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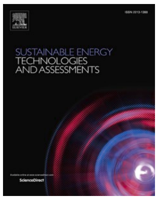

Original article

Assessing and enhancing the regional sustainability of electricity generation technologies in an energy-importing megaregion in China

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ABSTRACT

Decision-makers are increasingly concerned about the sustainability of power generation technologies to achieve a secure and sustainable electricity supply in the future. This study aims to assess the sustainability of the eight key electricity generation technologies in the energy-importing Yangtze River Delta region of China and further enhance the regional sustainability of the electricity generation mix. We employed the multi-criteria decision-making process to rank the sustainability of the eight electricity generation technologies from the perspective of various decision-makers. First, the results revealed that no technology is absolutely most sustainable. Second, the subjective findings show that hydropower is the most sustainable technology among the assessed ones, followed by nuclear and onshore wind power. Third, policymakers regard fossil fuel energy as more sustainable than investors and experts. Furthermore, local renewable diffusion and substantial electricity imports from renewable-rich areas can enhance the sustainability of the local electricity system. In addition, an interregional electricity transmission grid with the neighbor Anhui province as the primary backup power supplier can sufficiently enhance the sustainability of the electricity system in the Yangtze River Delta region.

Introduction

China has been electrifying its energy consumption across multiple sectors and increasing the share of its renewable energy in its power capacity to address the significant challenge of reducing carbon emissions [1] and health risks [2]. In 2022, the accumulated renewable energy capacity reached 1179 GW (gigawatts), constituting 45.87 % of the total power generation capacity [3]. However, a low-carbon energy mix heavily reliant on renewable energy sources may not ensure sustainable development if it fails to meet the local transmission capacity and -transmission stability requirements [4]. The high share of renewable or nuclear power would yield greater environmental benefits, but it would raise issues of economic investment, social trade-offs [5], and the technical standard of power generation technologies [6], and require considerable high power dispatchability and grid stability [5]. Therefore, the sustainability development of the power generation mix should be specific, taking into account regional supply–demand equilibrium and power transmission infrastructures.

In China, the distributions of renewable resources, power grids, and energy demand exhibit distinct regional characteristics. There is a discrepancy between regions with high renewable electricity output and regions with high electricity demand. Additionally, the electricity transmission network has been constructed regionally, with few high-voltage grid connections across regions. A more flexible and diversified electricity generation system needs to be established on a regional scale considering economic development, supply security, and ecological conservation [7]. To design a reasonable and sustainable mixed electricity generation system, it is necessary to provide information to decision-makers about the impacts of alternative electricity generation technologies on the environment.

The sustainability assessment approach could sufficiently support "decision-making and policy in a broad environmental, economic and social context, and transcend a purely technical/scientific evaluation" [8]. Although there is no standard method for evaluating sustainability, a set of indicators or criteria from multiple dimensions and their weights should be considered [9]. Experts have mostly customized the

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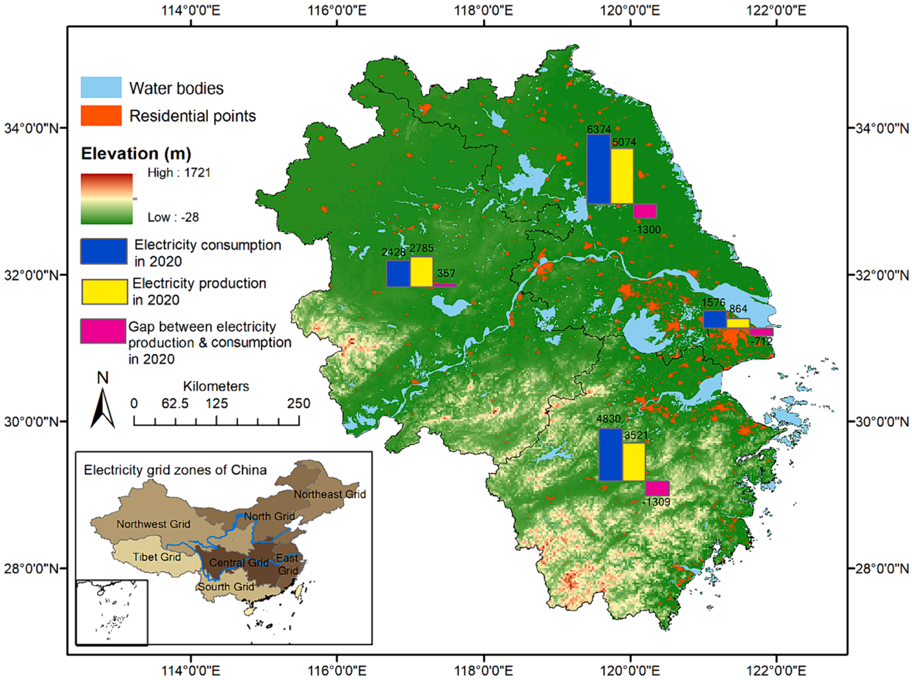

Fig. 1. Map of the Yangtze River Delta region showing its electricity production and consumption in 2020.

assessment approach according to study objects (power generation technologies) and scope (sustainable indicators), which closely relate to the study area's developing targets [10–12]. First, sustainability differs largely between individual technology schemes [13], therefore it is crucial to focus on regional mainstream power generation technologies. Second, the sustainability scope links to the electricity sector of the study region [14–16]. For example, Mangla (2020) included political indicators to emphasize the sustainability differences based on different countries' contexts [17]. There is also an increasing interest in the technical aspects of electricity generation technologies [18,19]. Third, the subjective weighting of indicators or criteria presents decision-makers' subjective perceptions of sustainability development. The weight primarily depends on experts' assessments [10,20], and varies depending on the region under investigation and the specific development goals being considered. In many developing countries, minimizing adverse economic consequences is a crucial factor in the process of shifting away from reliance on fossil fuels [21]. Additionally, certain countries, such as Algeria, assign considerable importance to social and environmental factors to acquire a ranking for sustainability [22].

There is no universally approved definition of sustainability [23]. "Sustainability" is generally considered in terms of three pillars: environmental, economic, and social dimensions [20]. Articles attempted to investigate the complex sustainability problem by applying experts' subjective perceptions of electricity generation technologies, which can be interpreted as the the weighting of indicators/criteria [24]. In order to reduce decision-makers' subjective judgments on the sustainability indicators, Maxim (2014) scaled the importance of each decision-maker based on their roles in the group decision-making process. Sibertin-Blanc and Zaraté (2014) used a cooperative decision-making approach to allow decision-makers to adapt their weight of indicators by sharing information [26]. However, real electricity systems are managed, controlled, advised, or otherwise influenced by policymakers, investors, and experts. These stakeholders are particularly important for the diffusion of renewable energy [27,28]. In this study, we also investigate the sustainability of the electricity generation system based on investors' and policymakers' perceptions.

Currently, there are still three significant shortcomings in sustainability research related to electricity generation technologies. First, there are few studies focused on the energy-importing megaregion. Different from other studies, our research aims to investigate how regions reliant on imported power can develop sustainable power generation systems to ensure electricity supply. Second, the sustainability of the electricity generation system based on different stakeholders' perspectives is rarely investigated. Previous studies largely relied on the subjective assessments of experts regarding sustainability indicators, while neglecting the perspectives of investors and policymakers. Third, the social impacts of electricity generation technologies in China are still understudied. Social acceptance and employment opportunities created by power installations are often ignored in electricity generation impact research in China [18,29].

This paper aims to fill these gaps and assess the sustainability of electricity generation technologies at the regional level in China using local data. We selected the major energy-importing region, the Yangtze River Delta region, as the study area. An analytic hierarchy process is designed to descend to four dimensions of sustainability and a set of sustainability indicators based on the national and regional development scope. Moreover, different decision-makers' perceptions of the sustainable development of the electricity system are considered. With this approach, the paper provides a better understanding of the sustainability determinants of electricity generation technologies in similar regions, including the Yangtze River Delta region, the Pearl River Delta region, the Beijing-Tianjin-Hebei region, and other electricity-importing megaregions worldwide.

The article is organized as follows: Section 2 introduces the overall research process and the relevant methodological details. Section 3 illustrates the sustainability evaluations. Section 4 presents our suggestions to enhance the sustainability of the local power generation system. Section 5 concludes the research outcomes.

Study area and methodology

Study area

The Yangtze River Delta (YRD) region is the most significant economic circle in China and one of the six giant urban circles globally, which encompasses Shanghai municipality, Jiangsu, Anhui, and

Table 1
The features of selected electricity generation technologies in YRD.

Electricity source	Technology	Description of the application in YRD	References
Coal	Coal-fired power plant with carbon capture systems	Capacity around 1000 MW; Lifetime around 35 to 40 years.	[18,46,47]
Natural gas	Natural gas combined cycles with the carbon capture system	Not consider natural gas extracted from other fossil fuels. Lifetime around 30 years.	[48–50]
Nuclear	Pressurised water reactors (PWRs)	Capacity between 1000 and 1500 MW; Lifetime between 30 and 60 years.	[18,49,51]
Wind	On-shore wind power	Overall capacity around 50 MW; Individual wind turbine capacity between 800 kW and 3 MW; Annual operation time around 2100 h; Lifetime 20 years.	[18,49,52]
Solar PV	Distributed solar PV (crystalline silicon and thin film)	With a median radiation of 1700 kWh/m^2/yr; Annual operation time around 1700 h; Lifetime between 25 and 30 years.	[18,49,53,54]
Hydro	Hydropower	Capacity around 1200–1600 MW; Annual operation time around 3500 h; Lifetime between 44 and 100 years.	[49,55,56]
Biomass (straw)	Steam turbine	Annual operation time of 6000 h, biomass consumption rate of 1.4 kg/kWh, and 20–40 km collection range.	[18,49,57–59]
Waste to Electricity	Incineration	Waste mainly generated from households, 20 km collection range	[60–62]

Zhejiang provinces. In 2019, 16.65 % of the national population (235.21*10^6 inhabitants) contributed to 23.94 % of China's national gross domestic product (GDP)[1] in the YRD region (358*10^3 km^2, 3.69 % of the national land area). The Yangtze River Delta region is also one of the largest electricity consumption regions (consumed 20.53 % of China's total electricity consumption in 2019) with limited fossil fuel resources. It has been historically supplied by China's inter-provincial and inter-regional electricity transmission projects, such as "power transmission from west to east" [30]. In 2020, the Yangtze River Delta region's electricity self-sufficiency rate was 80.51 %[2] (Fig. 1). Therefore, a continuously reliable energy supply has been one of the most critical issues in the YRD region. One way to solve this challenge is to improve the supply ability of the local electricity generation mix system. The study region is rich in wind, solar, and hydro resources. In the north coastal area of the YRD region, the wind resources are concentrated and stable, with an annual average wind speed of 7.14 m/s. The annual GHI is larger than 1250 kWh/m^2 in most spatial areas [31]. The Yangtze River Delta region is the siginificant for China's energy transition. In this regard, a comparative sustainability assessment of the mainstream electricity generation technologies, which could be applied to the region, is needed to guide future energy planning.

Methodology

Different approaches have been applied to assess the sustainability/environmental impact of energy systems or electricity generation technologies, including life-cycle analysis (LCA) [32–35], multi-criteria decision-making (MCDM) process [6,10,36], logic models [37] and strengths, weaknesses, opportunities, threats (SWOT) analysis [38]. In this study, we find the analytic hierarchy process (AHP) to be the most suitable method. First, AHP can disentangle a complex issue hierarchically by separating it into several dimensions [39]. The sub-indicators can be both qualitative and quantitative [39]. Second, in the hierarchy structure, the decision-makers' priority changes at an upper level, which influences the priority of lower-level criteria [40]. It can be a disadvantage for many studies because the process is time-consuming and human perceptions are hard to fix in numerical quality [41]. However, in our research, the hierarchy structure could facilitate decision-makers in weighting indicators [42,43]. On the other hand, there are also some limitations of AHP. Sahabuddin's research (2021) demonstrates that AHP is not as robust as the complex proportional assessment (COPRAS) [20]. Therefore, we applied a sensitivity analysis to examine the evaluation results. Another shortcoming of AHP is its inconsistency when the dimensions and alternatives are more than seven [44]. In our current research, the criteria and alternatives are placed within this constraint.

To assess the sustainability of electricity generation technologies, our research employs the following synthesis methods: 1) identifying study objects (i.e., electricity generation technologies with potential in the YRD region); 2) selecting sustainability indicators; and 3) conducting a sustainability assessment (using MCDM) to rank electricity generation technologies.

We focus on the mainstream electricity generation technologies in the energy-importing YRD region of China. By considering regional-specific constraints, we narrowed down our focus to eight types of technologies (Table 1). This research does not consider off-shore wind power, centralized solar power, or large-scale hydropower due to the limited potential to develop in the study region [45]. The studied specific technology schemes are established based on factors such as applicability and suitability for the YRD region.

Second, sustainability indicators identified in prior studies are collected and filtered for our study (1st step in Fig. 2). These indicators make particular issues measurable by quantifying their effects [63,64] and provide decision-makers with information to determine which actions are devoted to sustainable development [65]. The indicator selection involves a four-step procedure (Fig. 2). First, an bank of indicators was developed based on a literature review using various keywords, e.g. energy/electricity, indicators/indexes/criteria, and sustainability assessment. Only indicators used at the technology level are gathered into the bank by dimensions [25]. Second, the most frequently applied indicators are selected. Third, specific indicators were selected to reflect the institutional development plan (such as the 14th five-year plan) [66–68]. In addition, the indicators were presented to the stakeholders during the field trip and adjusted according to their suggestions. Notably, our research did not select a particular indicator associated with the risk or safety issue of nuclear power, although these indicators had been considered in numerous prior investigations [69]. Due to the supervision and regulation of nuclear power security issues by the National Nuclear Safety Administration, a central government agency in China, stakeholders frequently disregard this concern when strategizing

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[1] Calculated from the GDP statistical data sources: [86–89].

[2] Calculated from the electricity consumption statistical data sources: [86–89].

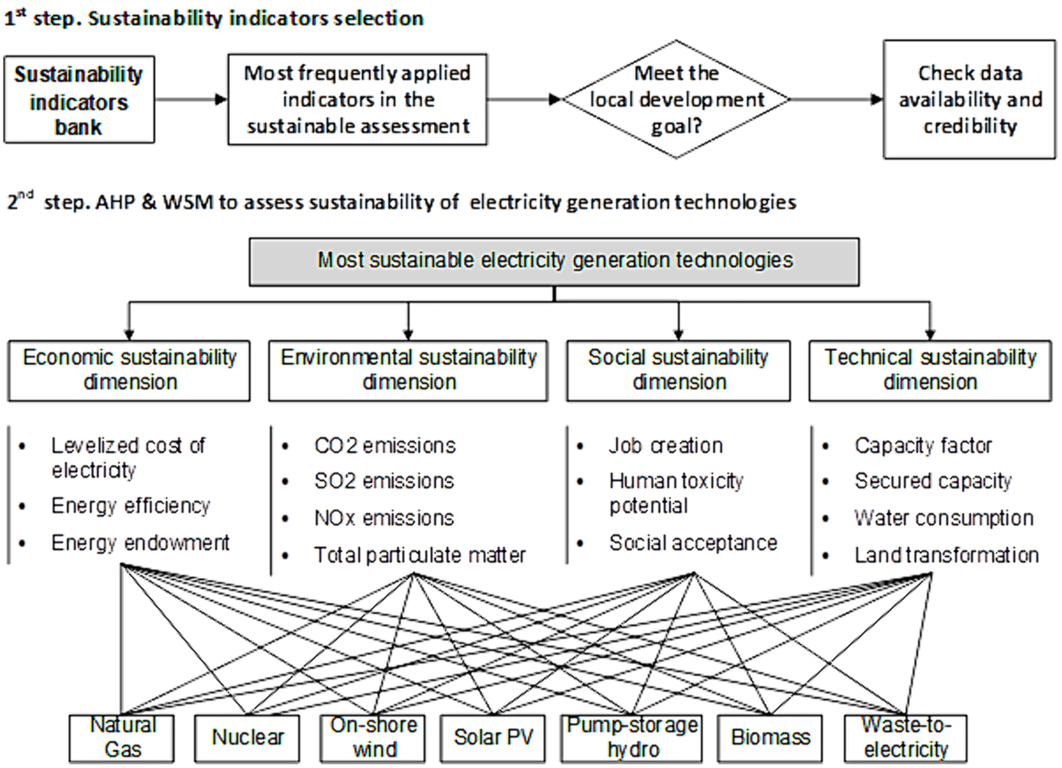


Fig. 2. Research steps and methodology.

Table 2
Indicator value of electricity generation technologies in general.

		Coal	NG	Nuclear	Wind	PV	Hydro	Biomass	WTE
ECO	**Levelized cost of electricity** (USD/kWh)	0.065	0.056	0.05	0.07	0.06	0.05	0.08	0.32
	Energy efficiency (%)	32.30	47.50	33.00	54.00	15.77	90.00	25.33	30.33
	Energy endowment (%)	3.80	0.00	0.02	0.03	0.03	0.03	0.10	0.20
ENV	**CO_2 emission** (g/kWh)	926.80	527.08	36.99	22.71	57.71	13.90	65.00	30.00
	SO_2 emission (g/kWh)	2.59	0.14	0.04	0.02	0.20	0.03	0.27	0.12
	NO_x emission (g/kWh)	1.53	0.78	0.06	0.04	0.14	0.02	0.65	1.04
	Total particulate matter (g/kWh)	0.35	0.37	0.02	0.01	0.04	0.07	0.12	0.09
SOC	**Human toxicity potential** (kg 1,4 DCB‡ eq./kWh)	2.08	0.38	0.03	0.04	0.14	0.03	0.76	0.64
	Job creation (jobs/MWa)	1.67	1.16	1.13	3.68	9.64	14.55	3.48	1.90
	Social acceptance (ordinal scale)	21.34	21.34	20.67	28.76	28.28	27.61	17.46	18.77
TEC	**Secured capacity** (%)	84.50	84.50	84.50	50.00	0.00	50.00	85.00	85.00
	Capacity factor (%)	85.00	42.00	90.00	38.00	20.00	40.00	65.00	65.00
	Water consumption (%)	2.58	0.91	2.51	0.27	0.13	18.96	98.75	2.52
	Land transformation (km^2 /TWh)	2.50	0.31	0.12	2.04	0.38	5.56	14.12	0.05

electricity production and do not factor it into sustainability rankings. In the final step, the selected indicators were checked for data availability [70–72]. More details of the selection procedure can be found in Appendix A.

Third, the analytic hierarchy process (AHP) and weighted sum approach (WSM) are used to assess the sustainability of electricity generation technologies (Fig. 2). The selected indicators cover four dimensions, including economic, environmental, social, and technical dimensions. Most indicators' values are rated from the previous literature, with restrictions imposed based on the technology schemes. Other indicators, such as energy endowment and social acceptance, are calculated from empirical data or quantitative surveys. The weights of sustainability indicators are investigated through qualitative interviews conducted with the most influential decision-makers from the energy planning and power generation systems. Meanwhile, to distinguish variations in decision-makers' judgments, we classified our respondents into groups based on their role in the electricity sector. The various indicators with different units and measured in different ranges are required to be normalized to the (01) range to scale features and integrated into a utility score to rank the sustainability of alternatives. A weighted sum approach is applied to rank the sustainability of electricity generation technologies.

Fig. 3. Normalized indicator values of electricity generation technologies.

Qualitative survey with decision-makers

We conducted two surveys in January 2021 with the assistance of our local research partners at Fudan University in Shanghai. One qualitative survey examines how decision-makers subjectively weight sustainability factors. The other is a quantitative survey designed to evaluate social acceptance.

In the first survey, the target interviewees are policymakers, experts, and energy investors in electricity investment or planning. In total, 35 decision-makers were contacted through email and phone, of whom 12 agreed to be interviewed. The responding decision-makers included 2 electricity planners from the government, 5 experts from universities and institutes working as think tanks, and 5 investors from the state-owned energy investment enterprise. The interviews are designed based on a structured questionnaire, including the initially selected indicators. Decision-makers were asked to evaluate our selected indicators' adequacy and rate the importance of sustainability indicators through pair-wise comparisons. An additional indicator of energy endowment was suggested to be included in the economic dimension.

The second survey is conducted using an online questionnaire, the "Tencent Questionnaire", which is integrated as a plug-in to the most-used social software in China. The questionnaire was quickly distributed and assessed early on the phone by the respondents. In total, we received 70 valid answers. The responders were asked to answer four questions, which included selecting their knowledge level of the different powers; selecting the acceptable level of the power installation in the YRD region or their residential location; and ordering the alternatives according to their acceptability.

Results

General sustainability evaluation of electricity generation technologies in China

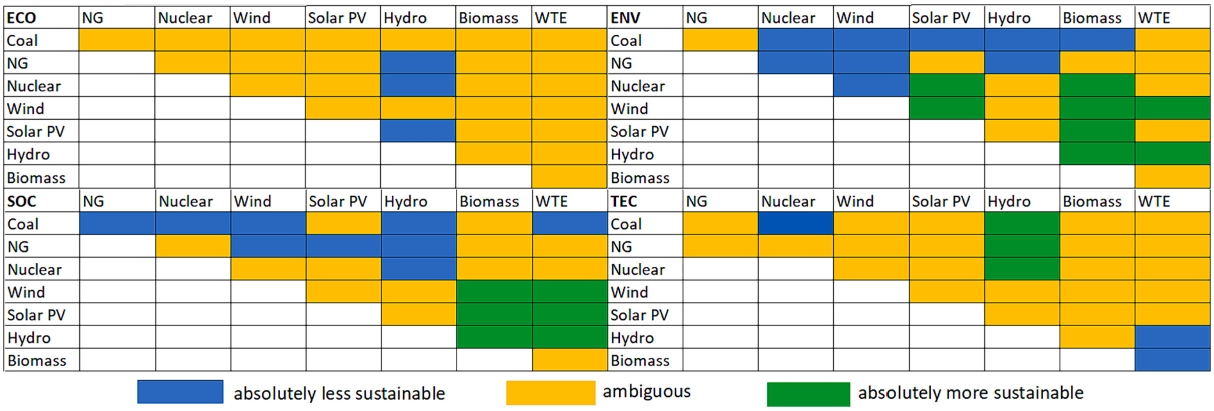
Sustainability indicators' value

We normalize the values of the indicators for various technologies (Table 2) and compare them through the four dimensions shown in Fig. 3.

As shown in Fig. 3, waste to electricity (WTE) is associated with the lowest score of LCOE due to the high labor costs associated with the waste collection and delivery processes. The LCOE of most renewable power has decreased in recent decades because of technological improvements, which have simultaneously increased the fixed investment costs and decreased the operation and maintenance costs [73]. Energy efficiency is defined as the ratio between useful electricity output and energy input [74,75]. Energy efficiency does not indicate fuel or power plant availability. It is evident that hydropower plants are the most efficient technology, featuring an average efficiency of 90 %. In contrast, photovoltaic systems exhibit the lowest efficiency, averaging around 15.77 %. The energy efficiency of fossil fuel and nuclear power plants falls within the intermediate range. For the energy endowment, WTE ranks highest due to abundant waste availability in this region (19.57 % of national waste).

The value of environmental indicators highly depends on the upstream equipment manufacturing processes and the fuel resources of electricity generation technologies. Coal-fired plants obtain the lowest score, being absolutely less sustainable than other technologies in the environmental dimension. Nuclear, hydro, onshore wind, and solar photovoltaic (solar PV) power generally receive high scores in general, except for the SO_2 emissions of solar PV, resulting in the silicon input in the infrastructure stage. Biomass and WTE have large effects on reducing CO_2 emissions while contributing to atmospheric pollution.

Significant differences are observed in the social dimensions among various electricity generation technologies. Hydropower receives high



ECO	NG	Nuclear	Wind	Solar PV	Hydro	Biomass	WTE
Coal	🟨	🟨	🟨	🟨	🟨	🟨	🟨
NG		🟨	🟨	🟨	🟦	🟨	🟨
Nuclear			🟨	🟨	🟦	🟨	🟨
Wind				🟨	🟨	🟨	🟨
Solar PV					🟦	🟨	🟨
Hydro						🟨	🟨
Biomass							🟨

ENV	NG	Nuclear	Wind	Solar PV	Hydro	Biomass	WTE
Coal	🟨	🟦	🟦	🟦	🟦	🟦	🟨
NG		🟦	🟦	🟨	🟦	🟨	🟨
Nuclear			🟦	🟩	🟨	🟩	🟨
Wind				🟩	🟨	🟩	🟩
Solar PV					🟨	🟩	🟨
Hydro						🟩	🟩
Biomass							🟨

SOC	NG	Nuclear	Wind	Solar PV	Hydro	Biomass	WTE
Coal	🟦	🟦	🟦	🟨	🟦	🟨	🟦
NG		🟨	🟦	🟦	🟦	🟨	🟨
Nuclear			🟨	🟨	🟦	🟨	🟨
Wind				🟨	🟨	🟩	🟩
Solar PV					🟨	🟩	🟩
Hydro						🟩	🟩
Biomass							🟨

TEC	NG	Nuclear	Wind	Solar PV	Hydro	Biomass	WTE
Coal	🟨	🟦	🟨	🟨	🟩	🟨	🟨
NG		🟨	🟨	🟨	🟩	🟨	🟨
Nuclear			🟨	🟨	🟩	🟨	🟨
Wind				🟨	🟨	🟨	🟨
Solar PV					🟨	🟨	🟨
Hydro						🟨	🟦
Biomass							🟦

🟦 absolutely less sustainable 🟨 ambiguous 🟩 absolutely more sustainable

Fig. 4. General sustainability comparison matrix across different dimensions.

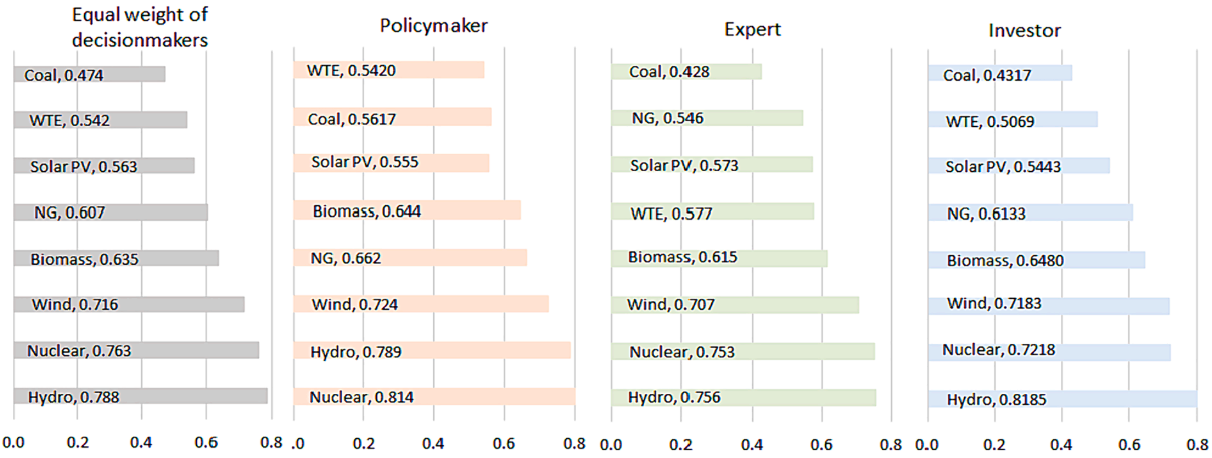


Fig. 5. Sustainability ranking of electricity generation technologies by applying the average weight of all decision-makers and applying the average weight of decision-makers from different groups.

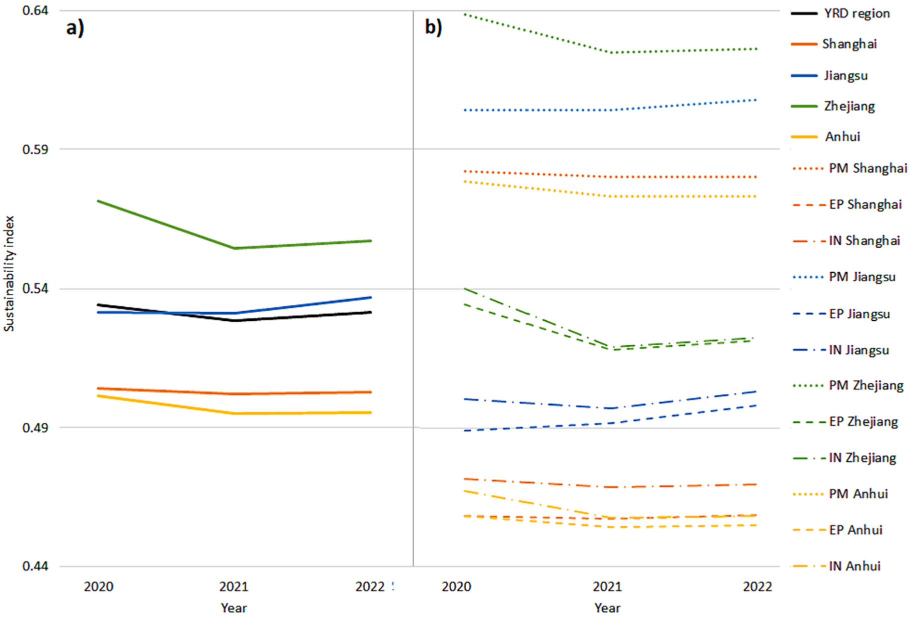


Fig. 6. Sustainability ranking of the region-specific electricity generation system by applying the average weight of all decision-makers and applying the average weight of decision-makers from different groups from 2020 to 2022.

Table 3

Electricity imports and exports between YRD and provinces in 2021 and the sustainability index of the electricity system of each province.

	Shanghai	Jiangsu	Zhejiang	Anhui	Fujian	Hubei	Sichuan	Sustainability index
Shanghai	95.471*	4.400	4.662			0.002	0.00001	0.5019
Jiangsu	16.452	556.939*	1.493	1.074				0.5310
Zhejiang	15.440	0.800	397.355*	0.102	0.625		0.00012	0.5540
Anhui		30.889	55.739	276.658*				0.4950
Shanxi		43.486						0.5428
Inner Mongolia		18.592						0.5489
Fujian			10.060					0.5693
Hubei	26.462	12.164						0.5885
Sichuan	28.299	36.195	27.160					0.6691
Ningxia			50.414					0.5472
Xinjiang				55.064				0.5511

*The self-production electricity amount.

Table 4

The sustainability of electricity system in YRD after power exchange in 2021.

	Electricity generation	Import electricity	Export electricity	Electricity consumption	Sustainability index of electricity consumption
Shanghai	95.471	86.653	9.064	173.059	0.5499
Jiangsu	556.939	146.524	19.019	684.444	0.5388
Zhejiang	397.355	149.529	16.967	529.916	0.5528
Anhui	276.658	56.241	86.628	246.271	0.5077

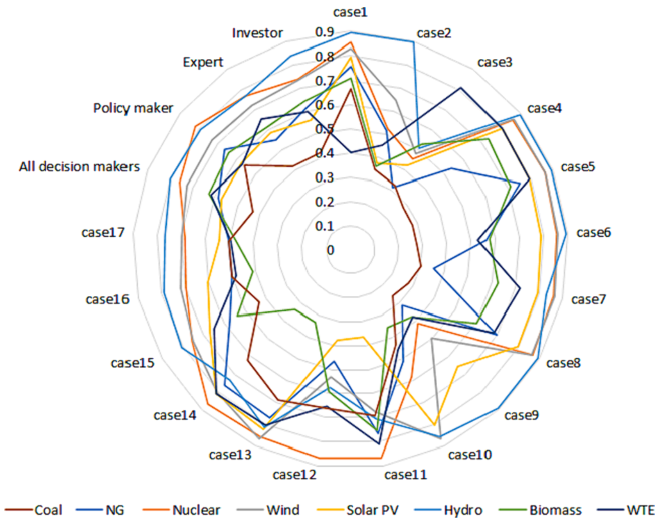


Fig. 7. The results of sensitivity analysis experiments.

scores across all indicators. It is not surprising to find that coal-fired power is rated lowest in human toxicity potential due to the high pollutant emissions and discharges. The social acceptances of coal, natural gas, and nuclear power are less than 0.5. The smog crisis that happened in the past 20 years decreased the Chinese public's social acceptance rate of fossil fuel power plants [76]. Although previous studies showed that the nuclear acceptance rate in China is high, which is facilitated by public environmental beliefs, it is compromised by the high level of place attachment [77]. Therefore, the social acceptance rate for nuclear power is at a moderate level. The biomass and WTE applied incineration technology results in high pollution and unpleasant smells, which potentially impact the public's daily lives and therefore reduce the acceptance rate to 0.13 and 0.23, respectively.

In the technical dimension, nuclear power and coal-fired power obtain very high scores, specifically for the secured capacity and capacity factor indicators, which are much higher than other alternatives. In comparison, the renewable electricity technologies of wind, solar PV, and hydro are relatively less secure in terms of energy supply.

Objective sustainability evaluation of electricity generation technologies

The objective sustainability ranking of electricity generation technologies is ambiguous. We illustrate a pair-wise comparison matrix to present the relative sustainability in each dimension (Fig. 4).

In summary, no technology is evaluated as absolutely more or less sustainable than others in the overall dimension. Notably, hydropower is superior to all other technologies except wind power in at least one dimension. However, hydropower is technically less sustainable than natural gas, nuclear, and wind power due to its low supply security, high water consumption, and extensive land occupation. In addition, the differences in sustainability are more pronounced in the environmental and social dimensions. In both dimensions, coal-fired power is less sustainable than most alternatives. NG and biomass are less environmentally sustainable than nuclear, wind, and hydropower. In the social dimension, NG, biomass, and WTE are less sustainable than wind, solar PV, and hydropower.

Assessment and ranking the sustainability of electricity generation technologies

This section presents subjective sustainability rankings of the key power generation technologies from different decision-makers in the Yangtze River Delta region (Fig. 5). The weight of the sustainability dimensions and the subsequent weight of indicators have resulted from the validated survey data, which passes the consistency measures (Appendix C).

Fig. 5 shows the sustainability ranking by different groups of decision-makers and the results after equally considering all their weights. All three groups have given onshore wind, nuclear power, and hydropower the top rankings. Policymakers ranked nuclear power higher than hydropower because of policymakers' higher consideration of the technical dimension. From experts' perspectives, they tend to strike a balanced development between the four dimensions, and therefore the weighted social dimension is considerably more important. This leads to higher rankings of hydropower (0.756) and nuclear power (0.753). Investors strongly prioritize the economic dimension, assigning it a weight of 0.46, and rank pumped-storage hydropower as the most sustainable technology.

The other five types of electricity generation technologies are ranked lower. Notably, solar PV power ranks low due to the high SO_2 emissions, insufficient secured capacity, and capacity factor, which could be

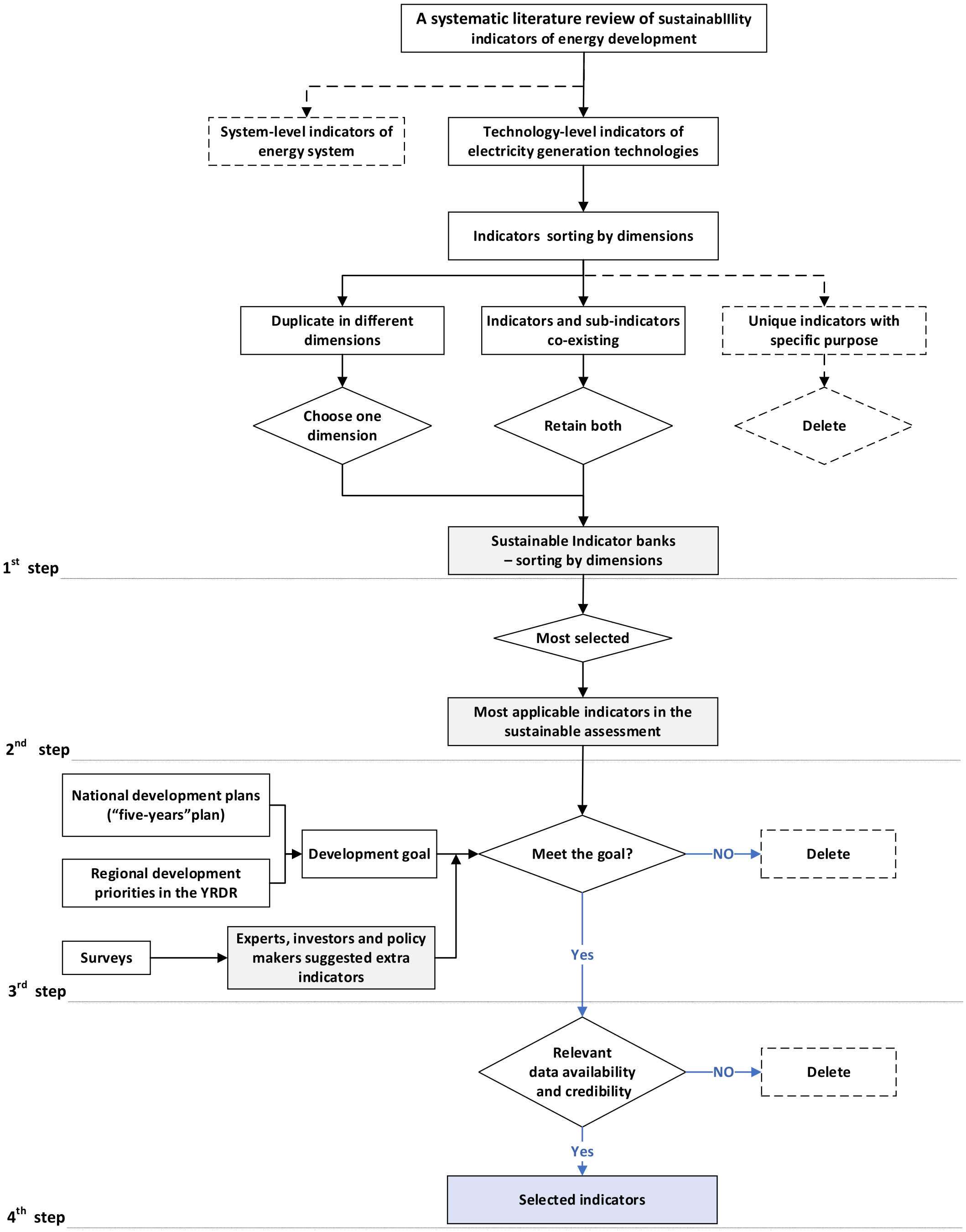


Fig. A1. The detailed selection procedure of sustainable indicators.

improved by integrating storage devices. Moreover, fossil-fuel powers are ranked lowest by experts due to the high weight placed by experts on environmental and social dimensions. In contrast, policymakers believe environmental issues should be mitigated by technology improvements and assigned fossil fuel power a relatively higher score compared to other decisionmakers. To be more specific, policymakers believe the improved desulphurization and denitrification technologies can minimize the negative environmental impact, and thus they attach great importance to securing the energy supply, which directly affects the living standards of citizens [68].

Assessment and ranking the sustainability of electricity generation systems

We applied the sustainability ranking scores to the empirical electricity generation to identify the historical sustainability index of electricity generation in the YRD region (Fig. 6). The electricity generation data was published by the China Electricity Council [78] (Appendix C).

Fig. 6a depicts the region- and province-specific sustainable index of power generation, considering decision-makers' weight equally from 2020 to 2022. Sustainability in 2020 was higher than in 2021 and 2022 due to the fossil fuel power reductions during the pandemic [79]. Afterwards, the sustainability of the electricity generation system bounced back to a lower level in 2021 and slightly increased again in 2022 due to renewable diffusion. Zhejiang was the most sustainable province during the three years in the study region because of its consistent large share of nuclear power. In particular, in 2020, nuclear power will account for 20.47 % of the total electricity production in Zhejiang, and coal-fired

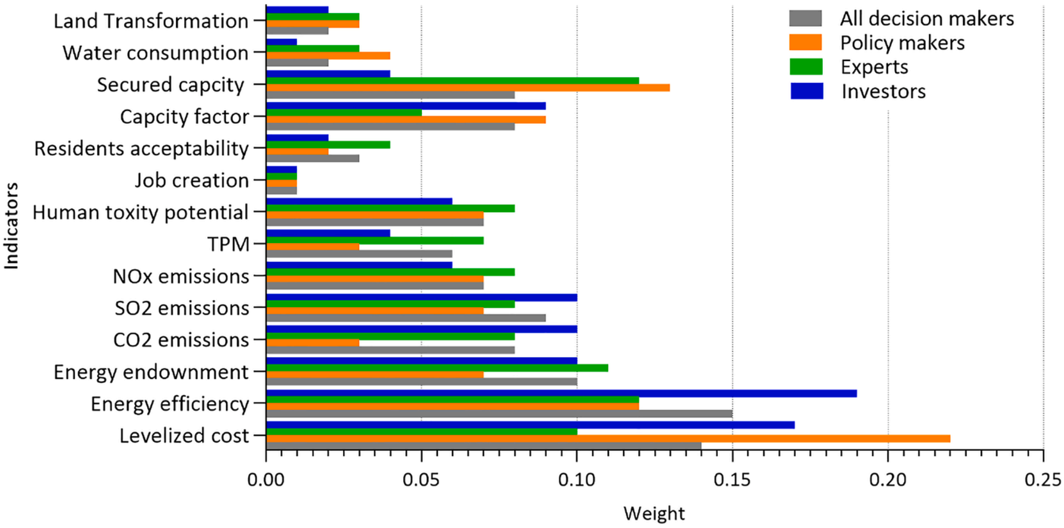


Fig. B1. Weight of sustainability indicators by different groups of decision-makers

power generation will account for 55.85 %. Jiangsu also obtains a high sustainable index due to its share of nuclear power generation. In addition, the lower sustainability of the electricity generation system in Shanghai and Anhui is due to the high share of coal-fired power plants. Shanghai is the center of the megaregion with a large population and limited land resources, which are theoretically unsuitable for implementing nuclear power, biomass power, and hydropower [31]. Anhui is a step back from electricity technology innovation and renewable diffusion. Therefore, there is only a very low share of renewable power generation (less than 91 % in 2021), which further decreases the sustainability of the power generation system.

Fig. 6b depicts the differences in decision-makers' perceptions of the sustainability of electricity generation systems. The power generation system, characterized by a significant share of non-renewable power with high capacity factor and secured capacity, is highly rated by policymakers. Experts and investors almost agreed with the sustainability index of the electricity system in Zhejiang in 2021 but rated it very differently in Shanghai due to the large proportion of NG power generation.

Sustainability of electrical system by including interregional power trading

In this section, we examine the empirical data on power exchange between the YRD region and other regions of China in 2021. And the results indicate that the regional electricity system's sustainability can be improved by importing electricity from renewable-dominated regions.

Table 3 presents the amount of electricity imported to or exported from YRD in 2021 and the sustainability index of the electricity systems of relevant provinces. Internal electricity trade occurs between Shanghai, Jiangsu, and Zhejiang, enhancing cross-province power dispatch flexibility. Zhejiang and Jiangsu are also largely supplied by the electricity produced in Anhui, which functions as the backup power station for the Yangtze River Delta region. In addition, YRD is also highly supplied by external electricity imports from the surrounding provinces (Hebei and Fujian); high-voltage transmission grids correlate with renewable-rich provinces like Sichuan and the NG-enriched provinces, including Xinjiang, Ningxia, and Inner Mongolia. As can be seen, YRD imports electricity from the provinces, which have a more sustainable electricity generation system and thus could also increase the sustainability of local electricity consumption (Tables 3 and 4).

As shown in Table 4, the sustainability of electricity consumption has increased slightly in Shanghai, Jiangsu, and Anhui but decreased slightly in Zhejiang due to a high proportion of electricity imports from Anhui. Anhui was the primary internal supplier for the entire region, but it has a less sustainable power generation system, which holds back the sustainability of electricity consumption in the entire region. It is necessary to improve the electricity generation system in Anhui.

Sensitivity analysis

Sensitivity analysis could efficiently identify which indicators have the highest impact on the final decisions. In addition to the group-decision weight cases, we conducted 17 additional weighting experiments to better understand the sensitivity of indicators (Appendix D). In cases 1–14, the weights of indicators are set as the highest one by one; other indicators are equal-weighted (Table A.3). All indicators in case 15 are assigned the same weight, which is 0.071. For case 16, the same weights (0.25) are allocated to four dimensions. In case 17, economic, environmental, technical, and social dimensions are weighted as 0.4, 0.3, 0.2, and 0.1.

In Fig. 7, the results of the 21 experiments show that our decision-making process is generally robust to criterion weight changes, with hydropower emerging as the most sustainable technology in most instances (13 out of 21). The results also show the importance of rational weighting for decision-makers. In cases 3, 12, and 13, the results vary significantly, which means that technical and social indicators are relatively more sensitive to the results than others. The WTE has been ranked as the most sustainable technology due to the high weight of energy endowment in case 3, and coal-fired power has been ranked second highest in cases 12 and 13 because of the high weights of security capacity and capacity factor.

Discussing and enhancing the sustainability of electricity generation

This section compares the results of this research with some previous research in other regions. In addition, we provide some suggestions to enhance the sustainability of the electricity generation system based on the current energy mix, the local spatial siting potential of different technologies [31], and the energy plans.

According to the results, the high sustainable electricity generation technologies are hydropower, nuclear power, and onshore wind power. Hydropower has been suggested to be the most sustainable technology in previous studies [15,25,80], which is the same as this research identifying hydropower with a capacity of 1200–1600 MW as the most sustainable technology. However, hydropower sustainability is notably low in the Liaoning province of China, resulting from the low energy resource potential [18]. These differences arise from variations in ecological and geographic conditions across the study areas. Except for the study area, the study scope is also a critical issue. For instance, for the given sustainability indicators, nuclear power is ranked second in our research, differing from other studies that include more social indicators [80]. Due to the suggestions of local decision-makers, the study does not assess the indicators of nuclear accidents, nuclear waste disposal, or other risks. Two main reasons explain why local decision-makers do not question the technological safety of China's nuclear power projects. The Chinese government guarantees safe nuclear production and disposal of radioactive waste in its policy regulations. As a result of innovation, nuclear technologies are moving toward minimizing the production of radioactive waste and the danger of nuclear dissemination. Consequently, decision-makers in YRD do not find safety-related and waste disposal-related indicators crucial for the sustainability assessment. We believe our research is most suitable for the study area because the indicator selection, evaluation, and weighting have strictly followed our research objects based on the localized condition of the energy-importing region and local development goals.

The sustainability index of a power generation system is evaluated differently by decision-makers. Policymakers prioritize the technology dimension, investors emphasize the economic dimension, while experts seek a balance between the four dimensions. Policymakers, experts, and investors collaborate on developing future energy plans that incorporate the sustainability of technologies. As a result, energy planning should take into account the sustainability assessments made by various decision-makers. The moderate sustainability index (around 0.5) of the power generation system in the Yangtze River delta region is a result of the high share of coal-fired power generation and the low share of NG power and other non-fossil powers. Therefore, one straight-forward strategy to enhance sustainability involves gradually phasing out less sustainable technologies and increasing the installation capacity of the sustainable technologies, as outlined in the governmental long-term development plan [68,81]. The current active coal-fired power plant was implemented after 2005 and will be gradually phased out [82]. NG power has a lower capacity, limited by the natural gas fuel reserve shortage. Surprisingly, solar PV technologies had high installed capacities (15 %) in 2021 [78], which does not fit the sustainable scheme of the decision-makers but adapts well to the land scarcity (roof-up PV for concentrated industrial parks and agricultural greenhouses; float PV for the water surface of the local massive aquaculture industry) [31] and fits well with public biased environmental beliefs. Under this circumstance, solar power technologies should be innovated to minimize the negative environmental impacts and increase the secured capacity to enhance the sustainability of solar PV. In addition, technologies with a high sustainability ranking only have a low share of the installation capacity, including 5.46 % of hydro, 4.18 % of nuclear, and 8.57 % of wind power in 2021 [78]. Pumped-storage hydropower, nuclear power, and distributed off-shore wind turbines offer viable alternatives to conventional power sources, promoting sustainability and addressing land resource scarcity in the YRD region.

As the electricity-importing region, the sustainability of electricity consumption can be improved by importing a greater proportion of electricity from regions fueled by renewable energy, such as Sichuan. The renewable diffusion in exporting provinces should also promote renewable power. Particularly, Anhui is the principal internal supplier with a substantial amount of coal-fired power capacity (62.29 %, 52.74 GW), which should be phased out soon. Natural gas and wind energies, which have greater spatial siting potential in Anhui [31], should be encouraged to be implemented. In addition, by promoting inter-province electricity transmission in the YRD region, power dispatch can be made more flexible, thereby enhancing local supply security and the sustainability of the power system.

Conclusion and policy implications

This article aims to assess and enhance the sustainability of electricity generation by applying a localized empirical dataset in the most significant electricity-importing megaregion of China, the Yangtze River Delta region. We assess the sustainability of eight mainstream technologies and further investigate the sustainability of power generation systems based on different decision-makers' perspectives. We aim to emphasize the practical significance of this research by investigating the sustainability variation of power consumption in an electricity-importing megaregion.

The research results show that hydropower, nuclear power, and onshore wind power are evaluated as the most sustainable electricity generation technologies in the YRD region. And the power generation system in YRD currently only obtains a moderate score, which needs to be improved in the near future. The sustainability assessment of the energy system serves as an altering signal to remind the electricity sector to keep on the sustainable development path. Different perspectives on sustainability from policymakers, investors, and experts could be referable for decision-makers in designing the future electricity generation mix plan.

To improve the sustainability of the electricity generation system within the electricity-importing megaregion, we would like to suggest some policy implications: 1. Renewable diffusion should be promoted in the YRD region and its power-sourcing regions. 2. To enhance the sustainability of the power system, renewable technology-related industries, such as waste separation, should be well regulated. 3. The participation of policymakers and investors should be considered when weighting sustainability indicators. 4. The share of electricity imported from regions with sustainable generation systems should be increased. 5. The region should establish an internal flexible transmission network with a sustainable power provider. 6. As the primary power supplier in the YRD, the wind and NG power capacities should be largely increased.

The sustainability assessment can be further integrated with an energy system optimization model, such as TIMES or MESSAGE, to obtain a more accurate assessment of the continuous developing energy system [4,21]. The sustainability of electricity generation technologies is not the only issue that decision-makers consider in energy planning. The geographic condition of a particular region determines the suitability of establishing a specific type of electricity generation plant [31,83,84]. The feature of the electricity supply–demand market does incline decision-makers' preferences for electricity generation technologies. Furthermore, to associate these factors, we will consider the temporal variation of decision-makers' preferences in future research [85].

CRediT authorship contribution statement

Yechennan Peng: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Liang Emlyn Yang:** Conceptualization, Supervision, Validation, Writing – review & editing. **Jürgen Scheffran:** Conceptualization, Funding acquisition, Project administration, Supervision, Validation, Writing – review & editing. **Ping Jiang:** Funding acquisition, Project administration, Writing – review & editing. **Hossein Azadi:** Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Indicators selection process

As Fig. A1 showed, first, the indicators assembling sustainability issues at the system-level should not be included, while this study only aims to assess the sustainability of electricity generation technologies. Second, the rest of the technological level indicators, demonstrating the sustainable issues of one specific electricity generation technology, could be separately distributed to economic, environmental, social, and technical dimensions. Third, to present our research object, the indicators should follow the country- or regional-specific development goals. The indicators chosen for each dimension from the indicators' bank (Table A.2) follow national and regional electricity development priorities. In China, the electricity generation transition is encouraged in our aspects: satisfying a median-to-high speed economic growth rate, improving energy technologies, securing energy supply, and minimizing environmental impacts (Table A.1). Relevant targets have been set in the 13th five-year plan, and the governmental working group will set up new precise targets in the 14th five-year plan by the end of 2021. The sustainable issues related to governmental development goals cover the aspects of reducing resource depletion, maximizing economic benefit, increasing energy security, minimizing global warming effects, improving air quality, and thus cutting down the negative impact of human health. According to these sustainable issues shown in Tab A.1, we select relevant indicators. From the stakeholders' survey, it was suggested that the energy endowment is also crucial for sustainable development.

Table A1
Goals of the development and related sustainability indicators.

	2016–2020 (13th Five-year plan)		**Related sustainability issues**
Electricity system	**80 % self-sufficient** 1. Power system safety increase 2. Power system flexibility increase		• Resource depletion • Energy security
Economic	Keep the median-high economic growth rate		• Cost & Benefit
Environment	CO_2	**−18 %**	• Climate change
	SO_2	Decrease	• Air quality • Human healthy impact
	NO_X	Decrease	• Air quality • Human health impact
	Particulate Matter (PM)	Decrease	• Air quality • Human health impact
Technology	**Power generation technologies improvement** 1. Energy efficiency increase 2. Desulfurisation and denitrification technologies improve 3. Carbon capture system improve		• Energy security • Climate change • Air quality

The information summarized from: General Office of the State Council of the People's Republic of China, 2019; Government office of Jiangsu Province, 2017; Government office of Shanghai, 2017; Government office of Zhejiang province, 2017; NDRC and NEA, 2016; NEA, 2016; State council, 2018.

Table A2
Indicators bank.

Economic		Environmental		Social		Technical	
no.	Indicator	no.	Indicator	no.	Indicator	no.	Indicator
1	Investment	1	CO_2 Emission	1	Accident fatalities	1	Efficiency coefficient
2	Burden of Energy Investments	2	NOx emission	2	Employee health care	2	Availability
3	Value of exports and imports of fuels	3	SO_2 emission	3	Reliability of energy provision	3	Capacity factor
4	Energy transmission loss	4	Carbon intensity	4	Household benefited	4	Reserves/production ratio
5	Net present cost	5	Transport NO emissions	5	New jobs creation	5	Ability to respond to demand
6	Cost of energy	6	Transport CO_2 emissions	6	Public acceptance	6	Water consumption
7	Return on investment	7	Total particulate matters	7	External cost	7	Efficiency of energy generation
8	Energy generation	8	Noise	8	External supply risk	8	Reliability of energy supply
9	Capital cost	9	Heavy metal pollutants	9	People displacement	9	Resource Potential
10	Fuel cost	10	Food competition	10	Disturbance to existing social infrastructure and services		
11	External cost	11	Loss of biodiversity	11	Visual disturbance		
12	Operation and maintenance costs	12	Loss of habitat	12	Odour		
13	Levelized cost of electricity	13	land use	13	Public health risk		
14	Efficiency	14	Environmental cost	14	Local economic development		
15	Capacity factor	15	Water use	15	Food competition		
16	Generation flexibility	16	Direct impacts on ecology	16	Bird strike		

(*continued on next page*)

Table A2 (*continued*)

Economic		Environmental		Social		Technical	
no.	Indicator	no.	Indicator	no.	Indicator	no.	Indicator
17	Resource availability and limitations	17	Smog	17	Seismic activity		
18	Electricity generation costs	18	Heat wave	18	Displacement		
19	Job creation	19	Air quality	19	River damage		
20	Cost of electricity	20	Water quality	20	Agriculture		
				21	Availability of cooking and heating fuel		
				22	Cultural resource		
				23	Ecological resource		
				24	Rehabilitation after use		

Appendix B. Weights of sustainable indicators

Table B1
Weight of sustainability indicators by different groups of decision-makers.

	Policymaker	Expert	Investor
Levelized cost of energy	0.2209	0.0996	0.16868
Energy efficiency	0.1216	0.1151	0.19138
Energy endowment	0.0669	0.11308	0.0967
CO2 emissions	0.028	0.08224	0.09632
SO2 emissions	0.0719	0.07872	0.09654
NOx emissions	0.0719	0.07762	0.05796
Total particulate matter	0.0329	0.0744	0.0407
Human toxicity potential	0.0705	0.07616	0.06198
Job creation	0.0078	0.01076	0.00874
Social acceptance	0.0182	0.03948	0.01982
Secured capacity	0.0899	0.05428	0.09278
Capacity factor	0.1272	0.11692	0.04298
Water consumption	0.0424	0.03122	0.00972
Land trandformation	0.03	0.03036	0.0157

Appendix C. Electricity generation and electricity import/export in YRD

Sustainability of electricity system is calculated by Eq. (1) [11] with the data from Table C1 and the sustainability of technologies calculated in section 3.2.

$$SI = \sum \left(SUS_n * \frac{E_n}{\sum E_n}\right) \tag{1}$$

- SI is the sustainability index of electricity system
  -SUS_n is the sustainability score of electricity generation technologies
  - E_n is the electricity production of technology n

Table C1
Electricity generation by technologies in YRD from 2020 to 2022 (unit: TWh).

	Shanghai			Jiangsu		
	2020	2021	2022	2020	2021	2022
Coal	65.00	75.00	70.99	351.24	400.40	390.64
NG	15.10	15.20	14.39	87.81	48.80	47.61
Nuclear	0.00	0.00	0.00	35.56	48.52	52.56
Wind	1.48	1.73	1.82	20.71	35.03	43.83
Solar	0.06	0.14	0.37	6.46	8.04	9.34
Hydro	0.00	0.00	0.00	3.16	3.05	3.07
Biomass	0.00	0.00	0.00	3.07	3.20	2.60
WTE	2.30	3.40	3.70	9.48	9.90	11.00

	Zhejiang			**Anhui**		
	2020	2021	2022	2020	2021	2022
Coal	194.256	261	261.51141	227.457	247.7	263.56433
NG	48.564	23.9	23.946831	25.273	0.3	0.319214

(continued on next page)

Table C1 (*continued*)

	Shanghai			Jiangsu		
	2020	2021	2022	2020	2021	2022
Nuclear	71.21	73.27	73.05	0	0	0
Wind	3.15	4.02	9.04	4.7	8.56	10.19
Solar	4.27117	5.15454	6.84966	6.67143	8.02762	9.7317
Hydro	15.19	15.91	17.11	4.07	5.57	5.28
Biomass	0.9480851	1.2	1.5	6.15	6.5	6.85
WTE	10.191915	12.9	13	4.92	5.2	5.55

Sustainability of electricity consumption is calculated by equation (2) [11] with the data from Table 2 in section 3.4 and the sustainability of electricity systems calculated based on Table C2:

$$SIC = \sum \left(SI_m * \frac{ET_m}{\sum ET_m}\right) \tag{1}$$

- *SIC* is the sustainability index of electricity consumption
  - SI_m is the sustainability index of electricity system of province m
  - ET_m is the electricity produced in province m and imported to be consumed in YRD region

Table C2
Electricity generation by technologies in power sourcing regions in 2021 (unit: TWh).

	Shanxi	Inner Mongolia	Fujian	Hubei	Sichuan	Ningxia	Xinjiang
Coal	688.4	983.4	359.6	337.2	182.5	333.3	684.5
NG	34.7	962	293.6	289.3	141.2	316.6	659.9
Nuclear	0	0	77.71952	0	0	0	0
Wind	212.325	96.7209	15.18749	13.43318	10.94291	28.11605	54.77515
Solar PV	145.7722	21.18973	2.503572	8.314262	2.964962	18.33326	19.58595
Hydro	22.4075	6.20873	27.42753	159.8892	372.4458	2.072204	28.59055

Appendix D. Indicators weighting table of sensitivity analysis

Table A3
The weights of indicators under different experiments.

	LCOE	Eff	EE	CO2	SO2	NOx	TPM	HTP	JC	SA	SC	CF	WC	LT	Note
case1	0.500	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	W1 = 0.5; other weights is 0.038
case2	0.038	0.500	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	W2 = 0.5; other weights is 0.038
case3	0.038	0.038	0.500	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	W3 = 0.5; other weights is 0.038
case4	0.038	0.038	0.038	0.500	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	W4 = 0.5; other weights is 0.038
case5	0.038	0.038	0.038	0.038	0.500	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	W5 = 0.5; other weights is 0.038
case6	0.038	0.038	0.038	0.038	0.038	0.500	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	W6 = 0.5; other weights is 0.038
case7	0.038	0.038	0.038	0.038	0.038	0.038	0.500	0.038	0.038	0.038	0.038	0.038	0.038	0.038	W7 = 0.5; other weights is 0.038
case8	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.500	0.038	0.038	0.038	0.038	0.038	0.038	W8 = 0.5; other weights is 0.038
case9	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.500	0.038	0.038	0.038	0.038	0.038	W9 = 0.5; other weights is 0.038
case10	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.500	0.038	0.038	0.038	0.038	W10 = 0.5; other weights is 0.038
case11	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.500	0.038	0.038	0.038	W11 = 0.5; other weights is 0.038
case12	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.500	0.038	0.038	W12 = 0.5; other weights is 0.038
case13	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.500	0.038	W13 = 0.5; other weights is 0.038
case14	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.500	W14 = 0.5; other weights is 0.038
case15	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	All indicators have same weight:0.071.
case16	0.083	0.083	0.083	0.063	0.063	0.063	0.063	0.083	0.083	0.083	0.063	0.063	0.063	0.063	All dimensions have same weight, sub-indicators in a dimension equal weighted.

(*continued on next page*)

Table A3 (*continued*)

	LCOE	Eff	EE	CO2	SO2	NOx	TPM	HTP	JC	SA	SC	CF	WC	LT	Note
case17	0.133	0.133	0.133	0.075	0.075	0.075	0.075	0.033	0.033	0.033	0.050	0.050	0.050	0.050	ECO, EVN,SOC,Tec are weight as 0.4, 0.3, 0.1, 0.2. Sub-indicators in a dimension equal weighted.
All decision makers	0.142	0.150	0.101	0.084	0.086	0.068	0.055	0.069	0.010	0.029	0.075	0.084	0.022	0.024	Data of average weighting from all decision-makers.
Policy maker	0.221	0.122	0.067	0.028	0.072	0.072	0.033	0.071	0.008	0.018	0.090	0.127	0.042	0.030	Data of average weighting from all policy makers.
Expert	0.100	0.115	0.113	0.082	0.079	0.078	0.074	0.076	0.011	0.039	0.054	0.117	0.031	0.030	Data of average weighting from all experts.
Investor	0.169	0.191	0.097	0.096	0.097	0.058	0.041	0.062	0.009	0.020	0.093	0.043	0.010	0.016	Data of average weighting from all investors.

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