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International Practices of Policy Mechanism and Social Consensus for Reaching Carbon Neutrality and Their Key Implications for China

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Abstract: Most developed countries have now reached their carbon emissions peak and entered a period of rapid carbon-emission decline. These countries have introduced measures to achieve carbon neutrality while hoping to occupy a dominant position in emerging industries. This article aims to identify the policies and mechanisms underlying the processes of achieving carbon peak, promoting carbon neutrality, and promoting social consensus in developed countries to provide a reference for China's carbon peak and carbon neutrality. By reviewing the experiences of different developed countries, this study compares and analyzes their lessons, summarizes the examples of carbon-neutral policy development mechanisms they provide and gives suggestions for China's path to carbon neutrality. International experience indicates that carbon neutrality is a systematic project that requires multiple measures and orderly progress. While reducing transformation costs, it is necessary to accelerate the development of emerging industries. Moreover, realizing the carbon neutrality vision requires a sound market mechanism to speed up energy market reform. Carbon neutrality is more than a transformation of energy and economy; it can also change individual lifestyles. Therefore, a general social consensus on the objective is essential. Our research suggests that, to achieve China's carbon neutrality goals, we must ensure top-level design and a step-by-step action plan for carbon emission reduction, accelerate and deepen energy market reforms, raise social awareness, promote the overall consensus on carbon neutrality, and continue to deepen international cooperation.

Keywords: carbon neutrality; energy efficiency; international experience; market reform; social consensus; systems engineering

1 Introduction

After 2020, due to the urgent need to tackle global climate change, many countries and regions increased their voluntary contributions and accelerated the process of carbon emission reduction [1]. According to the International Energy Agency (IEA), as of May 2021, countries and regions accounting for more than 70% of the world's carbon dioxide emissions have pledged to achieve carbon neutrality in various forms by the mid-21st century [2]. In September 2020, China announced at the United Nations Climate Conference that it would achieve its carbon peak by 2030 and carbon neutrality by 2060 ("double carbon" targets). Since then, the country has refined specific targets and indicators, which have been generally recognized and highly valued by the international community.

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As the world's largest developing economy, China's economic structure, with relatively high energy consumption, an energy mix with a significant share of coal, and a relatively short period of transition towards carbon neutrality, pose great challenges to the country. Considerable efforts are required to achieve the "double-carbon" targets. Therefore, it is important for China to carefully review the developed countries' carbon-neutral strategies and policies and learn from their experiences to avoid making unnecessary mistakes.

Scholars have analyzed domestic and foreign policies on carbon peaking and neutrality in many industrial sectors, such as natural gas and renewable energy [3,4]. This paper proposes that carbon neutrality be considered a systematic engineering project, summarizes existing foreign experiences in terms of market mechanisms and social consensus, analyzes in depth the policy measures in developed countries, and provides recommendations on China's path to carbon neutrality in the light of the current situation and country-specific challenges.

2 Carbon neutrality is a systematic project

The realization of carbon neutrality is a complex systematic project, and it involves not only low-carbon energy transformation but also the reformation of industries, economic structures, and even societies. Therefore, a top priority for governments worldwide is to act systematically and take multiple measures to promote staged progression to avoid excessive transition costs and facilitate the steady growth of the industries with competitiveness.

2.1 Energy efficiency is the primary energy source

Under the sustainable development scenario aligned with the Paris Agreement's goal (atmosphere temperature increase is maintained below 2 °C), the contribution of renewable energy (including wind, solar, hydropower, and biomass) is approximately 32%, and that of energy efficiency is approximately 37%, which is the highest, according to a study by the IEA [5]. Here, energy efficiency not only refers to energy savings in a narrow sense but also efficiency improvements associated with the energy system and economic structure. Similar studies have been conducted by the International Renewable Energy Agency (IRENA) using different classification criteria. According to the IRENA model, renewable energy and energy efficiency contribute 25% toward the Paris Agreement's target, while electrification contributes 20% [6]. One obvious advantage of electrification is that it can significantly improve energy efficiency. The concept that energy efficiency is the "first energy source" is well reflected in the analysis and projection of the IEA and IRENA. In addition to energy efficiency and renewable energy, hydrogen, carbon capture, utilization, and storage (CCUS), and other carbon sink technologies will play important roles.

2.2 Multiple paths to achieve carbon neutrality

Regarding models of energy transition, studies of European and U.S. institutions do not define a particular path, but they emphasize the possibility of multiple options. A typical example is the "Net Zero America" study [7], in which several U.S. government agencies participated. It presents five typical carbon neutrality models with fossil fuels taking up between zero and more than 30% of the total energy mix under the scenario of net-zero carbon emissions. These five typical models are as follows: high level of electrification + total renewable energy, high level of electrification + limited renewable energy, low level of electrification + high level of biomass, high level of electrification (widespread use of electric vehicles), and low level of electrification. The study provides references for optimizing net-zero carbon emission pathways and indicates that one of the most important factors driving the success of energy transition is cost reduction.

2.3 Step-by-step progress

Currently, more than 40% of the technologies associated with mitigating carbon emissions are in the laboratory or small-scale pilot stage [8]. Notably, CCUS and hydrogen technologies have not yet been implemented commercially on a large scale. On the other hand, wind and solar power have already been fully commercialized, meaning that the power sector moves forward more easily than other sectors in the early stage of carbon emission reductions.

To describe the additional cost induced by carbon emission reduction, the concept of "green premium" has been proposed [9]. For example, heat pump technology is cheaper than traditional heating methods, which generates a negative premium and is considered a "low green premium." However, in sectors such as cement or steel manufacturing, the cost to adapt zero-carbon technologies can be several times higher than the current system and these industries are considered to be "high green premium". Energy transition can be prioritized in sectors with a "low green premium."

A study by Agora et al. on Germany's carbon neutrality roadmap highlights the concept of a step-by-step progress to

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carbon neutrality in various sectors, such as energy and manufacturing industries [10]. According to this roadmap, the key carbon emissions reduction by 2030 will come from the power and energy sectors, with a target reduction of 2.07×10^8t, accounting for 50% of the total carbon reduction during this period and only 17% for the manufacturing industries. After 2030, with the large-scale application of low-carbon technologies such as hydrogen, the manufacturing industries will overtake the energy sector, achieving a target reduction of 1.11×10^8t, while the reduction in the power and energy sectors will be 0.95×10^8t.

While prioritizing carbon emissions reduction in different sectors, as part of a step-by-step progress toward carbon neutrality, it is important to focus on achieving reduction with minimum cost and improved technological reliability. It is worth noting that developed countries always emphasize the leverage of emerging businesses arising from energy transitions on the path of carbon neutrality. For key emerging areas such as renewable energy, energy storage, high-tech materials, electric vehicles, and advanced manufacturing, early planning and optimization of the market structure with the aim of developing a sustainable business model supported by well-planned and rational investment will exert significant impacts on achieving carbon neutrality as well as shaping the future industrial landscape.

3 Achieving carbon neutrality requires a sound market mechanism

3.1 Renewable energy system must be driven mainly by market prices

Decarbonization of the power industry, which relies on a high proportion of power generation from renewables, is the core element of carbon reduction for the entire energy system in a wide range of countries. For instance, the energy mix in Germany includes a high proportion of renewable energy, with the electricity generated by wind and solar accounting for approximately 70% of the total in Germany in 2021 [11]. However, the tendency to intermittency and lack of dispatch capability for wind and solar power pose challenges in maintaining the stability of the power system.

When the proportion of intermittent power generation from renewable sources, such as wind and solar, does not exceed 5%, grid integration can be achieved by appropriate power dispatch, which aligns with our early knowledge of the grid system [12,13]. As the proportion increases, the grid can no longer achieve full integration, and more backup storage capacity (e.g., pumped-storage hydroelectricity, supplementary natural-gas power station) is needed to increase grid flexibility and guarantee sufficient power output when wind or solar power is unavailable. However, investment in a normally underutilized standby capacity leads to high extra costs for the overall energy system [14]. Therefore, increasing the standby capacity solely to improve grid flexibility is not a sustainable solution for a power system with a high proportion of renewable energy.

Despite the variability across regions and grids, once the share of intermittent power generation exceeds 10%, power system optimization is required. In 2021, the National Development and Reform Commission and the National Energy Administration in China proposed guidelines to promote the development of an integrated source-grid-load-storage system [15], which elaborated on the requirements during the reforming process of the power system. Under these guidelines, the load side and energy storage would play important roles in increasing the system’s flexibility. The demand-side response, distributed energy deployment, energy storage, and electric vehicles are all active components of power systems. In an integrated source-grid-load-storage power system, the boundary between the demand side and supply side is no longer clear. Guided by price signals from real-time market supply and demand, demand-side response and distributed energy systems play a critical role in the supply–demand balance.

In Europe and the United States, marketization of the power and natural gas industries has led to market-driven energy systems. These systems have promoted the growth of renewable energy and driven the development of new business models. To give an accurate reflection of the supply and demand dynamics, most spot tariff bands have been shortened to 5 min to clear the price. Market-driven energy pricing mechanisms will fundamentally reduce the abandonment of electricity generated from wind and solar power, improve system flexibility, promote energy storage and growth of ancillary services markets, and establish new business models [16].

Marketization of the energy industry relies on concrete policy design aimed at securing power and energy supply, and capacity market mechanisms play an important role in this regard. Ensuring sufficient capacity in an energy system is vital for energy security, and capacity market mechanisms should be used to improve capacity adequacy in the system in parallel with the construction of energy markets.

3.2 New business models require a more open market system

Carbon neutrality cannot be achieved without continuous technological and business innovation across many fields and industries. It is, therefore, essential to stimulate innovation mechanisms and expand market access.

Unlike the traditional centralized and pyramidal energy supply models, the energy system dominated by renewable energy will be more decentralized, with distributed energy playing an increasingly important role. It is expected that the market for distributed energy will grow exponentially in the future. Taking the example of the rooftop distributed photovoltaic (PV) industry, by 2050, there will be 1.67×10^8 households and 2.3×10^7 companies worldwide installing PV equipment to generate electricity on the roofs of houses, factories, and other buildings. The total installed capacity is expected to be approximately 2.2×10^9 kW, an order of magnitude more than 2.7×10^8 kW in 2020 [17]. Novel development and operation models of distributed energy will emerge by utilizing technologies such as big data and blockchains. For example, the smart microgrid in Brooklyn in New York City has introduced blockchain technology, enabled direct user-to-user trade of renewable electricity, and improved the credit level of small-scale energy producers by utilizing consensus mechanisms and electronic contracts. Similar innovative models exist in Europe, leading to the roll-out of blockchain-based energy tokens [18]. In 2021, the National Energy Administration in China announced a list of 676 pilot points to promote rooftop distributed PV development covering many municipal areas in China, including districts, cities, and counties [19].

The cost and rate of return of distributed PV are key factors for their future growth, and they are not only influenced by geography and lighting conditions but also by the cost of technology, business models, and financing cost. Diversification of market development entities and business model innovations as well as technological progress while lowering the financing threshold and reducing grid constraints should be encouraged. This should stimulate the marketization of the power sector, expand the scale of distributed renewable energy, and improve the flexibility relative to the centralized energy system. A prerequisite for innovation in distributed energy business models is an open energy market allowing distributed energy projects to sell electricity directly to surrounding energy consumers through the distribution network.

Energy efficiency is essential for carbon neutrality. Therefore, further improvement in energy efficiency requires the dissolution of boundaries between electricity, gas, thermal, and other sectors that have led to long-standing fragmentation of the energy market. In 2020, the European Union released its energy integration strategy, calling for the integration of all types of energy to optimize efficiency [20]. An important prerequisite for ending the intrinsic fragmentation of the energy market and realizing energy integration is to accelerate the refinement of energy markets and provide a more open market environment.

The growth of renewable energy or the optimizing of energy efficiency requires the active participation of small- and medium-sized entities (SMEs) and the maximization of innovation. The EU has strongly supported SME development. For example, in the Green New Deal, its main policy framework for addressing climate change, the EU has specifically formulated development strategies for SMEs. Financial support is provided through the EU Green New Deal Investment Program, helping SMEs expand their financing channels, promote green innovation, and reduce market barriers [21].

3.3 Carbon trading is a powerful tool

In the field of carbon emission reduction, the construction of a carbon emission trading market is a powerful tool. The EU was the first region in the world to build a large-scale carbon emissions trading system, and the EU carbon emissions trading system (ETS) operates in all EU countries, as well as in Iceland, Liechtenstein, and Norway, covering about 40% of the EU's greenhouse gas (GHG) emissions. Since 2005, the carbon emissions of major industries covered by the ETS have decreased by 42.8% [22]. Moreover, rising carbon prices in Europe have boosted efforts to reduce carbon emissions in recent years.

The ETS has adopted the "cap and trade" principle. This sets an upper limit on the total amount of GHG emissions of the sectors covered by the system, within which companies acquire or purchase emission allowances and trade them as needed. The cap decreases annually to control for total emissions. Quota trading provides the flexibility to minimize the social costs of carbon reduction. A complete, consistent, accurate, and transparent monitoring, reporting, and verification system based on real data is a fundamental safeguard for trading markets. In addition, rising carbon prices have boosted investments in clean and low-carbon technologies.

In July 2021, the European Commission proposed modifications to the ETS system to achieve the goal of "reducing greenhouse gas emissions by at least 55% by 2030." The changes included phasing out free emission allowances for the aviation sector and establishing a bidding mechanism for allowances by 2027, integrating the shipping sector into

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the ETS system, creating independent trading systems for the road transportation and building sectors, and making fuel suppliers, rather than households or vehicle owners, responsible for purchasing allowances [23]. These new proposals are intended to promote further emission reductions in key carbon-intensive sectors through carbon trading and achieve increasingly ambitious climate control targets.

4 Social consensus is essential to achieve carbon neutrality

International experience shows that broad social consensus is essential for the implementation of relevant policies. Public consensus is the social foundation for achieving carbon neutrality, and new forms of employment and lifestyles associated with a low-carbon society will further promote public awareness and strengthen the consensus on energy transition.

4.1 Public consensus is the social foundation for achieving carbon neutrality

In addition to setting carbon neutrality goals, developed countries are actively working to promote social consensus, improve public awareness, and facilitate behavioral change.

To increase public awareness of energy transition and climate change, the UK government launched a series of "climate change and behavior change" guidelines and tools (e.g., reducing littering, encouraging cycling, and reducing car and air travel) in February 2021 to encourage people to live lower-carbon lifestyles [24]. Surveys show that 80% of the UK population is concerned about climate change, with 33% reporting very concerned [25]; most people support climate-change mitigation strategies and actions. After introducing a series of measures and gaining public consensus, the UK government rolled out climate legislation in April 2021 to reduce GHG emissions by 78% by 2035 compared to 1990 levels. Achieving carbon neutrality is both a technological and societal challenge; thus, individuals' societal and behavioral actions are critical in reaching net zero emissions targets [26]. The public should be involved in the development of carbon-neutral policies and take action to change their high-consumption behaviors and adopt a low-carbon, green approach in all aspects of their lives. Policy development and social consensus are complementary and mutually reinforcing.

In France, to achieve a 40% reduction in GHG emissions by 2030 compared to 1990, a Citizens' Convention for Climate was formed in 2019. The Convention comprises 150 elected individuals from across the country who advise the government on climate change and environmental issues [27], which is an important institutional innovation. Simultaneously, many cities in France have launched renovation projects to create green living environments and encourage lower-carbon lifestyles. For example, in 2015, Paris announced the transformation of motorways along the Seine into pedestrian paths to encourage residents to ride and walk, thereby reducing their travel by motor vehicle. Several "greenways" have also been launched to facilitate green travel.

4.2 Carbon neutrality can create more employment opportunities

In the process of achieving carbon neutrality goals, emerging industries will provide more employment opportunities, which will help strengthen social consensus on energy transition. The social consensus developed during the period of energy transition and carbon neutrality is, therefore, mutually reinforced.

According to IRENA, 11.5 million people were employed in the renewable energy industry worldwide in 2019 (an increase of 500 000 from 2018), including 3.8 million in the solar industry [28]. At all stages of energy markets, renewable energy can create jobs and increase local income. Although only a few countries are currently leading the way in the renewable energy industry, many have significant potential to increase employment and support energy transition by promoting the development of associated industries and training practitioners. Achieving carbon neutrality creates more job opportunities [29]. According to the IEA's net-zero emissions scenario, although 5×10^6 jobs in the global fossil fuel sector might be reduced, more than 3×10^7 jobs associated with clean energy implementation, energy efficiency improvements, and low-carbon technology development could be created by 2030.

Many developed countries connect energy transition with regional economic development to create more jobs. For example, with the goal of 100% electricity generated by non-fossil fuels for municipal power supply by 2025, New York City has launched two green energy infrastructure projects to generate renewable electricity (wind, solar, and hydroelectric) in the north of New York State and Canada. The two projects will create approximately 1×10^4 local jobs and bring economic benefits equivalent to 8.2 billion USD [30].

Thus, the energy transition can be effectively integrated with social, environmental, and economic development, resulting in broader synergistic benefits. Carbon neutrality not only mitigates climate change but also promotes employment, economic growth, environmental improvement, and better living standards. In turn, these changes will raise public awareness. Mitigating climate change has multiple benefits and far-reaching social impacts. Achieving carbon neutrality requires social support, and the process has significant implications for social development [31].

5 Lessons learned and recommendations

5.1 Lessons learned

It is crucial to formulate a top-level design and long-term strategy for achieving carbon neutrality. Achieving carbon peaking and neutrality is a long-term process requiring the formulation of macro-strategies. Individual sectors should formulate strategic plans, collaborate closely to promote staged progression, and implement the various policies accordingly. Most developed countries have formulated long-term strategies and plans to mitigate climate change and enhance energy transition, and some have set sectoral targets for GHG emission reduction in the medium and long term.

Accelerating marketization of the energy market is the basis for effectively promoting carbon peaking and neutrality. The establishment of a new energy system requires market price guidance, and new business models must be stimulated by more open markets. Several developed countries have completed market reforms in the electricity and natural gas sectors, which have played an active role in promoting renewable energy and new business models. For example, the EU has set up a relatively mature carbon market system to promote GHG reduction, encourage investment in new technologies, and support low-carbon energy transitions. Promoting marketization across every part of the energy industry is important for achieving carbon neutrality.

Social consensus is critical for a low-carbon energy transition. Common consensus can significantly improve the efficiency of policy implementation, and the social benefits of energy transition can make the public perceive the benefits more clearly, thus forming a virtuous circle. It has been shown that low-carbon policies not only contribute to the reduction of carbon emissions but also bring social, economic, and environmental benefits. The formation of social consensus can help promote the implementation of low-carbon programs, which, in turn, brings multiple benefits.

5.2 Recommendations

First, a top-level design and long-term strategy must be developed, and a step-by-step carbon-emission-reduction action plan needs to be established. Given the variance in the level of difficulty and cost of carbon emission reduction in different sectors, tailored strategies, rather than a “one-size-fits-all” approach, should be adopted to promote staged emission reduction. The long-term strategy should clearly define the carbon reduction target, while the step-by-step action plan should be carefully designed and moderately adjustable to ensure a smooth transition toward the final goal and optimization of the path.

Second, energy market reform must be addressed. Under the impetus of the energy revolution, energy market reform should be deepened, and reform in the power sector and the separation of transportation and sales in the natural gas sector should be promoted to embrace free markets. To improve resource allocation, the power sector should accelerate the construction of the electric power spot market and auxiliary services market and expand the pilot-scale of the distribution network reform to enable the “sale of electricity across walls”. The natural gas sector should introduce diversified market players, promote the construction of regional markets, and build an internationally recognized natural gas price index. For the recently launched carbon-emission trading market in the power industry, it is necessary to improve the auxiliary system, progressively involve the participation of trading varieties and subjects, and attract investments in the renewable energy field through carbon prices.

Third, social awareness should be raised, and public consensus promoted. Energy transition requires public support as a social foundation; it also creates job opportunities and promotes social transformation. The public should be encouraged to participate in the process of achieving carbon neutrality and actively contribute to policy recommendations. In addition, the public should be encouraged to change their way of thinking and consumption behaviors, use low-carbon transportation, and live sustainably to maximize the synergistic benefits to energy, society, economy, and the environment.

Fourth, international collaboration should be deepened. Achieving carbon neutrality is a global process of making mutual contributions and gaining mutual benefits, which is essential for a shared future for humankind. On the one hand, international experience provides valuable lessons for China’s policy development and implementation. On the other hand, China is a good reference for other developing countries. It is necessary for China to strengthen collaboration and

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exchange experiences with other countries, as well as to study and evaluate the paths and measures taken by countries that have already achieved their carbon peak. In the meantime, China should tell others the "Chinese story" and lay the foundation for the country to share its best practices with other nations. China also needs to maintain close collaboration with international organizations such as IEA and IRENA, exchange international energy standards and technologies, follow up on cutting-edge international research and industrial development, and develop professionals with enriched carbon neutrality knowledge and international vision.

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