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Towards a sustainable distributed energy system in China: decision-making for strategies and policy implications

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Abstract

Background: The conflict between the Chinese fossil fuel-based economy and worsening environmental conditions requires further research to be carried out. Due to their clean, highly-efficient and flexible properties, distributed energy systems (DESs) have become a global research focus in the field of energy conservation. China, as the largest coal-fired energy user and highest power consumer in the world, has to conduct further research and apply the DESs to resolve the conflict. This study aims to provide a comprehensive review of DES development in China as well as improvement suggestions for the development of DESs by use of scientific analysis.

Methods: The analysis of strengths-weaknesses-opportunities threats (SWOT) was adapted for the analysis of improvement strategies. The directions for how to improve the application of these strategies were selected by the prioritization method of analytic hierarchy processes (AHP) and evaluated by the best-worst method (BWM). The suggestions were provided according to the ranks figured out by AHP and BWM. Five enablers were selected from the respective economic, environmental, technological and social aspects for participating in this analysis.

Results: Resulting from the SWOT analysis, capital investment, technology development and regulation completeness are three aspects of strategies summarized as SO strategies, ST strategies, WO strategies and WT strategies. The research perspectives of DESs that are suggested for investment, technology development and regulation completeness are illustrated by AHP and BWM. The results show that the reduction of solid particle emissions, the improvement of generation reliability, the improvement of the production rate, the reduction of production costs, the improvement of on-site safety, the fulfilment of electricity demand, the reduction of noxious gas emissions as well as the improvement of energy efficiency need to be carried out for the sake of environmental protection and quality of DES generation in China.

Conclusions: There are high potentials for China to further develop and apply DES approaches. The direction of current development might be set to solve three problematic aspects, which are capital investment, technology development and regulation completeness.

Keywords: Distributed energy systems, Analytic hierarchy process, Best-worst method, Efficient energy generation, Sustainability, Chinese energy development

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Introduction

With a continuous growth of the economy, China has faced severe environmental issues. Air, water and soil pollution are the trade-offs of the rapid growth of manufacturing industries and energy supply industries. China has become the largest energy consumer and CO_2 emitter [1]. Fog and haze have developed to a common phenomenon in major cities, covering 14 million km and affecting more than 80 million residents [2]. While air conditions are not satisfying, water pollution is serious as well. The latter contributed more than 40% to the annual accidental environmental problems in China during 1995 to 2007, while water pollution has remained very high [3]. Likewise, solid waste, especially some toxic solid waste, has placed a lot of pressure on land management in China. China is the largest resource consumer and producer of more than 10 billion tons of solid wastes per year with an increasing trend [4]. At the same time, both electricity demand and the power generating capacity in China show a continuous upward trend, with a growth rate much higher than that of the global average value [5]. The main energy is coal-based in China [6] with 57.3% of installed capacity and 65.5% of electricity production [7]. This has caused many severe environmental problems such as a smog problem, water pollution and an impropriate waste treatment [8]. The number of deaths and illnesses caused by coal electricity production was larger than that of gas, oil, nuclear and biomass electricity generation [9]. Likewise, China faces great challenges in energy supply security [1]. The traditional electricity generation industry worsens the situation, as it occupies large amounts of resources that are restricted in China. The conflict between the Chinese fossil fuel-based economy and worsening environment conditions requires further research to be carried out. Distributed energy systems (DESs) are one of the potential solutions for this conflict.

DESs are systems where decentralized energy is generated or stored using a variety of small grid-connected devices. There are several concepts similar to or as same as DES. Decentralized energy (DE), distributed generation (DG), captive power and distributed resources (DRs) refer to a general concept of electricity production close to the place of consumption, while DRs also include conservation measures at the point of consumption. Cogeneration and trigeneration denote the simultaneous production of two and three different phases of energy, connected with combined heat and power (CHP) as well as combined cooling heating and power/cooling heating and power (CCHP), which are normally interchangeable with cogeneration and trigeneration. Both uninterrupted power supplies (UPS) and backup generators serve as emergency power when the electricity supply network faces incidents. Microgeneration is distinct due to its particularly small size. All DESs in one area constitute a microgrid.

Likewise, there are still subtle differences in DES definitions mentioned by different authors. Ackermann et al. [2] summarized some differences between various definitions with regard to the purpose, the location and the rating of distributed generation, as well as the power delivery area, the technology, the environmental impact, the mode of operation, the ownership and the penetration of distributed generation. All descriptions define the location and purpose of DESs identically: They aim to provide active electric power directly to the distribution network or are connected to the network on the customer side of the meter, while the rest has more complex definitions [2]. The ratings of DES power units are slightly different, but all DESs commonly present small volume generator systems generating power at less than 100 MW [3–6].

According to the various distributed generation DESs used, the DESs could be classified as reciprocating engine-based DESs, gas turbine-based DESs or DESs based on electrochemical devices and renewable devices, respectively, as presented in Fig. 1. DES energy storage technologies are divided into battery energy storage systems, flywheels, superconducting magnetic energy storage, compressed air energy storage and pumped storage systems.

It is evident from Fig. 1 that resource types of DESs vary from fossil resources to renewable resources. Feature of each DES type shows their particularities as well. In other words, DES is a general approach to apply different types of power generation on a small scale. If CHP and CCHP systems are excluded, the environmental protection value of DESs depends on the energy resource of the system. Generally speaking, the DESs which are recommended by scientists and governments are CHP and CCHP systems, since their multiple energy phase outputs steadily increase the energy usage rate.

Thanks to its environmental-friendly, safe, flexible and high-energy efficient properties [8, 9], DESs have become a globally popular research topic. DES technology has currently enabled multiple renewable or reused materials to be power resources; meanwhile, energy transmission efficiency has been promoted to over 80% theoretically [10]. DESs might effectively mitigate environmental problems, reduce energy supply risk and lower CO_2 emissions [11], and are regarded as technologies that might resolve the conflict between increasing electricity demand and worsening environmental conditions. Hirsch et al. [12] summarized the development directions of microgrids into two categories, which were “generation and storage options” and “control and functionality”. From the generation and storage perspective, new research is focussed on stability [13] and higher

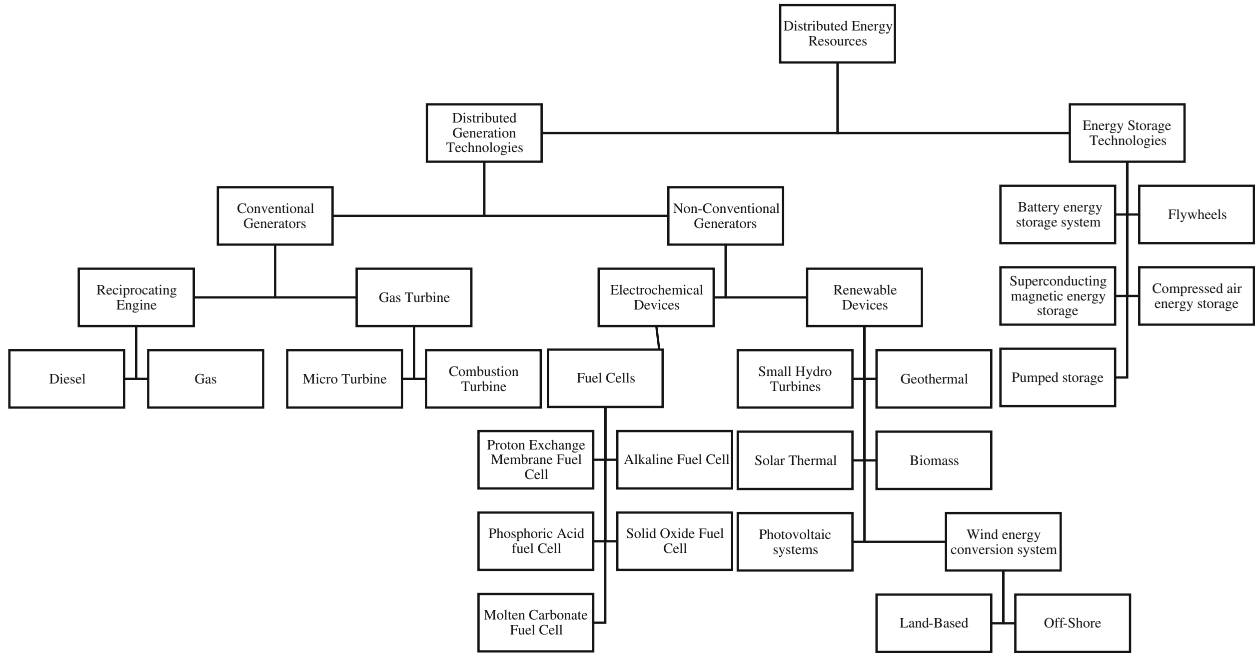


Fig. 1 Classification of distributed energy systems [7]

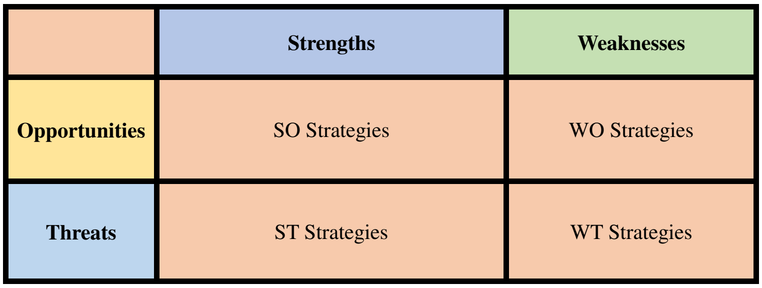
performances such as frequency [14]. Control and functionality research pay more attention to the control requirements and strategies to balance the demand and production and to optimize the profits [15–19]. In addition, DES technology is mainly applied in institutions [20, 21], residential neighbourhoods [22, 23], military energy support [24, 25] and rural energy support [26–28]. In different scenarios, DES is determined by different demands and a lot of research has been carried out for each specific application.

However, compared to the DES system under ideal conditions, there is still gaps between the development of DESs in China at present and the status quo in Western countries in terms of the transformation efficiency, energy supply, regulation support and penetration rate [10]. China started the first DES project in 1998. The research, development and application of DES technology started late compared to those of western countries. However, DES technology has developed rapidly due to the great energy demand and severe environmental problems in China [29–31]. Now, a large number of DES projects are at the planning stage, approval stage, construction stage or in use. In the meantime, the government has promulgated relevant policies to encourage, guide and standardize the long-term operation of the management of DES projects. The advantages of DESs attract many researchers to study system optimization, system performance evaluation and influence factors of DESs [29]. The optimization conditions of DESs including their design (e.g. [32–34]) and operation (e.g. [35–37]) are discussed in a variety of investigations. Those studies consider the problem of the internal development of DESs. The discussions of influential factors of DESs include topics of policies, technical limitations and profits (e.g. [38–42]). However, previous studies paid less attention to providing a multiple-perspective suggestion for improvement. In this case, guidance in multiple perspectives for DES development based on scientific analysis methods needs to be proposed. At this stage, two questions should be asked of how China's DES project might further be developed and which measures might be taken to improve the long-term development of DES projects?

In order to answer these questions, this study is carried out in four steps:

- Summarizing the current situation of the development of distributed energy in China
- Conducting a strengths-weaknesses-opportunities-threats (SWOT) analysis to figure out the strategies for DES development
- Employing the analytic hierarchy process (AHP) method and the best-worst method (BWM) for improving the selection of a specific direction
- Proposing relevant suggestions for promoting the development of distributed energy combined with the current situation in China

Apart from the introduction section, the methods for strategy planning and improved selection of perspectives



	Strengths	Weaknesses
Opportunities	SO Strategies	WO Strategies
Threats	ST Strategies	WT Strategies

Fig 2 SWOT matrix analysis

are presented in "Methods" section. "The status quo of DES in China" section introduces the status quo and regulations for DESs in China. The SWOT analysis is presented in "SWOT of DES" section. Enablers of DESs are listed and selected to be improved by applying AHP and BWM in "Enablers of DES development" section. "Results and discussions" section discusses the results of SWOT analyses for strategy making, and AHP and BWM for improving the enabler selection. "Conclusion" section concludes this article.

Methods

This section introduces methods used for analysing and advising DES development in China. The status quo of DES in China is summarized in "The status quo of DES in China" section to illustrate the whole picture of the development progress. SWOT analysis is used for the exploration of the development direction, as it is an efficient and effective tool for strategy making. The revised SWOT analysis adapted in this article does not merely analyse the performance and future potential of DESs, but also raises strengths-opportunities (SO) strategies, weaknesses-opportunities (WO) strategies, strengths-threats (ST) strategies and weaknesses-threats (WT) strategies according to each pairwise feature of the DESs in the SWOT analysis results. A suggestion could be generated after a strategy analysis, which is cross-checked with the literature with regard to their feasibility and consistency. However, SWOT and following strategies provide no implemental details but actions. In this case, the enablers of sustainable development of DESs should be examined and compared to figure out the most significant enabler for improvement. The AHP method is a method used to prioritize attributes by pairwise comparison. The adaption of this method helps to discover the vital aspects to be focussed on. The BWM is another weighting method as AHP, and it is adapted to evaluate the results of AHP.

Strengths-weaknesses-opportunities-threats analysis

Strengths-weaknesses-opportunities-threats (SWOT) analysis is a common practical tool for strategy planning [43]. The strengths refer to characteristics of a business or a project that is ranked as a disadvantage compared to others; weaknesses are defined as characteristics of a business that ranked a business or a project as a disadvantage compared to others. Opportunities are elements in the environment that a business or project might employ for its advantage. Threats indicate elements in the environment that might cause trouble for the business or project [43]. By analysing the SWOT of a project, the decision maker is able to judge where and how to improve the project. The SO strategies, the WO strategies, the ST strategies and the WT strategies are generated by analysing each two of the SWOT attributes according to a SWOT matrix analysis by discovering interrelationships between each attribute as shown in Fig. 2. In this case, the SO strategies propose opportunities that fit well with the DES's strengths. ST strategies are used to identify the ways that can be chosen to reduce the vulnerability to external threats. WO strategies overcome weaknesses and suggest opportunities. WT strategies are useful for establishing a defensive plan to prevent those weaknesses and threats.

AHP

An analytic hierarchy process (AHP) method is used to analyse the dealing urgency level of each existing problem by an estimated linguistic pairwise comparison invented by Saaty [44]. By applying an AHP method, the related importance is delivered from upper layer to lower layer through the hierarchy structure of the enablers. Therefore, the weights of enablers can be obtained through the hierarchical analysis.

Assuming that the weight of importance with respect to the nth enabler is indicated as w_n, the relative

Table 1 Pairwise comparison matrix

	A_1	A_2	A_j	A_n
A_1	w_1/w_1	w_1/w_2	w_1/w_j	w_1/w_n
A_2	w_2/w_1	w_2/w_2	w_2/w_j	w_2/w_n
A_i	w_i/w_1	w_i/w_2	w_i/w_j	w_i/w_n
A_n	w_n/w_1	w_n/w_2	w_n/w_j	w_3/w_n

Table 2 AHP priority standard [44]

Score	Priority
1	Equally important
2	Weak or slight
3	Moderately important
4	Moderately plus
5	Strongly important
6	Strongly plus
7	Very strong or demonstrated as important
8	Very, very strong
9	Extremely important

importance between the *i*th enabler and the *j*th enabler should be given by $a_{ij} = w_i/w_j$ as shown in Table 1. The pairwise comparison matrix should be expressed as Eq. (1).

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \tag{1}$$

In the AHP method, the score of pairwise comparison a_{ij} is given by linguistic terms in the first step by experts or decision makers. The expression such as "equally important", "moderately important", "very important", or "extremely important" will be used for describing the standard of priority denoted by 1 to 9. The congruent relationship between linguistic terms and numerical numbers is indicated in Table 2 and Fig. 3 according to Saaty [44]. The lower triangle of the pairwise matrix is the reciprocal of the upper triangle of the pairwise matrix, which is inferred by $a_{ij} = w_i/w_j = 1/(w_j/w_i) = 1/a_{ji}$ as shown in Table 1.

Taking the comparison of environmental, economic and social aspects as an example, the comparison matrix is shown as Table 3. The environmental factors in decision makers' opinions are more important than economic factors, whereas the former are far more important than the social factors. In addition, the economic factors are relatively more significant than the social perspective. Therefore, the environmental factors are recognized as "moderately important" comparing to the economic factors, the environmental factors are also recognized as "demonstrating important" comparing to social factors The importance level of each perspective in the decision-making of a biorefinery selection could be determined using the priority standard table (see Table 2) [44]. From the description above, a_{12}, a_{13} and a_{23} can be presented as 3, 7 and 5, respectively, and a_{21}, a_{31} and a_{32} are 1/3, 1/7 and 1/5 accordingly.

After the pairwise comparison matrix had been estimated, the weights of enablers were calculated by Eqs. (2) and (3)

$$a^*_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \text{ for all } j = 1, 2, \ldots, n \tag{2}$$

$$w_i = \frac{\sum_{j=1}^{n} a^*_{ij}}{n} \text{ for all } i = 1, 2, \ldots, n \tag{3}$$

There is a relationship between the vector weights, and the pairwise comparison matrix, as shown in Eq. (4).

$$Aw = \lambda_{\max} w \tag{4}$$

where w is the vector of the absolute values and $\lambda_{\max}$ is the highest of the eigenvalues of the matrix A.

A consistency ratio (CR) is calculated by comparing the consistency index (CI) of the matrix in question with the consistency index of a random-like matrix (RI). A random matrix is one where the judgments have been entered randomly and therefore it is expected to be highly inconsistent. RI is the average CI of 500 randomly filled in matrices (as shown in Table 4). Therefore, the CR is determined by Eqs. (5) and (6).

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{5}$$

$$CR = \frac{CI}{CR} \tag{6}$$

A CR of 0.10 or less is acceptable to continue the AHP analysis.

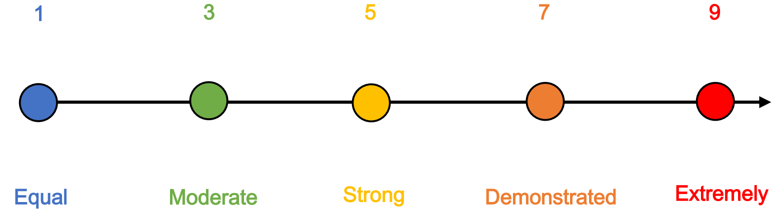


Fig. 3 The fundamental scale of absolute numbers [44]

Table 3 AHP pairwise comparison matrix

	Environmental	Economic	Social
Environmental	1	3	7
Economic	1/3	1	5
Social	1/7	1/5	1

BWM

The best-worst multi-criteria decision-making method (BWM) is a theory to solve such multi-attribute decision problems raised by Jafar Rezaei [45]. The rational behind this weighting method is that the best and the worst attributes were estimated for comparison with the other attributes, so that the relative information is sufficient to infer the relationships between each attribute.

The decision maker identifies the best enabler in one comparison, and then determine the preference of the best enabler over the other enablers using the numerical expression is denoted by 1 to 9 indicated in Table 2 and Fig. 3 according to Saaty [44]. The resulting best-to-others vector is given by Eq. (7).

$$A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn}) \tag{7}$$

where a_{Bj} indicates the preference of the best enabler B over the jth enabler.

Then the decision maker identifies the worst enabler in one comparison, and then determines the preference of the other enablers over the worst enabler using the numerical expression is denoted by 1 to 9 indicated in Table 2 and Fig. 3 according to Saaty [44]. The resulting others-to-worst vector is given by Eq. (8).

$$A_W = (a_{1W}, a_{2W}, \ldots, a_{nW})^T \tag{8}$$

where a_{jW} indicates the preference of the jth enabler over the best enabler B.

The optimal weights $(w_1^*, w_1^*, \ldots, w_1^*)$ and the minimum objective function ξ^* are obtained by solving programming Eq. (9).

$$\text{Minimize } \xi \tag{9}$$

Subject to

$$\left| \frac{w_B}{w_j} - a_{Bj} \right| \leq \xi \text{ for all } j = 1, 2, \ldots, n$$

$$\left| \frac{w_j}{w_W} - a_{jW} \right| \leq \xi \text{ for all } j = 1, 2, \ldots, n$$

$$\sum_{j=1}^{n} w_j = 1$$

$$w_j \geq 0 \text{ for all } j = 1, 2, \ldots, n$$

The consistency ratio is determined by Eq. (10).

$$CR = \frac{\xi^*}{CI} \tag{10}$$

where the value of the consistency index (CI) of BWM is presented accordingly [45] in Table 5. Similarly, the CR of 0.10 or less is acceptable to continue the BWM.

The status quo of DESs in China

Regulations of DESs in China

This section summarizes the regulations and policies in China for the DESs from 1989 to 2017, categorizes the stages of regulations in relation to the DESs and emphasizes each stage of policy concentrations (see Table 6).

Table 6 lists the relative regulations and policies issued from 1989 to 2017 and witnesses some changes in the number and content of the Chinese regulations. Since the Instructions of the Nature Gas Based Distributed Energy Systems (Energy No. [2011] 2196) and the Notification of the Release Control of Greenhouse Gases (SC No. [2011] 411) in 12th Five-Year Plan published, the number of regulations increased significantly. Joining the environmental issues have brought unprecedented attention to the development of DESs, which has played a catalytic role in the development of the regulatory framework. In addition, the regulations are mainly classified into three types, which are concept establishment, implementation instruction and management system superlatively. The changes in content are summarized in Fig. 4.

The percentage of policy types in each Five-Year Plan period demonstrates in an early stage of DES development that the focus lies merely on concept establishment regulations, such as the law of Electricity Power and the Law of Energy Conservation, to encourage research and a new trial of DESs. From the 11th Five-Year Plan period, the number of regulations with regard to the instructions for implementation and management system completion started to increase. The percentage

Table 4 Table of AHP Random Index [44]

No. of x	1	2	3	4	5	6	7	8
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41

Table 5 Table of BWM Consistency Index (CI) [45]

a_{BW}	1	2	3	4	5	6	7	8	9
CI	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

Table 6 Relative regulations published from 1989to 2017

FYP[a]	Time	Type	Title of document
7th	1989	Concept Establishment	The State Development Planning Commission (SDPC) published Regulations on Encouraging Small-scale Combined Heat and Power System Development and Regulations on Restricting Small-scale Condensate Thermal Power Generation System Constructions (SDPC Resource No. [2013] 937)
8th	1995	Concept Establishment	The Standing Committee of the National People's Congress passed the Law of Electricity Power.
9th	1998	Concept Establishment	The Standing Committee of the National People's Congress passed the Law of Energy Conservation.
9th	1998	Concept Establishment	The SDPC published Regulations on the Development of Combined Heat and Power Systems (SDPC Transportation & Energy No. [1998] 220)
9th	2000	Concept Establishment	The SDPC, the State Economic and Trade Commission (SETC), the Ministry of Housing and Urban-Rural Development (MDHURD), the Environmental Protection Agency (EPA) jointly issued a Regulation for the Development of Combined Heat and Power Systems (SDPC Basis No. [2000] 1268)
10th	2004	Concept Establishment	The National Development and the Reform Commission (NDRC) published a Report on the Relative Problems of Distributed Energy Systems. (NDPC Energy No. [2004] 1702)
11th	2006	Implementation Instruction	The NDPC and other 7 Commissions issued Suggestions on the Implementation of the Top 10 Major Energy Conservation Projects in the 11th Five-Year Plan.
11th	2006	Implementation Instruction	The National Energy Administration (NEA) proposed Preliminary Opinions on the Implementation of Middle-term and Long-term Science and Technology Development.
11th	2007	Concept Establishment	The NDRC published a Policy of Nature Gas Utilization.
11th	2007	Management System	The NDRC and MDHURD printed and distributed the notification of Temporary Provisions of Establishment and Management of Combined Heat and Power and Coal Gangue Power Generation Projects.
11th	2010	Implementation Instruction	The State Grid Corporation of China (SGCC) issued Regulations on Intermittency Technologies of Distributed Energy System and National Electricity Networks.
12th	2011	Implementation Instruction	The NDRC and other 3 commissions published Instructions of Nature Gas Based Distributed Energy Systems.
12th	2011	Implementation Instruction	The State Council issued a notification for Release Control of Greenhouse Gas in the 12th Five-Year Plan. (SC No. [2011] 411)
12th	2012	Concept Establishment	The NEA published a Research Report about a New Energy Industry Development Tendency.
12th	2012	Concept Establishment	The MOHURD issued the 12th Five-Year Plan of National Country's Nature Gas Application Development.
12th	2012	Concept Establishment	The NDRC published a notification of The First National Modelling Projects of Nature Gas Distributed Energy Systems.
12th	2013	Concept Establishment	The State Council issued the 12th Five-Year Plan for Energy Development.
12th	2013	Implementation Instruction	The NEA published Temporary Provisions of a Distributed Generation Management.
12th	2013	Management System	The SGCC published Suggestions for Distributed Energy System Intermittency.
12th	2013	Implementation Instruction	The NDRC published a notification of Achieving the Goal of Energy Conversation and Pollution Reduction. (NDRC Environment & Resource No. [2013] 1585)
12th	2014	Management System	The NDRC published the Management Regulations for Small-scale Enterprise Power Generation Standardization.
12th	2014	Concept Establishment	The NEA published a notification of Promoting the Establishment of Distributed Photovoltaic Power Generation and the Applied Demonstration Region. (NEA New Energy No. [2014] 512)
12th	2015	Concept Establishment	The NEA published the Instruction for Promoting the Development of New Energy Sources Based Micro-Grid Power Generation Projects (NEA New Energy No. [2015] 265)
12th	2015	Management System	The NEA published a notification for Implementing Information Management of Power Generation Projects based upon Renewable Energy Sources (NEA New Energy No. [2015] 358)
12th	2015	Management System	The NDRC published a notification regarding Planning and Construction after Delegation of Approving Power Generation Projects (NDRC Energy No. [2015] 2236)
12th	2015	Implementation Instruction	The NDRC published Instructions for Accelerating the Establishment and Renovation of Distribution Networks (NDRC Energy No. [2015] 1899)

Table 6 Relative regulations published from 1989to 2017 *(Continued)*

FYP[a]	Time	Type	Title of document
13th	2016	Management System	The NEA published Instructions for Establishing Guidance with regard to the Development Goal of Renewable Energy. (NEA New Energy No. [2016] 54)
13th	2016	Concept Establishment	The NDRC published Instructions from Promoting the Development of Electricity Substitutes (NDRC Energy [2016] 1054)
13th	2017	Management System	The NDRC and NEA published a Notification with regard to the Establishment of Distributed Energy Marketization Trading Trials.
13th	2017	Management System	The NDRC and NEA published Implementation Instructions for Promoting the Development and Renovation of Power Generation Safety.
13th	2017	Management System	The NDRC published a Notification with regard to the Price Policy of Photovoltaic Power Generation in 2018. (NDRC Price No. [2017] 2196)
13th	2017	Implementation Instruction	The NDRC published the Instruction for the Establishment of Biomass Power Electricity Projects (NDRC Environment & Resource No. [2017] 2143)
13th	2017	Implementation Instruction	The NDRC published a Notification with regard to a Printing and Distributing Pricing Law of Area Network Power and Inter-Province Power (NDRC Price No. [2017 2269]
13th	2017	Implementation Instruction	The NDRC published a Notification with regard to Cancelling Temporary Electricity Network Intermission Fee and Clarifying Fee Policy of Private Power Plants/ (NDRC Price No. [2017] 1895)
13th	2017	Implementation Instruction	The NDRC published a Notification with regard to Printing and Distributing Tentative Measures for Promoting Micro-Grid Networks Which can be Combined to the National Power Network (NDRC Energy No. [2017] 1339)

[a] *FYP* five-year plan

of management system completion started gradually to increase and reached more than 40% of the total regulations in the 13th Five-Year Plan. It is evident that the DES project has developed rapidly in China, and the management system is maturing. Based on the above-mentioned progress, we can draw a rough timeline and classify the stage of DES development in China.

The promotion of DESs in China could be divided into three main stages (see Fig. 5), which are concept establishment, implementation instruction and management system completion. From 1995 to 2003, the Chinese government published a series of regulations to encourage the development of DESs and CHP application. Among those documents, most of them emphasized the significance of DESs and CHP application in China and encouraged the establishment of relative projects. From 2004 to 2010, the government prepared detailed instructions and suggestions to accelerate the

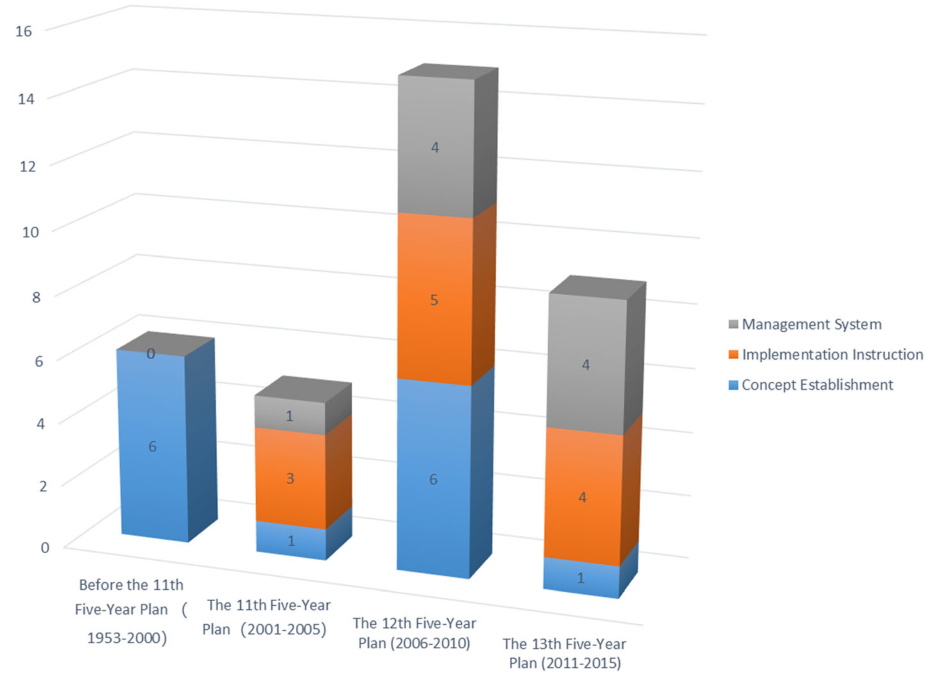


Fig. 4 Percentage of policy types in each five-year plan period

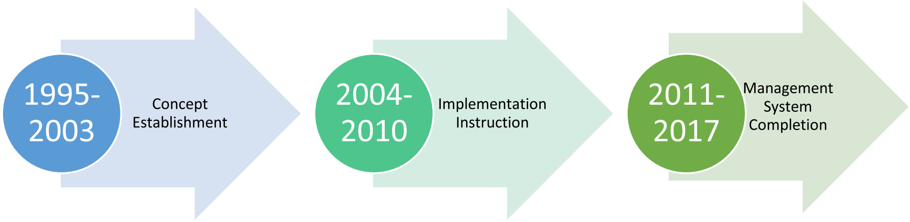


Fig. 5 Important development stages of distributed energy systems in China

development and technological improvement of this industry. Starting from 2011, the Department of National Energy Control paid more attention to consummate the management system, the supervisory system and cooperation with the existing energy organizations. In addition, the focus has been transferred to solve the current problems occurring in the industry, such as employment security and interconnection policies.

The DES development progress in China

This section reviewed the development progress of DESs in China from 1989 to 2017 and summarized the major DES projects in China and their current stage.

From 1989, the awareness of environmental protection motivated the Chinese government to promote DESs, especially natural gas distributed energy systems by publishing encouragement policies. From the beginning of the twenty-first century, DES were widely built in well-developed cities, especially in Beijing, Shanghai and some cities in the Guangdong province. Up to 2013, China's natural gas distribution energy industry was in its infancy stage, with a capacity of power generation less than 1% of the national total installed capacity and a great development potential in the Chinese market [46]. Some major distributed energy systems projects are presented in Table 7.

Distributed energy systems were treated as one of the major programs in China and developed further step by step. As shown in the Table 7, several distributed energy system projects are currently established. However, parts of those projects were built merely for teaching purposes or have even been shut down after few years of operation, which leads to the conclusion that there are only a few distributed energy systems that have been built for

Table 7 Summary of the Chinese major distributed energy system projects

Year	Current Status	City	Project
1998	Shut off	Shanghai	Shanghai Huangpu District Central Hospital
2000	Operating	Shanghai	Shanghai Pudong International Airport
2002	Shut off	Shanghai	Shanghai Shuya Health and Leisure Center
2003	Teaching Purpose	Shanghai	Shanghai University of Science and Technology
2003	Operating	Beijing	Beijing sub-station station building
2004	Teaching Purpose	Shanghai	Shanghai Zizhu Science and Technology Park Software Building
2004	Teaching Purpose	Beijing	Tsinghua University for Energy Efficiency Building
2004	Operating	Beijing	Beijing Gas Group Monitoring Center
2007	Operating	Shanghai	Shanghai Minhang District Central Hospital
2007	Operating	Beijing	Beijing Olympic Energy Exhibition Center
2008	Shut off	Beijing	Beijing South Railway Station
2009	Operating	Guangzhou	Guangzhou University City
2009	Operating	Changsha	Huanghua Airport
2011	Operating	Guangzhou	Guangdong Aluminum Group
2013	Operating	Xiangtan	Xiangtan Jiuhua Demonstration Zone
2014	Operating	Dongguan	Dongguan, Guangdong shoe factory
–	Incomplete	Beijing	Beijing Zhongguancun Software Park Software Square
–	Incomplete	Beijing	Beijing International Trade Center Phase III Project
–	Incomplete	Beijing	Beijing International Shopping Center

Fig. 6 Locations of major DES projects in China at early stages

long-term electricity supporting purposes and China has not stepped into a stage where distributed energy systems are applied nationwide.

Demonstrated by the location map (see Fig. 6), there are early-stage DES projects located in Beijing, Shanghai and some cities in the Guangdong province. Those cities have a large electricity demand as their economy is booming and technology development advances. Beijing is the capital city of China and it is the national center of politics and economics of China as well. Shanghai is one of the most important ports in China where most international enterprises choose to stay. Guangdong province, consisting of two to four of the most well-developed cities in China, represents the most prosperous district of South China. These frontier cities have a greater demand for sufficient capital, with some of the most excellent universities worldwide exporting elite talent and providing the latest technology in research and development. In addition, the development of DESs is treated as one of major supported projects in the sector of energy policies. Therefore, it is reasonable to start early-stage innovative projects in certain cities.

However, the initial product is still not perfect. It is evident from Fig. 7 that only about half of the major projects were published and remained operating. In addition, incomplete DES projects, DES projects for teaching purposes and projects no longer in use contribute evenly, which also accounts for a large proportion. Therefore, there is still much room for improvement in the field of DES projects both with regard to their technique and their long-term operation.

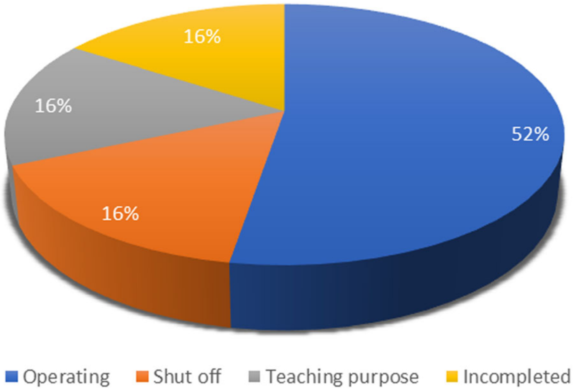


Fig. 7 Percentage of current status of major DES projects in China

Table 8 SWOT analysis table

	Strengths	Weaknesses
	1. Benefit for environment protection 2. Energy saving 3. Meet fluctuated electricity demand 4. Multiple power phases 5. High power generation quality 6. Job creation	1. High influence on the surroundings 2. Resource restrictions 3. High cost 4. Low efficiency of electricity generation 5. High technical requirements
Opportunities	SO strategies	WO strategies
1. New renewable energy sources 2. Awareness of environment protection 3. Increasing electricity demand 4. Policy support by the Chinese government 5. Advanced techniques support	1. Encouraging the adaption of new energy sources in DESs. 2. Selecting renewable energy resources as the system inputs when applying this technology to the real-time project in China. 3. Selecting DESs as the first priority when electricity demand cannot be supplied by the national network. 4. Emphasizing the advantages, such as energy saving to potential DES users. 5. DESs could be applied more as demonstrative projects 6. Cooperating with educational institutes to further develop DES technology	1. Developing DES technology with new energy sources that can reduce the impacts to the neighbourhood. 2. Enhancing techniques to reduce transmission cost and production cost. 3. The government financially supports DES researchers and owners for green power generation generalization.
Threats	ST Strategies	WT Strategies
1. State Grid Corporation of China. 2. Uncompleted regulation system	1. The green concept should be considered and emphasized when competing with the low price for traditional thermal power generation 2. DES should be used as a back-up power supply for enterprises and public areas. 3. Decentralization of energy controls should be used. The end-users should be allowed to choose their energy sources on an open market.	1. Education and research enable DES technology evolution for reducing transportation and production cost. 2. More supporting projects should be established to accelerate DES technique development. 3. Technology improvement helps to achieve more efficient generation ways. In this case, new renewable energy resources might be adapted as one of DES input. 4. Potential government subsidization helps reduce cost.

SWOT of DESs

In this section, SWOT analysis was used to analyse the situation of DES development in China (presented in Table 8). Two academic researchers studying energy chemistry, three experts in energy policy and three engineers working in an electricity generation factory were invited to conduct a SWOT analysis. They were interviewed to discuss the topic individually, and the author gathered the information in order to complete the SWOT analysis. The SWOT analysis and the respective strategies were cross-checked with the literature.

Strengths

The strengths of DESs in China include their environmental-friendly features, job creation opportunities, energy saving capabilities, multiple power output phases, flexible generation time and its high quality of power generation.

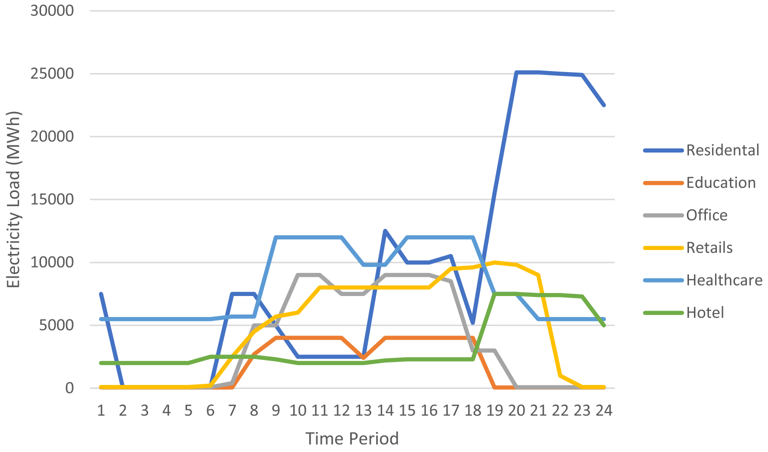


Fig. 8 Electricity demand for different areas [54]

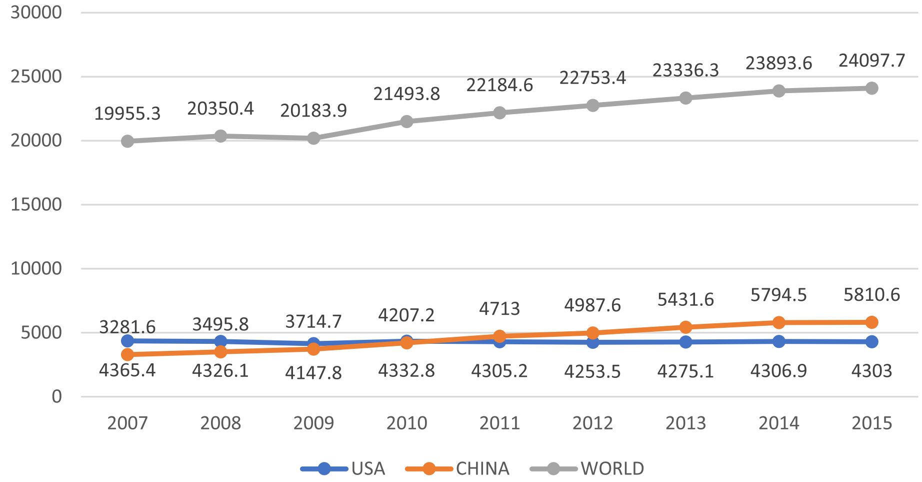


Fig. 9 Comparison regarding generating capacity [66]

Some types of DESs would help to reduce not only the emission of poisonous gasses and the release of solid particles, but also water pollution and land occupation. Poisonous gas emissions, which might increase acid rain effect and cause lung and respiratory diseases, has seriously affected the human health [47]. Increased combustion of fossil fuels in the last century is responsible for the progressive change in atmospheric composition. Air pollutants, such as carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxides (NOx), volatile organic compounds (VOCs), ozone (O_3), heavy metals and respirable particulate matter ($PM_{2.5}$ and PM_{10}) differ in their chemical composition, reaction properties, time of disintegration and ability to diffuse in long or short distances [48]. In 2013, there were 2.9 million deaths (5.3% of all global deaths) caused by outdoor fine particulate air pollution and an additional 215,000 deaths from exposure to ozone. The rate of respiratory diseases has continuously increased over the past two decades. Compared to thermal power electricity generation, distributed energy systems using renewable resources show great advantages in environmental protection. Various DESs using clean resources have a high possibility to mitigate environmental degradation. Taking natural gas distributed energy system as an example [10], the emission of SO_2, CO_2, NOx could be reduced by 90%, 60% and 80%, respectively, by using natural gas distributed energy systems.

Solid waste produced during traditional thermal power electricity generation contains a high degree of harmful substances. The physicochemical behaviour in heterogeneous aqueous environments of trace elements such as Cd, Cu, Pb, Zn, As, Se, and Cr was studied. All of these elements are known to be trace contaminants in waste fluids from various operations in coal-fired power plants [49]. Those substances potentially cause lung diseases as

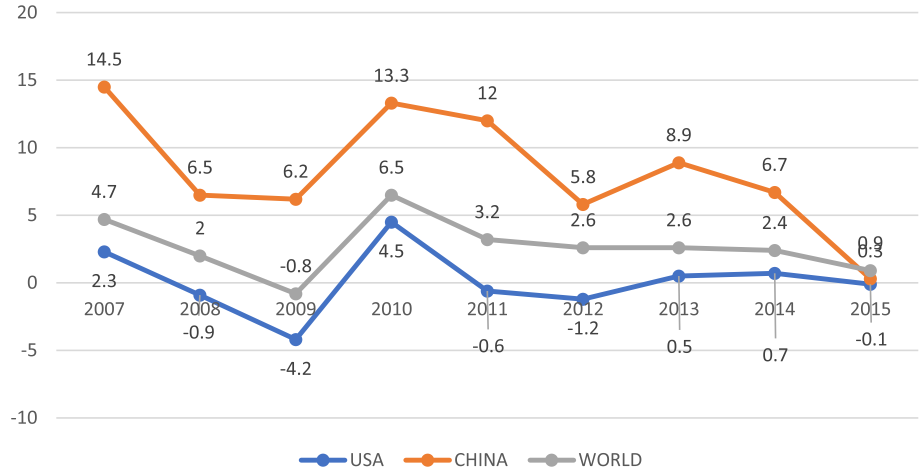


Fig. 10 Comparison regarding the growth rate [66]

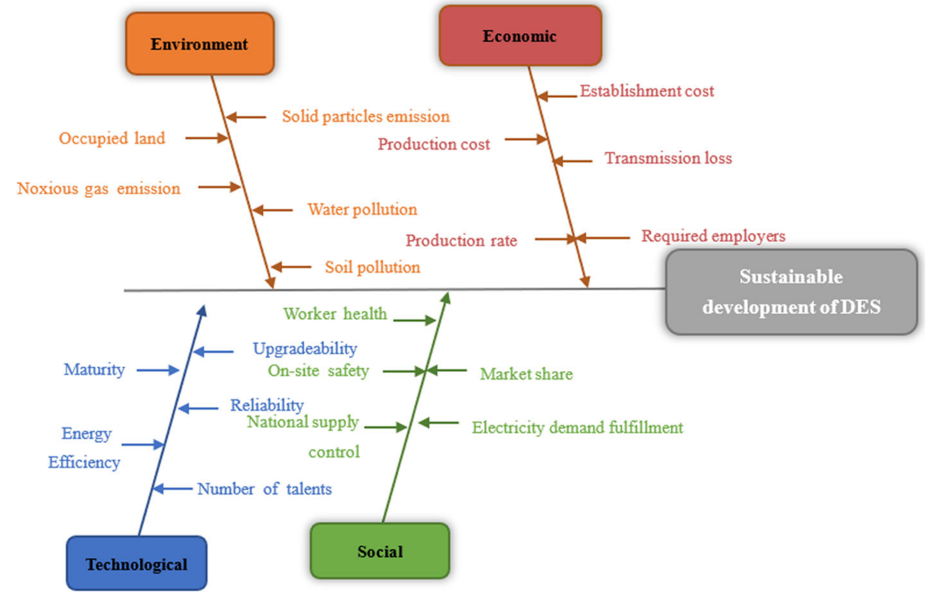


Fig. 11 Enablers of distributed energy system development in China

well as river or land pollution. Fossil-fuel electric power generation was found to be the main cause of air pollution in the past century [50]. The general and widespread treatment of those hazardous particles in current China is landfilling [51]. As those wastes require a long term to be degraded, the land which is occupied by landfill is far from being used for other purposes. Natural gas distributed energy systems produce almost no solid waste, which eases the burden of urban waste treatment.

Water pollution caused by electricity reached about 2 billion cubic meters [52]. Several worldwide environmental conferences mentioned worsening situations of water pollution. In conferences, researchers continuously reported that changing the structure of fossil-based electricity generation would make a significant contribution to sustainable environmental protection. DESs helps to reduce the fossil usage percentage in national power generation. For instance, distributed energy systems based upon natural gas help reduce the amount of used water and consequently improve the rate of water use because heated water is employed as one of the power outputs by other end-users.

Nowadays, the total area of land on the earth is 148.94 million square kilometres [53] and global population has raised to 7.6 billion. With an increasing global population, the limited land on the earth remains insufficient for human activities. However, the traditional thermal power generation industry occupies a large number of acreages of land since it is supposed to supply millions of residents and manufacturers nearby. To alleviate land pressure for a nation, DESs are one of the most worthy trials. Small-grid application transforms the electricity issue into an individual or scattered task. DES projects are generally located in public areas such as airports and railway stations and some indoor places such as teaching buildings at universities. The application of DESs

Table 9 AHP analysis results regarding environmental enablers

	Solid particles emission reduction	Occupied land reduction	Noxious gas emission reduction	Water pollution reduction	Soil pollution reduction	Weight
Solid particle emission reduction	1	2	3	9	4	0.434241
Occupied land reduction	1/2	1	1/3	5	2	0.163512
Noxious gas emission reduction	1/3	3	1	7	2	0.257965
Water pollution reduction	1/9	1/5	1/7	1	1/3	0.035972
Soil pollution reduction	1/3	1/2	1/2	3	1	0.108309
Consistency ratio						0.062167

Table 10 The best-to-others vector of environmental enablers

	Solid particles emission	Occupied land	Noxious gas emission	Water pollution	Soil pollution
Solid particle emission	1	2	2	9	4

demonstrations the advantage of small scale, which could help mitigate land pressure on the earth, especially in heavily populated countries such as India and China.

The benefits for local residents are found in the flexible generation time, various input resources and multiple output phase properties as well as the job creation capacity of DES's.

The electricity demands for different areas fluctuated and varied according to the time and area demand. Figure 8 presents a peak in the use of electricity of residential communities and hotels that exists after 6:00 pm and before 00:00 am, while that of the public facilities such as schools, office and hospitals exists in the middle of a day. DESs were designed to solve this problem, since the DES output volume is adjustable. Thermal electricity generation was included in the national supply network, to adjust the electricity amount allocated by coordination and management from the National Electric Energy Agency.

Various generation resources might be the input material of DESs. Ease of resource availability determines the main power resource of a local power system. A DES takes advantage of its various generation resources to assist a special area in developing its own power system. For instance, some projects located in the countryside use marsh gas as a primary resource and Chinese rural areas replace coal with straw. Therefore, DES solves the problem of resource limitation in certain areas, and lead to the lower production costs.

Users need different types of power. For example, the heating and electricity system were separated for residents, but some manufacturers require both heating and cooling functions. In the case of the latter, CHP or CCHP are suitable in this situation as they might provide more than one phase of energy at the same time, while less energy is wasted. In addition, DESs help local governments create job vacancies. Small-grid generation separates the locations of power generation plants, giving local residents more opportunities to work locally.

Table 11 The others-to-worst vector of environmental enablers

	Water pollution
Solid particle emission	9
Occupied land	5
Noxious gas emission	8
Water pollution	1
Soil pollution	3

High power generation quality is characterised by a high rate of energy use, the amelioration of energy construction and reliability of power supply. Distributed energy systems enhance the rate of energy used by power recycling. According the Instructions of the Nature Gas Based Distributed Energy Systems (Energy No. [2011] 2196) by the Chinese government, the rate of multipurpose utilization is up to 70% by supplying users with heat, cool and electricity. Liu et al. [55] mentioned in their research paper that natural gas CCHP systems allow energy to be degraded, which avoids about 40% energy waste. Furthermore, DESs are beneficial for the adjustment of energy construction [56]. The percentage of industries using coal as an energy source is up to 70%, which leads to a low energy usage efficiency, high environment pollution, serious transportation problems, safety issues and heavy pressure on CO_2 reduction. Renewable energy used in DESs might ameliorate the current situation. In addition, Xu [56] also demonstrated that the use of DESs might also enhance the reliability of power supply. As DESs are not only used as daily power source, but also as emergent power supply, they reduced the risk of energy supply interruption, which helps to ensure the safety and reliability of electricity supply. High-energy transformation ratios reflect the DESs as efficient power generation systems, which reduces energy waste during the electricity generation procedures. Compared to thermal energy generation based on concentrated natural gas, the natural gas-based DESs are advantageous because they enable an efficient energy consumption that might help to reduce the costs [57].

Weaknesses

The drawbacks of DESs include low efficiency of electricity generation, high production costs, high technical requirements, high influence on the surroundings and restricted resource location.

Table 12 BWM results regarding environmental enablers

	Weight
Solid particle emission	0.3738
Occupied land	0.1924
Noxious gas emission	0.2828
Water pollution	0.0386
Soil pollution	0.1125
Consistency ratio	0.1297

Table 13 AHP analysis results regarding economic enablers

	Production cost	Establishment cost	Production rate	Transmission loss	Required employer	Weight
Production cost	1	3	1	2	9	0.335261
Establishment cost	1/3	1	1/4	1	3	0.116512
Production rate	1	4	1	2	8	0.350906
Transmission loss	1/2	1	1/2	1	5	0.159808
Required employer	1/9	1/3	1/8	1/5	1	0.037513
Consistency ratio						0.011073

The main disadvantage of DESs is the low efficiency of a single generator due to its distributed property. Although DESs help use different phases of energy generation and, in this perspective, increases the energy efficiency, DES performs worse than traditionally centralized energy plants with regard to electricity production efficiency. As shown in the definition, DESs are small volume generator systems generating power less than 100 MW [3, 58–60]. A turbine in a traditional fossil plant might produce more than 1 billion kW. The larger the power equipment, the higher the efficiency. Therefore, the efficiency of DESs is much lower than that of a centralized energy generation plant.

The cost of generating electricity is high [61]. A smaller power generation system also needs the full function of a large power plant, as the price of power generation equipment is not low and does not decrease according to the proportion of power generated. Furthermore, power generation efficiency is low, the number of consumables required is relatively large and the cost of feedstocks and raw materials is high. In addition, the operators and administrators required for the operation of the power station will not have less to do with regard to the smaller scope, and labour costs will not be greatly reduced. Therefore, the unit power generation cost of DESs is much larger than that of large power plants.

DESs need higher technical requirements, because the technology of DESs is not yet popular, and the technology is not mature enough [62, 63]. The decentralized application of DESs requires a large number of relevant professionals to achieve high popularization. This has caused difficulties for the implementation and operation of DESs.

The impact of DESs on residents is greater than that of large traditional power stations. Distributed systems need to be dispersed close to the user to achieve low loss and high flexibility of adjustment. Security issues need to be focused on [64], when the plant has security issues, not only may employees be injured; the surrounding residents will also be affected by different aspects, such as financial and physical injuries. The prevention and control of such disasters is more difficult than that of larger power stations, as the distance from the affected residents is smaller, and the response time for people is shorter, and the damage is greater. In addition, environmental pollution generated during operations, such as harmful gases, dust, noise, etc. will affect the residents more directly and to a greater extent [65].

The resources required for DESs are restricted depending on local limits and scarcities. In some areas, biomass is a limited resource that costs more than coal. Hence, the limited resource also causes difficulties for material transportation. Therefore, the transportation of rare resources for DESs does not reduce harm to the environment, and may even weaken the environmental issues during the collection and transportation processes.

Opportunities

The increasing awareness of environmental protection and policies supported by the Chinese government, advanced technical support, increasing electricity demand and the continuous discovery of new renewable resources are opportunities for the further development of DES in China.

Firstly, studies show that the population is paying more attention to green concepts and sustainable development [65]. The Chinese government issued the Law of Renewable Energy and the Law of Energy Conservation during 2000–2015 and published 31 energy conservation policies and regulations during 2000–2018, as mentioned above. Secondly, policy support by the Chinese government encourages DES development. Starting from the publication of the 12th Five-Year Plan, the Instruction of Nature Gas Based Distributed Energy System (Energy [2011] 2196) and the Notification of Release

Table 14 The best-to-others vector of economic enablers

	Production cost	Establishment cost	Production rate	Transmission loss	Required employer
Production cost	1	3	1	2	9

Control of Greenhouse Gas (SC No. [2011] 411), the number of regulations related to energy conservation is higher than ever before. The DES projects have received particular attention due to their unique features. Thirdly, innovative techniques should be further supported. DESs have been a hot topic in recent years. Around 600,000 papers dealing with DESs were published during 2014–2018.

Comparing to world's average rate of increase for electricity generation, China shows a growing amount of electricity generation and a tendency to further increase in the future. Analysing the data (see Fig. 9), China has gained a great opportunity in energy generation and its technological improvement. The power generation has shown its significance in the Chinese market with its higher supply of energy, higher efficiency, and wider scope of application.

The generating capacity of the USA remained unchanged from 2007 to 2015, while China showed an increasing tendency of generating capacity, which increased from 3281.6 to 5810.6 TWh in 2015. As shown in the figure, the requirement for electricity around the world continues to rise with China presenting a more obvious tendency for this increase.

Figure 10 demonstrates the Chinese hidden potentials for electricity generation and requirements for rising power supply. To deal with the problem, distributed energy systems are one of the great solutions to relieve the pressure brought by increasing power supply needs, since it holds the advantages of flexible and reliable power supply, high rate of energy utilization efficiency and environmentally friendly features. Comparing to developed countries, the utilization percentage of renewable resource energy in China is far lower than the average level. In this case, the usage of CHP or CCHP systems might promote the potential development progress of replacing fossil resources in China. As science and technology have developed, China faces heavier pressure for its electricity supply. It would be beneficial to adapt distributed energy systems to relieve the pressure on electricity generation, since it provides external energy to that which is already being generated in the integrated electricity generation network [67].

Finally, the new energy industry has developed rapidly over the years. A huge share of renewable resources is expected [68]. Beyond photovoltaic power, solar power, wind energy, water energy and other natural sources, artificial resources such as artificial photosynthesis, bioenergy, nuclear, hydrogen, fusion and fission energy technology have shown their unique features and provide a potential possibility to meet the global energy demand [69–71]. As all renewable energies are potential input resources for DESs, the development of new energies accelerates the technological innovation of DES.

Table 15 The others-to-worst vector of economic enablers

	Required employer
Production cost	8
Establishment cost	3
Production rate	9
Transmission loss	4
Required employer	1

Threats

The main threats to DESs in China include the State Grid Corporation of China and uncertain regulations. The Chinese State Grid Corporation is a company established by the government with the purpose to integrate regional electricity supply networks and to complete the electricity management system [72]. In China, the industrial electricity fee is levied to support residential electricity users since 2015. In this case, the average electricity price for residents in China, which is the lowest electricity price in the world, is only 0.079 dollars per 1 kWh. At the same time, clean energy costs more than coal and other fossil resources. The low price provided by an integrated network becomes a great burden for residential users of DES, as renewable energy resources for DESs cannot acquire subsidies for clean power generation.

Although the Chinese government encourages the establishment and development of DESs, the regulations, especially the interconnection to the national electricity grid, are now burdening the users to adapt this technology widely in common life. Hirsch et al. [12] listed four challenges for the development of DESs that are legislative uncertainty, interconnection policy, utility regulation and utility opposition. The legislative uncertainty refers to the unclear definition of applicative regulations. The utility regulation indicates the restrictions of DES when it is deemed as a utility. The utility opposition refer to the regulations to protect utility when DES is deemed as a threat. Among the four challenges, all of them refer to regulations which shows that global challenges for DESs are interrelated with incomplete regulation systems.

SO strategies

The SO strategies emphasize the potential implementation that might help DES technology take advantage and

Table 16 BWM results regarding economic enablers

	Weight
Production cost	0.3162
Establishment cost	0.1207
Production rate	0.3564
Transmission loss	0.1665
Required employer	0.0402
Consistency ratio	0.0268

Table 17 AHP analysis results regarding technological enablers

	Maturity	Energy efficiency	Reliability	Upgradeability	Number of talents	Weight
Maturity	1	1/2	1/3	2	3	0.139037
Energy efficiency	2	1	1/3	4	8	0.263082
Reliability	3	3	1	5	9	0.479453
Upgradeability	1/2	1/4	1/5	1	2	0.076741
Number of talents	1/3	1/8	1/9	1/2	1	0.041687
Consistency ratio						0.022082

seize opportunities. As some new renewable energy sources have been discovered and studied, the application of these new energy sources might help DESs to enhance their advantages. Sustainable DES systems go along with a tendency to increase awareness of environmental protection: When applying DES technology in real-time projects in China, renewable energy resources should be selected as system inputs. Furthermore, new energy sources should be studied as the key targets to be applied in DESs techniques. In addition, it might be advantageous to select DESs as the first priority, when electricity demand cannot be supplied by the national network. In this case, DESs might help to adjust the unbalanced electricity supply to meet the fluctuating electricity demand. Likewise, taking the advantage of high power quality, DES systems might be applied for more purposes than only in demonstrative projects to improve the power shortage problem. Lastly, DESs are one of the most discussed topics with many numerous researchers participating, which helps to enhance technical innovation. If enterprises could cooperate with educational institutes to further develop DES technology, newly discovered renewable energy resources could likely be introduced in DES projects that would assist the further improvement of the quality of electricity generation.

ST strategies

The ST strategies are used to identify methods that can be employed to reduce the vulnerability of DES development threats caused by the State Grid Corporation of China. Green concepts need to be considered and emphasized when competing with low electricity prices from traditional thermal power generation. At this moment, the end-users should be allowed to choose their energy sources in an open market. They have high potential to choose DESs when the advantages of DESs have been well promoted to the end-uses. Since electricity supply from the State Grid Corporation of China cannot flexibly adjust the electricity supply to the demand changes, DESs used as a back-up power supply for enterprises and public areas helps adapt under changing situations.

WO strategies

The WO strategies help overcome weaknesses by suggesting opportunities. As new energy sources are discovered with technological development, the application of DES technology, which uses new energy sources, might reduce the impact on their surroundings. As it was mentioned in the SO and ST strategies, enterprises need to cooperate with research organizations to enhance DES techniques, so that transmission and production costs might be reduced. Poland currently uses geothermal heating technologies that successfully reduce the production price [73], although the price of it is still higher than the price of coal but much lower than that of biomass, natural gas and oil. In this case, the development of a new technology and an application of the new technology into real life practice are important. Likewise, the government would be able to better financially support DES researchers and owners involved in sustainable energy generation.

WT strategies

The WT strategies are useful for establishing a defensive plan to prevent those weaknesses and threats. The major disadvantage to DES is the high cost, when competing with centralized power generation plants. Therefore, the costs need to be reduced. Such a reduction of operation and manufacturing costs could be achieved through education and further research. Research might enable both a DES technology evolution for reducing transportation and production cost and a better support of projects established to accelerate DES technique development. Technology improvement also helps to achieve a more efficient energy generation. Cogeneration [74] and new technology development are two directions for this

Table 18 The best-to-others vector of technological enablers

	Maturity	Energy efficiency	Reliability	Upgradeability	Number of talents
Reliability	4	2	1	6	9

improvement. In that case, new renewable energy resources might be adapted to be among the DES input. Potential government subsidization, for instance, realized by tax reduction for DESs, could help to reduce costs for the end-users. To attract more talents to devote themselves to DES technology development and further research, the government could provide thematic sponsorships for high school education in this field and encourage high schools to add more relative courses to their engineering programmes.

Enablers of DES development

This section discusses enablers of DESs, analyses them by applying the AHP method and the BWM method, and in a final step selects enablers for improvement. Since the distributed energy system is a high-cost project, the decision making should be made with some sacrifices. The decision maker should choose extending the advantages or modifying the weaknesses of an energy system. In this case, the perspective being considered first is quite important and arguable. AHP and BWM are two methods helping to determine the direction of improvement after the market is analysed. The AHP method and the BWM represent two weighting methods that could rank options by pairwise comparisons and could assist decision makers to select which perspective has to be improved as the most urgent. To enhance the reliability of analysis results, two methods are used and compared in this study.

When considering the enablers of an energy system, most academic researchers classify indicators into three categories that are the social, environmental and economic perspectives [73–78]. Some researchers however consider a technical category as well [79–81]. To study the development of DESs in China thoroughly, four aspects of enablers including the environmental, economic, technological and social perspectives are adapted in this study. Five enablers of each perspective are selected to illustrate the performance of DES development in China. From an environmental perspective, water pollution, air pollution, particle emission, land pollution and land occupation are five important factors that researchers have to regard when energy systems are analysed. Water pollution, air pollution and land pollution can conclude all types of pollution. Land occupation and particle emission are the main concerns for neighbourhoods where DESs are settled, since these two aspects would affect resident lives. With regard to the economic perspective, production costs, establishment costs, number of labourers, production rate and transmission loss should be included in the benefits and costs of performance of DES. Both the cost and the benefit should be analysed. The cost performance of DES incorporates the fixed costs, such as establishment costs, and the operating costs in relation to the production cost and the number of labourers. The profits could be estimated through the production rate and transmission loss. The technological performance of the DES might be analysed by maturity, energy efficiency, upgradeability, reliability and number of working talents. From a social perspective, on-site safety, worker health, power demand fulfilment, future market share and national supply control attracted the most attention. Society's perspective should be examined whether it fulfils the needs of the respective residents, workers, investors and the nation. These 20 factors that will affect DES development in China are discussed in this chapter shown in Fig. 11. Three academic experts in the energy system field and three engineers working in energy systems are invited to evaluate the performance of DESs in pairwise matrix format. The values provided in a comparison matrix in this study are the average result of six comparison matrix tables. The author calculated the AHP and BWM results according to the methods mentioned in "Methods" section.

Table 19 The others-to-worst vector of technological enablers

	Number of talents
Maturity	3
Energy efficiency	6
Reliability	9
Upgradeability	2
Number of talents	1

AHP analysis and BWM analysis

Five key enablers of each perspective were selected to form the enablers system (see Fig. 11). An equal number of enablers for each perspective are selected to avoid differences caused by different average values for enablers in different perspectives.

Environmental enablers

Considering the environmental aspects, air pollution, water pollution, soil pollution and land occupation are problems the Chinese government should not ignore. According to the Chinese Environmental Bulletin, China is facing serious air pollution problems, especially excessive solid particle emissions. The reduction of solid

Table 20 BWM results regarding technological enablers

	Weight
Maturity	0.1289
Energy efficiency	0.2774
Reliability	0.4648
Upgradeability	0.0794
Number of talents	0.0495
Consistency ratio	0.0754

Table 21 AHP analysis results regarding social enablers

	Worker health	On-site safety	Market share	National supply control	Electricity demand fulfilment	Weight
Worker health	1	1/2	5	3	1/2	0.193624
On-site safety	2	1	9	4	1	0.348024
Market share	1/5	1/9	1	1/2	1/8	0.039623
National supply control	1/3	1/4	2	1	1/4	0.078601
Electricity demand fulfilment	2	1	8	4	1	0.340128
Consistency ratio						0.0040374

particle emissions, occupied land, noxious gas emissions, the reduction of water pollution and soil pollution reduction are selected to be assessed in a 5 × 5 matrix. Tables 9, 10, 11 and 12 illustrate the AHP analysis and the BWM analysis of environmental enablers. The pairwise comparison matrix is presented in Table 9 for the AHP analysis. The best-to-others vector and the others-to-worst vector are shown in Tables 10 and 11. The weights generated through AHP and BWM are shown in Tables 9 and 12, respectively. The two rankings indicate a high similarity, such as the reduction of solid particle emission, which is the most important factor of environmental aspects to improve for the development of DESs in China.

Economic enablers

Economic effects play significant roles in the development of DESs. From an economic perspective, we exam the establishment cost, production cost, production rate, transmission loss and number of required employers. Tables 13, 14, 15 and 16 illustrate the AHP analysis and BWM analysis of economic enablers. The pairwise comparison matrix is presented in Table 14 for AHP analysis. The best-to-others vector and the others-to-worst vector are shown in Tables 15 and 16. The weights generated through AHP and BWM are shown in Tables 13 and 16, respectively. They share a high similarity in ranks of production rate and production cost for the most important factors of the economic aspects for the improvement of DES development in China.

Technological enablers

Technological enablers include maturity, energy efficiency, reliability, upgradeability and number of professional talents educated in the field. Maturity, energy efficiency and reliability are used for judging the current technique. The upgradeability and the number of talents are standards for further development potential of the technique. Tables 17, 18, 19 and 20 illustrate the AHP analysis and BWM analysis of technology enablers. The pairwise comparison matrix is shown in Table 17 for the AHP analysis. The best-to-others vector and the others-to-worst vector are shown in Tables 18 and 19. The weights generated through the AHP and BWM are shown in Tables 17 and 20, respectively. Both results demonstrate that the most important factors of the technological aspects for an improvement of the DES development in China would be improving system reliability.

Social enablers

Regarding social aspects, worker health, on-site safety, market share of electricity supply, national supply control and electricity demand fulfilment are considered. Tables 21, 22, 23 and 24 illustrate the AHP analysis and BWM analysis of social enablers. The AHP pairwise comparison matrix is shown in Table 21. Tables 22 and 23 present the best-to-others vector and the others-to-worst vector. The weights generated via AHP and BWM are presented in Tables 21 and 24, respectively. The results show similarity in ranks of on-site safety and electricity demand fulfilment which are the most important factors of social aspect to improve the DES development in China.

The consistency ratios for every analysis is lower than 0.1, except the one for environmental enablers of the BWM analysis with a value of 0.1297. Those consistency ratios are small enough to prove that this assessment is acceptable.

As categories have no priority, same weights are given to all categories, which is equal to 0.25 each. The global weights for AHP and BWM analysis are summarized in Table 25.

By comparing pie charts representing weight percentages of enablers for AHP (see Fig. 12) and BWM (see Fig. 13), we discover that each enabler shows similar weight percentage in those two analysis methods, excepting a slide difference of the factor of electricity

Table 22 The best-to-others vector of social enablers

	Worker health	On-site safety	Market share	National supply control	Electricity demand fulfilment
On-site safety	3	1	5	4	2

Table 23 The others-to-worst vector of social enablers

	Market share
Worker health	2
On-site safety	5
Market share	1
National supply control	2
Electricity demand fulfilment	4

demand fulfilment, solid particle emission reduction, occupied land reduction and noxious gas emission reduction. In this case, the result of this assessment has a slight difference to real life judgement.

Enablers could be separated on the basis of the rankings of weight percentages into three categories which are "particularly significant issue", "important issue" and "not-urgent issue", respectively (shown as Table 26).

Therefore, solid particle emission reduction, generation reliability improvement, production rate improvement, production cost reduction, on-site safety improvement, electricity demand fulfilment, noxious gas emission reduction and energy efficiency improvement are the most urgent goals to be addressed currently in China. In this case, suggestions to those three aspects are expected to be summarized and become part of potential government policies and restrictions guidance. Scholars in China analysed the development of distributed energy systems in the country and came up with some potential policy implications and insights to improve the DES application in China. Aimed at three enablers mentioned above, the government policies should focus on the following aspects presented in the next section.

Results and discussions

From the results of SWOT analysis shown in Table 8, the SO strategies, the WO strategies, the ST strategies and the WT strategies are given. To optimize the opportunities and strengths of DES, the SO strategies suggest using more renewable energy resources to further enhance the environmental advantages, applying more demonstrative projects for promotion and further develop advanced techniques. To overcome the threats and avoid weaknesses, the technology should further be improved. The strategies can be summarized in three categories which are capital investment, technology development and regulation completeness. Capital is one the most important factors for implementing innovation and development [82]. Foreign direct investment and governmental subsidies are major capital resources for encouraging DES generalization, waste treatment and technology improvement.

Table 24 BWM results regarding social enablers

	Weight
Worker health	0.1951
On-site safety	0.3655
Market share	0.0400
National supply control	0.0750
Electricity demand fulfilment	0.3243
Consistency ratio	0.0243

Table 25 Summary of AHP and BWM analysis results

Enablers	AHP weight	BWM weight	Ahp Rank	BWM rank
Solid particles emission	0.120194	0.093439	2	2
Occupied land	0.045258	0.048089	10	10
Noxious gas emission	0.071402	0.070689	8	7
Water pollution	0.009957	0.009655	20	20
Soil pollution	0.029979	0.028129	14	14
Production cost	0.083386	0.079042	6	6
Establishment cost	0.028979	0.030169	13	13
Production rate	0.087277	0.089099	3	4
Transmission loss	0.039747	0.041634	11	11
Required employer	0.00933	0.010056	19	18
Maturity	0.034581	0.032229	12	12
Energy efficiency	0.065434	0.069338	7	8
Reliability	0.11925	0.116204	1	1
Upgradeability	0.019087	0.019860	16	15
Number of talents	0.010368	0.012369	17	17
Worker health	0.043714	0.048786	9	9
On-site safety	0.078573	0.091375	4	3
Market share	0.008946	0.010011	18	19
National supply control	0.017746	0.018751	15	16
Electricity demand fulfilment	0.076791	0.081077	5	5

Building talented teams and improving technologies are efficient methods to accelerate development of this industry. As the major targets of DES development, environment protection and electricity supply reliability need to be enhanced through more research, DES investors and administrators are encouraged to corporate with universities, support relative projects financially, provide application and testing opportunities, set up DES laboratories and encourage academic exchange. In addition, demonstration projects help researchers discover real-time problems and help to accelerate technology improvement and environmental protection.

It is significant to adapt the regulatory framework. As mentioned in the SO strategies, the decentralization of energy controls should be used. Once the end-users should be allowed to choose their energy sources on an open market, the competition activates the motivation of management team to innovate and develop. Free-market

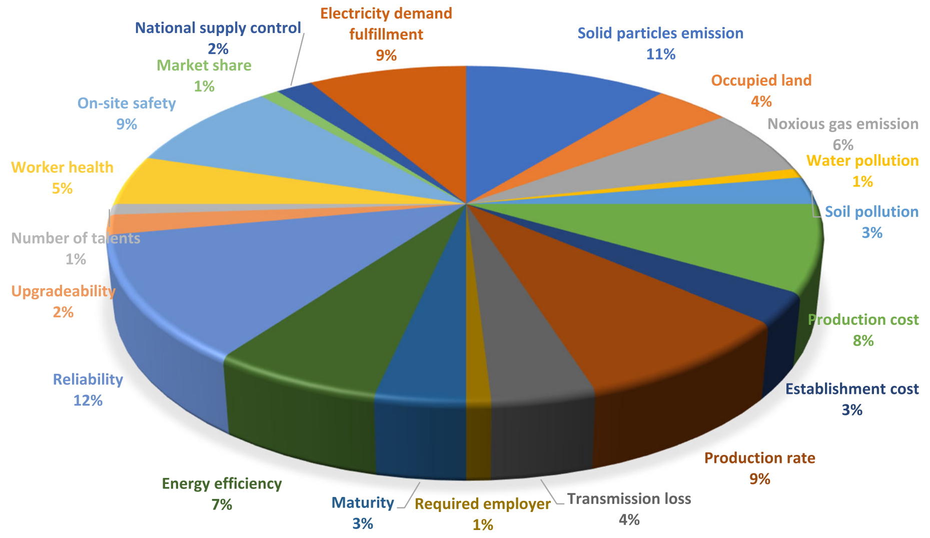


Fig. 12 AHP weights of enablers

economics speed up industrial development [83]. Opening the energy supply market to individuals and enterprises, improving the price compensation system [84] and implementing market-oriented management systems [85] benefit DES generalization since competition accelerates demand fulfilment [86]. Therefore, government should help to complete the regulations for DES to solve the challenges of legislative uncertainty, interconnection policy, utility regulation and utility opposition [12] and to promote the market liberalization in energy generation.

Any suggestion provided in SWOT analysis requires a specific direction for improvement. On the basis of the SWOT analysis, the detailed improvements could hardly be discovered, so that AHP and BWM were conducted to identify the best method for DES improvement. For example, subsidizing a research team for DES development is suggested in SWOT analysis. However, which method should be the focus of the research is not specified in the results. To figure out the enablers that are the most significant for DES development in China, AHP and BWM weighting methods were adapted. The results of AHP and BWM from the figures show that the reduction of solid particle emissions, the improvement of reliability generation and of the production rate, the reduction of production costs, the improvement of on-site safety, the fulfilment of electricity demand, the reduction of noxious gas emissions and the improvement of energy efficiency improvement are ranked as the highest of all enablers. This result means that those

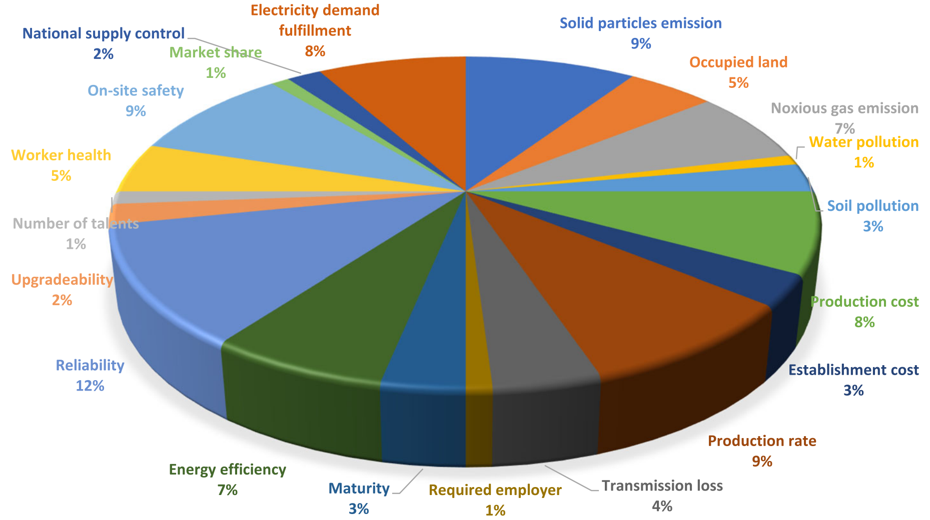


Fig. 13 BWM weights of enablers

Table 26 Classification of enablers

Emergency level and enablers	AHP rank	BWM rank
Particularly significant issues		
Solid particles emission	1	1
Reliability	2	2
Production rate	3	4
Production cost	4	3
On-site safety	5	5
Electricity demand fulfilment	6	6
Noxious gas emission	7	8
Energy efficiency	8	7
Important issues		
Occupied land	9	9
Worker health	10	10
Transmission loss	11	11
Maturity	12	12
Soil pollution	13	13
Establishment cost	14	14
Non-urgent issues		
Upgradeability	15	16
National supply control	16	15
Number of talents	17	17
Water pollution	18	19
Required employer	19	18
Market share	20	20

enablers are the most valuable perspectives for improvement and should be emphasized in improvement projects.

There are several directions that might be considered to address solid particle emission and gas emission problems. The energy resources used in current technology could be studied to be replaced by new materials with low particle emissions or even no emission. Some clean energy production technologies such as biomass or wind generation might be studied for use in the DES to improve their efficiencies. New technology might be invented to solve the emission problem, such as the technology to treat waste gas, or the technology to control the burning process.

Production cost reduction is another important aspect to be solved. Resources for energy generation contribute most to the energy production, and the cost for the resources is a variable cost which remains the same for every unit of energy produced. The study of low-cost resources will be meaningful for the reduction of production costs. The study of how to improve the efficiency of energy transformation also helps to reduce the resource costs as is discussed later. The production costs also consist of operational costs and labour costs. In this case, the optimization of labour arrangement and minimization of administrative fees points to their significance in cost reduction.

The safety issue is vital in any engineering studies, especially in those with regard to on-site safety. Safety should not only be considered in the industry establishment and policy supply but also at the design stage. Technologies need to be well studied before they might be widely applied in reality. Instructions and suggestions should be delivered to employees, surrounding residents and other stakeholders. It is also of basic interest to build safety infrastructures such as a protective cover of motor, efficient fire extinguishers and ventilation equipment, to facilitate the DES in implementation. Policies and regulations cannot be ignored. Government need to take responsibility for regulation completeness to protect companies' rights and to motivate enterprises to innovate the technology.

Energy efficiency is expected to be improved as it is the biggest drawback compared to traditional fossil energy plants. Should this problem be solved, DESs would have absolute priority in energy generation systems. The DES equipment should be further investigated and developed for efficiency improvement.

Conclusion

In conclusion, the conflict between an increasing energy need and limited raw resources encourages China to develop distributed energy systems that are characterised by green, efficient and flexible properties. Government policies related to the DES systems in China had experienced concept development and implementation stages, and now turned to focus more on the management system completion. Enablers of the DESs were analysed by applying the AHP and the BWM method. Among those enablers, the most urgent goals to be achieved currently in China have been identified as solid particle emission reduction, generation reliability improvement, production rate improvement, production cost reduction, on-site safety improvement, electricity demand fulfilment, noxious gas emission reduction and energy efficiency improvement. Accordingly, implications in capital and technology as well as regulation aspects in capital, talent team building, technology improvement and regulation completion aspects were proposed to modernise the environmental protection and quality of the DES generation in China.

Abbreviations

AHP: Analytic hierarchy process; BWM: Best-worst method; CCHP: Combined cooling heating and power/cooling heating and power; CHP: Combined heat and power; DE: Decentralized energy; DESs: Distributed energy systems; DG: Distributed generation; DR: Distributed resource; SO: Strengths OPPORTUNITIES; ST: Strengths threats; SWOT: Strengths-weaknesses-opportunities threats; UPS: Uninterrupted power supply; VOC: Volatile organic compound; WO: Weakness opportunities; WT: Weakness threats

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Authors' contributions
RL designed the study, analysed the research results and drafted the manuscript. YL organized the interviews for SWOT analysis and mathematic modelling and participated in the sequence alignment. YM organized the revision and content supplementary of the paper. JR conceived the study, participated in its design and coordination and helped to revise the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
All datasets on which the conclusions of the manuscript rely are mentioned or presented in the main paper.

Ethics approval and consent to participate
It is declared that this paper does not involve any human participants, human data or human tissue.

Consent for publication
All interview participants provided written consent to allow for any comments provided in the interview to be used within the research results and within any relevant publications, with the understanding that any quotations would be anonymous.

Competing interests
The authors declare that they have no competing interests.

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