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Analysis of carbon reduction potential based on carbon flow theory

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Abstract. As the severity of global climate change and energy crises continues to escalate, reducing carbon emissions and transitioning to a low-carbon power system have become shared objectives within the international community. To thoroughly understand the effectiveness and complexity of emission reduction strategies within the power sector, this paper delves into the carbon reduction potential of power systems, covering three key areas: generation, transmission, and consumption. It explores how systemic improvements in these sectors can drive large-scale low-carbon transformations of power networks, and elucidates the carbon reduction strategies and potentials of each sector. This paper examines and analyzes significant data and scholarly research from the power industry, as well as relevant policies, to measure the impact of various technological and policy approaches on carbon emission reduction. It also compares differences and synergies between different studies. The research findings indicate that the cornerstone for achieving a low-carbon power system lies in systematically promoting the low-carbon transformation across three dimensions based on carbon flow theory: power generation, electrical grid distribution, and consumer-side practices. In terms of power generation, integrating clean energies like wind and solar, coupled with improvements in low-carbon generation technologies, can significantly reduce carbon emissions. For the electrical grid, carbon reduction is mainly achieved through optimizing grid infrastructure, including minimizing transmission and distribution losses and SF_6 emissions, as well as promoting distributed grids and storage technologies to enhance system flexibility. On the consumer side, optimizing industries with high carbon emissions, advancing the integration of electric vehicles with Vehicle-to-Grid (V2G) systems, and implementing low-carbon demand response is crucial for carbon reduction. Furthermore, policy support, incentive measures, and technological innovation are extremely vital in enhancing the effectiveness of these measures.

Keywords: Power system, low carbon, carbon reduction potential analysis, low carbon demand side response.

1. Introduction

Since the Industrial Revolution, global carbon emissions have grown exponentially. By the end of World War II in 1945, carbon emissions had risen to 4.26 billion tons, and by 2022, they had nearly increased ninefold to 371.5 billion tons [1]. Reducing carbon emissions has become an imperative. The power sector, being a principal source of global greenhouse gas emissions, faces numerous challenges such as high emission levels, heavy reliance on fossil fuels like coal, and unstable energy

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supply. Hence, analyzing the decarbonization potential within the electricity system is of paramount importance.

The current state of carbon emissions from the global power system is of significant concern. Limited by the need to ensure energy security and slow transition of energy supply structures, fossil fuel-based thermal power generation remains the primary source of carbon emissions. Although nuclear power generation is a low-carbon energy source, its application globally is constrained by factors about safety and environmental concerns. Additionally, energy wastage in the power system due to transmission and distribution losses further escalates carbon emissions.

Most countries and regions around the world have adopted carbon reduction measures and policies. Entities such as the European Union, the United States, China, Japan, and others have formulated a spate of policies supporting the development of renewable energy, encompassing subsidies and generation quotas. However, due to technological limitations and investment costs, the proportion of renewable energy in the electricity system remains relatively low. Concurrently, the current market pricing mechanisms do not fully reflect the range in electricity cleanliness, resulting in high-carbon emission generation methods still maintaining a competitive advantage.

The current carbon emission situation within the power system remains critical. To achieve the goal of carbon neutrality, it is necessary to vigorously promote the development of renewable energy, improve the design of electricity markets, and continuously explore new technologies and innovative solutions to reduce carbon emissions. This paper comprehensively assesses the decarbonization potential of the power system from three dimensions: electricity generation, grid, and consumption, to provide a reference for the global path toward carbon neutrality.

2. Assessment of power system carbon reduction potential

2.1. Assessment of carbon reduction potential on the power generation side

2.1.1. Clean Energy Alternative Strategies. The strategy of substituting fossil fuels with clean energy transitions from a paradigm of heavy reliance on fossil energy, with clean energy as a supplement, to a model where clean energy takes precedence, supported by fossil fuels as necessary. The global theoretical potential for harnessable clean energy sources such as water, wind, and solar amounts to 150,000 trillion kilowatt-hours. This vast capacity more than satisfies human demand, solidly affirming the viability of substituting fossil fuels with clean energy sources.

In essence, the primary source of carbon emissions from thermal power generation is the process of generating electricity itself. Conversely, clean energy sources have a significantly lower carbon footprint during their electricity production process. Through the application of the fuel carbon emissions factor method[2], we can calculate the average annual carbon emissions for various methods of electricity generation as shown in equation (1)

$$\mathrm{P_{t,j}} = \mathrm{D_{t,j}} \times \mathrm{e_{t,j}} \tag{1}$$

Where $\mathrm{P_{t,j}}$ denotes the annual CO_2 emissions of the ith power generation mode in the jth year, g; i=1, 2, 3... denotes coal, gas, oil, biomass, hydropower, the nuclear, wind, and solar power, respectively; $\mathrm{D_{t,j}}$ denotes the annual electricity generation of the ith power generation mode in the jth year, kw·h; and $\mathrm{e_{t,j}}$ denotes the carbon emission factor(CEF) of the fuel of the ith power generation mode of the jth year.

It becomes evident that, for a given amount of electricity produced, the lower the fuel CEF of an electricity generation method, the lower its annual carbon emissions will be. Taking China as an example, the respective fuel CEFs for coal, gas, and oil-powered electricity are 838.6g/(kw·h), 420.0g/(kw·h), and 710.0g/(kw·h)[3, 4]. In contrast, the CEFs for hydroelectric, wind, and solar power generation can all be considered negligible, effectively approaching zero. It is clear, therefore, that substituting fossil fuels with clean energy can profoundly diminish the CEF of the electrical grid, facilitating a substantive reduction in grid-associated carbon emissions.

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2.1.2. Low-carbon Power Generation Technologies. As previously mentioned, given the short-term indispensability of thermal power generation, enhancing power generation technology to boost efficiency while concurrently diminishing the carbon emissions produced during power generation stands as a critical measure in achieving carbon reduction currently. In Ref.[5], it has been elucidated that the impact of various power generation methods on carbon emissions factors ranges from high to low as follows: coal power, gas power, hydropower, biomass power generation, solar power, nuclear power, wind power, and oil power, with the latter six methods exhibiting minimal influence. Hence, the essence of enhancing power generation technology primarily revolves around optimizing coal and gas power technologies.

In terms of coal power advancements, as Jing Li[6], initiatives can span across three dimensions: advanced coal power technologies, retrofitting technologies for operational coal power units, and low-carbon technologies. Advanced coal power technologies encompass ultra-supercritical power generation and high-parameter ultra-supercritical key technologies, high-efficiency coal-fired power generation techniques, etc., aimed at ensuring more complete combustion; retrofit technologies for existing coal power units include energy-saving and carbon-reducing modifications, flexibility enhancements, and heating system upgrades, intended for conservation and reduction of emissions as well as amplifying the load adjustment capability of coal power units; low-carbon technologies predominantly involve coal blending techniques and Carbon Capture and Storage (CCS), targeted at reducing coal consumption and preventing CO_2 emissions. Regarding gas power enhancements, they can be achieved through micro gas turbine technology, combined operation of multiple generating units, and waste heat recovery utilization. Introducing micro gas turbines facilitates superior accommodation to small-scale generation and distributed energy provision, featuring elevated generation efficiency; concurrent operation of multiple units enhances the stability and reliability of gas power plants, thereby enabling more efficacious power generation; waste heat recovery and utilization technology allows for optimal energy use. Altogether, whether it's coal or gas power technological enhancements, both directly or indirectly contribute towards achieving carbon reduction objectives through varied approaches.

2.2. Assessment of grid-side carbon reduction potential

2.2.1. Decarbonisation of power transmission and distribution technologies. The electrical power grid functions as a conduit for the flow of electrical energy; however, energy losses during transmission and distribution are an inherent consequence. Based on data from the World Bank in 2014, it is estimated that these losses represent approximately 8% of total electricity generated globally. Consequently, a significant quantity of electrical power is dissipated annually during grid transmission and distribution. While transmission and distribution processes themselves do not emit carbon directly, they necessitate additional power generation to compensate for the losses, inadvertently leading to increased carbon emissions overall. Furthermore, the power grid employs numerous switching devices that utilize sulfur hexafluoride (SF_6) as an insulating agent. Given that the global warming potential of SF_6 is an estimated 23,900 times greater than that of CO_2, annual SF_6 emissions to the atmosphere are tantamount to releasing 125 million tons of CO_2 equivalent.

As such, optimizing carbon emissions from transmission and distribution involves two primary strategies: minimizing transmission and distribution losses, and reducing the usage and leakage of SF_6 within grid infrastructure. Firstly, advancing high-efficiency transmission technologies will boost the grid's conducting capacity, lower energy losses, and enhance overall energy efficiency. Secondly, deploying technologies to reduce losses captures the grid's inherent potential for mitigating losses and enhancing the management of line losses, propelling low-carbon grid development. Thirdly, implementing low-carbon power dispatch methods will refine joint economic dispatch, optimize grid operation, and prioritize energy consumption for diverse types of generation units based on clean energy usage.

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Fourthly, incorporating modern, energy-efficient transformers is crucial. Power grid companies must consider total transformer losses, systematically phase out outdated, substandard, and high-loss transformers, and expedite the adoption of new, energy-saving transformer models. Fifthly, robust management and recycling practices for SF_6 are paramount. Grid operators should have concrete measures in place for SF_6 emission reduction, and future initiatives should bolster scientific research efforts to advance leakage monitoring, as well as recovery and recycling techniques for SF_6. There is also an imperative to investigate and develop alternative technologies to supplant SF_6, and to procure equipment suitable for the recovery, purification, and reuse of SF_6 suitable for grid applications.

2.2.2. Advancements in Power System Energy Storage Technologies. Power system energy storage technology facilitates the spatial and temporal transfer and transformation of energy. Importantly, in the realm of carbon mitigation, these technologies enhance the efficiency of renewable energy usage. Power system energy storage systems play an instrumental role in balancing the grid by accommodating the intermittent, fluctuating, and unpredictable nature of clean energy sources such as wind and solar, thereby bolstering their development and consumption. Furthermore, such systems contribute to grid stabilization through peak load leveling and valley filling processes, which optimize the utilization of generated electrical industry energy and curtail power energy wastage.

In a notable instance from 2021, China's State Grid Shanghai Electric Power carried out large-scale peak-shaving and valley-filling operations. Over a timeframe of less than two days, the company managed a grid load adjustment of 562,000 kW and utilized 1,236,000 kW·h of clean energy, consequently reducing carbon emissions by approximately 336 tons [7]. Presently, beyond the technical hurdles in energy storage, challenges persist with the market operation mechanisms of energy storage power plants. The lack of a sophisticated mechanism hinders the engagement of market participants, which affects the overall utilization of energy storage resources.

Currently, in the field of energy storage, there are challenges not only on a technical level but also in the imperfect market operation mechanism for energy storage power stations, which fails to effectively incentivize market actors to participate, thereby impacting the level of energy storage utilization. Consequently, in addition to strengthening technology research and development, it is crucial to enhance the management of energy storage grid-connection operations, refine and standardize market entry conditions for energy storage, and improve market mechanisms and the types of practical market applications.

2.2.3. Promotion of Distributed Energy Grids. A distributed energy grid comprises a network of power sources located at the point of consumption and interconnected with the electrical grid at voltage levels up to 35kV; these sources are primarily used for local demand and encompass diverse power generation and energy storage modalities. Due to the proximity of distributed generation to the load centers, it significantly curtails the need for expansive transmission and distribution infrastructures, as well as diminishes losses during transmission. In parallel, distributed grids exhibit remarkable versatility, predominantly employing small to medium-sized modular equipment that boasts superior performance, rapid activation, and deactivation cycles, straightforward maintenance, and governance, coupled with the inherent autonomy of each power generator, which collectively contributes to realizing more efficient load leveling and peak shaving. This enhances the overall utilization efficacy of electrical power.

Furthermore, the distributed energy paradigm transcends conventional power generation techniques by integrating innovations in automatic control systems, advanced materials technologies, and adaptable production processes. It often prioritizes the inclusion of renewable energy sources, thus substantially mitigating local carbon emissions. Despite these advantages, distributed grids confront several challenges. Technically, they must address issues related to energy management, storage techniques, and intelligent regulatory mechanisms to bolster their stability and dependability. Economically, establishing and maintaining distributed grids entails significant investment, and presently, their financial viability is relatively modest, with a pressing need for robust business models

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and market frameworks. On the policy and regulatory front, existing measures are not fully matured, necessitating refinement through the adoption of market strategies and business models to amplify economic attractiveness, thereby drawing more investments and stakeholders to this sector.

2.3. User-side carbon reduction potential

2.3.1. Optimization of Industries with High Energy Consumption and High Emissions. Through the use of electric power big data and carbon emissions generated by energy consumption in the process of industrial production to establish a machine learning model, the carbon emission flow in the power system is dependent on the trend, through the carbon flow calculation can be accounted for the carbon emissions generated in the process of industrial production, the use of the grid company's electric power big data center of the mature and complete electric energy data, to achieve the application of the machine learning model for the engineering. Industries such as steel, chemicals, and building materials have traditionally been characterized by high energy consumption and emissions. By integrating advanced electric propulsion technologies and energy management systems, such as the Demand Side Management (DSM) model, there has been an enhancement in predicting and regulating electricity demand for large industrial users[8]. This integration not only optimizes their operational scheduling and peak load consumption but also effectively reduces the pressure on the power grid and the overall energy consumption. Such industries should also be subjected to policy incentives and technological support that encourage the phasing out of outdated equipment and the adoption of modern equipment, such as high-efficiency motors and variable frequency drives, which facilitate improved energy efficiency and reduced carbon emissions. For the manufacturing sector, adopting renewable energy-based smart and green manufacturing technologies is equally critical. For instance, the incorporation of the ISO 50001 Energy Management Standard and Motor System Optimization (MSO) strategies can reduce excess energy use through upgraded equipment designs and enhanced control system efficiency thereby facilitating a low-carbon transition in manufacturing.

In the field of transportation, electric vehicles (EVs) and their interactive technologies with the grid, especially Vehicle-to-Grid (V2G) systems, have become crucial in reducing carbon emissions and enhancing grid flexibility. The widespread adoption of EVs directly reduces carbon emissions from the transport sector, while V2G technology allows EVs to feed electrical energy back into the grid during peak demand periods, providing additional reserves and stability. Ref.[9] analyses that a surge in the number of EVs, coupled with smart charging and V2G technology, can significantly reduce the need for electrical and thermal energy storage—cutting down the capacities required for electric power by 35% and thermal energy by 25%, and subsequently lowering overall system costs by 4%. Moreover, V2G and smart charging technologies facilitate the flexible operation of electrolysis units for the production of liquid e-fuels (electricity-derived fuels), further decreasing the overall system costs by an additional 8%. These technologies not only improve the integrated efficiency of electric and thermal energy use but also highlight the importance of adopting a combination of various technological and managerial strategies in the future energy system. Concurrently, V2G and smart charging bring economical profit to EV users by reducing energy expenses and providing potential revenue, thereby motivating consumers to adopt EVs and accelerating the shift from traditional fossil-fuel vehicles to low-carbon, efficient electric cars. Therefore, electric vehicles and their grid-interactive technologies play an essential role in promoting low-carbon transportation and enhancing grid stability, bearing significant implications for achieving the goals of clean energy and sustainable development.

2.3.2. Low-carbon demand response. Low-carbon demand response(DR) involves providing electric power consumers with information on the carbon emissions associated with their electricity usage, thereby guiding them to change their consumption behaviors to reduce carbon emissions within the power system and promote the use of renewable energy sources. In this process, an electricity CEF signifies the differential in carbon emissions resulting from various electricity usage behaviors, indicating the direct carbon emissions per unit of electricity consumed. This factor serves as a bridge connecting the direct carbon emissions from fuel consumption on the generation side to the indirect carbon emission due to electricity use on the demand side. According to research conducted by Li Yaowang et al. [10], the effectiveness of low-carbon DR relies on foundational implementation, technological support, and policy backing, as illustrated in Figure 1. The carbon reduction impact is more pronounced in regions with significant differences in load adjustment and CEFs. Moreover, under the current level of new energy generation, the guidance effect of low-carbon DR on consumer behavior intersects with that of peak-valley time-of-use electricity pricing.

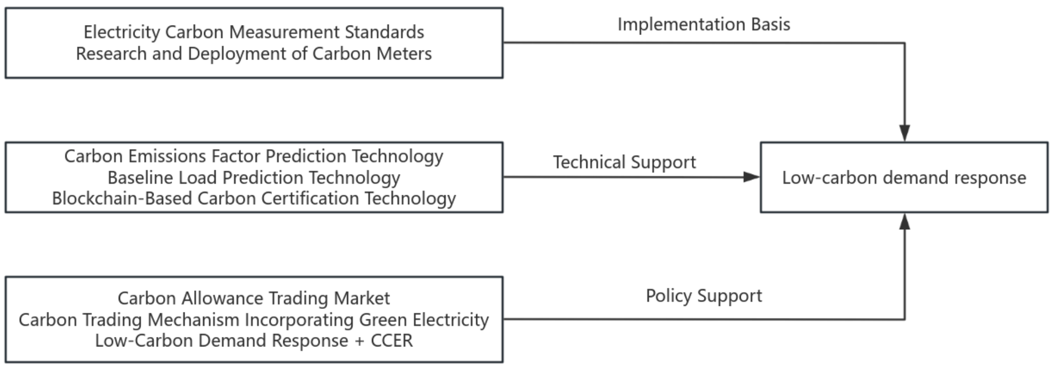

Figure 1. Key factors which affect the carbon reduction effect of low-carbon DR

Furthermore, as per the studies by Yuqing Ye et al. [11], using carbon signals as incentive indicators can motivate users to adjust their loads for greater carbon reduction, thereby optimizing the energy output structure on the supply side and effectively capping carbon emissions. Employing a leader-follower game model to establish an interactive dynamic between energy providers and consumers leads to the development of rational and effective incentive schemes. Such models not only further tap into the carbon reduction potential on the consumer side but also reduce the costs associated with carbon trading while simultaneously enhancing the profit margins for energy providers and the consumer surplus for users on the demand side.

3. Conclusion

In summary, carbon flow-based carbon reduction potential analysis relies on carbon flow accounting, which connects the power generation side, the grid side and the customer side. On the supply side, integrating clean energy sources such as wind and solar energy, implementing high-efficiency thermal power generation technologies, and adopting carbon capture technologies can all significantly reduce carbon emissions. On the grid side, carbon reduction can be achieved mainly through optimizing the infrastructure of electrical grids, which includes reducing transmission and distribution losses and SF_6 emissions, as well as promoting distributed grids and energy storage technologies to enhance system flexibility. On the consumer side, optimizing high-emission industries, advancing the integration of electric vehicles with V2G systems, implementing low-carbon demand response, and encouraging user participation in carbon reduction is pivotal. Additionally, policy support, incentive measures, and technological innovation are crucial for enhancing the effectiveness of these measures.

Analysis of carbon reduction potential based on carbon flow and the future outlook of carbon emission can be carried out in three dimensions, namely, expansion application, core support, and

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scientific and technological empowerment. In terms of expanding applications, it includes panoramic carbon map, product carbon content, intelligent carbon management, and user carbon evaluation; in terms of core support, it mainly includes key technologies and key equipment for power carbon measurement; in terms of scientific and technological empowerment, it includes comprehensive carbon analysis, proactive carbon response, accurate carbon certification, and scientific carbon planning.

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