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Delphi Survey on China's Advanced Energy Technology towards 2035

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Abstract

Facing the multiple challenges of low-carbon transformation, China urgently needs to adopt a new energy development path. This study used the Delphi method combined with vision analysis to analyze the advanced energy fields and gain insights into the development trends of energy technology towards 2035. The Delphi survey convened 762 domestic experts to predict the development demands and trends of advanced energy technology, and to identify important technology topics. A key list, including 91 technology topics in 9 sub-fields, was analyzed with respect to promoting economic growth, improving quality of life, and safeguarding national security. Furthermore, we conducted a research on these technology topics in context of technology research and development (R&D) level, leading countries, technology realization possibility, and constraints. The results from the Delphi survey show that the R&D level of China's advanced energy technology is still at an elementary stage, and China, significantly, lags behind the US and the EU in the fields of advanced energy. These results reveal that insufficient R&D investment is the primary factor restricting the technology development in China's advanced energy, though human resources, infrastructure, regulations, policies and standards also play significant roles in restricting technology development. The results from the Delphi survey may serve as a reference and help in exploring the development path of low-carbon transformation and achieving goals for addressing climate change in China.

Keywords

advanced energy; Delphi survey; vision analysis; China towards 2035

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1. Introduction

In 2020, the government of China announced its new goal of achieving carbon neutrality by 2060 and anticipated a possibility of controlled decline in carbon dioxide emission by 2030 (Xinhua, 2020). This indicates an unflinching determination of Chinese government to cope with increasing pollution and threats of global climate change. However, aiming for such a goal requires the introduction of new policy elements as well as refinement of existing energy policies in the country. In this context, the development and application of low-carbon technology may become the focus for both policymakers and researchers in the future.

Bibliometrics, expert panels, scenario analysis, and several other methods have been employed to explore the technology development trends towards 2035 in China's advanced energy fields. However, Delphi survey remains the major method at the national level (Yang and Chen, 2021) due to its wide applications. This method can help build a platform for better communication and information sharing among research institutions, government organizations, enterprises and the public, which can help stakeholders establish good partnerships, identify new market opportunities, and eliminate various obstacles in the process of technology development and its applications. In addition, this method is an effective means for government departments and enterprises to move toward democratization and socialization of scientific as well as technological decision-making processes.

Despite its benefits, the Delphi method has also some limitations. This method is costly and time-consuming and the survey results are often mixed with the subjective preferences of experts, which may lead to unreliability. Thus, improving its efficiency and quality has become a focal point for scholars at home and abroad (CID-CAS, 2019)[1]. Significant contributions have been made in this regard. Halal (2013) used an online survey and carried out different statistical methods to make it more effective. Chen (2016) and Hussain (2017) introduced the system dynamics method and scenario analysis method, respectively, into the survey. Such efforts effectively improved the efficiency of this method. However, optimization research on the organization and management is not well described in Delphi method, which needs further study.

The present study uses the Delphi method for anticipating the trends in technology development and contributes to China's advanced energy development strategy towards 2035. This paper reports both i) methodological contributions by improving the Delphi method, and ii) practical contributions by putting forward the policy implications for the energy transformation in China. The entire Delphi survey in this study has been organized into two rounds, as illustrated in the following section. We invited a large number of experts to identify the key factors for promoting technology developments in the fields of energy. Based on the survey results, this paper provides a list of key technology topics and foresees the future developments in China's advanced energy fields.

The rest of this article is organized as follows: Section 2 presents the overall framework and survey process using the Delphi method; section 3 gives a description of the statistical methods used in this study; section 4 reports the key survey results; section 5 discusses the key factors to the technology development in the fields of energy; and finally, section 6 unfolds a series of enlightenment and suggestions.

[1] CID-CAS is the abbreviation of "Center for Innovation and Development of Chinese Academy of Sciences".

2. Overview of the Delphi Survey

2.1. Delphi process

The Delphi process relies on a group of experts who are involved in several rounds of investigations and give a detailed opinion about their respective fields of interest. An expert group, including well-known experts in the advanced energy fields in China, and a project team to organize the survey are established before the survey. The research on different fields of advanced energy technology is the main objective of our study. For this reason, the advanced energy technology field is divided into "wind energy" "energy conservation and storage" "new power" "nuclear energy and safety" "hydrogen energy and fuel cell" "solar energy" "biomass and renewable energy" "fossil energy", and "new energy system". In order to carry out the Delphi survey, the project team took the previous research such as Japan's tenth technology foresight and Britain's third technology foresight as references. Based on China's innovation development stage and the global competition, the project team presented a vision for China's future innovation and development towards 2035 in accordance with the trends of globalization, industrialization, urbanization, intelligentization, greenization, and healthicization. Similarly, major technology topics, which needs to be broken through to achieve these development goals, have been put forward. To pick up the frontier information of advanced energy technology, the project team translated the reports of the 4th and the 5th technology foresight from South Korea, the 9th and the 10th technology foresight from Japan, and the 3rd technology foresight from Britain for as references. In the next step, considering the development level of China's advanced energy technology, strategic development demands towards 2035 and the major technology topics collected by the project team, experts from various sub-fields put forward a preliminary list of technology topics after discussion. The expert group reviewed, discussed, and determined the list of alternative technology topics for the first round of the Delphi survey. The next step was to carry out the first round of the large-scale Delphi survey and collect opinions from experts who filled out the questionnaires. Those opinions were introduced to the expert group for discussion to revise technology topics. Finally, a new list with alternative technology topics for the second round of the Delphi survey was formed. In the following processes, those experts who participated in the first round of the Delphi survey, were invited to the second round survey, and the survey results were analyzed to form a research report (Fig. 1).

2.2. Results of the Delphi survey

In the first round of the Delphi survey, 708 questionnaires were issued, and 385 valid questionnaires were returned. According to the survey results, the average number of experts answering each technology topic was found to be 167. The average number of technology topics answered by each expert was 42. Six hundred questionnaires were issued in the second round of the Delphi survey, and 331 valid questionnaires were returned. The average number of experts answering each technology topic was 105, and the average number of technology topics answered by each expert was 29 (Table 1).

Table 1 Summary of the Delphi survey results in the fields of advanced energy

Rounds	Number of sub-fields	Number of topics	Number of questionnaires issued	Number of questionnaires returned	Response rate	Average number of experts answering each topic	Average number of topics answered by each expert
1st round	9	95	708	385	54.38%	167	42
2nd round	9	91	600	331	55.17%	105	29

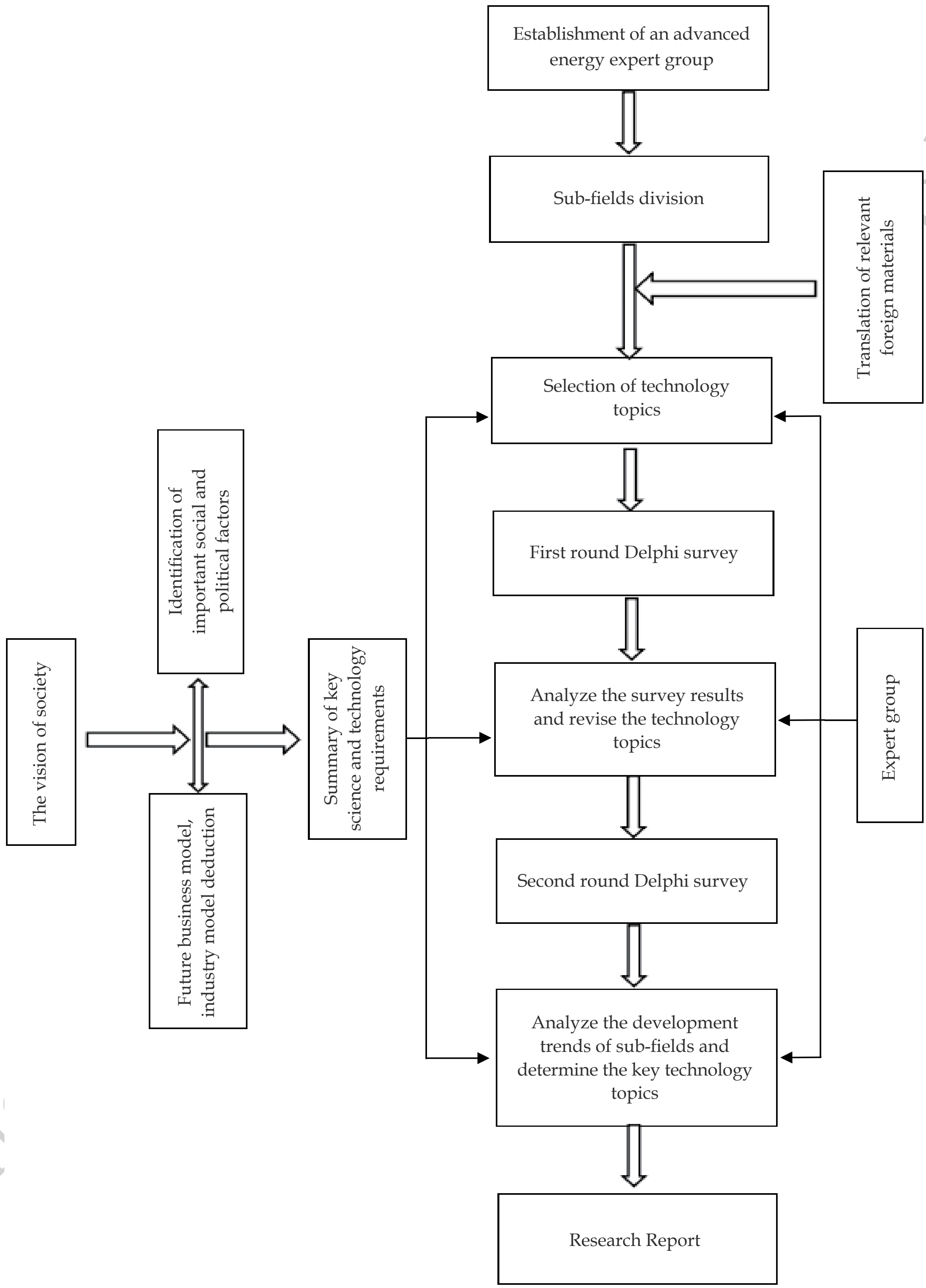

Fig. 1 Flow chart of the Delphi survey in the fields of advanced energy

The proportion of respondents in the first round from universities, research institutes, government departments, and enterprises was 39.8%, 33.4%, 1.3% and 24.0%, respectively, while 44.2%, 19.7%, 1.5% and 23.6% answered, respectively, in the second round. Furthermore, 1.5% and 10.9% of the experts in the two rounds of the Delphi survey were categorized as "others". Respondents of the Delphi survey were mainly selected from universities and research institutes in the first round. The proportion of experts from research institutes dropped from 33.4% to 19.7% in the second round. The proportion of experts from enterprises were no more than 25% in both two rounds, while the number of the experts from government departments was the least (Fig. 2).

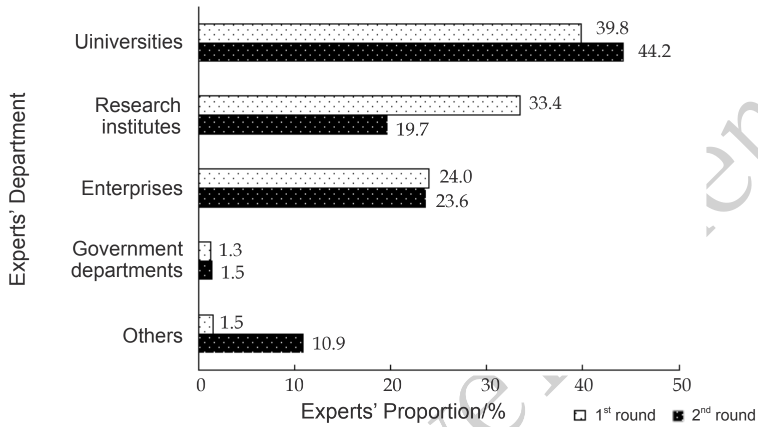

Fig. 2 Composition of experts in response

The professional background of experts responding to the Delphi survey has an important influence on the survey results. Therefore, this study designed specific items according to the experts' familiarity with technology topics. In the first round of the Delphi survey, experts who were "very familiar" and "familiar" with technology topics accounted for 11.7% and 25.6%, respectively, while "unfamiliar" experts accounted for 32.1%. In the second round of the Delphi survey, experts who were "very familiar", "familiar", "general", and "unfamiliar" on technology topics accounted for 14.3%, 30.4%, 30.8% and 24.6%, respectively. To maximize reliability of the survey, experts were asked to answer familiar technology topics in the second round of the Delphi survey. This significantly increased the proportion of "very familiar" and "familiar" from 37.3 % to 44.7%, and reduced the overall proportion of "unfamiliar" from 32.1% to 24.6% (Fig. 3).

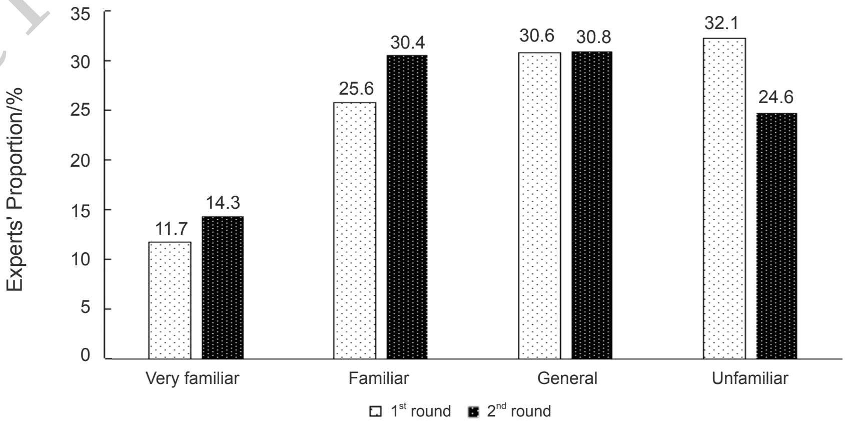

Fig. 3 Familiarity of respondents to technology topics

3. Delphi Survey Results Statistical Methods

The Delphi survey, used in this study, is based on two fundamental assumptions: i) The "very familiar" experts may give a reliable and better judgment on the importance of technology topics than "familiar" experts, while the judgments from experts who are "unfamiliar" with the technology topics can be ignored. ii) "Promoting economic growth", "improving quality of life" and "safeguarding national security" may be taken as equally important indicators in determining the importance of technology topics.

Assumption 1 is determined by the proprietary nature of the technology which relates the judgments from experts to the level of their professional knowledge. High-level experts have been engaged in research and development of technology for a long time, and their judgments on related technology development trends are consequently more reliable than "familiar" experts. It is difficult for an expert, unfamiliar with technology topics, to judge future technology trends. In evaluating the different judgment skills of the four types of experts including "very familiar", "familiar", "general", and "unfamiliar" in the Delphi questionnaire, this study gives weights of 4, 2, 1, and 0, respectively. This method replaces the actual number of experts with the weighted number to validate our results in relation to the judgments of experts who were familiar with technology topics.

Economic growth can lay an important foundation for improving quality of life and safeguarding national security. Improving life standards help in building a united society with improved creativity. Safeguarding national security can develop a harmonious social atmosphere, thereby promoting economic growth and improving quality of life. In the statistical analysis of the Delphi survey, the weights of three indicators were set to be equal because "promoting economic growth", "improving quality of life", and "safeguarding national security" can be considered as equally important indicators, which makes the second assumption valid in an appropriate way.

3.1. Importance index of single factor

The single factor importance index of technology topics includes three items: "importance index of promoting economic growth", "importance index of improving people's quality of life", and "importance index of safeguarding national security". The calculation formula is as follows:

$$I= \frac{I_1\times T_1\times 4+I_2\times T_2\times 2+I_3\times T_3\times 1}{T_1\times 4+T_2\times 2+T_3\times 1} \tag{1}$$

Among them, T_i represents the number of respondents at the familiarity level i, and $I_i=(100\times N_{i1}+N_{i2}\times 50+N_{i3}\times 25+N_{i4}\times 0)/(N_{i1}+N_{i2}+N_{i3}+N_{i4})$, i=1,2,3,4. I_1, I_2, I_3, and I_4 represent the importance index calculated on the basis of answers of experts who are "very familiar", "familiar", "general", and "unfamiliar" with the technology, respectively. When all experts consider the topics as "very important", the importance index will be 100, and when all experts consider it as "not important", the index will be 0. N_{i1}, N_{i2}, N_{i3} and N_{i4} represent the number of answers to the topics in "very important", "important", "relatively important", and "not important" categories at the familiarity level i (Table 2).

3.2. Comprehensive importance index of three factors

In addition to separately calculating the "importance index of promoting economic growth," "importance index of improving quality of life," and "importance index of safeguarding national security", it is also

Table 2 Definition of cross variables of importance and familiarity

Familiarity \ Importance	Very important	Important	Relatively important	Not important	Total
Very familiar	N_{11}	N_{12}	N_{13}	N_{14}	T_1
Familiar	N_{21}	N_{22}	N_{23}	N_{24}	T_2
General	N_{31}	N_{32}	N_{33}	N_{34}	T_3
Unfamiliar	N_{41}	N_{42}	N_{43}	N_{44}	T_4

necessary to consider these three factors for determination of the comprehensive importance degree of technology topics. Thus, we should find a reasonable calculation method for the comprehensive importance index of three factors to determine the priorities for development of technology topics. This study proposes that it is necessary to fully consider the marginal contribution rate of the single index which shows a non-linear increasing trend for selecting technology topics with emphasis on single factor. In addition, when calculating the comprehensive importance index, it is worth mentioning that the choice of the calculation method must fully consider the two assumptions, described above.

This study uses the square sum weighted method to calculate the comprehensive importance index of three factors on technology topics. It satisfies the requirement proposed in this study that the marginal contribution rate of importance index of single factor is nonlinearly increasing, and the calculation formula is as follows:

$$I=\sqrt{I_e^2+I_q^2+I_s^2} \tag{2}$$

In the formula, I_e, I_q, and I_s represent the importance index of each single factor: "importance index of promoting economic growth", "importance index of improving quality of life", and "importance index of safeguarding national security".

3.3. Forecasted time of realization for technology topics

The median method is a common method to calculate the forecasted time of realization for technology topics in the Delphi survey. In the Delphi questionnaire, there are four choices in the "forecasted time of realization" column: i) Before 2020; ii) 2021–2030; iii) after 2030; and iv) unforeseeable. The time span of "after 2030" refers to the years "2031–2035" and "unforeseeable" refers to the years after 2035.

In the process of using the "median" to calculate the forecasted time of realization for each technology topic, the "forecasted time", anticipated by each expert, was arranged in order on the time axis, and the weighted number of experts with respect to their familiarity level, was divided into four equal parts. The forecasted result of the midpoint represents the median (M). Q_1 and Q_2 represent the lower quarter point and upper quarter point with respect to the position of the midpoint. T_i refers to the forecasted time of realization for a technology topic while "i" is considered equal to M (Fig. 4).

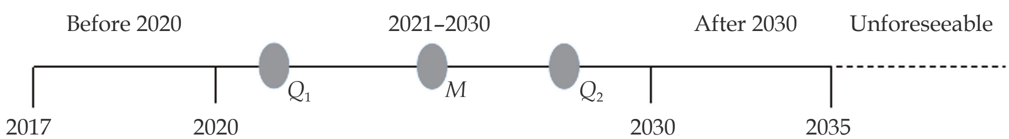

Fig. 4 Estimated realization time of technology topics

3.4. Expert recognition

Expert recognition refers to the proportion of the weighted number of experts with respective familiarity levels, giving the same answer, to the total weighted number of participating experts with respective familiarity levels. The calculation formula is as follows:

$$I= \frac{Q_{i1}\times4+Q_{i2}\times2+Q_{i3}\times1+Q_{i4}\times0}{E_1\times4+E_2\times2+E_3\times1+E_4\times0} \quad (3)$$

In the formula, I indicates expert recognition; Q_{i1}, Q_{i2}, Q_{i3} and Q_{i4} refer to the number of experts who are "very familiar", "familiar", "general" and "unfamiliar" with the option "*i*". E_1, E_2, E_3, and E_4 represent the total number of experts who are "very familiar", "familiar", "general", and "unfamiliar" with the technology topics, respectively.

3.5. Index of technology topics' realization possibility

The index of technology topics' realization possibility mainly depends on the "technology driving force" (technical feasibility) and "market pulling force" (commercial feasibility). For this reason, we define the "index of technology topics' realization possibility" as the product of the "technical feasibility" index and the "commercial feasibility" index. If we use T_i and C_i to indicate the degrees of constraint on technology topic "*i*" by technical feasibility and commercial feasibility, respectively, then the realization possibility index R_i on the technology topic "*i*" can be calculated as follows:

$$R_i= (1-T_i)(1-C_i) \quad (4)$$

3.6. R&D level of technology topics in China

This study uses experts' recognition on "lag behind the international level" "close to the international level" and "international advanced level" of technology topics to represent the R&D level in China. "R&D level of technology topics in China" is defined as follows:

$$RI= \frac{R_a+0.5R_c}{R_a+R_b+R_c} \quad (5)$$

In the formula, RI refers to the R&D level of technology topics in China, R_a refers to the number of experts who thought the technology topic is at the "international advanced level" , R_b refers to the number of experts who thought the technology topic "lags behind the international level" and R_c refers to the number of experts who thought the technology topic is "close to international level" .

4. Delphi Survey Results of the Technology Topics

4.1. Top 10 technology topics for promoting economic growth

The top 10 technology topics based on the importance to promoting economic growth were selected. "Large-scale energy storage batteries characterized with a life cycle of more than 10,000 times, fast charge/discharge speed, and low cost" was ranked as most important. The others include "a new type of Li-battery with low cost, long life cycle, high energy density, good safety, and easy recycling", "major breakthroughs in silicon battery material preparation and device efficiency", and "realization of flexible DC transmission systems with voltage levels of ±500 kV and above". Additional ones include "the deep integration and coordinated operation of renewable energy and fossil energy", "an ultra-supercritical steam generator set that uses 750oC steam and has a thermal efficiency of more than 50%". Further topics include "all solid-state

Li-batteries with an energy density of 600 Wh/kg and more than 10,000 cycles", "vehicle fuel cells with 100 kW full power and lifespan of more than 5,000 hours". The final topics were "a wind turbine design system suitable for our country's environment and climate characteristics" and "large-capacity solar energy storage systems" (Table 3).

Table 3 Top 10 technology topics for promoting economic growth

Technology topics	Sub-fields	Forecasted time of realization /year	Realization possibility index	Leading country		Constraints	
				1st	2nd	1st	2nd
Large-scale energy storage batteries characterized with a life cycle of more than 10,000 times, fast charge/discharge speed, and low cost will be widely used	Energy conservation and storage	2025	0.23	Japan	US	R&D investment	Infrastructure
A new type of Li-battery with low cost, long life cycle, high energy density, good safety, and easy recycling will be developed	Energy conservation and storage	2026	0.23	Japan	US	R&D investment	Infrastructure
Major breakthroughs in silicon solar cell material preparation and device efficiency will be made	Solar energy	2024	0.32	EU	US	R&D investment	Regulations, policies and standards
Flexible DC transmission systems with voltage levels of ±500 kV and above will be put into practical use	New power	2022	0.24	EU	US	R&D investment	Infrastructure
The deep integration and coordinated operation of renewable energy and fossil energy will be realized	New energy system	2026	0.20	EU	US	Regulations, policies and standards	R&D investment
An ultra-supercritical steam generator set that uses 750°C steam and has a thermal efficiency of more than 50% will be developed	Fossil energy	2028	0.15	EU	US	R&D investment	Infrastructure
All solid-state Li-batteries with an energy density of 600 Wh/kg and cycle times exceeding 10,000 will be used on a large scale	Energy conservation and storage	2028	0.14	Japan	US	R&D investment	Human resources
Vehicle fuel cells with 100 kW full power and lifespan of more than 5,000 hours will be put into practical use	Hydrogen energy and fuel cell	2026	0.24	Japan	US	R&D investment	Infrastructure
A wind turbine design system suitable for our country's environment and climate characteristics will be established and related equipment will be developed	Wind energy	2024	0.38	EU	US	R&D investment	Infrastructure
Large-capacity solar energy storage system will be actually applied practical application	Solar energy	2024	0.19	US	EU	R&D investment	Regulations, policies and standards

In terms of the distribution of sub-fields, three of the above ten technology topics belong to the sub-field of "energy conservation and storage", and two topics belong to the sub-field of "solar energy". Sub-fields such as "new power", "new energy system", "fossil energy", "hydrogen energy and fuel cell", and "wind energy" each include one technology topic. The results show that technology topics of "energy conservation and storage" are the most important for promoting economic growth, followed by other technology topics of" solar energy".

In terms of the forecasted time of realization, five of the above ten technology topics are expected to be realized in the mid-term (2020–2025), and five technology topics are expected to be realized in the mid-to long-term (2025–2030).

In terms of the realization possibility, "a wind turbine design system suitable for our country's environment and climate characteristics" is the most likely to be realized. Whereas, "all solid-state Li-batteries with an energy density of 600 Wh/kg and cycles exceeding 10,000" is the least likely to be realized.

In terms of the constraints, among the above ten technology topics, the primary constraint faced by nine technology topics is "R&D investment", and the primary constraint on "the deep integration and coordinated operation of renewable energy and fossil energy will be realized" is "regulations, policies and standards". The secondary constraint of six technology topics is "infrastructure".

In terms of the current leading countries with respect to these technology topics, the EU has five topics ranking first in the world. The US has one topic ranking first and nine topics ranking second. Japan has four topics ranking first.

4.2. Top 10 technology topics for improving quality of life

The top 10 technology topics based on the importance to improving quality of life were selected. Among them, "large-scale energy storage batteries characterized with a life cycle of more than 10,000 times, fast charge/discharge speed, and low cost" ranks first. Others include "a new type of Li-battery with low cost, long life cycle, high energy density, good safety, and easy recycling", "all solid-state Li-batteries with an energy density of 600 Wh/kg and cycle times exceeding 10,000", "LED lamps with an overall efficiency up to 250 lm/W", and "vehicle fuel cells with 100 kW full power and lifespan of more than 5,000 hours". The remaining topics are, "major breakthroughs in silicon solar cell material preparation and device efficiency", "regional energy systems based on renewable energy", "distributed micro-energy networks", "thermochromic smart energy-saving glass", and "high-efficiency civil air-conditioning technology with cooling energy efficiency COP>10 and heat pump energy efficiency COP>6" (Table 4).

In terms of the distribution of sub-fields, five of the ten technology topics belong to the sub-field of "energy conservation and storage", two topics belong to the sub-field of "solar energy", two topics belong to the sub-field of "new energy system", and one topic belongs to the sub-field of "hydrogen energy and fuel cell". The results show that the technology topics of "energy conservation and storage" are the most important for improving quality of life, along with other technology topics of "solar energy", "new energy system", and "hydrogen energy and fuel cell".

In terms of the forecasted time of realization, six topics from above ten technology topics are expected to be realized in the near-to mid-term (2020–2025), and four topics are expected to be realized in the mid-to long-term (2025–2030).

In terms of the realization possibility, "major breakthroughs in silicon solar cell material preparation and device efficiency" is most likely to be realized. "All solid-state Li-batteries with an energy density of 600 Wh/kg and cycle times exceeding 10,000" is the least likely to be realized.

In terms of the constraints, the primary constraint for nine technology topics is "R&D investment"

Table 4 Top 10 technology topics for improving quality of life

Technology topics	Sub-fields	Forecasted time of realization / year	Realization possibility index	Leading country		Constraints	
				1st	2nd	1st	2nd
Large-scale energy storage batteries characterized with a life cycle of more than 10,000 times, fast charge/discharge speed, and low cost will be widely used	Energy conservation and storage	2025	0.23	Japan	US	Investment in R&D	Infrastructure
A new type of Li-battery with low cost, long life cycle, high energy density, good safety, and easy recycling will be developed	Energy conservation and storage	2026	0.23	Japan	US	Investment in R&D	Infrastructure
All solid-state Li-batteries with an energy density of 600 Wh/kg and cycle times exceeding 10,000 will be used on a large scale	Energy conservation and storage	2028	0.14	Japan	US	Investment in R&D	Human resources
The LED lamps with an overall efficiency up to 250 lm/W will be developed	Energy conservation and storage	2024	0.26	US	Japan	Investment in R&D	Infrastructure
Vehicle fuel cells with 100 kW full power and lifespan of more than 5,000 hours will be put into practical use	Hydrogen energy and fuel cell	2026	0.24	Japan	US	Investment in R&D	Infrastructure
Major breakthroughs in silicon solar cell material preparation and device efficiency will be made	Solar energy	2024	0.32	EU	US	Investment in R&D	Regulations, policies and standards
Regional energy systems based on renewable energy will get practical applications	New energy system	2025	0.20	EU	US	Investment in R&D	Regulations, policies and standards
Distributed micro-energy network will be widely used	New energy system	2025	0.22	EU	US	Regulations, policies and standards	Investment in R&D
Thermochromic smart energy-saving glass will obtain practical application and large-scale promotion	Solar energy	2023	0.18	US	EU	Investment in R&D	Regulations, policies and standards
High-efficiency civil air-conditioning technology with cooling energy efficiency COP>10 and heat pump energy efficiency COP>6 will be developed	Energy conservation and storage	2027	0.21	Japan	US	Investment in R&D	Infrastructure

while the primary constraints for "distributed micro-energy grids" are "regulations, policies, and standards". The secondary constraint for five technology topics is "infrastructure", while that for another three technology topics includes "regulations, policies and standards". In addition, "human resources" and "R&D investment" are also important for realizing the ten technology topics.

In terms of the current leading countries, Japan ranks first worldwide in five of the above ten technology topics, the EU in three, and the US in two. In eight technology topics, the US ranks second.

4.3. Top 10 technology topics for safeguarding national security

The top 10 technology topics based on the importance to safeguarding national security were selected. Among them, "nuclear fuel reprocessing technology" is the most important, with the others, in order, being "compact and integrated small pressurized water reactors", "fusion reactor with demonstrative application results", "commercial application of sodium-cooled fast reactor power station", "large-scale energy storage batteries characterized with a life cycle of more than 10,000 times, fast charge/discharge speed, and low cost", "gas turbine combined technology with a comprehensive thermal efficiency of more than 60%", "commercial application of exploitation of natural gas hydrate in safe and efficient manner", "low-rank coal classification liquefaction and Fischer-Tropsch synthesis coupling technology", "hundred-megawatt accelerator-driving advanced nuclear energy systems", and "all solid-state Li-batteries with an energy density of 600 Wh/kg and cycles exceeding 10,000"(Table 5).

In terms of the distribution of sub-fields, five of the above ten technology topics belong to "nuclear energy and safety", three topics belong to "energy conservation and storage", and two topics belong to the "fossil energy". The results show that the technology topics of "nuclear energy and safety" are essential to safeguarding national security, followed by other technology topics of "energy conservation and storage" and "fossil energy".

In terms of the forecasted time of realization, among the above ten technology topics, three topics are expected to be realized in the near-to mid-term (2020–2025), six are expected to be realized in the mid-to long-term (2025–2030), and only one topic is expected to be realized in the long term (after 2030).

In terms of the realization possibility, most of these technology topics have lower chances because they emphasize the basic, forward-looking, and strategic nature. Among them, "large-scale energy storage batteries characterized with a life cycle of more than 10,000 times, fast charge/discharge speed, and low cost" are most likely to be realized, and "fusion reactor with demonstrative application results" is the least likely to be realized.

In terms of the constraints, the primary constraint for the above ten technology topics is "R&D investment". The secondary constraint for six technology topics is "infrastructure", while for three technology topics it is "regulations, policies and standards", with only "all-solid-state Li-batteries with an energy density of 600 Wh/kg and cycle times exceeding 10,000 will be used on a large scale" facing "human resources" as the secondary constraint. It can be seen that, "R&D investment", "infrastructure" and "regulations, policies and standards" are important to realize the above ten technology topics which cannot be ignored.

In terms of the current leading countries, among the above ten technology topics, the US has four topics ranking first and five topics ranking second. The EU has three topics ranking first and three topics ranking second, and Japan has one topic ranking first and two topics ranking second. Russia excels in one topic ranking first and one topic ranking second.

Table 5 Top 10 technology topics for safeguarding national security

Technology topics	Sub-fields	Forecasted time of realization /year	Realization possibility index	Leading country		Constraints	
				1st	2nd	1st	2nd
Nuclear fuel reprocessing technology will get practical application	Nuclear energy and safety	2029	0.22	EU	US	Investment in R&D	Infrastructure
Compact and integrated small pressurized water reactors will get practical application	Nuclear energy and safety	2025	0.23	US	Russia	Investment in R&D	Regulations, policies and standards
Fusion reactor with demonstrative application results will be achieved	Nuclear energy and safety	2032	0.07	EU	US	Investment in R&D	Infrastructure
Commercial application of sodium-cooled fast reactor power station will be realized	Nuclear energy and safety	2029	0.21	Russia	EU	Investment in R&D	Regulations, policies and standards
Large-scale energy storage batteries characterized with a life cycle of more than 10,000 times, fast charge/discharge speed, and low cost will be widely used	Energy conservation and storage	2025	0.23	Japan	US	Investment in R&D	Infrastructure
Gas turbine combined technology with a comprehensive thermal efficiency of more than 60% will be developed	Energy conservation and storage	2027	0.18	US	EU	Investment in R&D	Infrastructure
Commercial application of exploitation of natural gas hydrate in safe and efficient manner will be realized	Fossil energy	2028	0.14	US	Japan	Investment in R&D	Infrastructure
Low-rank coal classification liquefaction and Fischer-Tropsch synthesis coupling technology will be developed	Fossil energy	2024	0.19	US	EU	Investment in R&D	Regulations, policies and standards
Hundred-megawatt accelerator-driving advanced nuclear energy systems will get practical applications	Nuclear energy and safety	2030	0.13	EU	US	Investment in R&D	Infrastructure
All solid-state Li-batteries with an energy density of 600 Wh/kg and cycle times exceeding 10,000 will be used on a large scale	Energy conservation and storage	2028	0.14	Japan	US	Investment in R&D	Human resources

4.4. Top 10 technology topics for China's future development

Based on the comprehensive importance index of three factors, the top 10 important technology topics were selected which include "large-scale energy storage batteries characterized with a life cycle of more than 10,000 times, fast charge/discharge speed, and low cost", "a new type of Li-battery with low cost, long life cycle, high energy density, good safety, and easy recycling", "all solid- state Li-batteries with an energy density of 600 Wh/kg and cycle times exceeding 10,000", "fusion reactor with demonstrative application results", "compact and integrated small pressurized water reactors", "the deep integration and coordinated operation of renewable energy and fossil energy", "vehicle fuel cells with 100 kW full power and lifespan of more than 5,000 hours", "major breakthroughs in silicon solar cell material preparation and device efficiency", "regional renewable energy-based energy systems", and "nuclear fuel reprocessing technology" (Table 6).

In terms of the distribution of sub-fields, three of the above ten technology topics belong to the sub-field of "energy conservation and storage", three topics belong to the "nuclear energy and safety", two topics belong to "new energy system", one topic belongs to "hydrogen energy and fuel cell", and one topic belongs to "solar energy". The results show that the technology topics of "energy conservation and storage" are essential to safeguard national security, followed by other technology topics of "nuclear energy and safety" and" new energy system". In terms of the forecasted time of realization, four technology topics are expected to be realized in the near-to mid-term (2020–2025), five technology topics are expected to be realized in the mid-to long-term (2025–2030), and only one topic is expected to be realized in the long run (after 2030). In terms of the realization possibility, the technology topic of "major breakthroughs in silicon solar cell material preparation and device efficiency" is the most likely to be achieved, and the "fusion reactor with demonstrative application results" is least likely to be achieved.

In terms of their constraints, among the above ten technology topics, the primary constraint for nine technology topics is "R&D investment", while the remaining one is constrained by "regulations, policies and standards". The secondary constraint is "infrastructure" for five technology topics, "regulations, policies and standards" for three technology topics, "human resources" for two technology topics and "R&D investment" for one topic. It can be observed that all of "R&D investment", "infrastructure", "regulations, policies and standards", and "human resources" are important to realizing the above ten technology topics.

In terms of the current leading countries, among the above-mentioned ten technology topics, the EU has five topics ranking first in the world while four topics are led by Japan and one by the US. The US has nine topics ranking second worldwide, and Russia has one, which is "compact and integrated small pressurized water reactors".

5. Key Factors to the Technology Topics

5.1. Overview of technology research and development level

The results from the Delphi survey show that the R&D level of the most advanced energy technology in China are close to the international level. A total of 55 technology topics are "close to the international level" with the experts' recognition rate above 50%, while 13 technology topics are at the level of lagging behind the international (Fig. 5). Only three technology topics, of which the experts' recognition rate is more than 50%, are at the international advanced level. The experts' recognition of "key coal-to-propylene technology", "modular high-temperature gas cooled reactor ", and "the flexible DC transmission system with voltage level of ± 500 kV and above" is 57.24%, 55.94% and 60.78%, respectively.

Table 6 Top 10 technology topics for China's future development

Technology topics	Sub-fields	Forecasted time of realization /year	Realization possibility index	Leading country		Constraints	
				1st	2nd	1st	2nd
Nuclear fuel reprocessing technology will get practical application	Nuclear energy and safety	2029	0.22	EU	US	R&D investment	Infrastructure
Compact and integrated small pressurized water reactors will get practical application	Nuclear energy and safety	2025	0.23	US	Russia	R&D investment	Regulations, policies and standards
Fusion reactor with demonstrative application results will be achieved	Nuclear energy and safety	2032	0.07	EU	US	R&D investment	Infrastructure
Commercial application of sodium-cooled fast reactor power station will be realized	Nuclear energy and safety	2029	0.21	Russia	EU	R&D investment	Regulations, policies and standards
Large-scale energy storage batteries characterized with a life cycle of more than 10,000 times, fast charge/discharge speed, and low cost will be widely used	Energy conservation and storage	2025	0.23	Japan	US	R&D investment	Infrastructure
Gas turbine combined technology with a comprehensive thermal efficiency of more than 60% will be developed	Energy conservation and storage	2027	0.18	US	EU	R&D investment	Infrastructure
Commercial application of exploitation of natural gas hydrate in safe and efficient will be realized	Fossil energy	2028	0.14	US	Japan	R&D investment	Infrastructure
Low-rank coal classification liquefaction and Fischer-Tropsch synthesis coupling technology will be developed	Fossil energy	2024	0.19	US	EU	R&D investment	Regulations, policies and standards
Hundred-megawatt accelerator-driving advanced nuclear energy systems will get practical applications	Nuclear energy and safety	2030	0.13	EU	US	R&D investment	Infrastructure
All solid-state Li-batteries with an energy density of 600 Wh/ kg and cycle times exceeding 10,000 will be used on a large scale	Energy conservation and storage	2028	0.14	Japan	US	R&D investment	Human resources

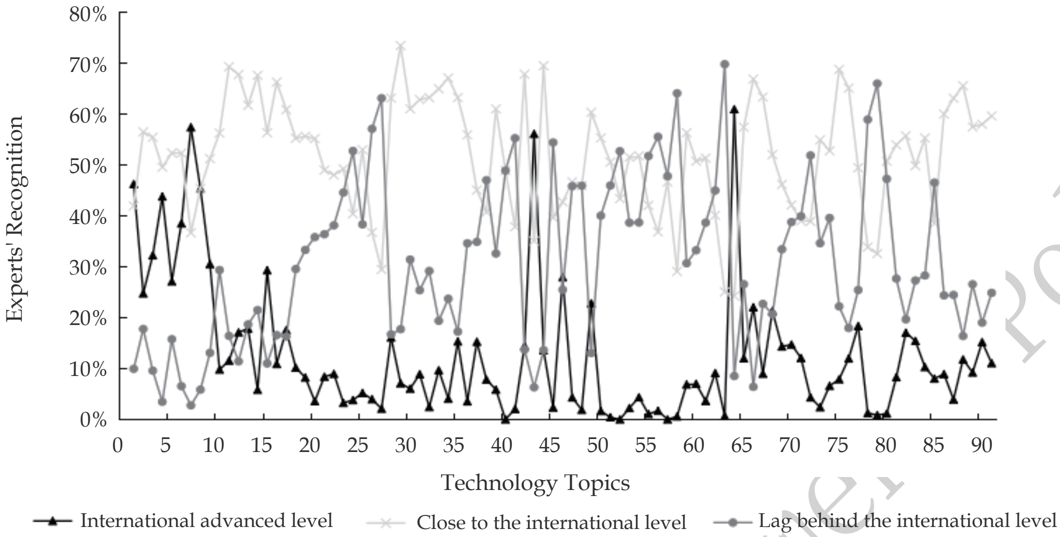

Fig. 5 Distribution map of experts' recognition on R&D level

The R&D level of "key coal-to-propylene technology" is up to 0.78, ranking first among 91 technology topics in advanced energy fields, while the R&D level of "megawatt-level solid oxide fuel cell and gas turbine combined cycle power generation system" is the lowest with 0.14. There are 5 technology topics for which the R&D level is greater or equal to 0.7, and 86 the R&D level of technology topics are in the range of 0.10-0.70.

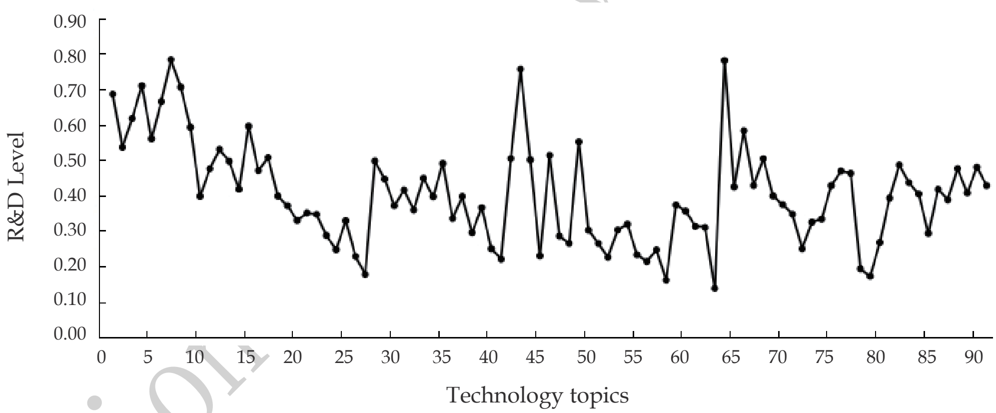

Fig. 6 China's R&D level of technology topics

5.2. Overview of technology topics of leading countries

The Delphi survey results show that the US is in the leading position in the advanced energy fields, with 41 technology topics ranking first worldwide and 47 technology topics ranking second (Fig. 7). The EU ranks second with 34 technology topics ranking first and 33 technology topics ranking second. Japan follows the US and the EU with 15 technology topics ranking first and 10 technology topics ranking second.

5.3. Overview of the technology topics' realization possibility

According to the index of technology topics' realization possibility, the average value of 91 technology topics on the index is 0.21. The realization possibility index of "a typical wind energy resource database

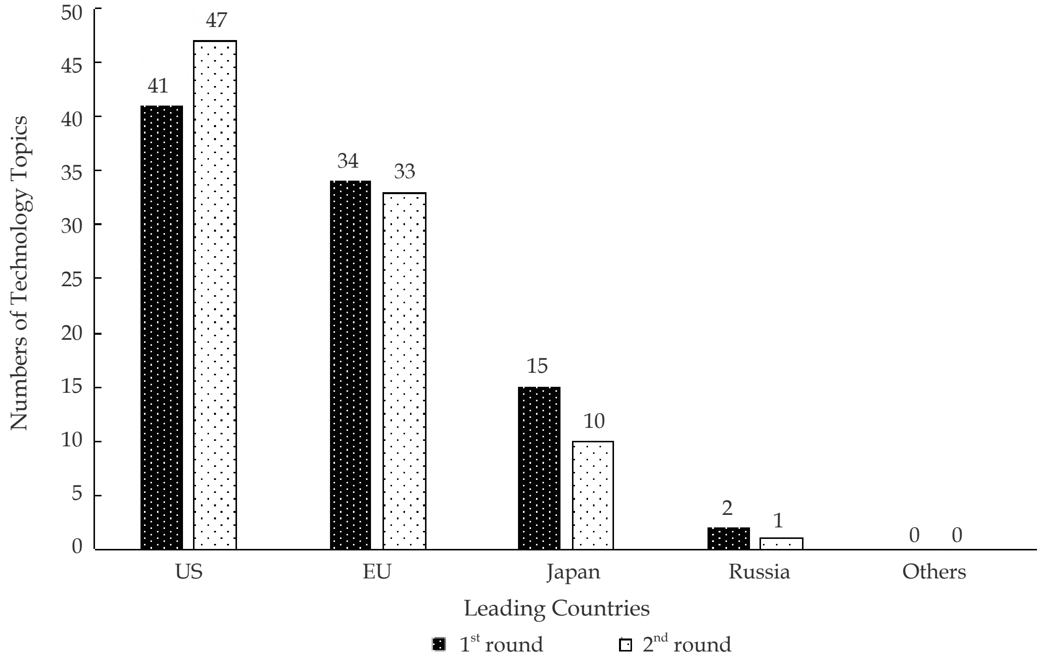

Fig. 7 Distribution map on technology topics of leading countries

and shared service system under different regions and terrains in China" is highest at 0.54, while "fusion reactor with demonstrative application results" has the lowest index value with 0.07. The technology topics with an index between 0.1 and 0.5 account for 94.5% (Fig. 8).

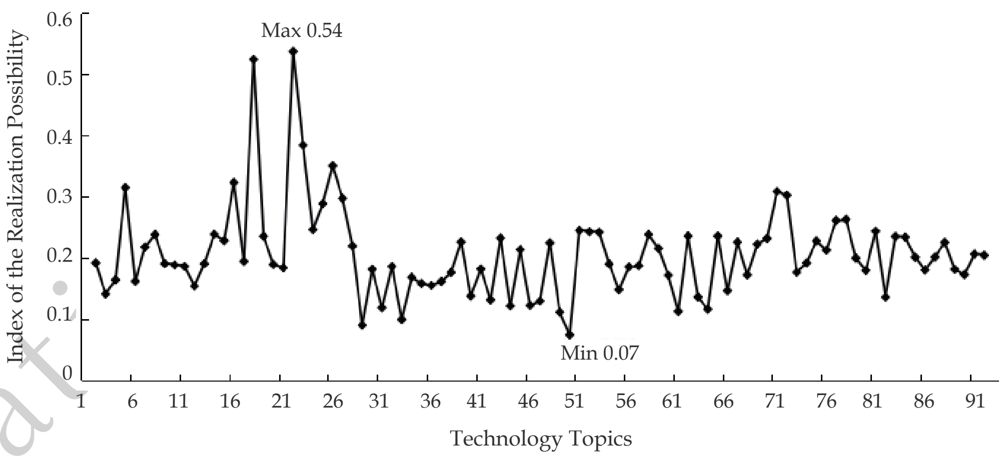

Fig. 8 Realization possibility index of technology topics

5.4. Overview of constraints for technology development

The primary constraint for 73 technology topics for development is "R&D investment", while for the other 18 technology topics the primary constraint is "regulations, policies, and standards". The secondary constraint of 17 technology topics and 35 technology topics for development are "R&D investment" and "infrastructure", respectively. There are 4 technology topics taking "human resources" as the secondary constraint and 35 technology topics taking "regulations, policies and standards" as the secondary constraint (Fig. 9).

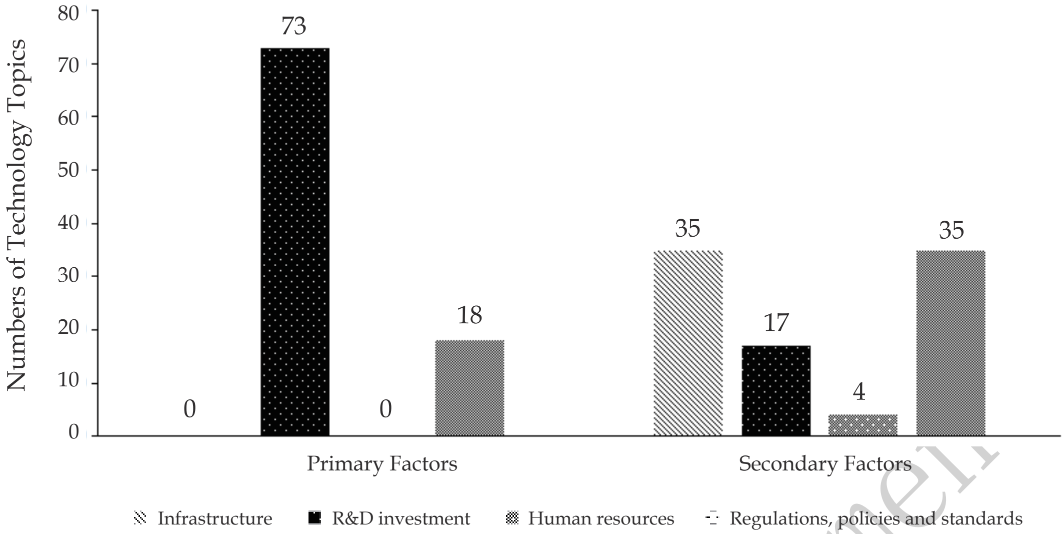

Fig. 9 Distribution of constraints of technology topics

6. Discussion

To improve the Delphi method, this paper integrates vision analysis into the survey. In previous practice, there have been many attempts to integrate the two methods. For example, in the Delphi survey organized by CID-CAS in 2003, vision analysis was applied to the research S&T needs towards the next 20 years in China. And in the 11th technology foresight, Japan positively constructed the social vision to guide the Delphi survey (NISTEP, 2019). But vision analysis changes with development goals which will result in different ways of integration. This study proposed a specific Delphi process combined with vision analysis for the technology development of advanced energy fields. First, a vision analysis was conducted to refine the development trends of advanced energy in the future. Second, two rounds of large-scale Delphi surveys were organized to select the key technology topics. Then, the key technologies list, including 91 technology topics, were analyzed to identify the trends of the advanced energy fields.

According to the Delphi survey results, the US and the EU have a significant advantage when it comes to technology development in advanced energy fields, Japan and Russia are in the leading position in some fields, while China is still in the developing stage. The majority of R&D in China is mainly concentrated on the traditional fields like "fossil energy", and China lags behind in the development of advanced energy fields such as "energy conservation and storage", "hydrogen energy and fuel cell", and "new energy system".

The Delphi survey results show that insufficient R&D investment has become the primary factor restricting the development of China's advanced energy technology. Factors such as human resources, infrastructure, regulations, policies and standards are also important for improving energy technology development. According to the results above, the government should continue to increase the investment in major national S&T projects, key R&D plans and infrastructure construction, and actively expand financing sources. Moreover, China needs to improve the regulations, policies, and standards systems in the advanced energy fields and create a healthy innovation environment to accelerate technology development. Especially for the development of "new energy system", "nuclear energy and safety", and "solar energy", new regulations, policies and standards are urgently needed to bridge the gap between China and other advanced countries.

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