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PREREQUISITES AND KEY MEASURES FOR THE IMPLEMENTATION OF SUSTAINABLE ENERGY INNOVATIONS IN CHINA[1]

ПЕРЕДУМОВИ ТА КЛЮЧОВІ ЗАХОДИ ДЛЯ ВПРОВАДЖЕННЯ СТАЛИХ ЕНЕРГЕТИЧНИХ ІННОВАЦІЙ В КИТАЇ

The article is devoted to the study of prerequisites, directions and measures to ensure China's energy transition. The purpose of the article is to study China's experience in ensuring the energy transition and identify key directions and policy initiatives for the implementation and development of sustainable energy innovations. It has been established that China is the world's largest energy consumer and in recent years has been characterized by continuous economic growth and acceleration of industrialization, development of the energy industry. The energy structure was analyzed and the dominance of coal production and consumption was determined – the first place in the world. The activity of green energy development has been revealed, but the share of clean energy sources in total energy consumption is still low. It was determined that the implementation of the principle of sustainable development and energy innovation is a priority for the further development of the Chinese economy. The key directions for ensuring the energy transition have been identified: diversified energy supply; green and low-carbon development; technological transformation and development. The dynamics of China's energy imports from 2013 to 2022 are analyzed. It was established that China ranked 17th in the Energy Transition Index in 2023, and for the first time entered the TOP-20 countries according to this ranking, which indicates the growing potential of China's energy transition. It analyzed the reasons for reducing energy consumption by 10,000 yuan of GDP from 2013 to 2022. In particular, it is notable that individual companies have reduced energy consumption and environmental pollution, promoting energy conservation, emission reduction and circular economy. It found that, along with the problem of high industrial emissions, China has become a leader in the adoption of clean energy technologies with investments in clean energy technologies exceeding US$650 billion per year. Key political initiatives contributing to the reduction of carbon dioxide emissions and the introduction of energy innovations are analyzed.

Key words: energy innovations, sustainable energy, energy transition.

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Стаття присвячена дослідженню передумов, напрямів та заходів для забезпечення енергетичного переходу Китаю. Метою статті є дослідження досвіду Китаю у забезпеченні енергетичного переходу та визначення ключових напрямків та політичних ініціатив для впровадження та розвитку сталих енергетичних інновацій. Встановлено, що Китай є найбільшим у світі споживачем енергії та останні роки, і характеризується безперервним економічним зростанням та прискоренням індустріалізації, розвитком енергетичної промисловості. Проаналізовано енергетичну структуру Китаю і визначено домінування виробництва та споживання вугілля – перше місце у світі. Виявлено активність розвитку зеленої енергетики, проте частка чистих джерел енергії в загальному споживанні енергії залишається порівняно низькою. Визначено, що впровадження принципів сталого розвитку та розвиток енергетичних інновацій є пріоритетними для стратегічного розвитку економіки Китаю. Визначено ключові напрями для забезпечення енергетичного переходу: диверсифіковане енергопостачання; зелений та низьковуглецевий розвиток; технологічна трансформація та розвиток. Проаналізовано динаміку енергетичного імпорту Китаю з 2013 по 2022 роки. Встановлено, що Китай у 2023 році зайняв 17 місце в рейтингу Energy Transition Index, і вперше увійшов у ТОП-20 країн за цим рейтингом, що свідчить про зростання потенціалу енергетичного переходу Китаю. Проаналізовано причини скорочення споживання енергії на 10 000 юанів ВВП з 2013 по 2022 рр. Зокрема, визначено, що окремі компанії зменшили споживання енергії та рівень забруднення навколишнього середовища, сприяючи енергозбереженню, скороченню викидів і циркулярній економіці. Визначено, що поряд з проблемою високого рівня викидів промисловості в атмосферу, Китай став лідером у впровадженні технологій чистої енергії завдяки інвестиціям у ці технології, що перевищують 650 млрд дол США на рік. Проаналізовано ключові політичні ініціативи, що сприяють скороченню викидів вуглекислого газу та впровадженню енергетичних інновацій. До пріоритетних інвестицій в ключові енергетичні інновації віднесено уловлювання вуглецю, водень, декарбонізація промисловості, інтелектуальні мережі та альтернативне автомобільне паливо.

Ключові слова: енергетичні інновації, стала енергетика, енергетичний перехід.

Problem statement. China, as the world's largest energy consumer, faces challenges due to its heavy reliance on coal and rising energy demand. To address this, sustainable energy innovations are imperative. Three main directions guide this transformation: diversified energy supply, green and low-carbon development, and technological advancement. Despite being a major emitter, China progresses in energy transition, ranking 17th in the 2023 according The Global Energy Transition Index, which is published by the World Economic Forum annually to measure countries' global change to the renewable energy transition. China's policies, outlined in its Five-Year Plans, prioritize clean energy innovation and R&D spending. Targets include carbon neutrality by 2060, increased clean energy capacity, and advancements in key technologies like carbon capture and hydrogen. That is why it is appropriate to consider China's experience in ensuring the energy transition and implementing energy innovations, which determines the relevance of this study.

Analysis of recent studies and publications. The scientific works of many modern scientists are devoted to issues of sustainable development and energy innovations. In particular, the article [1] defines main directions of promoting clean energy innovation. The study [2] presents an analysis of the impact of energy innovations on the sustainable development of 26 countries, including the EU, USA, China, and Ukraine. The role of energy innovations, digital technological transformation, and environmental performance in enhancing the sustainable economic development of the EU countries defined in the study [3]. A number of scientists are investigating the issue of sustainable energy development in in clusters of countries. However, the experience of individual countries, in particular, China, needs additional study, which will allow to substantiate effective measures for the development of sustainable energy innovations.

The purpose of the article is to investigate China's experience in ensuring the energy transition and identify key directions and policy initiatives for the implementation and development of sustainable energy innovations.

Presentation of the main material. China is the world's largest energy consumer, and its energy industry occupies an important position in the national economy. In recent years, with the continued growth of China's economy and the acceleration of industrialization, energy demand has continued to rise, driving the rapid development of China's energy industry. China's energy structure is dominated by coal, with coal production and consumption ranking first in the world. At the same time, China is also actively developing clean energy, such as wind energy, solar energy and hydropower, but the proportion of these clean energy sources in total energy consumption is still low (Figure 1).

In the last decade, China accounted for more than 50% of global energy demand growth and 85% of the rise in energy sector CO2 emissions. As far back as 2007, China’s then Premier Hujintao warned that "the biggest problem with China's

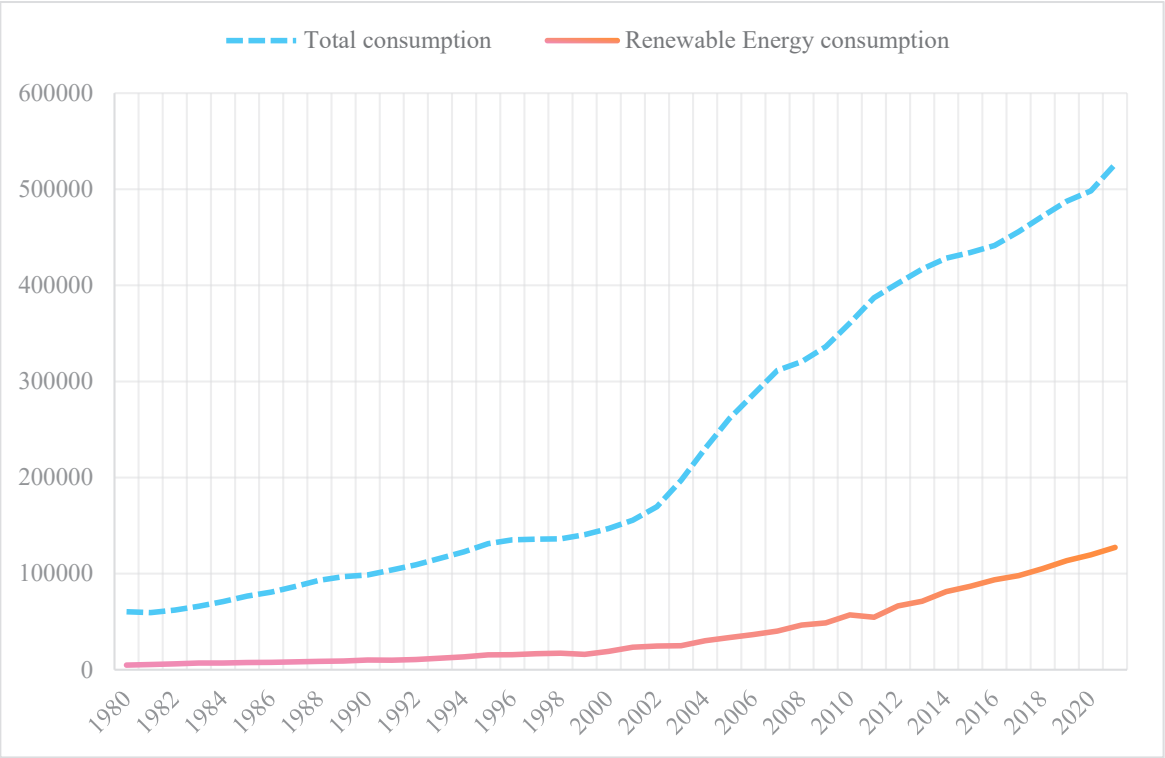

Figure 1. China's total energy consumption, 10000 tce

Source: [4]

economy is that growth is unstable, unbalanced, uncoordinated and unsustainable" [5]. In such conditions, changes based on the principles of sustainable development and the implementation of innovative solutions become a mandatory condition for the further development of China's energy industry. The abovementioned transformations can be distributed into such directions:

– diversified energy supply;
– green and low-carbon development;
– technological transformation and development.

1. Diversified energy supply

With the adjustment of China's energy structure and the increase in demand for clean energy, the restructuring of Chinese energy companies will pay more attention to diversified energy supply. This means that on the basis of traditional energy, there will be increased investments in new and renewable energy, optimize the energy structure, and improve energy utilization efficiency to meet the needs of sustainable development.

The Chinese government has taken a series of measures to promote the development of clean energy. The government has implemented subsidy policies for new energy sources such as wind power, solar power and hydropower to encourage companies to increase investment in clean energy. In addition, the government also encourages enterprises to increase the transformation and upgrading of traditional energy sources and improve energy utilization efficiency through tax incentives and credit policies.

In the past ten years, the proportion of different types of energy has shown different trends (Figure 2). The proportion of raw coal production continues to decline, falling by 8.4% in 2021 compared with 2013. However, due to the guarantee of supply, this trend will temporarily reverse in 2022, and the proportion in 2022 will increase by 2.2% compared with 2021.

The proportion of total crude oil production continues to decline, and will be 2.1 percentage points lower in 2022 than in 2013. The proportion of natural gas production has declined slightly year-on-year. Overall, it will increase by 1.6 percentage points in 2022 compared with 2013. The proportion of primary power production such as hydropower, nuclear power, and wind power has narrowed slightly, but the overall trend is expanding, with an increase of 6.8 percentage points in 2022 compared with 2013. In 2022, China's non-fossil energy power generation installed capacity will historically exceed 1.2 billion kilowatts, reaching 1.27 billion kilowatts, a year-on-year increase of 13.8%, accounting for 49.6% of the total installed capacity, an increase of 2.6 percentage points from the previous year, continuing the trend of green and low-carbon transformation.

The rate of economic growth of China over the past ten years has shown an extraordinary speed,

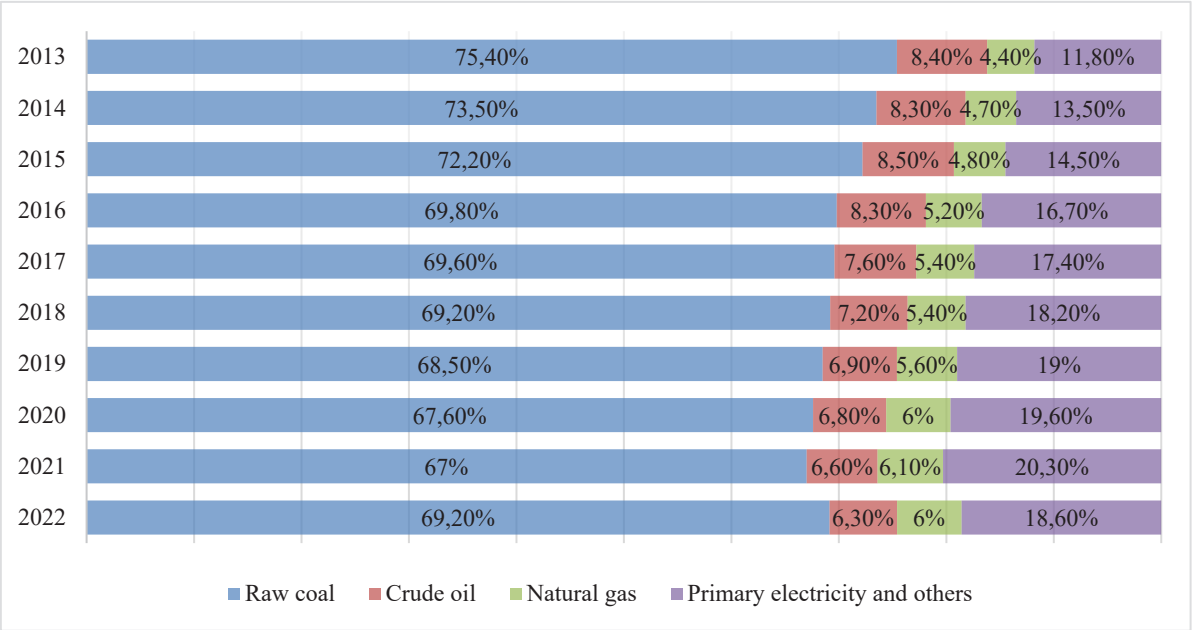

Figure 2. Energy production structure 2013–2022

Source: [4]

and the inability to independently meet the growing needs for energy resources has led to a constant increase in the volume of their imports (Table 1).

In 2022, China's imports of energy products will decline to varying degrees. In 2022, China will import 508.28 million tons of crude oil, a year-on-year decrease of 0.9%; it will import 109.25 million tons of natural gas, a year-on-year decrease of 9.9%. Imported coal was 293.2 million tons, a year-on-year decrease of 9.2%.

In 2022, China's crude oil imports will be 508.28 million tons, a year-on-year decrease of 0.9%, and the amount will be 2.435 billion yuan, a year-on-year increase of 45.9%. Refined oil imports were 26.45 million tons, a year-on-year decrease of 2.5%, and the amount was 130.9 billion yuan, a year-on-year increase of 21.2%. Natural gas imports were 109.25 million tons (approximately 150.8 billion cubic meters), a year-on-year decrease of 9.9%, and the amount was 468.3 billion yuan, a year-on-year increase of 30.3%. Imported coal and lignite amounted to 293.2 million tons, a year-on-year decrease of 9.2%, and the amount was 285.5 billion yuan, a year-on-year increase of 22.2% [4].

2. Green and low-carbon development

As global climate change intensifies and environmental awareness increases, Chinese energy companies need to pay more attention to green and low-carbon development in their activities. Increasing investment in clean energy and low-carbon technologies, promoting energy conservation, emission reduction and circular economy can reduce energy consumption and carbon emissions and achieve sustainable development goals.

Table 1

China's energy import situation from 2013 to 2022

	Coal and lignite (10,000 tons)	Crude oil (10,000 tons)	Natural gas (billion cubic meters)	Electricity (billion kilowatt hours)
2013	32702	28174	525	75
2014	29122	30837	591	68
2015	20406	33548	611	62
2016	25555	38101	746	62
2017	27092	41946	946	64
2018	28210	46189	1246	57
2019	29977	50568	1332	49
2020	30361	54201	1397	48
2021	32294	51292	1675	-
2022	29320	50828	1508	-

Source: [6]

Ranked 17th on the 2023 ETI (Energy Transition Index), China joins the top 20 countries for the first time. This progress comes despite being the world's largest energy producer, consumer, and GHG emitter (one-third of global emissions). Notably, China has shown consistent improvement in system performance and transition readiness over the past decade [7].

In 2022, new progress was made in energy conservation and efficiency improvement under the constraints of the "double carbon" goal. Under many unfavorable conditions such as constant challenges in the external energy environment and

Figure 3. Energy consumption reduction rate per 10,000 yuan of GDP from 2013 to 2022

Source: [4]

recurring domestic epidemics, China has insisted on increasing energy conservation and emission reduction. In 2022, national energy consumption per 10,000 yuan of GDP decreased by 0.1% compared with the previous year (Figure 3) [8].

At present, China's thermal power plants' ultra-low emission, large-scale waste incineration, and coal-fired flue gas treatment technology and equipment have reached the world's leading level, and the world's largest ultra-low-emission thermal power plant group has been built. It is reported that since the "13th Five-Year Plan", thanks to technological progress, China's coal-fired power plants have been transformed into ultra-low emission 950 million kilowatts.

In terms of green and low-carbon development, some Chinese energy companies have made some progress. Some companies have reduced carbon emissions and improved energy efficiency by adopting clean energy and low-carbon technologies. In 2022, China's renewable energy maintained a high utilization rate. The water energy utilization rate in the country's main river basins was 98.7%, the average wind power utilization rate was 96.8%, and the average photovoltaic power generation utilization rate was 98.3%.

In addition, some companies also reduced energy consumption and environmental pollution by promoting energy conservation, emission reduction and circular economy.

In 2022, the comprehensive energy consumption per unit of calcium carbide of key energy-consuming industrial enterprises decreased by 1.6%, the comprehensive energy consumption per unit of synthetic ammonia decreased by 0.8%, the comprehensive energy consumption per ton of steel increased by 1.7%, the comprehensive energy consumption per unit of electrolytic aluminum decreased by 0.4%, and the comprehensive energy consumption per unit of thermal power generation decreased by 0.8%. Standard coal consumption dropped by 0.2%. Carbon dioxide emissions per 10,000 yuan of GDP nationwide fell by 0.8% (Figure 4) [4].

In the past decade, pollutant emissions have dropped significantly. The total amount of smoke and dust emissions dropped from 1.51 million tons in 2012 to 123,000 tons in 2021. The smoke and dust emissions per unit of thermal power generation dropped from 0.39 grams per kilowatt hour to 0.022 grams per kilowatt hour; the total sulfur dioxide emissions dropped from 2012 to 2012. 8.83 million tons dropped to 547,000 tons in 2021. Sulfur dioxide emissions per unit of thermal power generation dropped from 2.26 grams per kilowatt hour to 0.101 grams per kilowatt hour; total nitrogen oxide emissions dropped from 9.48 million tons in 2012 to 2021. From 862,000 tons per year, the nitrogen oxide emissions per unit of thermal power generation dropped from 2.4 grams per kilowatt hour to 0.152 grams per kilowatt hour [4].

China remains the largest emitter in the world in 2050, but it is the leader in deployment of several clean energy technologies on the back of average investment in clean energy technologies of well over USD 650 billion per year, and by 2050 it accounts for half of global solar PV capacity, 40% of wind capacity, one-third of all nuclear power

Figure 4. Decline in carbon dioxide emissions per 10,000 yuan of national GDP from 2017 to 2022

Source: [4]

Table 2

Key China's policy initiatives on the reduction of carbon dioxide emissions

Policy	Description
Updated Nationally Determined Contribution	– Aims to peak CO_2 emissions before 2030; carbon neutrality before 2060. – Lower CO_2 intensity of GDP by 60% by 2030 from 2005 levels. – Reach 1 200 GW of installed solar and wind capacity by 2030.
14th Five-year Plan for Energy	– Reduce CO_2 intensity of GDP by 18% by 2025 relative to 2020. – Reduce energy intensity of GDP by 13.5% by 2025 relative to 2020. – 20% non-fossil fuel share of energy mix by 2025, and 25% by 2030.
14th Five-year Plan for Renewables	– Targets 3 300 TWh of renewables electricity generation by 2025. – Over 50% of electricity consumption growth by 2025 met by renewables.
14th Five-year Plan for Buildings	– Efficiency retrofits for 350 million square metres (m^2) of existing buildings and 50 million m^2 of near-zero-energy buildings constructed by 2025. – Solar PV capacity of 50 GW by 2025 in new buildings. – Geothermal energy for more than 100 million m^2 of buildings by 2025.
Made in China 2025	– Supports innovation capability, digitalisation and greening manufacturing. – Raising domestic share of core components and materials to 70% by 2025.
New Energy Vehicle Industry Development Plan	– Promotes widespread adoption of new energy and clean energy vehicle sales, targeting 25% of new vehicle sales by 2025.
Carbon peaking and neutrality blueprint for urbanisation and rural development	– Carbon emissions from urban and rural construction peak before 2030. – Retrofits for public buildings in key cities to be collectively 20% more energy efficient by 2030. – Electricity accounts for 65% of energy demand in urban buildings by 2030.

Source: [9]

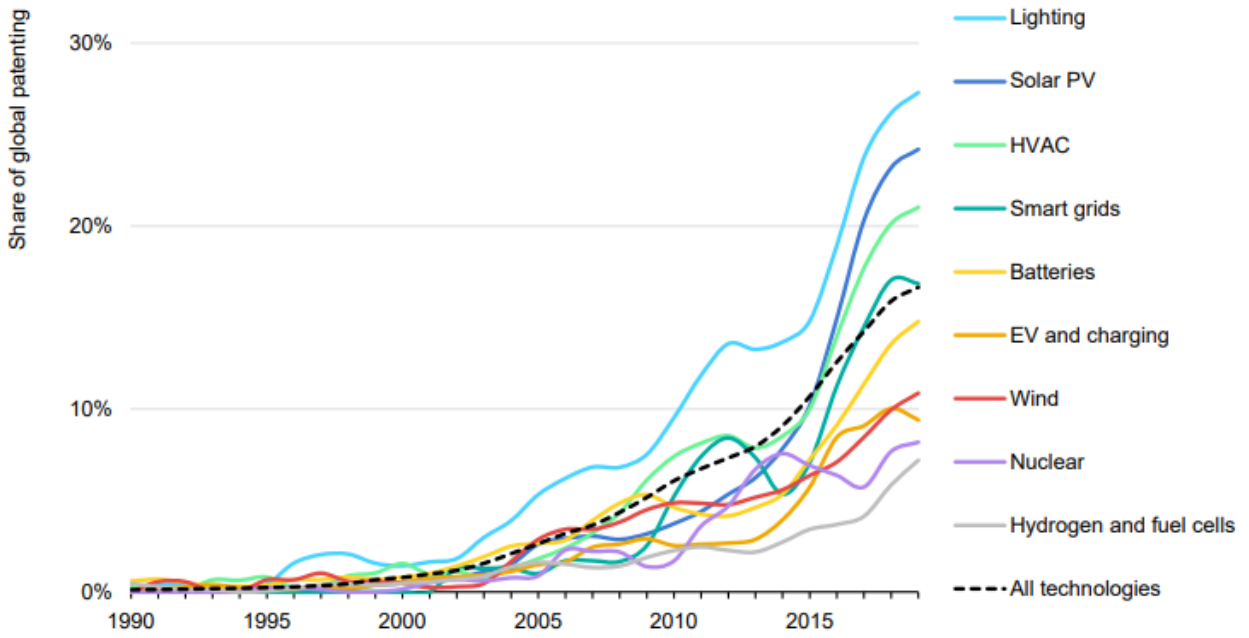

Figure 5. China's share of global patenting in selected low-carbon energy technology areas and for all technologies (1990–2019)

Source: [11]

capacity and 40% of the global electric car fleet [9]. The key China's policies on the reduction of carbon dioxide emissions represented in Table 2.

In the future, with the continuous improvement of environmental awareness and the intensification of global climate change, green and low-carbon development will become one of the important directions for the restructuring of Chinese energy companies.

3. Technological transformation and development

The technological transformation of the energy industry itself is based on the development and implementation of energy innovations. China dominates many aspects of the clean energy technology supply chain. In terms of technology manufacturing, it is currently the largest producer of solar photovoltaics, wind energy, batteries, heat pumps and hydrogen production electrolyzers, with plans to expand further. It also produces more aluminum and steel than any other country and is a world leader in the processing of cobalt, lithium, copper, graphite and rare earths.

The extraction of critical minerals is one of the few areas where it is not at the forefront of the cleantech supply chain. China's "14th Five-Year Plan" sets the development direction for the energy industry through 2025 and envisages continued expansion of clean energy. With annual average investment in clean energy technologies well over $650 billion, China remains a leader in deploying multiple clean energy technologies, accounting for half of global solar photovoltaic capacity, 40% of wind power capacity, and nuclear power generation capacity by 2050 one-third of the global electric vehicle fleet and 40% of the global electric vehicle fleet. In addition, China will become a leader in electrolytic hydrogen production and heat pump manufacturing [10].

Clean energy innovation saw strong growth from 1990 to 2019, with renewables claiming 29% of patents. Solar PV and wind led the charge, while batteries emerged as a Chinese strength (27%). Other sectors like EVs, lighting, and hydrogen fuel cells also saw significant activity (Figure 5) [11].

China's comprehensive FYPs and accompanying policies go beyond setting priorities and timelines. They offer a realistic, industry-driven approach to clean energy innovation while actively shaping a supportive environment for clean technologies and industries to flourish (table 3). This creates a clear investment path for businesses and fosters confidence in the sector's future.

Main proposals in the innovation sections of the 14th FYP or in complementary announcements concerning energy innovations include [11]:

– China is ramping up R&D spending with aggressive increases of over 7% annually between 2021 and 2025, exceeding recent GDP growth and setting a target of USD 580 billion by 2025 – surpassing both the US and Europe. This ambitious plan prioritizes basic research, aiming for over 8% of total R&D, and removes import taxes on S&T equipment until 2025 to empower research institutions.

– Prioritize investments in key energy innovations like carbon capture, hydrogen, industry

Table 3

Key energy innovation priorities outlined in China's recent five-year plans

	11th FYP (2006–2010)	12th FYP (2011–2015)	13th FYP (2016–2020)	14th FYP (2021–2025)
General innovation approach	Ramp up technology manufacturing to boost exports	Prime domestic markets and manufacturing innovations	Seek novel innovations in priority technology areas	Keep edge in manufacturing and prime breakthrough innovations
Key focus areas for energy innovation	Nuclear, coal, automobiles and new materials	Solar, wind, EVs and charging	Next-generation renewables, energy storage, new energy vehicles and batteries, smart power grids, and buildings energy efficiency	Next-generation batteries and new energy vehicles, hydrogen and fuel cells, advanced biofuels, CCUS, industry, and smart digital systems

Source: [11]

decarbonization, smart grids, and sustainable transport fuels, with sustained funding.

– Encourage businesses to increase R&D spending and cultivate closer connections between their innovations and the clean energy supply chain, creating opportunities to capitalize on the rapidly growing clean energy sector.

Conclusions. China's journey towards sustainable energy involves multifaceted approaches, including policy support, technological innovation, and green development initiatives. By prioritizing these measures, China aims to mitigate environmental challenges while driving economic growth and energy security. It was established that in the conditions of a large number of high-carbon activities in China and the level of CO_2 emissions, changes based on the principles of sustainable development and the implementation of innovative solutions are necessary for the further development of China's energy industry. The main directions for energy transformation are highlighted: diversified energy supply; green and low-carbon development; technological transformation and development. The directions of development of China's energy sector and political initiatives to ensure energy innovation are analyzed.

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