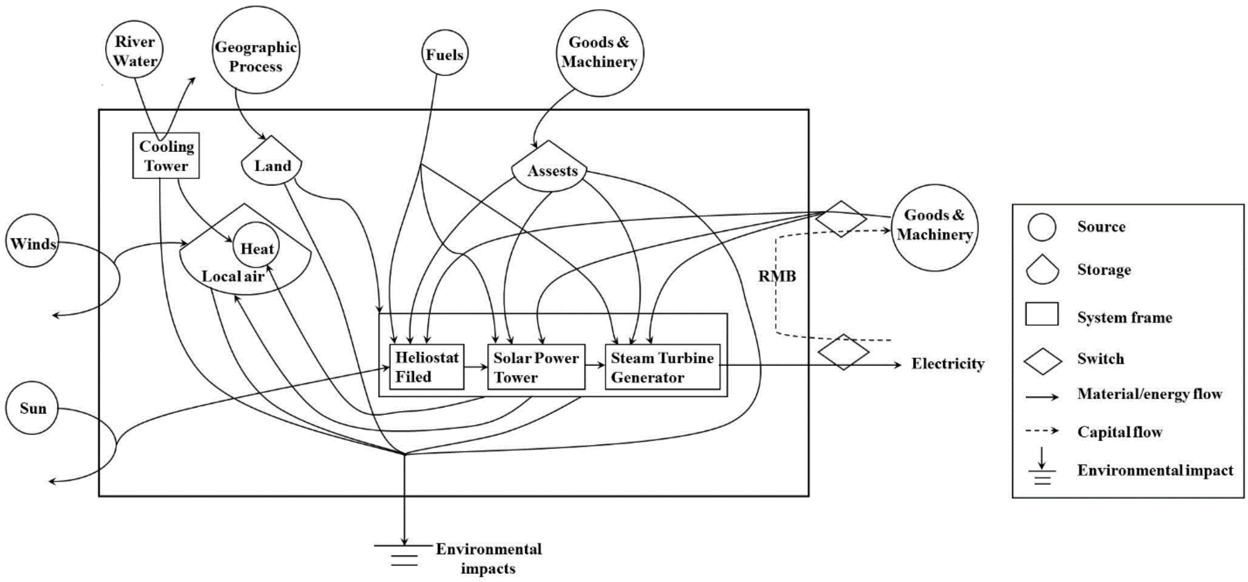

Fig. 2 Emergy diagram of the SPT plant [12]

3. Results and discussions

3.1. Input inventory associated with the input-output sectors

The most detailed list of inputs and the proportion of each input to the total is given in Supplementary 1. There are 54 kinds of inputs in total which include not only the inputs of natural resources, but also the inputs purchased from the commercial market (including labor and services) which are quantified in monetary units to correspond to macro economy. Conversion factors are derived from the “consolidated database based on input-output analysis" [43]. Over a designed life time of 30 years, the total emergy input of this SPT system is 4.04E+19 seJ. Specifically, the renewable input is 6.59E+18 seJ, while the nonrenewable input is found to be 3.38E+19 seJ. More specifically, renewable inputs of natural resources (including solar radiation, wind, kinetic, rain, and geothermal) amount to 1.07E+18 seJ; Nonrenewable inputs of natural resource (soil loss) are 1.95E+11 seJ; Renewable inputs purchased from commercial market are calculated to be 5.52E+18 seJ; Nonrenewable purchased inputs reach 3.38E+19 seJ.

In contrast, the total input emergy accounted by Zhang et al. [50] (6.25E+17 seJ) is far less than the accounting result of this study (4.04E+19 seJ) under the same expecting life time. There are three possible reasons accounting for this discrepancy. First of all, only 27 kinds of inputs are considered in Zhang's accounting, which means that input projects such as insulation paint, luminaire and other electrical material are not taken into account. While each input of each subsystem in this power generation system is listed in greater detail in this study. Secondly, the inputs are only converted into primary materials, namely the input of concrete, iron, steel, rock wool and glass, ect. in Zhang’s study, which leads to an underestimated result. For example, only steels and glasses are considered when accounting the relevant input for heliostats. However, apart from steels and glasses, each heliostat requires considerable design, testing, installation and cleaning costs. Therefore, Zhang's accounting result shows that heliostats take up 2.23E+16 seJ of emergy for this SPT system while ours is 5.04E+18 seJ, plus 4.08E+17 seJ of emergy for its installation. Thirdly, the inconsistency of conversion factors is also an important reason for the discrepancy of the two calculation results. Zhang et al. only consider the inputs of primary materials, and then choose the corresponding conversion factors according to these primary materials for accounting. Furthermore, the conversion factors for purchased inputs used by Zhang et al. are not updated according to economic community and particular year [52]. However, the conversion factors in this study are obtained based on the input-output analysis method and the national economy database of China in 2007, which ensures the veracity of this accounting.

The uncertainties of the results and the limitations of the work mainly involve the following two aspects. On the one hand, the conversion factors based on the input-output table in different periods may lead to uncertainty in the results. In fact, there are two versions of the input-output classification of the Chinese economy in 2007, namely the 42 sector breakdowns and the 135 sector classifications. In addition, in the 2012 input-output table, the national economy of China is characterized by 139 sectors. In this work, the emergy conversion factors related to the classification of 135 sectors in China Economy 2007 were selected. One of the reasons is that the SPT project was launched in 2007. Another reason is that the 135-sector table covers delicate classifications that match the economic inputs of the SPT plants. On the other hand, the conversion factors related to the input-output tables of different regions may also lead to variation of the results. The monetary costs of resources and labor in Beijing may be very different from those in other parts of China. For SPT plants in different regions, the cost of buying the same material as well as doing the same work may be different. Therefore, if the conversion factors related to the input-output table of Beijing are used in this study, the results may be more accurate. However, due to the difficulties of cross-scale input-output modeling, Beijing economy based conversion factors have not been reported yet. The influence of different emergy conversion factor database on the accuracy of the results needs to be further studied.

3.2. The components of solar emergy based inputs

During the construction and operation of the SPT system, it requires not only a large amount of inputs purchased from the commercial market, such as heat reservoir, turbo-generator and cable, but also inputs of natural resources such as solar radiation, soil and geothermal. It could be found that the inputs of natural resources are 1.07E+18 seJ when converted into emergy, accounting for 2.65% of the total inputs. The value of purchased emergy is 3.93E+19 seJ, responsible for 97.35% of the total (Figure 3). The emergy inputs of natural resources have a minor share of the total because they are subject to the land area of the power generation system and have a certain threshold value. The purchased inputs from commercial market of the system are in a dominant position, namely the construction, operation and maintenance process of the plant are highly dependent on the resources from the economic system, which is consistent with the conclusion drawn by Zhang et al [50] and Fan et al [12].

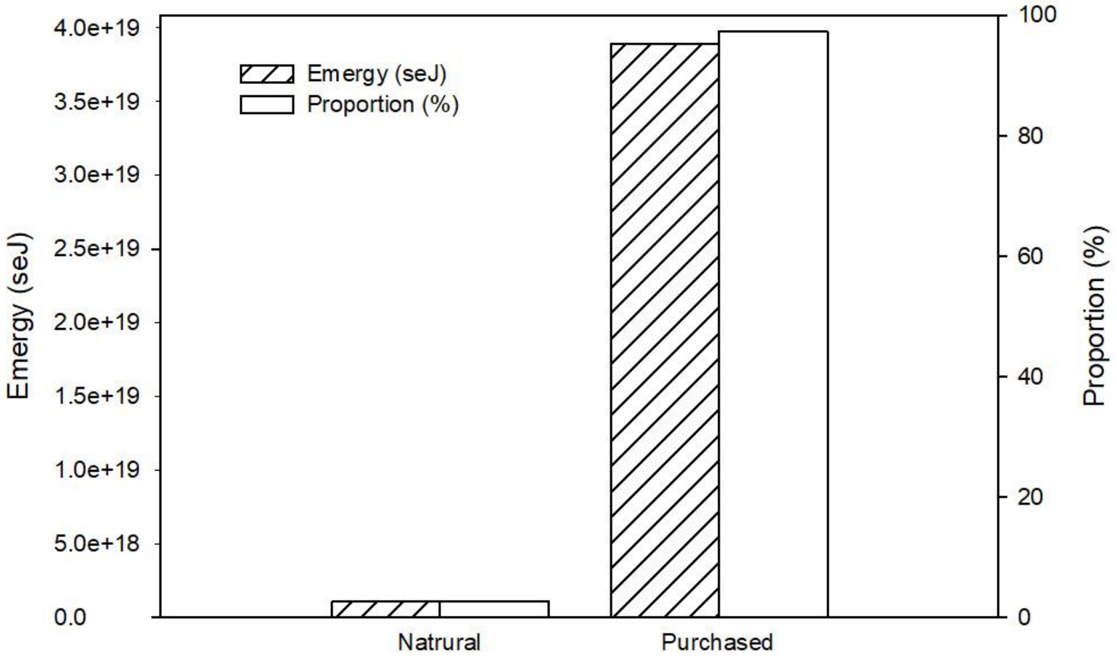

Fig. 3 The components of emergy based inputs

The traditional view about the green (renewability and sustainability) of solar power plants put more emphasize the environmental cost of operating phase than that of construction phase [54]. However, Chen et al., [50] have found that the nonrenewable energy consumed during the construction phase was approximately 80% of that in the entire life cycle for a solar power system. Previous studies have revealed that wind power generation may require higher initial investment in infrastructure compared to fossil energy generation systems [55]. Due to the inputs purchased from commercial market accounting for over 97% of the total investment, we focus on the emergy of this part. The comparison in this study shows that, emergy input by purchasing during the construction stage is 2.69E+19 seJ, which doubles that of the operation stage (1.24E+19 seJ, Figure 4). This indicates that the influence of investments in the infrastructure construction stage must not be ignored in the assessment of power generation systems. There are two main reasons for the difference between these two stages. Firstly, the inputs in the operation stage mainly consist of operation and maintenance, labor and service, oil and water costs while the investments in the construction phase are up to 50 items, including machinery, auxiliary systems, and transmission cables and so on. Secondly, machinery, equipment, transmission cables and other input items in the construction stage are very emergy-intensive; in other words, there is a large amount of emergy consuming for these items' production.

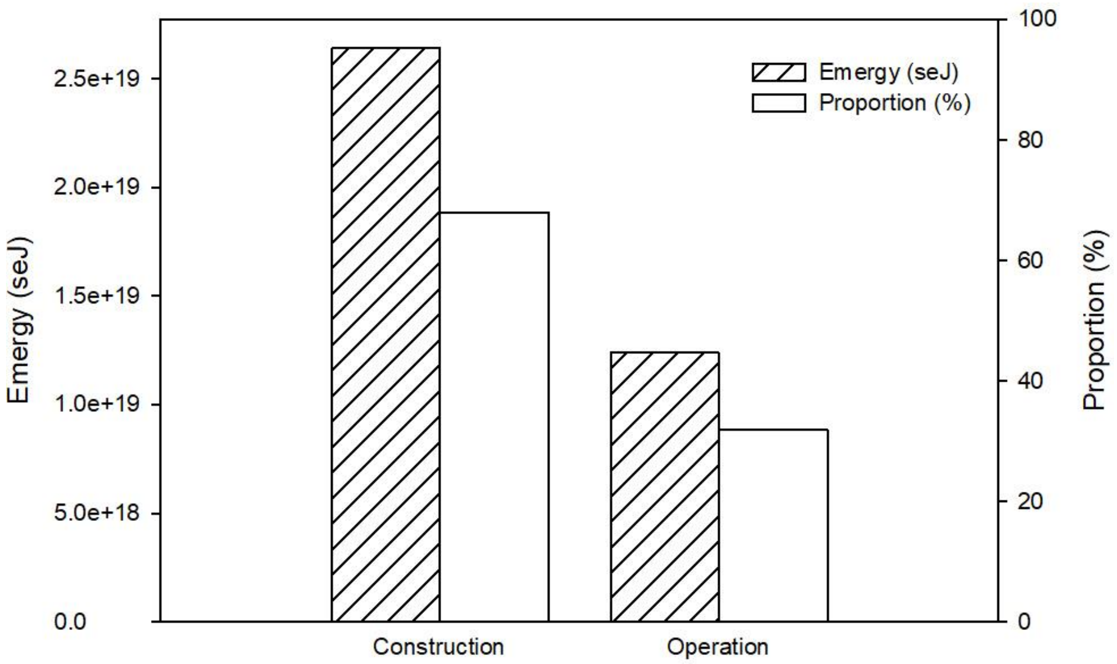

Fig.4 The components of emergy based purchased inputs associated with phases

The purchased inputs are divided into 47 items in this study. Corresponding to the input-output table of 135 sectors of Chinese economy 2007, it is found that the system involves 17 social economic sectors, including professional technical services etc. (Figure 5). A deeper analysis to reveal the sectoral emergy characteristic will not only help us understand more about the composition of system input, but also provide guidance for the sustainability improvements of this power generation system. Results indicate that the three sectors with the smallest share are sector 81 (transports of other electrical machinery and equipment), sector 97 (transports via road), and sector 74 (the manufacture of automobiles). The three sectors with the largest share are sector 7, 88 and 95. Sector 7 refers to extraction of petroleum and natural gas accounting for 10.40% of the total; sector 88 represents the manufactures of instruments accounting for 13.85% and sector 95 mainly stands for construction accounting for 45.34% of the total emergy inputs. The dominant emergy consumption sectors identified in this study show a great potential in the system emergy reduction in order to improve the sustainability and ecological efficiency of the case plant. Construction sector is the largest dedicator, accounting for more than 45% of the total emergy of the case plant, which is consistent with the result of Fan et al., [12]. There are two main reasons. On the one hand, the construction sector is highly emergy-intensive, which means large amounts of emergy are induced in the supply chain of building products, construction, and equipment installation, etc. On the other hand, more than a quarter of total monetary investment comes from construction and installation, both of which belong to the construction sector.

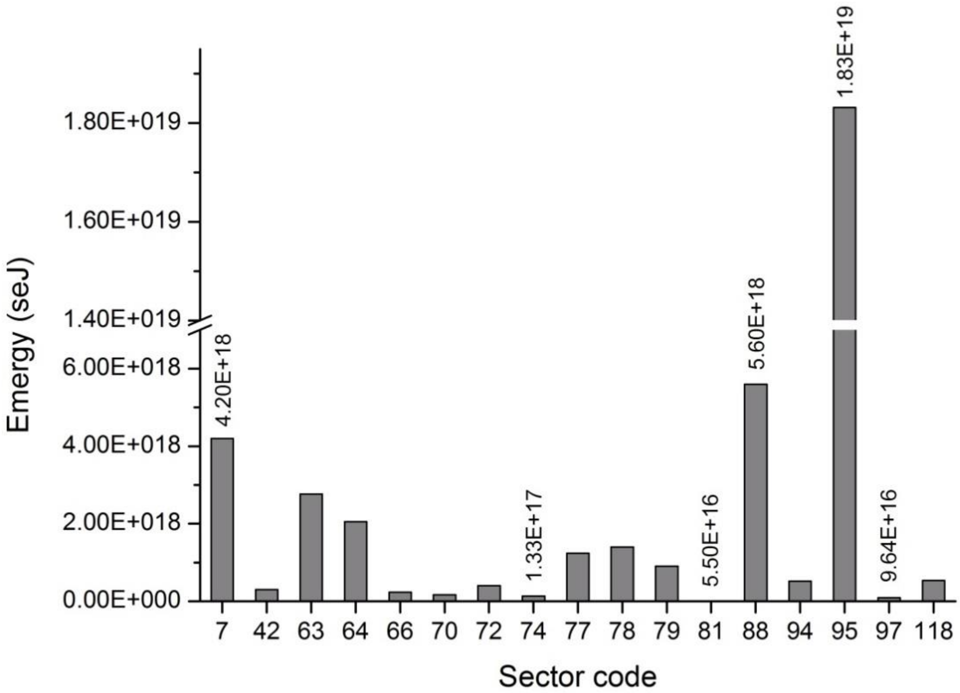

Fig.5 The components of emergy based purchased inputs associated with input–output sectors

Note: Match-up of the input items with corresponding economic sectors: 7, Extraction of petroleum and natural gas; 42, Manufacture of paints, printing inks, pigments and similar products; 63, Manufacture of metal products; 66, Manufacture of lifters; 70, Manufacture of special purpose machinery for chemical industry, processing of timber and nonmetals; 72, Manufacture of other special purpose machinery; 74, Manufacture of automobiles; 77, Manufacture of generators; 78, Manufacture of equipment for power transmission and distribution and control; 79, Manufacture of wire, cable, optical cable and electrical appliances; 81, Manufacture of other electrical machinery and equipment; 88, Manufacture of measuring instruments; 94, Production and distribution of water; 95, Construction; 97, Transport via road; 118 Professional technical services [43].

3.3. Emergy-based indexes

According to the detailed component input list, emergy based fluxes and indexes of this SPT plant are calculated, as shown in Table 1. Tr represents the amount of emergy required to produce one unit of output, which could be used as the measurement of the ecological efficiency of the entire system [44, 53]. Based on this definition, the smaller the Tr is, the more conversion efficient the system is. The results indicate that this SPT plant needs to consume the same amount of emergy for each unit of output produced, while according to Zhang's research, 6.39E+4 seJ is consumed for each Joule of output.

The EYR is emergy yield divided by all emergy of purchased inputs. The greater it is, the more power generated for per unit of purchased input, and the more competitive the system is. According to Ulgiati and Brown (2002) [34, 56], electric production processes with an EYR value below two can’t denote as a source of energy, while with EYR value less than five and more than two could be treated as primary materials, such as cement and steel. The EYR value of secondary and primary energy resources which could be alternatives to conventional power plants is usually greater than five [33]. Compared with EYR value obtained by Zhang's accounting (equals to 5.06), it is 1.02 in this study, indicating the system's highly dependent on human society, the relatively low exploitation efficiency for local resources and the weak system competitiveness.

The ELR measures the pressure to the environment of a specific system. In general, the lower the ELR is, the less pressure on the local environment for the system. An ELR smaller than two indicates low environmental burden, an ELR value between three and ten shows average environmental pressure, and an ELR more than ten means extremely high environmental pressure [57-59]. Compared with the value obtained by Zhang et al. (ELR = 0.39), ELR calculated in this study turns out to be 5.12 in this study, suggesting that this SPT system is indeed exerting large pressure on its surroundings.

The ESI is the ratio of EYR and ELR, and it can be used to weigh the impact of the system on the local environment against its social profit [60, 61]. The system with ESI less than one is considered unsustainable, while it would be defined as a sustainable system with optimistic performance if ESI is more than five [53]. According to Zhang et al., this SPT plant shows strong sustainability with the ESI of 13.10. However, the ESI is calculated to be 0.20 in this study, indicating the depletion of this system with high environmental pressure.

There are three reasons for the different results between this and Zhang's study. Firstly, only primary materials of the inputs are considered by Zhang et al., while a most complete component input inventory is used in this study. Thus, the methods adopted in Zhang et al. will lead a remarkable underestimation of emergy input into the system. Secondly, conversion factors are obtained and applied in completely different ways in the two studies, as mentioned above. Thirdly, all inputs and outputs are measured in different units. Zhang's research uses the Joule as the uniform unit, while this research adopts monetary values. Actually, some scholars have pointed out that the research based on energy or mass content is suitable for energy or mass flow analysis, respectively. But neither approach takes into account the impacts of economic activity and supply chain [62].

The difference from the unified accounting based on cosmic-exergy above mentioned is that they approach problems on different scales [63]. Cosmic exergy theory considers the cosmic exergy flux due to thermal difference between cosmic background microwave and solar radiation as the driving force of the earth [63-65]. However, according to emergy theory, solar energy is the only source of all other energies on the earth and emergy refers to the available solar energy directly or indirectly used to make services or products [15]. But since both the Cosmic-exergy based study and the present study advocate tracking all nonrenewable inputs in the industry chain, both studies surprisingly found that SPT plants performed poorly in terms of sustainability.

Finally, this case is the first MW-level CSP pilot power station in China. Less skillful or reliable technologies in design and installation may be important reasons for the enormous renewable and nonrenewable costs. In the future, this accounting framework will be applied to the more technologically mature, newly built CSP plants, so as to more accurately assess the sustainability and ecological efficiency of low-carbon power generation plants.

Table 1

Emergy based fluxes and indexes with a designed life time of 30 years

Item	Equations	Values
Renewable inputs of natural resources (seJ)	Ires-r	1.07E+18
Nonrenewable inputs of natural resources (seJ)	Ires-n	1.95E+11
Renewable inputs purchased from commercial market (seJ)	Ieco-r	5.52E+18
Nonrenewable inputs purchased from commercial market (seJ)	Ieco-n	3.38E+19
Total renewable inputs (seJ)	Ir = (Ires-r) + (Ieco-r)	6.59E+18
Total nonrenewable inputs (seJ)	In = (Ires-n) + (Ieco-n)	3.38E+19
Total inputs (seJ)	I= Ir+ In	4.04E+19
Total yield (seJ)	Y	4.02E+19
Transformity (solar)	Tr = I / Y	1.00
Emergy yield ratio	EYR = Y / Ieco	1.02
Environmental loading ratio	ELR = In / Ir	5.12
Environmental sustainability index	ESI = EYR / ELR	0.20

3.4. Comparison with other kinds of power technologies

By referring to existing research about sustainable evaluation for various power generation systems based on emergy analysis, it can be found that the relative conclusions are inconsistent even for the same kind of clean energy, mainly due to the discrepancies in accounting methods, as summarized in Table 2. Accounting of a biogas power plant in the United States indicates that the system is ecologically productive, environmentally friendly and highly sustainable [66]. Another accounting in Italy shows that a biogas system with a capacity of 171MW has great environmental pressure and low sustainability [33]. Brown et al.(2002) suggests that wind power is a kind of highly sustainable clean energy [33], while two other studies draw the opposite conclusion [27, 67]. There are also disagreements on sustainability performance of hydroelectric systems [31, 33, 74-77]. The reasons for these disputes may include the difference in installed capacity. It may also attribute to the inconsistency of accounting methods. An analysis that ignores infrastructure costs or only considers primary materials will significantly underestimate the actual costs of a system. Therefore, it is very necessary to establish a unified framework based on systems accounting to evaluate the sustainable performance of different plants.

A report on biomass-fired power system in China [26] and another on biomass CHP (combined heat and power) system in Finland [68] suggest that biomass combustion is a sustainable way for power generation. Similarly, two studies on geothermal power systems [25, 33] conclude that geothermal is also a kind of suitable clean energy to meet the demand of sustainable development.

Assessments for three different bioethanol systems from Malaysia [69], China [70], and Brazil [71]; four different bioethanol [72-74] systems from China and Brazil; and two solar PV power systems from Italy [75] and India [76] indicate that the biodiesel, bioethanol and PV power systems are environmentally unfriendly, poorly sustainable generation systems. In addition, studies have shown that coal [33], oil [33] and tidal [77], as well as solar thermal power generation (in this study), are also less desirable forms of power generation.

Overall, solar thermal is almost as undesirable as solar PV and bioethanol (Cassava) power generation technology in poor sustainability. Solar thermal power plants are kinds of clean energy power generation systems which are greatly affected by seasons, weather and time, while the heat storage time of this system is only about one hour. Moreover, the early inputs such as various forms of high emergy-intensive ones in the construction stage, will have a great negative impact on the overall sustainable performance of these systems [12]. Finally, the installed capacity of this pilot SPT system is very small under a phase of technology trigger. It means that the marginal cost of this system is still high, which would also lead to the low sustainability of the case system. The low conversion rate of Cassava into bioethanol for the limitations of biotechnology, has led to the unsatisfactory performance of the bioethanol system [78]. Geothermal power system converts geothermal heat into mechanical and then into electrical energy. This form of power generation is significantly better than others in terms of conversion efficiency and environmental friendliness, mainly because it is continual in power generation and is much less affected by the seasons. Wind and hydropower systems in areas with extremely abundant wind and water resources may perform better than other kinds of power systems in terms of sustainability. For example, offshore wind power which has sparked interest in Europe, the United States, China and elsewhere, offers a much higher capacity factor than solar PV and onshore wind, thanks to higher and more stable wind speeds far from the shore [79].

Table 2

Comparison of emergy based indicators with other electricity production systems

Types of energy	Project	Capacity	EYR	ELR	ESI
Solar thermal	Concentrating solar power, China (This study)	1.5 MW	1.02	5.12	0.20
Solar photovoltaic	Solar PV, Italy [75]	--	1.03	48.93	0.02
	Solar PV, India [76]	8,350 kW he/year	1.10	70.00	0.02
Oil	Oil, Italy [33]	1280 MW	4.21	14.20	0.30
Coal	Coal, Italy [33]	1280 MW	5.48	10.40	0.53
Tidal energy	Tidal power, China [77]	4.1 MW	1.52	3.72	0.41
Biomass related	Biofuel refinery, Malaysia [69]	--	1.05	3.02	0.35
	Bioethanol (Wheat), China [72]	--	1.24	4.05	0.31
	Bioethanol (Corn), China [72]	--	1.14	7.84	0.15
	Bioethanol (Sugarcane) , Brazil [73]	--	1.57	2.23	0.71
	Bioethanol (Cassava) , China [74]	--	1.14	32.06	0.03
	Biodiesel (Vegetable oil) , China [70]	--	3.68	3.55	1.04
	Biodiesel (Soybean), Brazil [71]	--	1.62	2.26	0.72
	Biomass-fired power, China [26]	24 MW	2.03	0.94	2.15
	Biomass CHP, Finland [68]	71.7 MW	2.63	0.62	4.27
Geothermal energy	Dry steam geothermal power, Italy [25]	20 MW	3.73	0.59	6.31
	Geothermal, Italy [33]	20 MW	4.81	0.44	11.00
Wind energy	Wind power, Italy [33]	2.5 MW	7.47	0.15	48.30
	Wind power, China [67]	1.5 MW	1.17	5.84	0.20
	Wind power, China [27]	30 MW	1.25	4.00	0.31
Hydro energy	Hongyan small hydropower, China [28]	8 MW	4.40	0.92	4.77

	Hydro, Italy [33]	85 MW	7.65	0.45	16.90
	Three Gorges Dam, China [80]	--	4.58	0.11	41.60
	Pa Mong, Thailand [81]	--	1.32	3.17	0.42
	Chiang Khan, Thailand [81]	--	1.32	3.12	0.42
	Multipurpose dam, Korea [82]	125.5 Gwh/yr	1.34	2.94	0.63
	Small hydropower, China [83]	1.6 MW	1.46	3.82	0.38
Biogas	Biogas, USA [66]	--	2.93	0.52	5.67
	Methane, Italy [33]	171 MW	6.60	11.80	0.56

3.5. Sensitivity analysis under different scenarios

Many factors affect the performance of the case system in terms of sustainability and ecological efficiency. To explore the influences of different factors, a sensitivity analysis based on 12 hypothetical scenarios is carried out in this study (Table 3). The extension of service lifetime will dilute the huge inputs in the infrastructure construction phase and increase the power output of the system, thus improve the sustainability and ecological efficiency of the entire system [12]. Therefore, the impact of service lifetime changes on system performance is studied first (scenarios 1 and 2). For power generation systems, technological advances can improve energy conversion efficiency, while aging equipment may lead to opposite results. Previous research [84] has divided CSP technology into three generations according to the differences of power cycle form and power generation efficiency. The first-generation uses a steam Rankine cycle only with a cycling efficiency of 28-38%, and demonstrated annual solar to electric efficiency of the system is as low as 9-16%. However, Islam et al. point out that the expected annual solar to electric efficiency for SPT plants can reach as high as 35% [85]. Thereafter, the impact of power yield changing on system performance is analyzed in scenarios 3 and 4. According to the analysis above, Sector 95 accounts for the largest proportion of the total investment among the 17 economic sectors involved. Hence, the sensitivity of the conversion factor with regard to Sector 95 to the system sustainability and ecological efficiency is measured in scenario 5 and 6. Assumptions of overall changes in conversion factors of all corresponding sectors are then included in scenarios 7 and 8. The long-term downtrend of weighted average levelized cost of electricity by new CSP plants will go on or even accelerate according to Lilliestam et al., [86]. In fact, the economic cost reduction of CSP ranks only second to that of solar PV power generation, with an reduction rate of 47% from 2010 to 2019 estimated by the International Renewable Energy Agency [87]. As mentioned above, heliostats have the highest monetary cost of all the investments, so the purpose of scenarios 9 and 10 is to figure out the impact of monetary cost changes of heliostats on system performance. Finally, the sensitivity of the monetary costs of all input items is analyzed by scenarios 11 and 12. Moreover, referring to the service lifetime of existing SPT plants [83], the outlook for improvement of electric efficiency [82, 83] and the potential of economic cost reduction [84, 85] mentioned earlier, the variation range of each factor is set at ±20%.

Table 3

Different scenarios for sensitivity analysis

Scenario	Item	Unit	Change

1	Service lifetime	year	+ 20%
2	Service lifetime	year	- 20%
3	Power yield	kWh	+ 20%
4	Power yield	kWh	- 20%
5	Conversion factor of Sector 95	(seJ/1.00E+04CNY)	+ 20%
6	Conversion factor of Sector 95	(seJ/1.00E+04CNY)	- 20%
7	Conversion factors of all Sectors	(seJ/1.00E+04CNY)	+ 20%
8	Conversion factors of all Sectors	(seJ/1.00E+04CNY)	- 20%
9	Monetary cost of heliostat	1.00E+04CNY	+ 20%
10	Monetary cost of heliostat	1.00E+04CNY	- 20%
11	Monetary costs of all purchased items	1.00E+04CNY	+ 20%
12	Monetary costs all purchased items	1.00E+04CNY	- 20%

The impacts on Tr, EYR, ELR and ESI of these 12 scenarios compared to the basic scenario are shown in Figure 6. The impacts of monetary costs of all purchased items, service lifetime and power yield on system performance are significantly greater than that of other factors. For the construction and operation stage, the economic cost reduction will reduce the direct and indirect renewable and non-renewable costs in the generation process. The extension of service lifetime stands for the smaller infrastructure investment allocated annually, thus the greater sustainability and ecological efficiency of the system. Increased generating efficiency means that more electricity can be produced with the same inputs. Therefore, strictly monetary costs controlling for purchased inputs, service lifetime extending and power generation efficiency increasing are proposed to alleviate the low sustainability and ecological efficiency of the SPT system.

In addition, due to limitations of the space, this study focuses on scenario analysis related to service life, cost and output, and lacks attention to detailed technologies. other studies show that increase of hours of thermal energy storage and power plant capacity will reduce the levelized cost of electricity of SPT system [88-90], thus improve its environmental friendliness and sustainability. In this regard, we will further elaborate it in the subsequent research reports on the demonstration projects of SPT systems in China.

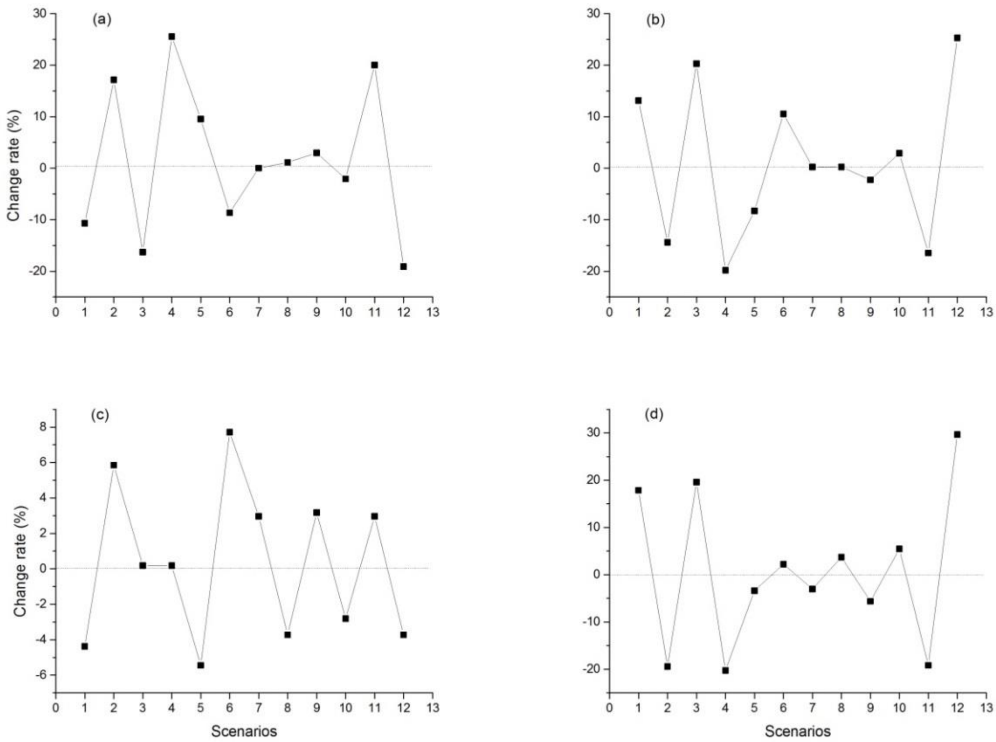

Fig.6 Impacts on (a) transformity, (b) emergy yield ratio, (c) environmental loading ratio and (d) environmental sustainability index of 12 scenarios for the SPT plant

4. Concluding remarks

In recent years, the electricity market is undergoing a unique transformation. Technological changes such as the booms of digital economy and electric vehicles have brought with it higher demands. Renewable energy, mainly solar and wind energy, has enjoyed strong momentum of development. This has raised a number of significant environmental and social implications, and policymakers need a clear and comprehensive understanding of the environmental impacts, social benefits, and sustainability of renewable energy to formulate rational policies. Emergy analysis covers virtually all aspects of sustainability and ecological efficiency by considering different forms of materials inputs, environmental support and human labor on the same unit of solar Joule. The previous emergy analyses of low-carbon power generation plants convert each input into primary materials (steel, iron, cement, etc.), and then multiply their amounts by the corresponding conversion factors. These analyses do not take into account the emergy of each input in the supply chain and greatly underestimate the non-renewability of the plants. The input–output analysis based systems accounting could be used to trace the complete emergy embodied in the supply chain for all product materials of the given plant against the back ground of complex economic network, thus improves the accuracy of accounting.

In this study, emergy analysis with integrated systems accounting method is adopted for the first time to conduct an ecological accounting for a pilot SPT plant reported previously. In addition, the effective ways to improve the sustainability and ecological efficiency of this system are elaborated through a sensitivity analysis. The results indicate that when evaluating the sustainable performance of power generation systems, not only the purposes of fossil energy conservation and emissions reduction, but also the nonrenewable investments in the supply chain for all inputs of the objective systems should be taken into full consideration. In addition, the cost for construction phase, which is often overlooked, is twice as much as the operational phase, demonstrating the inputs of infrastructure cannot be ignored. The emergy yield ratio and environmental sustainable index also show that the performances of the case system in terms of ecological efficiency and sustainability are not encouraging. It is recommended to deploy SPT plants with more caution in this region. Sensitivity analysis of different scenarios concludes that the ecological efficiency and sustainability of case system can be improved from the perspectives of monetary costs reduction, service life extension and power generation efficiency improvement.

Notably, energy policy makers need to take an empirical and comprehensive look at the consequences and implications of the projects and policies that have already been implemented. The purpose of this study is to provide a clear picture of sustainability performance and ecological efficiency for an operational SPT plant. However, this case is a pilot SPT station with limited installed capacity and short heat storage time, aiming at scientific research and technology promotion exploration. As a matter of fact, SPT station has been promoted from pilot operation to large scale deployment in China. Thereafter, we will continue to evaluate the operational SPT stations with installed capacity of more than 50MW and heat storage duration of more than 10 hours. These will allow critically thinking about the future of low-carbon power generation plants in the context of complex new geopolitical impacts on energy markets, lower costs for key clean energy technologies, the continued dynamism of shale gas, and rapidly changing of energy investments.

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