Study on coupling factors between green development of power grid and ecosystem—from the perspective of energy industry chains

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Abstract. The green power grid development, with industry and regional characteristics, impacts energy systems and eco-friendly production. Ecosystem services are vital for sustainable development. Urgent research is needed to adapt to new situations. This study establishes index systems for power grid green development and ecology. Key factors affecting their coordination are identified, guiding the promotion of green power grid development. Focus on enhancing cross-regional clean energy allocation, waste disposal, noise monitoring, and increasing electric energy use in terminal consumption.

1. Introduction

Currently, China's ecological civilization construction includes the "double carbon" goal. Replacing fossil energy and reducing emissions in the energy sector are crucial for achieving carbon neutrality in China. The trend is towards constructing a new energy system centered on new energy sources\cite{1}. The power grid will serve as the main hub for clean energy production and consumption, playing a key role in leading energy transformation and encouraging the advancement of carbon-reduced manufacturing and daily living. As the functional forms of the electrical network continue to evolve, its influence on both upstream and downstream sectors in terms of green development is also shifting. Regarding the sustainable advancement of the electrical grid proper, China's current environmental protection system has adopted a supervision mode characterized by "simplified approval procedures, enhanced oversight, and strict accountability", imposing stricter environmental protection requirements on the power grid. Ecosystem provides important ecological services for society, which is very important for supporting green production and maintaining the sustainable development of society \cite{2}. In recent years, most studies tend to focus on the advancement of electrical grid proper. Wang Hua \cite{3} established the indicators for the evaluation of electricity network energy conservation and environmental safeguarding concerning grid loss, energy consumption in operation, and environmental stewardship of the power network; Wang Wei \cite{4} analyzed the evaluation system for the advancement of the eco-friendly power grid covering aspects such as safety, reliability, green initiatives, and economic sustainability. The sustainable advancement of the electrical grid should not only focus on its own environmental protection, but also take into account its crucial role. Therefore, it is necessary to research the development of both aspects to meet new challenges and determine the crucial elements impacting the eco-friendly advancement of the electrical grid. This study will design an index system for the green development of the electrical grid and the natural environment from the energy industry chain perspective, and analyze the interaction among the influencing factors of the electrical grid's green development and the natural environment using a coupling analysis method.

2. Index system for coupling evaluation

2.1. Index system for evaluating the eco-friendly advancement of electrical grids

Assessment criteria are set based on three perspectives \cite{5}, it includes three indicators. The primary indicators of integrated upstream green advancement of electrical grid (A1) include: the proportion of clean energy power generation to total power generation (B1), new energy usage ratio (B2), transmission capacity of trans-regional lines (B3) and energy storage on grid side scale (B4); The green advancement (A2) of electrical grid itself includes: assessment rate of the building environment project (B5), qualification rate of completed environment project (B6), sulfur hexafluoride reclamation rate (B7), integrated line loss ratio (B8), yearly electromagnetic interference monitoring extent at the substation (B9), treatment ratio of ordinary waste (B10), disposal ratio of used transformer oil (B11) and disposal lead storage battery disposal rate (B12). The downstream advancement of electrical grid cooperation (A3) includes:
the substitution amount of electric energy (B13), the ratio of electric power to terminal energy application (B14) and the latest electric vehicle charging station (B15).

2.2. Index system for evaluating the ecosystem

The influence of electricity system on the natural environment is thoroughly assessed. The Pressure-State-Response model [6] serves as the foundational framework for constructing an ecosystem evaluation index system, comprising three primary indicators: pressure, state, and response. The pressure indicator reflects the environmental impact of human activities, encompassing effects like resource demand, material consumption, and emissions from industrial operations. Key metrics include per capita CO2 emissions, individual SO2 emissions, individual NOx emissions, individual particulate matter (dust) emissions, and individual industrial solid waste output. State indicators track environmental conditions at specific time points, evaluating ecosystem status, natural environment quality, and human life quality. Metrics selected include annual average concentrations of CO2, SO2, NO2, PM2.5, and regional acoustic environmental monitoring compliance rates. Response indicators focus on societal and individual actions to mitigate and rectify the adverse effects of human activities on the environment. Investment indicators for general industrial solid waste disposal, industrial hazardous waste disposal, and industrial pollution control are considered for remedial actions.

2.3. Index system for evaluating coupling

Coupling refers to the collaborative connection between multiple systems, including coupling degree and coupling fitting degree [6]. The level of coupling indicates the extent of interconnection between systems, while the degree of coupling collaboration reflects the level of synchronization between systems. In the context of carbon neutrality and the energy revolution, the coupling and collaborative advancement of green power grid development and ecological environment preservation involve a shift from conventional energy consumption and power system expansion models to align with the natural system's material circulation and energy flow patterns. This aims to optimize energy utilization, minimize waste emissions, achieve a balance between economic and ecological benefits, and foster a positive interaction between the power grid and the environment. This research concentrates on green power grid development, assigning a higher evaluation weight of 0.6 to the power grid's green development system compared to the ecological environment system. This choice enables an in-depth analysis of the coupling dynamics between these two systems.

3. Research method

3.1. Green advancement of electrical grid

The standardization method involves using the target value of strategic plan for energy advancement or the predicted projected trend-based indicator as a benchmark.

\[
X_{ij} = \begin{cases} 
1 - \frac{q_j - x_{ij}}{\max(q_j - \min_{t=0} x_{ij}, \max_{t=0} x_{ij}) - q_j}, & x_{ij} < q_j \\
1 - \frac{x_{ij} - q_j}{\max(q_j - \min_{t=0} x_{ij}, \max_{t=0} x_{ij}) - q_j}, & x_{ij} > q_j \\
1, & x_{ij} = q_j 
\end{cases}
\]

\(X_{ij}\) is the standardized value of the j-th indicator in the i-th evaluated year; \(q_j\) is the ideal value of the j-th indicator; \(x_{ij}\) is the value of the j-th indicator of the i-th evaluated year.

3.2. Ecosystem

Due to the indeterminacy of the reference value for the eco-environmental system, the range method is employed for normalization. equations (2) and equations (3) are positive and negative indicators respectively.

\[
Y_{ij} = \frac{y_{ij} - \min(y_{ij})}{\max(y_{ij}) - \min(y_{ij})} \\
y_{ij} = \frac{\max(y_{ij}) - y_{ij}}{\max(y_{ij}) - \min(y_{ij})}
\]

\(y_{ij}\) is the original value of the j-th index in the i-th year; \(Y_{ij}\) is the normalized value after the treatment of the j-th index in the i-th year; \(\max(y_{ij})\) and \(\min(y_{ij})\) is the peak and trough value of the j-th index in all years.

4. Empirical research

4.1. Data selection

The data selected for analysis spans from 2006 to 2019 and is primarily sourced from the China Energy Statistics Yearbook, Environmental Statistics Yearbook, Environmental Bulletin, and other industry-specific data sources. In the context of fostering sustainable advancement within the electrical grid sector, reference values are established based on the target metrics outlined in the company's 2030 strategic goals, such as the share of clean energy generation and the transmission capacity of cross-regional power lines, or through index values derived from trend extrapolation methods.
4.2. Assessment outcomes of green advancement of electrical grid

Since the initiation of the "Eleventh Five-Year Plan", the green development of the electrical grid has shown continuous improvement across its three dimensions. The self-assessment level of the electrical grid's overall green advancement has consistently ranked the highest, signifying a relatively high environmental protection standard in current power grid construction projects. Although the evaluation level of downstream power grids remains low, the rate of improvement is rapid. As the green advancement level of downstream electrical grids continues to enhance gradually, the overall green advancement of the electrical grid in the future is expected to further advance, as shown in Figure 1.

4.3. Assessment outcomes of eco-environmental system

Since the implementation of the "Eleventh Five-Year Plan", China's overall environmental ecosystem has been steadily enhancing. Specifically, while energy consumption in various sectors has been increasing along with economic development, the ecological pressure has been kept relatively stable, thanks to the macroeconomic policies implemented by the government. Except for a slight decline in 2012-2013, the ecological environment in other years increased year by year, and finally stabilized, indicating that the ecological environment in China is constantly improving. The level of eco-environmental response is also increasing year by year, which shows that under the national policies and measures, China's ability to deal with eco-environmental disturbances and protect the eco-environment is getting stronger and stronger, as shown in Figure 2.

4.4. Influencing factor

4.4.1. Collaborative upstream green advancement of electrical grid.

Within the context of promoting the coordinated green advancement of the electrical grid upstream, key positive indicators include the ratio of clean energy in overall power generation, the deployment rate of renewable energy, trans-regional transmission capacity, and grid-side energy storage capacity. As each of these indicators increases, the degree of coupling coordination also rises, demonstrating a strong correlation between positive indicators and the coordination degree of the two systems. This relationship has a facilitating effect and illustrates a consistent growth trend. Therefore, it is imperative to further advance the development of various...
clean energy sources, such as solar, wind, and hydro power, facilitate the regional distribution of new energy, enhance utilization efficiency, and maximize the green advancement benefits of the electrical system, as shown in Figure 3.

**4.4.2. Green advancement of electrical grid itself.**

Within the framework of the electrical grid's own green development, the overall line loss ratio stands as the sole negative indicator. As the line loss rate decreases and positive indicators increase, the degree of coupling coordination also grows. Notably, the ratio of environmental impact assessment for construction projects, the ratio of environmental approval for completed projects, the comprehensive line loss ratio, the annual monitoring coverage rate of electromagnetic noise in substations, and the general waste disposal ratio have a more significant impact on coupling coordination. This underscores the importance of intensifying environmental protection measures in power grid construction projects, emphasizing scrap recycling management throughout the entire lifecycle of electrical grid construction, operation, and decommissioning, and advancing efforts to reduce line loss rates through technical and managerial interventions, as shown in Figure 4.

**4.4.3. electrical grid coordinates downstream green advancement.**

In the downstream green advancement coordination of the electrical grid, the electric energy proportion in terminal energy consumption significantly influences the ecological environment. Other indicators have a more substantial impact on coupling collaboration in the early stages of advancement, eventually stabilizing. This highlights the importance of implementing electric energy substitution strategies and enhancing overall societal electrification levels in downstream green power grid development. Promoting replacement of electric energy in critical sectors, restructuring final energy consumption, and leveraging the positive impact of downstream electrical grid cooperation on the natural environment are crucial steps, as shown in Figure 5.
5. Conclusion

From the standpoint of the energy industry chain, we have established systems for green development in the electrical grid and ecosystem evaluation indices, and the following conclusions are obtained by digging back the key influencing factors through the indicators:

In the context of green advancement in the electrical grid, it is essential to prioritize boosting interregional transmission capacity and optimizing the distribution of clean energy in the upstream sector. To promote green advancement within the power grid, it is crucial to introduce enhanced management and technical strategies aimed at reducing overall line loss rates, expanding the monitoring in substations electromagnetic noise, and improving the efficiency of transformer oil and disposal of waste lead batteries. Furthermore, downstream green advancement efforts in the electrical grid should focus on promoting the adoption of electric energy and increasing the ratio of electric energy in final energy consumption.

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