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Optimization of Renewable Energy Systems under Carbon Neutrality

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Abstract. With the increased severity of climate change, there's increased urgency for the globe to achieve carbon neutrality. Thus, optimizing the current energy system, which accounts for nearly two-thirds of total emission, has become essential. This study aimed to address this issue through a case study of the renewable energy development in China, analyzes the challenges behind current advancement in energy system, and proposes potential solution. Despite China as a global leader in renewable energy development, significant challenges remain, including high operation cost and low energy efficiency, which limit the transition to carbon-free energy system. The uncertainty in governmental policy and the predicted impact of climate change further elaborate the problem. In response to these challenges, several energy system models have been proposed, including the Dual Residual Electricity Treatment System (DREST) for improving energy storage, the Improved Integrated Energy System (IIES) for integration between different energy source, and the Stepped Carbon Penalty Response (SCPR) for adaptive response to governmental policy. The findings of the research can be used to cope with the current problems of renewable energy development and promote worldwide efforts towards carbon neutrality.

Keywords: Renewable Energy, Carbon Neutrality, System Optimization

1. Introduction

Since the post-industrial period, numerous attempts have been set out by the globe to control the rapid development of climate change. In 1992, the United Nation Framework Convention on Climate Change was established that aim to control the greenhouse gas emission level to prevent the effect of climate change [1]. Similarly, the UN Intergovernmental Panel on Climate Change (IPCC) carried out five major climate change assessment cycles that hope to evaluate the consequences of the rapidly developing climate change [2]. In 2015, the Paris Agreement was signed by 185 countries, urging nations to work together in solving climate change, controlling the global temperature to be below 1.5°C compared to the pre-industrial level. Achieving carbon neutrality, a state of net-zero carbon dioxide emissions, requires immediate actions on transforming the global energy system. Since energy sector accounts for approximately two-thirds of the total emission, decreasing the dependence on fossil fuel, the main source of energy nowadays, and increasing the efficiency of current energy system become essential under the context of carbon neutrality.

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Previous research had explored the optimization of energy systems to achieve Carbon Neutral Energy System (CEDC), energy systems that have near zero carbon emission levels. It is aimed to be achieved through the incorporation of Integrated Energy System (IES) and the Carbon Capture System (CCS). IES refers to energy systems that combines different types of energy sources, including electricity, heat, and gas. By incorporating different energy source, IES ensure the reliability of energy production while minimizing environmental impact. Zhang et al. [2] and Yang et al. [3] demonstrated the possibility of reducing the operational cost and decreasing the carbon emission level for energy system through the optimization of IES. Ma et al. [4] explored the optimization of IES through the usage of natural gas and cascade utilization, which is proven to be feasible and effective in improving energy efficiency. Li et al. [5] and Zhou et al. [6] discuss the inclusion of Power-to-Gas (P2G), using electricity to produce hydrogen or synthetic natural gas, into the IES, which had enhanced the stability and reduce the operational cost for IES. Zhou et al. [7] further demonstrates that the coupling between IES and hydrogen energy storage (HES), the process in which electrolysis was used to produce hydrogen through excess renewable electricity, can increase energy efficiency and enhance the production of clean energy. Meanwhile, the Carbon Capture System (CCS), a technology aiming at capturing carbon dioxide that is emitted during industrial pollution, helped to deal with the unavoidable emission from the IES system before releasing it to the atmosphere. Dong et al. [8] talks about an integrated energy system that incorporate P2G and Gas-Fired Unit, generator that burns natural gas to produce electricity, and CCS. The whole system has proven to have positive effect on reducing carbon emission levels. However, Ye et al. [9] and Al-Hamed et al. [10] highlights that the inclusion of CCS in factories may reduce the energy efficiency of the system. Wang et al. [11] quantified that CCS integration in thermal power plants reduces overall efficiency by approximately 13%. These findings indicate that while IES and CCS can achieve CNES, significant challenges remain in maintaining energy efficiency, highlighting the need for further system innovations.

Despite advancements in energy system optimization, substantial gaps remain. The impacts of climate change have increased both annual operational costs and carbon emissions over time. Traditional P2G systems face the problem of low storage capacity, limiting their efficiency. Current CCS systems experience high energy consumption and operational costs. Even when coupled with CNES, temporal mismatches between excess heat availability and CO_2 capture demand can reduce system effectiveness. Without improvements, these inefficiencies may compromise cost reduction, energy efficiency, and carbon mitigation goal. This study addresses these gaps using the CAS framework to analyze current conditions and propose solutions for energy system optimization, which is essential for achieving net-zero emissions and combating the global climate crisis.

2. Renewable energy development and challenges in China

China, one of the world's largest energy consumer and carbon dioxide emitter, recognized the urgency of decarbonization. With the global pursuit of net-zero carbon emission, China had become a leading countries in renewable energy development. In terms of hydropower, one of the most frequently used renewable energy in China, China had invested heavily into it. China had built more than 47,000 hydropower stations, with a total capacity of around 75,000 MW [12]. Most hydropower stations have more than 1,000 MW capacity, demonstrating the potential for future development. Hydropower provides a stable power source, making it the core energy for China's renewable energy transition strategy. China is also a leading country in wind energy generation, with the largest wind energy capacity in the world. By 2020, China had increased the wind capacity by 220 GW, reducing 140 million tons of CO2 and decrease coal consumption by 150 million tons

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annually [12]. Furthermore, China had high potential for solar energy, reaching a capacity of 1200 MW and continue to expand rapidly to regions with high solar irradiance. These figures demonstrate China's investment in renewable energy had led to significant progress.

But the reality is adoption of renewable energy with high installed capacities is very low. The reason for this is the high capital cost of renewable technologies, low grid flexibility, and abundant availability of dirty cheap fuel. This points to the importance of integrating and reducing the cost of RE technologies. Resource, operational, and infrastructure constraints are significant barriers to a total renewable switch in China. Geographically, resource distribution affect the renewable energy development in China. The northeastern coastal area has a significant requirement for wind power but is not adequately endowed with available wind. On the other hand, in northern areas, large wind resources exist but energy consumption is low. Similarly, solar energy resources are found in the western and northwestern parts of the country. Since the distances from these areas to major urban load centers are large, transmission and grid integration would be problematic. Renewable power generation runs on natural and geographical limitations such as climate, wind, solar, water supply, and it requires sophisticated technologies to store energy or transmit it. Capacity expansion of renewable energy cannot be done without proper allocation of resources and adequate power transmission. Besides, energy storage systems are immature and uneconomic so far even for massive implementation. Due to storage capacity, energy density, and price constraints, it is challenging to accommodate the intermittent supply of renewable energy, as well as integrating renewable energy into the national grid [13]. It is this unevenness of resources along with the lack of developed storage that has been holding back a widespread and effective roll-out of renewable energy right across the country.

Operational challenges also play a role that reduces the availability of renewable energy. Despite China being one of the largest producers of renewable energy across the globe, the energy production failed to meet up with the energy demand. As of 2024, China had used around 1.1*1016 MW of electricity, which is much higher compared to the renewable energy capacity [14]. Even the hydropower in China, one of the most commonly produced and used renewable energy with the capacity of around 75000 MW, are not sufficient to fulfill the full energy demand. In addition, because of the resource-dependent characteristic of renewable energy, energy storage became essential. Most renewable energy, such as solar energy or wind energy, is dependent on certain nature resources. During nighttime where there is less sunshine, solar energy cannot function properly. In locations where wind is not abundant, wind energy production can be a problem. This may lead to mismatch between energy production and demand. Current energy storage technologies faced difficulties such as low power density, high capital cost, and challenges in grid integration. These problem have made renewable energy a less feasible energy source compared to conventional fossil fuel, which is cheap to produce and can be used at any time.

Despite the technological and geographical limitation, Chinese government had put in immense effort to promote the development of renewable energy. Policies such as the Renewable Energy Law, the Wind Power Concession Program, and several other regulations attempt to promote the energy transition. These regulations aim to catalyze the transition through subsidizing renewable energy installation and implementing specific tax policy for renewable energy firm, which had been proven successful in reducing the cost of renewable energy, promoting investment, and influencing localization of wind power related manufacturing, especially the Wind Power Concession Program [15]. These policies demonstrate the effort done by the government to promote energy transition and meeting the global climate goal.

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The Chinese example, in particular, was very clear-cut in what had to happen. We need to change our current energy system. Although a country that is seen as one of the most significant countries in renewable energy production, capacity is not yet sufficient to cater to the needs. Methodological bottlenecks and geographically heterogeneous contexts underscore the need for a holistic approach in optimizing energy system design. Achieving carbon neutrality will depend on investment in additional capacity of new renewable energy, systems to manage energy and power, storage of energy efficiently, as well as adaptive policy actions. These steps are vital for China to truly achieve its renewable energy potential and cut the overall global climate challenge.

3. Factors influencing energy system optimization

Energy system optimization under the context of carbon neutrality requires a comprehensive understanding of the factors influencing their design and efficiency. Different energy system models may reveal different results depending on the factors included, which can create uncertainty in determining the effectiveness of system optimization. Based on the case study of renewable energy development in China, factors influencing system optimization can be divided into two major categories: climate change and governmental policy.

3.1. Climate change impact

The effects of climate change on energy can be approached from the supply and demand side. In the context of climate change, when considering the impact on energy demand, as average global temperatures rise, so will the need for cooling and less heating. RCP 4.5 and RCP 8.5, which represent intermediate emission and high-emission scenarios, respectively, are two trajectories for the future climate changing direction. Under RCP 4.5, where greenhouse gas emission can be stabilized under 2100, cooling demand is expected to increase by 6.869% every ten years, while heating demand decreases by 3.339% every ten years. On the other hand, under RCP 8.5, where carbon emission continues to grow significantly throughout 21st century, cooling demand rises by 10.263%, and heating demand falls by 4.602% every ten years [14]. Through these figures, it can be seen that the energy demand varies significantly depending on the future climate change consequences, meaning that new energy planning adjustment is required depending on the current climate situation in order to ensure the reliability and cost-effectiveness of the energy system.

Understanding the changes in demand pattern is important. Without careful consideration of the impact of climate change, energy systems may face unexpected sudden increase or decrease in energy demand, causing reliability problems. For instance, sudden heatwaves can cause increase in cooling demand, potentially overloading electrical grids. Oppositely, milder winters may lead to less usage of heating systems. If the impact of climate change was not included in energy planning, it may lead to inefficiencies, increased operational costs, and fail to meet energy demand.

Another impact that climate change can have on energy system optimization is the changes in energy supply. On the supply side, climate change will affect the efficiency of energy system. With the increase in temperature brought by climate change, traditional power grid and power generation unit (PGU) face decrease in power generation efficiency. From 2020 and 2060, the efficiency of PGU is expected to decrease from 36.64% to 36.43%, and power grid efficiency is expected to decrease from 42.69% to 42.23% [14]. Higher temperature reduce the maximum possible efficiency of heating engine. As described by the Carnot Efficiency Limit, increase in global temperature will increase the temperature of heat sink, thus decrease the temperature difference between the heat source and heat sink and reduce theoretical maximum efficiency of power conversion. The real-

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world implication of energy production will also be effected. Gas turbines face decreased efficiency in that warmer air, which has less density, will requires the gas turbine to do more work in compressing the air, thus leaving less useful energy as output. Similarly, steam turbines experience reduced condensation efficiency under warm air, causing decrease in energy production. Photovoltaic technology is also sensitive to changes in temperature. As temperature increase, system face reduced energy output and overall efficiency. These considerations highlight the relevance of considering climate impacts on the system optimization for guaranteeing energy production under any environmental conditions.

3.2. Government policy impacts

Government policy can also play a role in affecting energy system optimization. Depending on the different policies being implemented, such as subsidies, tax incentives, and regulatory framework, there will be different affect on the energy system development. In China, subsidies for wind and photovoltaic energy help industries to better adapt to renewable energy. These subsidies allowed for overcoming the challenges of renewable energy being more expensive, thus allowing more firms to have the incentive of investing in renewable energy over fossil fuel. However, by 2030, most subsidies on wind energy and photovoltaic will ceased, which will hinder future renewable energy investment because of the lack of the financial help from government. The financial uncertainty can result in changes in the operational cost for energy systems, affecting the economic feasibility for certain renewable project, forcing energy operators to reconsider the design for energy system.

Policy uncertainty can also influence the operational cost structure. A shift in subsidies or a new carbon price could make it that energy providers would need some other kind of storage technology, or an entirely different system that can meet the policy. Governments can also decide on a cap for emissions, require renewable energy use, or impose a carbon offset. These will affect how operators choose to design the energy system. For example, integrating carbon capture and storage (CCS) systems becomes more favorable under stricter emissions regulations, despite their negative impact on overall energy efficiency [8–11].

The analysis of climate change and policy uncertainties demonstrates the challenges in energy system optimization. Energy systems will need to gradually adapt to the rapid changes around the globe, flexibly adapting to demand changes, climate variation, and changing governmental regulation. Only through a comprehensive review of the climate and governmental uncertainty, can optimized energy systems be effective and reliable in achieving the goal of carbon neutrality.

4. Proposed solutions for energy system optimization

4.1. Dual Residual Electricity Treatment System (DREST)

In terms of energy storage, the Dual Residual Electricity Treatment System (DREST) can optimize the traditional single-layer electric energy storage system. When the excess electric energy exceeds the capacity of a traditional Energy Storage System, the surplus energy will go into the Power-to-Gas system for electrolysis, generating H2. When coupling the P2G system with the CCS, the excess energy produced during P2G can be used to absorb the CO_2 being emitted in the energy system, thus increase the energy efficiency of the system and control the carbon emission. Simulation studies demonstrate that DREST can help to reduce 2.513% of the average total cost, 0.578% of the carbon emission, 7.244% primary energy consumption, and 14.86% energy wastage. This whole optimizes energy system ensures minimum energy loss in the process of energy production and controls the

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carbon emission in the energy system, thus addressing the limitation of traditional energy storage system.

4.2. Improved Integrated Energy System (IIES)

IIES aims to produce energy using several energy sources, including photovoltaic, wind turbine, solar thermal collector, auxiliary boiler, and power generation unit. Electric energy will be mainly produced using wind turbine and photovoltaic. However, if these two-energy sources cannot fulfill the energy capacity, it would be necessary to burn natural gas in order to fulfill the energy demand. In terms of thermal energy, it would be mostly produced by the solar thermal collector, with excess PGU heat as a backup. This approach of combining multiple energy source enable the optimal utilization of resources while enable the reliability of energy output. Through this process, IIES is able to minimize operational disruption, lower carbon emission, increase energy efficiency.

4.3. Stepped Carbon Penalty Response (SCPR)

SCPR implements a dynamic carbon pricing response to optimize CCS operation. When carbon costs exceed CCS operational costs, the system activates CCS using surplus energy. If excess energy is insufficient, auxiliary boilers supplement CCS operation. The CCS energy supply is derived from four sources: residual system heat, P2G, electric boilers, and auxiliary boilers. Surplus CO_2 is temporarily stored until capture is feasible. SCPR ensures efficient CO_2 collection while minimizing energy consumption and operational costs, demonstrating an adaptive approach to carbon neutrality under fluctuating policy conditions. DREST, IIES, and SCPR form a universal set for energy systems optimization. They allow combining the renewable-based sources, enhance efficiency for energy storage systems, and maintain flexibility against policy or climate uncertainties. These tailored energy systems minimize costs and maximize the utilization of energy and the amount of associated CO2 generated. Also, these can be developed to meet regional demands, with implications for other regions. Taken together, these developments point to what's possible in carbon-neutral energy systems.

5. Conclusion

Based on the analysis of renewable energy development in China, it can be indicated that although there is great progress and success in the renewable industry, by the Chinese case, serious challenges remain. Geopolitical constraints and operational obstacles preclude the complete switch from fossil fuel to renewable energy, an integral part of the carbon neutrality objective. Climate change and policy volatility add to optimization difficulties, influencing energy demand, supply, and operational efficiency.

To address the current challenges in energy system optimization, several suggestions had been proposed, including the Dual Residual Electricity Treatment System (DREST), the Improved Integrated Energy System (IIES), and the Stepped Carbon Penalty Response (SCPR). Through these advancements, energy systems will be able to operate at a lower cost, higher efficiency, and become more environmentally friendly. These new strategies address previous research gap through the integration of different energy systems, enhance energy storage efficiency, and adapt different responses to governmental policy. This provides a potential pathway for future carbon-neutral energy systems

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Despite the potential in the proposed solution in creating more eco-friendly energy systems, limitations still remain that hinder the practical implication. The proposed energy system model may face technical and financial barriers, limiting the large-scale implementation of such energy systems. Also, the models didn't account for the uncertainty in climate change development and the governmental policy, which may alter the actual operational cost for this energy system. Future research should focus on the real-world implication of theoretical energy systems, using technologies such as AI simulation to create more practical energy system models that include the potential uncertainty in the future.

To sum up, the study underscores the importance of optimizing the current energy system to achieve global climate target. By integrating renewable energy source, improved energy storage and carbon capture technologies, and adaptive response to policy and climate uncertainty, the proposed energy system can better advance the global pursuit of sustainable energy transition and limit the consequence of climate change.

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