CHEMICAL ENGINEERING TRANSACTIONS

VOL. 120, 2025

A publication of AIDIC

The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Bing Shen How, Viknesh Andiappan, Denny K.S. Ng, Hon Loong Lam, Petar S. Varbanov

ISBN 979-12-81206-21-2; **ISSN** 2283-9216

DOI: 10.3303/CET25120059

Techno-economic and Environmental Feasibility of Grid-integrated Wind Power for Energy-intensive Industry Under Policy and Market Uncertainties

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Considering the increasing energy costs and decarbonization requirements of the energy sector, economical and sustainable power supplies have gained significant attention for the long-term development of energy-intensive industries. With advancements in wind power generation technology, the integration of local wind resources present a viable solution for providing clean power for industrial production while reducing electricity costs, grid dependence, and emissions. This study aimed to develop an assessment method to evaluate the techno-economic feasibility and environmental benefits of a large-scale grid-integrated wind power plant for industrial applications. In this study, a case study of oilfield electrification in Northeast China was conducted. The internal rate of return (IRR) was used as the primary indicator for techno-economic evaluations. Additionally, a sensitivity analysis was conducted to investigate the impact of wind curtailment and carbon price variations on the IRR of the proposed power plant. The results indicated that despite the wind curtailment challenge, the wind power plant maintained an IRR exceeding 6%, with carbon benefits of approximately 32,000 t CO_2 reduction per year and nearly $440,000 in annual revenue, demonstrating the economic viability and sustainability of large-scale wind power plant deployment for energy-intensive industrial applications.

1. Introduction

Given the global energy structure's accelerating transition towards low carbonization, the construction of clean energy facilities connected to existing grids has become an integral component in the development of a modern energy system that is characterized by safety, efficiency, and environmental sustainability (Li et al., 2025). According to the IEA report, industrial energy consumption accounts for >70% of the total energy consumption globally, and carbon emissions from the energy sector comprise 85% (IEA, n.d). Given its status as the primary domain of energy consumption and the predominant contributor to greenhouse gas emissions, the industrial sector is currently grappling with dual challenges: the need to manage energy costs and the mandate to reduce carbon emissions. Against this background, exploring a green development path that considers both energy cost optimization and carbon emission reduction synergy has become a key issue for the energy transition of the industrial sector.

In recent years, renewable energy sources, particularly wind and solar power, have notably increased. According to statistics from the International Renewable Energy Agency (IRENA), the new installed capacity of renewable energy in 2024 reached 585 GW globally, accounting for 92.5% of the new power installed capacity. Photovoltaic power and wind power contributed 451.9 GW and 113 GW, respectively (IRENA, 2025). Despite the continuous growth in installed capacity, the development of renewable energy is encumbered by systemic challenges. On the one hand, the lagging development of grid infrastructure results in inadequate capacity for absorbing new energy, with a significant portion of new energy unable to be connected to the grid (Farrokhabadi et al., 2020). On the other hand, the carbon trading market has a substantial positive impact on the development of new energy. However, the cooperative development between the current carbon market mechanism and renewable energy projects is incomplete, and the value of environmental rights has not been

Paper Received: 21/04/2025; Revised: 10 September 2025; Accepted: 11 October 2025
Please cite this article as: Hang J., Li J., Liu P., Zhang G., Liu H., 2025, Techno-economic and Environmental Feasibility of Grid Integrated Wind Power for Energy-Intensive Industry Under Policy and Market Uncertainties, Chemical Engineering Transactions, 120, 349-354 DOI:10.3303/CET25120059

effectively internalized into project economic benefits, thereby exacerbating investment uncertainty (Xu and Yang, 2024). The present technical and economic evaluation system does not adequately account for these practical constraints, resulting in deviations in life-cycle assessment.

A comparison of wind power generation with other renewable energy sources reveals several distinctive advantages. These include a reduction in land use and a decrease in costs due to technological advancements, such as increased single-unit capacity, enhanced output stability, and improved adaptability to specific conditions (Enevoldsen and Xydis, 2019). According to data from IRENA, the global onshore wind power unit installation cost decreased by 49% (from \$2,272 to \$1,160 per kW) and the levelized cost of electricity (LCOE) decreased by 70.3% (from \$0.111 to \$0.033 per kWh) between 2010 and 2023 (IRENA, 2024). Currently, grid-integrated wind turbine units have become the prevailing configuration as they can reduce energy loss and enhance power supply reliability (Farrokhabadi et al., 2020). Nevertheless, the translation of cost benefits into viable investment opportunities is encumbered by two primary constraints. First, wind power curtailment due to physical grid limitations is a risk. Second, environmental benefits cannot be reflected owing to the absence of a carbon market pricing mechanism. These challenges result in deviations from traditional cost-benefit analyses, particularly in the context of the rapid growth of carbon trading on the carbon market.

Considering these issues, this study developed an economic feasibility assessment method for renewable energy grid-integrated power generation projects. This assessment method incorporated carbon market benefit and policy change considerations. The internal rate of return (IRR) was employed as a pivotal indicator for economic analysis, and sensitivity analysis was performed to consider the impact of feed-in tariffs and on-grid energy on IRR. The effectiveness and reliability of the method were demonstrated through a case study of a large-scale wind power project connected to the grid in a specific oilfield in Northeast China. This study provided quantitative support and a practical reference point for the economic analysis of renewable energy grid-integrated power generation projects in energy-intensive industrial scenarios.

2. Methodology

The interaction between wind turbine units and the grid was obtained, as well as equipment maintenance records through on-site tracking investigation. Several key technical and economic parameters were acquired, including equipment purchase costs and full life cycle operation and maintenance costs. Utilizing feed-in tariffs and on-grid energy, the revenue of wind turbine units throughout their life cycle was calculated. The IRR is a pivotal indicator in economic feasibility analyses. When constructing the discounted cash flow model for the full life cycle, the carbon benefits were also considered. The dynamic carbon benefits that the wind farm could obtain were calculated based on the CO_2 reduction of the project and the dynamic carbon price on the carbon market. Furthermore, a sensitivity analysis was performed to assess the impact of policy alterations on the economic viability of the project, with the feed-in tariff and on-grid energy serving as the primary sensitivity analysis variables.

The IRR was defined as the discount rate that resulted in a net present value of zero for the project. This formula demonstrated the net value changes at each timeline throughout the entire life cycle of the project. The net value change was defined as the net cash inflow of each period minus the net cash outflow of each period. The net cash inflow encompassed the project's alternative electricity income, output tax, and carbon emission reduction income. The specific calculation formula is as follows:

$$\sum_{t=1}^{n} \frac{C_t}{(1+IRR)^t} - C_0 = 0 \tag{1}$$

where C_0 (\$) is the initial investment and construction cost, C_t (\$) is the net cash flow change in period t, and n is the time of the project. IRR (%) is the internal rate of return of the project, which is the interest rate that causes a net present value of zero. C_t (\$) includes the project's net cash inflow, $C_{i(t)}$, and outflow, $C_{0(t)}$, and the specific formula is:

$$C_t = C_{i(t)} - C_{0(t)} \tag{2}$$

where the formula for $C_{i(t)}$ is:

$$C_{i(t)} = Revenue_{sellback} + Tax_{vat,output} + Revenue_{CO_2} \tag{3}$$

The formulas for the revenue from returned electricity, $Revenue_{sellback}$; output tax, $Tax_{vat,output}$; and carbon emission reduction income, $Revenue_{CO_2}$, were:

$$Revenue_{sellback} = Price_{sellback} \times E_{sellback} \tag{4}$$

$$Tax_{\text{vat, output}} = Revenue_{sellback} \times r_{vat,output} \tag{5}$$

$$Revenue_{CO_2} = Price_{CO_2} \times M_{CO_2} \tag{6}$$

where $\text{Price}_{\text{sellback}}$ is the feed-in tariff, $\text{E}_{\text{sellback}}$ is the on-grid energy, $r_{\text{vat, output}}$ is the output tax rate (set at 13%), $Price_{CO_2}$ is the carbon price which changes dynamically over time, and M_{CO_2} is the carbon emission reduction quantity.

The specific formula for the net cash outflow $C_{0(t)}$ was:

$$C_{0(t)} = C_{goods} + V_{input} + Tax_{vat} + Tax_{cit} + Tax_{other} \tag{7}$$

C_{goods} represents operating costs, while V_{input} represents input VAT, Tax_{vat} represents value-added tax, Tax_{cit} represents corporate income tax, and $\text{Tax}_{\text{other}}$ represents other taxes.

The formula for input, VAT V_{input}, was:

$$V_{input} = C_{goods} \times r_{tax,vat,input} \tag{8}$$

Where the input VAT rate, $r_{\text{tax, vat, output}}$, was set at 5%.

The formula for the value-added tax amount, Tax_{vat}, was:

$$Tax_{vat} = V_{output} - V_{input} \tag{9}$$

The formula for the corporate income tax amount, Tax_{cit}, was:

$$Tax_{cit} = (Revenue_{sellback} - C_{total}) \times r_{tax,cit} \tag{10}$$

where C_{total} represents the average annual total cost, and the corporate income tax rate, $r_{\text{tax, cit}}$, was set at 25%.

The formula for other taxes, $\text{Tax}_{\text{other}}$, of the project was:

$$Tax_{other} = Tax_{vat} \times r_{other} \tag{11}$$

The rate of other taxes, r_{other}, was set at 12%.

3. Case Study

3.1 Site description

The study site is situated within the confines of the oilfield production area (45° to 50° N). The climate in this region exhibits distinct seasonal characteristics, featuring high wind speeds in spring and autumn and low wind speeds in winter and summer.

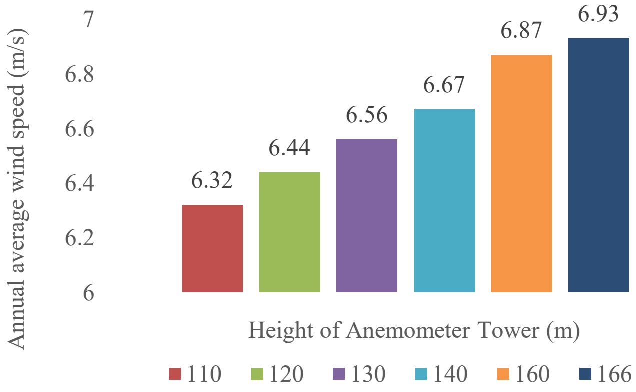

Figure 1: Annual Average Wind Speed at Different Heights of Anemometer Towers in 2024

The assessment of wind energy resources in the region revealed the project area was particularly conducive to wind energy production. At an altitude of 100 m, the wind power density in this area ranges from 250 to 330 W/m^2, with an average wind speed of 6.1 to 7.0 m/s. The annual average wind speeds measured at different heights in 2024 are shown in Figure 1. The annual cumulative hours of effective wind speed (3-25 m/s) in this region are greater than or equal to 5,200 h, demonstrating the resource endowment suitable for the construction of a large-scale wind farm.

3.2 Technical and economic parameters of wind turbines and grid conditions

The technical and economic characteristics of various units, the projected demand, and the accessibility of the grid were comprehensively evaluated. Power generation, unit investment, and technical maturity of different wind turbine units were considered, and two wind turbine units with a power of 6,250 kW and a hub height of 160 m were proposed. The technical and economic parameters of the wind turbines are delineated in Table 1.

Table 1: Technical Parameters of Wind Turbines

Content	Value
Cut-in wind speed (m/s)	2.5
Cut-out wind speed (m/s)	20
Safe wind speed (m/s)	52.5
Rotational speed (rpm)	361
Blade diameter (m)	204
Hub height (m)	160
Single-unit capacity (Mw)	6.25
Cost of wind turbine ($/kW)	271
Number of units	2

The calculated annual theoretical power generation of the project based on the local wind energy resources was 55.52 GWh. After considering realistic and objective factors, including but not limited to blade contamination, wind turbine unit utilization rate, on-site power consumption, line loss, and climate impact, the total reduction coefficient was 27 %. The annual on-grid energy was 40.53 GWh, and the equivalent full-load operating hours were 3,242 h. The oilfield site of the proposed project has its own power transmission and distribution network facilities for production energy use. The electricity generated by the project is transmitted to the substation via a 35 kV collection line and subsequently integrated into the grid. Currently, the oilfield is in the nascent stage of green power substitution (renewable energy power generation project). The scale of on-grid renewable energy remains relatively constrained, precluding the emergence of large-scale wind power curtailment issues due to its impact on the grid.

4. Results and Discussion

4.1 Feasibility analysis

An economic feasibility analysis was conducted for the proposed wind power grid-integrated project under the base scenario (feed-in tariff of 0.068 USD/kWh and annual on-grid energy of 40.53 × 10^6 kWh). The initial investment was 17.89 × 10^6 USD, and its annual operating cost was 0.68 × 10^6 USD. The IRR was projected to reach 7.6 %, which exceeded the industry benchmark of 6 % when carbon benefits were not accounted for.

In addition, the fluctuations in carbon prices in relation to the evolution of the regional carbon trading market were examined to calculate the dynamic carbon benefits. The initial carbon price was set at $12 per t, with an annual increase of $2 per ton, culminating in a stabilized price of $ 20 per t after a five-year period. The project was estimated to generate 40.53 × 10^6 kWh of clean wind power annually, concurrently reducing CO_2 emissions by approximately 32,000 t y^{-1}. The findings revealed that incorporating a carbon trading mechanism within the base scenario of allowing for carbon benefits significantly enhanced the project's resilience. The introduction of the carbon trading mechanism increased the IRR of the base scenario by 55 %, reaching 11.8 %, and maintained an IRR of 9.1 % in the extreme scenario. This indicated that the calculation method of "electricity revenue + carbon emission reduction revenue" effectively enhanced the project's IRR.

4.2 Sensitivity analysis

The sensitivity analysis focused on the impact of fluctuations in on-grid energy and tariffs on the project's IRR. Considering the anticipated advancements in the local grid's capacity to accommodate renewable energy generation, the reduction in the on-grid energy due to variations in wind curtailment rates was 0-20 %. Concurrently, the range in tariff fluctuations was ±15 % of the benchmark price, which was 0.068 yuan. The outcomes are illustrated in Figure 2, with the horizontal axis representing the feed-in tariff and the vertical axis representing the reduction due to wind curtailment. The IRR values exhibited a clear increase from dark blue to dark red. These findings indicated that the IRR was considerably influenced by the simultaneous fluctuations in tariffs and wind curtailment rates. When the tariff was at the benchmark level of 0.068 yuan, for every 5 % increase in the wind curtailment rate (corresponding to a 5 % reduction in the amount of electricity fed into the grid), the IRR decreased by an average of 0.65 %, gradually decreasing from 11.8 % (0 % wind curtailment) to 9.1 % (20 % wind curtailment). The downward pressure on tariffs exerted a significant inhibitory effect on the IRR. When the tariff decreased to 0.0578 yuan (-15 %) and the wind curtailment rate reached 20 %, the IRR declined to a minimum of 7.4%, a decrease of 4.4 % compared to the benchmark scenario. However, when the tariff declined by 10 % ($ 0.0612), under the same wind curtailment rate, the IRR decreased to 8.0 %. Conversely, an increase in tariffs partially offset the impact of the wind curtailment rate. For example, when the tariff increased by 15 % ($0.0782), even if the wind curtailment rate increased to 20 %, the IRR was maintained at 10.8 %, which was 1.7% higher than that of the scenario with the same wind curtailment rate under the benchmark tariff. When the tariff increased by 5-15 %, the decrease in the IRR due to shifts in the wind curtailment rate stabilized at 0.7 % to 0.9 % for every 5 % increase in the wind curtailment rate. This suggested that the positive impact of rising tariffs on project returns had a diminishing marginal effect. This was because, under elevated tariffs, the revenue loss per kilowatt-hour increased, thereby intensifying the adverse impact of the wind curtailment rate on the IRR. The project's capacity to withstand risk was substantially influenced by the interplay between tariffs and wind curtailment rates. Relying exclusively on an increase in tariffs is challenging in terms of continuously offsetting the risk posed by increasing wind curtailment rates. A heightened level of scrutiny is warranted when considering the possibility of a concurrent decline in tariffs and a high wind curtailment rate because this scenario posed a pronounced risk to the project's financial stability.

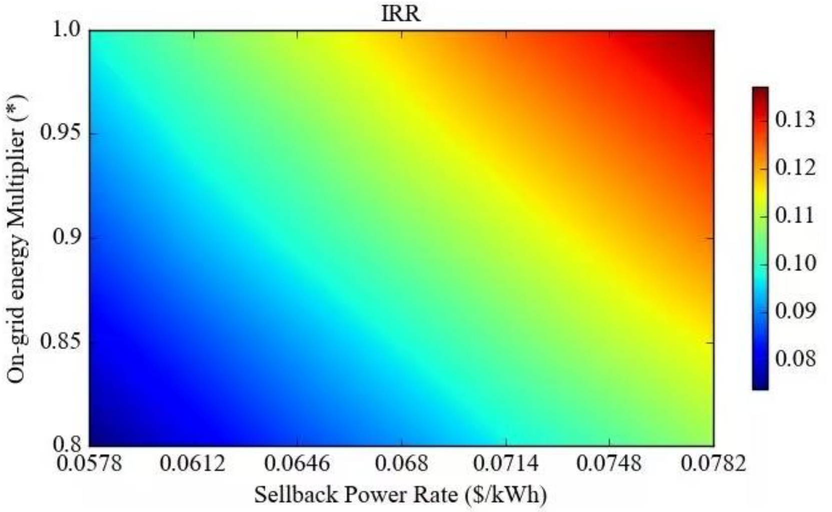

Figure 2: Sensitivity Analysis Result

4.3 General observations

The impact of changes in external conditions (allowable on-grid energy) and policy changes on the economic feasibility assessment of grid-integrated wind power projects should be prioritized. Wind power project constructors and investors should enter long-term contracts to mitigate the risks of feed-in tariff volatility. Concurrently, at the policy level, power market reform and the associated subsidy policies for the utilization of renewable energy must be monitored closely. To ensure the sustainable development of the renewable energy industry, policymakers must perform regional grid absorption capacity assessments and rationally judge medium and long-term grid planning and corresponding incentive policies based on future development needs.

5. Conclusion

This study explored the discrepancy between conventional economic assessment methodologies and actual development outcomes. An economic feasibility assessment method for grid-integrated renewable energy projects that considered both carbon market benefits and policy changes was proposed. A case study of a large-scale wind power project in an oil-gas field in China was conducted. The findings of the research indicated that in the absence of integrating carbon benefits, the project's capacity to withstand risk was considerably constrained. Furthermore, when the wind curtailment rate was >10 % or the feed-in tariff declined by a similar margin, the IRR approached a critical value of 6 %, which is considered the industry standard for viability. In a worst-case scenario, where the wind curtailment rate reached 20 % while the feed-in tariff remained constant, the IRR declined to 4.4 %, rendering the project unfeasible from an investment perspective. This underscored the substantial impact of wind curtailment on project feasibility assessments. In the same extreme scenario, incorporating carbon benefits (the dynamic discounting of carbon quota trading benefits) can augment the project's IRR to 9.1 %, mitigating the constraint of relying solely on electricity revenue. This study quantified the marginal contribution of carbon prices to revenue and considered changes in external conditions. The economic feasibility assessment method for grid-integrated renewable energy projects was improved, providing scientific support for investment decisions in developing projects in energy-intensive industries (such as oil and gas, chemical, and metallurgical industries). Future research should combine regional carbon market trading rules and renewable energy consumption policies as well as consider dynamic carbon prices and real-time interaction with the grid to enhance the depiction of real-world scenarios.

Author contributions

Jihong Hang: Methodology, Investigation, Data Curation, Writing-original Draft. Jinze Li: Methodology, Investigation, Project Administration, Conceptualization, Writing – Review & Editing. Pei Liu: Writing-review & editing, Validation. Guosheng Zhang: Validation, Funding acquisition. He Liu: Supervision, Funding Acquisition.

Acknowledgments

The authors gratefully acknowledge support from The National Natural Science Foundation of China (72140005).

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