Review

A Review of Synergies Between Advanced Grid Integration Strategies and Carbon Market for Wind Energy Development

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Abstract: The integration of wind energy into power systems is essential for achieving global decarbonization goals but poses significant challenges, including transmission losses, grid instability, and risks of wind farm disconnection during contingencies. This review focuses on advanced grid stability technologies, optimization strategies, and carbon trading mechanisms, proposing a synergistic framework to address these issues. By enhancing transmission efficiency and maintaining grid stability, these solutions reduce energy losses, contribute to carbon reduction, and create economic incentives through carbon credits. Moreover, optimization models enable wind farms to remain operational during severe faults, ensuring their active participation in carbon markets. This review connects recent technical advancements with economic and policy frameworks, offering a comprehensive pathway to achieving sustainable and stable power systems while maximizing the economic potential of wind energy.

Keywords: wind energy integration; grid stability technologies; security-constrained optimal power flow; optimization strategies; carbon markets; renewable energy; emission reduction

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1. Introduction

The global transition to a low-carbon economy has intensified the need for integrating renewable energy sources into power systems. As highlighted in the Paris Agreement, countries worldwide are committed to achieving carbon neutrality by 2050, making the energy sector—a major contributor to global greenhouse gas emissions—a critical area for decarbonization efforts [1,2]. Wind energy, with its vast potential and scalability, has emerged as a cornerstone of these efforts, offering a sustainable and cost-effective solution for meeting rising electricity demand while reducing emissions.

Global wind power capacity has seen rapid growth, with 117 GW of new installations in 2023 alone, bringing the total cumulative capacity to 1021 GW and surpassing the 1 TW milestone [3]. This growth has been driven by both technological advancements and supportive policy frameworks, particularly in key markets like China, the United States, and Brazil. China alone contributed 75 GW in 2023, representing nearly 65% of the global total [4]. As shown in Figure 1, 2023 marked a record year for onshore wind installations, with 106 GW added—54% more than the previous year. Offshore wind also experienced notable growth, with 10.8 GW of new capacity added, marking the second-best year on record for offshore wind [5].

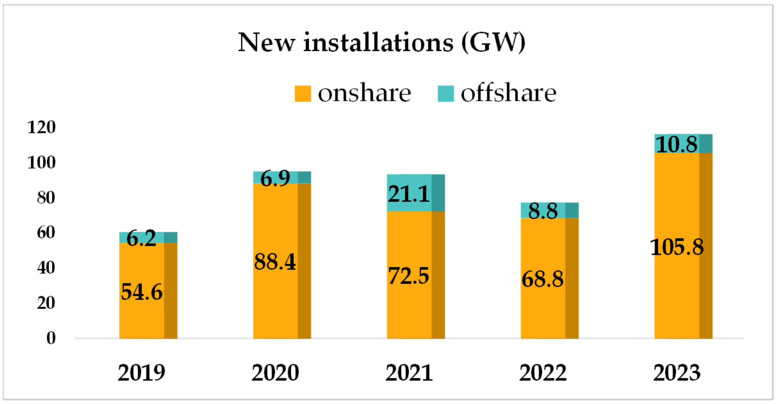

Figure 1. Record growth of onshore and offshore wind power installations in 2023 (data source: GWEC [5]).

Despite this progress, integrating large-scale wind power into existing grids remains challenging due to its variability and intermittency. These characteristics lead to grid instability, such as voltage fluctuations, frequency deviations, and reactive power imbalances, particularly in regions with high wind energy penetration [5,6]. Traditional grid infrastructures, originally designed for dispatchable power sources, are ill-equipped to manage these fluctuations, necessitating advanced control strategies to maintain grid stability and operational efficiency.

Among emerging solutions, static synchronous series compensators (SSSCs), key components of flexible AC transmission systems (FACTSs), have gained attention for their ability to address these challenges [6,7]. SSSC technology enhances grid performance by providing dynamic compensation for power flow variations, reducing transmission losses, and stabilizing voltage under fluctuating wind conditions [8,9]. For instance, Ma et al. demonstrated that integrating SSSC with hybrid control strategies effectively mitigates voltage drops and enhances microgrid resilience [10]. By improving transmission efficiency, SSSC enables general power producers and wind energy operators to reduce energy losses, contributing to carbon reduction and generating carbon credits that can be partially allocated as incentives to transmission operators [11,12].

Meanwhile, wind energy operators face additional challenges related to grid stability during severe faults. Disconnections caused by grid contingencies force wind farms to exit carbon trading markets, disrupting both economic returns and emission reduction goals. The security-constrained optimal power flow (CSCOPF) model has been proposed to address this issue by optimizing power dispatch under fault conditions [13]. CSCOPF ensures that the grid maintains stability without requiring immediate manual adjustments, allowing wind farms to remain connected and continue participating in carbon trading markets [14].

At the policy level, carbon trading systems have emerged as a key mechanism for supporting renewable energy adoption. For example, the European Union Emissions Trading System (EU ETS) has successfully reduced emissions by over 30% since its inception while promoting investments in renewable technologies [15,16]. Carbon trading assigns a financial value to emission reductions, creating incentives for industries to adopt cleaner energy solutions. When combined with technologies like SSSC and CSCOPF, carbon trading provides a unified framework for achieving economic benefits and grid stability, aligning the goals of transmission operators and wind energy producers [17].

Despite these advancements, the existing research primarily focuses on either technical solutions (e.g., grid stability technologies) or economic mechanisms (e.g., carbon trading), often treating them in isolation. Several review papers have explored specific aspects of wind energy integration. For instance, Ghadimi et al. [6] focused on FACTS devices like SSSC for improving grid stability, while Zhang et al. [18] emphasized the potential of ladder-type carbon trading models in incentivizing renewable energy adoption. Gao et al. [19] highlighted policy-driven frameworks for energy system optimization but lacked discussion on the interaction between grid technologies and market mechanisms. These studies provide valuable insights into isolated aspects of energy systems but fail to address the synergies between technical advancements and policy-driven frameworks. This review builds on these studies by presenting a coordinated framework that integrates these domains, bridging the gap between technical and economic approaches. Understanding this interaction is crucial for enhancing wind energy integration and achieving decarbonization goals.

This review addresses these gaps by proposing a synergistic framework that combines wind energy integration, SSSC technology, CSCOPF strategies, and carbon trading mechanisms. Specifically, this study aims to:

(1) Evaluate the role of SSSC technology in reducing transmission losses and improving grid stability [6–12].
(2) Analyze how CSCOPF strategies maintain grid resilience during severe contingencies, enabling continuous wind farm operation and market participation [13,14].
(3) Explore the integration of SSSC, CSCOPF, and carbon trading systems to optimize grid performance, reduce emissions, and create economic incentives for stakeholders [15–19].

While these objectives align with existing efforts, recent studies highlight the need for a more coordinated approach that bridges technological advancements with policy-driven frameworks to fully unlock the potential of low-carbon energy systems [20].

By synthesizing recent advancements, this study provides a comprehensive overview of the interactions between technical solutions and carbon trading mechanisms. It highlights the potential for aligning advanced grid technologies with market-based policies to achieve resilient, sustainable, and economically efficient power systems.

The remainder of this paper is organized as follows: Section 1 introduces the background and motivation for this study, highlighting the challenges of integrating wind energy into power systems and the need for coordinated technical and economic frameworks. Section 2 explores advanced control strategies, focusing on static synchronous series compensators (SSSCs) and their role in mitigating transmission losses and enhancing grid stability in wind energy systems. Section 3 analyzes the role of carbon trading mechanisms, emphasizing their impact on incentivizing renewable energy adoption and aligning economic incentives with decarbonization goals. Section 4 highlights the synergies between advanced grid technologies and carbon trading mechanisms, proposing a unified framework to address both technical and economic challenges. Section 5 presents case studies validating the proposed framework through practical scenarios, demonstrating its applicability and benefits. Finally, Section 6 summarizes this study's key findings, discusses implications for policy and practice, and outlines potential directions for future research.

2. Control Strategies in Wind Energy Integration

The global shift towards renewable energy sources has positioned wind energy as a central pillar in the decarbonization of the power sector [21,22]. However, the integration of wind energy presents significant challenges, primarily due to its intermittency and variability. Efficiently integrating wind energy while maintaining grid stability requires the implementation of sophisticated control strategies and optimization models. This chapter explores the application of static synchronous series compensators (SSSCs) [23] and security-constrained optimal power flow (CSCOPF) models [24] in wind energy integration, focusing on their potential to stabilize power flows, improve grid reliability, and contribute to carbon reduction goals.

2.1. SSSC and Its Application in Wind Energy Integration

SSSC is a critical device for stabilizing power systems when integrating renewable energy sources like wind power. Given the intermittent nature of wind generation, power systems often face voltage instability and power flow imbalances. SSSC addresses these issues by dynamically injecting a series voltage into the transmission line, aligned with the current phase, thereby controlling power flow and stabilizing voltage fluctuations [23]. As illustrated in Figure 2, SSSC utilizes a voltage source converter (VSC) and pulse width modulation (PWM) techniques to regulate voltage magnitude and phase, reducing transmission losses and enhancing overall grid stability. In high wind penetration regions, SSSC acts as a dynamic stabilizer, injecting controlled reactive power to mitigate grid disturbances caused by fluctuating wind power.

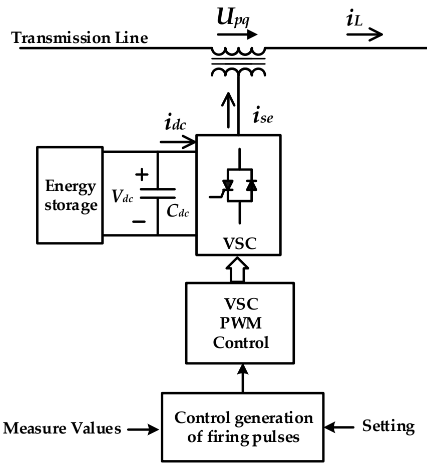

Figure 2. Overview of the SSSC structure [23].

Practical Studies and Carbon Market Implications:

Recent studies, such as Sadiq et al. (2024) [25], demonstrate that SSSC effectively mitigates power oscillations and improves voltage stability during periods of significant wind generation variability. However, these studies primarily focus on small-scale systems or ideal conditions, limiting their applicability to large-scale wind-integrated grids. For example, Zunnurain et al. [26] explored the resilience benefits of SSSC but did not address its economic implications. Similarly, Ma et al. [12] demonstrated improvements in microgrid voltage stability but left gaps regarding its integration within carbon trading mechanisms. While Sadiq et al. [25] highlighted SSSC's effectiveness in stabilizing grid voltage, their focus was primarily on small-scale systems under ideal conditions. Zunnurain et al. [26] further explored SSSC's resilience benefits but did not address its economic implications within large-scale wind-integrated grids. Ma et al. [12] demonstrated SSSC's potential to reduce voltage drops in microgrids; however, the broader integration of SSSC within carbon trading frameworks remains insufficiently studied.

Moreover, integrating SSSC technology within carbon trading frameworks offers substantial economic benefits. By reducing transmission losses, SSSC indirectly generates carbon credits through improved wind energy utilization. These carbon credits can serve as economic incentives for transmission operators, encouraging further adoption of SSSC technology. This integration not only supports grid stability but also aligns with policy-driven carbon reduction frameworks, fostering a mutually beneficial relationship between technical advancements and market-based mechanisms. This improved efficiency not only enhances renewable energy delivery but also creates opportunities to align technological investments with carbon market incentives. By quantifying transmission loss reductions and linking them to carbon credits, SSSC could serve as a key enabler for transmission operators to actively participate in carbon markets, fostering a win–win scenario for both grid stability and economic returns.

As Lu et al. (2023) highlighted [23], optimizing power flow with SSSC allows renewable generation to displace fossil fuel-based power, leading to measurable reductions in emissions. These carbon credits can be allocated to transmission operators as economic incentives, aligning grid stability solutions with market-based mechanisms for carbon reduction.

The interaction between SSSC and wind energy systems can be modeled using the equivalent current injection (ECI) method [24]. Ma et al. [12] demonstrated that, by integrating SSSC with hybrid dual-vector controllers, voltage drop compensation and microgrid resilience were significantly improved. These findings emphasize the role of SSSC in mitigating reactive power imbalances in high wind penetration grids, further reinforcing its potential to support grid stability while enabling greater renewable energy utilization. By introducing a virtual bus (Figure 3), SSSC regulates real and reactive power flow dynamically, enhancing load flow analysis and providing greater control over grid stability. The resulting improvements in power quality and transmission efficiency play a pivotal role in promoting the economic viability of wind energy projects in carbon markets. While SSSC effectively addresses power flow challenges and reduces transmission losses, further research is needed to evaluate its scalability and long-term economic impact within carbon trading systems. The complementary role of CSCOPF in maintaining grid stability and enhancing market participation will be discussed in the following section.

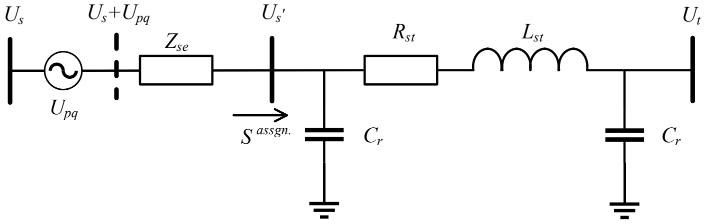

Figure 3. The modified model of the SSSC equivalent circuit.

Table 1 provides a comprehensive overview of the practical applications of SSSC and CSCOPF, alongside a comparative analysis of traditional dispatch methods under standard constraints. The summarized cases highlight the capabilities of SSSC and CSCOPF in enhancing grid stability, optimizing power dispatch, and facilitating continuous participation in carbon trading markets.

In contrast, traditional dispatch approaches, although effective in minimizing generation costs under conventional conditions, face limitations in accommodating high wind energy penetration and integrating carbon market mechanisms. This comparison underscores the growing importance of advanced technologies like SSSC and CSCOPF in addressing the challenges of modern power systems. The findings reinforce their potential to improve operational efficiency, support renewable energy integration, and contribute to global carbon reduction efforts.

Table 1. Practical applications of SSSC and CSCOPF.

Case Name	Application Scenario	Technology Used	Key Outcomes	Practical Implications
Traditional Dispatch [18,23,24,27]	Economic load dispatch under standard constraints	Traditional OPF	Minimized generation costs, limited response to contingencies	Suboptimal for high wind penetration regions, lacks carbon market integration
High Penetration Wind Area [7,8,11,12,25]	Voltage stability management	SSSC	Reduced voltage fluctuations, optimized power flow	Improved transmission stability
Fault Power Dispatch [9,10,21,24]	Fault recovery and reliability analysis	CSCOPF	Maintained wind farm connection, optimized generation costs	Ensured wind power market participation
Microgrid Operation [23,24]	Dynamic load balancing	SSSC + CSCOPF	Reduced transmission losses, improved efficiency	Increased carbon credits, reduced emissions
SSSC in Renewable Systems [9,26,28]	Optimal placement of SSSC in renewable-integrated grids	SSSC	Enhanced system reliability, reduced power losses	Demonstrates SSSC's role in improving renewable integration
Hybrid Wind-Driven Systems [12,29,30]	Optimization of hybrid renewable energy systems	SSSC + CSCOPF	Improved voltage stability, minimized emissions	Synergistic benefits of integrating wind and solar energy

2.2. Power Flow Instability and CSCOPF in Wind Energy Integration

The variability of wind generation introduces significant power flow instability, causing issues such as voltage sags, frequency deviations, and line overloads. Traditional grid management techniques are often inadequate to handle these challenges, necessitating the development of advanced optimization models like security-constrained optimal power flow (CSCOPF) [24].

The CSCOPF model ensures that the grid remains stable while accommodating large-scale wind energy integration. By optimizing power generation dispatch under security constraints (e.g., voltage limits, line capacities), the CSCOPF model minimizes operational costs while maintaining grid reliability. While Lu et al. [24] successfully demonstrated CSCOPF's role in grid stability, their study focused on static conditions, leaving its performance under dynamic fault scenarios less explored. Additionally, the existing research often simplifies wind variability, neglecting its real-time impact on carbon credit generation and market participation. Addressing this gap requires stochastic models that simulate the dynamic interaction between wind fluctuations and power flow optimization. The objective function of CSCOPF considers both economic factors (e.g., minimizing generation costs) and operational constraints, as expressed in Equation (1):

$$\begin{gathered}\min \sum_{i=1}^{N} C_i(P_i) \\ \text{subject to}: \quad P_{min} \le P_i \le P_{max}, \quad V_{min} \le V_i \le V_{max}, \left|P_{flow}\right| \le P_{max\_flow},\end{gathered} \tag{1}$$

where C_i (P_i) is the cost function of generation i, P_i is the generated power, P_{min} and P_{max} are the minimum and maximum limits for generation at node i, V_i is the voltage magnitude at node i, P_{flow} is the power flow across the transmission line, and P_{max_flow} is the maximum allowable power flow.

Ensuring Market Participation through CSCOPF

One of the critical roles of CSCOPF is maintaining grid stability during severe contingencies, which prevents wind farms from disconnecting. This stability ensures that wind energy producers can continuously participate in carbon trading markets. By ensuring uninterrupted power delivery, CSCOPF safeguards the economic viability of wind farms in carbon markets. Prioritizing renewable energy dispatch during high wind availability reduces dependency on fossil fuels and generates consistent carbon credits, which are critical for achieving long-term emission reduction targets. As Lu et al. (2024) demonstrated [24], the application of CSCOPF enables grids to prioritize wind energy over fossil fuel generation during high wind availability, leading to significant emission reductions.

The integration of CSCOPF into wind power systems directly supports carbon market goals by:

(1) Ensuring grid reliability under fluctuating wind conditions.
(2) Maximizing the utilization of wind energy, thereby reducing reliance on fossil fuel generation.
(3) Sustaining wind farm participation in carbon markets, ensuring continuous generation of carbon credits.

This dual impact (technical stability and economic sustainability) positions CSCOPF as a crucial strategy for achieving low-carbon power systems. The model's ability to optimize power flow and stabilize the grid while supporting market participation aligns with global decarbonization goals.

Compared with traditional optimal power flow (OPF) models, the CSCOPF strategy provides significant improvements in ensuring grid stability under contingencies by incorporating security constraints [24]. It is particularly effective in high wind energy penetration scenarios, as it optimizes dispatch considering stochastic variations in wind generation. However, CSCOPF requires higher computational resources due to its complexity and reliance on advanced forecasting models, which can limit its applicability in resource-constrained regions. In contrast, simpler OPF models or distributed voltage control techniques are less computationally demanding but may not adequately address security and reliability concerns during grid contingencies [19,23].

In summary, CSCOPF provides a robust optimization framework for balancing grid stability and economic efficiency under fluctuating wind conditions. By ensuring continuous carbon credit generation and prioritizing renewable energy dispatch, CSCOPF bridges the gap between technical solutions and carbon market objectives. The synergistic integration of SSSC and CSCOPF technologies with carbon trading mechanisms will be further explored in subsequent sections. Together, SSSC and CSCOPF provide a holistic framework for stabilizing grids, optimizing renewable energy dispatch, and ensuring sustained carbon market participation. The following sections will analyze their combined impact on achieving a resilient and economically sustainable low-carbon power system.

3. Carbon Markets and Wind Energy Integration

The integration of wind energy into power systems is increasingly essential for achieving global decarbonization goals [12,26]. However, this integration brings various challenges related to the stability of power systems, transmission, and grid balancing [31,32]. Alongside technical innovations, carbon market mechanisms have emerged as a crucial policy tool to incentivize the adoption of renewable energy technologies, including wind power [33]. This chapter discusses the global carbon market mechanisms, strategies for integrating wind energy into these markets, and the synergies between policy and technology. Additionally, the chapter explores the role of international cooperation in addressing the challenges and advancing the integration of wind energy within the context of global carbon markets.

3.1. Overview of Global Carbon Trading Mechanisms

Carbon markets have become a central part of climate policy frameworks around the world. These markets provide financial incentives for industries and countries to reduce carbon emissions by setting a price on carbon, thus promoting the adoption of cleaner energy technologies. The European Union Emissions Trading System (EU ETS) is one of the most established and successful carbon trading mechanisms globally [34,35]. Since its inception in 2005, the EU ETS has played a pivotal role in reducing emissions from sectors like power generation and manufacturing, which are major contributors to greenhouse gas emissions.

In 2022, the EU ETS covered more than 40% of the EU's total emissions, making it one of the largest carbon markets in the world. The price of carbon allowances has risen significantly over the years, reaching around EUR 80 per ton of CO_2 in 2023, compared with around EUR 30 per ton in 2019. This rise in carbon prices has provided a stronger economic incentive for companies to reduce their emissions and invest in low-carbon technologies like wind energy [36,37]. As shown in Figure 4, the price of EU ETS carbon allowances has fluctuated significantly over the years, with a notable increase in recent years [38].

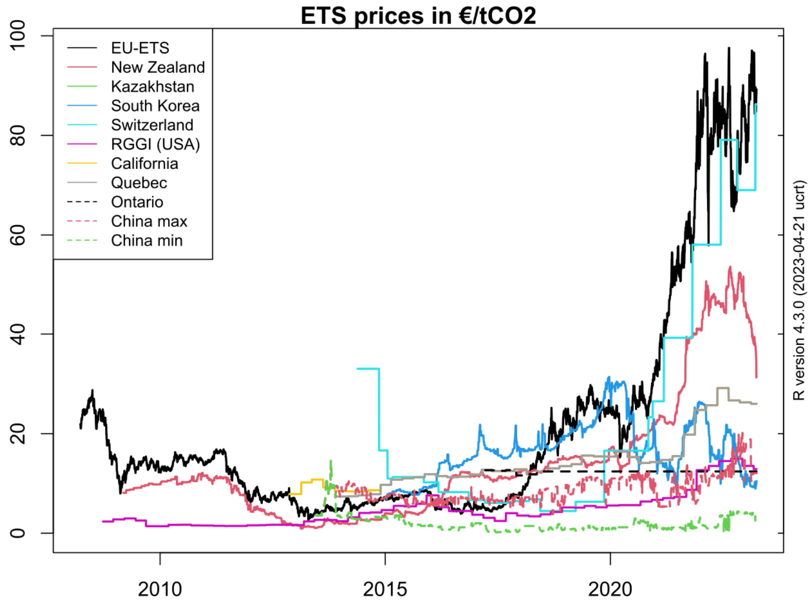

Figure 4. EU ETS allowance prices from 2008 to 2023 [37].

Figure 4 illustrates the price trends of EU ETS carbon allowances from 2008 to 2023, with the y-axis representing the carbon price in EUR/tCO_2 and the x-axis showing the timeline in years. The clear labeling of the axes ensures that readers can easily interpret the significant fluctuations in carbon prices over the years. The data highlight a sharp increase in carbon allowance prices after 2019, reflecting enhanced market dynamics and stricter emission reduction policies. This trend demonstrates the growing economic pressure on companies to invest in low-carbon technologies, aligning with the EU's long-term climate goals.

Successful Case: The EU ETS

The EU ETS operates on a cap-and-trade principle, where a total cap on emissions is set for participating sectors. Companies are allocated emission allowances, which they can trade with one another. This system has incentivized industries to innovate and efficiently reduce their carbon emissions. Over the years, the EU ETS has contributed significantly to the EU's emissions reduction targets. In 2022, the EU's emissions were 33% lower than in 1990, which directly correlates with the success of the carbon market in promoting cleaner energy technologies [39].

Within the EU, the adoption of the EU-ETS has led to significant reductions in greenhouse gas emissions. Between 2005 and 2020, emissions from power generation and heavy industries covered by EU-ETS decreased by approximately 35% [34,35]. This reduction has been accompanied by substantial investments in renewable energy technologies, with the EU witnessing a 70% increase in installed renewable energy capacity during the same period [2,4]. Additionally, countries such as Germany and Denmark have successfully leveraged EU-ETS revenues to fund innovative clean energy projects, further accelerating their energy transitions.

As wind power is a key renewable resource with virtually no emissions, the EU ETS has created financial incentives for wind energy projects. Wind farm developers can generate carbon credits by offsetting emissions from fossil fuel-based generation, making wind energy more economically attractive. According to the European Commission, wind power in the EU reduced carbon dioxide emissions by approximately 300 million tons per year in 2022, contributing to the achievement of the EU's climate targets [40].

The European Union Emissions Trading System (EU-ETS) has not only driven substantial emissions reductions within the EU but has also created significant opportunities for non-EU countries. Through mechanisms like the clean development mechanism (CDM), non-EU countries have attracted over EUR 1.5 billion in foreign direct investment (FDI) for clean energy projects between 2008 and 2020 [19,23]. These investments have enabled the development of large-scale wind and solar farms, reducing greenhouse gas emissions by approximately 200 million tons during this period. Additionally, the EU's introduction of the carbon border adjustment mechanism (CBAM) has further incentivized non-EU industries to adopt low-carbon technologies to maintain competitiveness in the EU market [33]. This alignment has encouraged a global shift toward cleaner production practices. Within the EU, the system has achieved a reduction of over 40% in emissions from covered sectors since 2005, with revenues from the auctioning of allowances reinvested in renewable energy projects [33,34]. For example, Germany and Denmark have used EU-ETS revenues to fund wind and solar energy initiatives, strengthening their leadership in the global energy transition. The combined impact of EU-ETS demonstrates its potential as a global benchmark for carbon trading systems, fostering international collaboration in emissions reductions and clean energy development.

3.2. Carbon Trading Strategies in Wind Energy Integration

Wind energy projects have the potential to directly benefit from carbon market mechanisms. By producing clean energy, wind farms displace fossil fuel-based generation, thereby reducing greenhouse gas emissions. By improving wind power transmission efficiency, SSSC technology reduces line losses, enabling higher utilization of wind energy. For instance, studies have shown that SSSC can reduce transmission losses by 10–12% in high wind penetration scenarios [23]. This efficiency directly translates to increased carbon credit generation, providing additional economic incentives for wind farm operators to participate in carbon markets. Through this displacement, wind energy projects can generate carbon credits, which can be sold or traded on carbon markets. These credits provide an additional revenue stream for wind farm operators, improving the financial viability of wind energy projects. The amount of carbon emissions reduced by a wind energy project can be estimated using the following formula:

$$\Delta E = P_{wind} \cdot t \cdot CF_{wind} \cdot \eta_{SSSC} \quad (2)$$

where ΔE represents the total carbon emissions reduction (in tons), P_{wind} is the installed capacity of the wind farm (in MW), t is the annual operational time (in hours), CF_{wind} is the wind farm's capacity factor, and η_{SSSC} is the efficiency improvement brought by the integration of SSSC technology. By enhancing transmission efficiency and reducing losses, SSSC contributes directly to increasing the carbon credits generated by wind energy projects. In fact, studies have shown that wind farm developers can earn between EUR 5–10 million annually in carbon credit revenues, depending on the size and location of the project [41].

In some regions, wind energy developers can receive subsidies or tax incentives based on the amount of carbon they offset through their generation. For example, the United States' renewable energy production tax credit (PTC) provides a financial incentive of USD 23 per MWh of wind energy produced, and these incentives can significantly reduce the levelized cost of wind energy [42]. Furthermore, the integration of SSSC into wind farms can further optimize power flow and enhance grid stability, increasing the value of wind energy projects in carbon markets. As SSSCs improve the efficiency and reliability of wind energy integration, they can also generate additional carbon credits by stabilizing the grid and reducing curtailment.

In addition to stabilizing grid performance, SSSC technology plays a key role in boosting carbon credit generation by improving power flow efficiency and minimizing transmission losses. However, these technical advancements need to be complemented by well-structured carbon market policies to fully realize their potential, creating a synergistic framework that benefits both grid operators and renewable energy stakeholders. According to recent research, integrating SSSCs into wind power transmission systems can reduce transmission losses by up to 15% and improve system efficiency by 10–12% in high-penetration wind energy scenarios [8,43]. These improvements reduce the need for fossil fuel-based backup generation, thus generating carbon credits through emission reductions. These improvements are particularly critical in carbon markets, as they reduce the reliance on fossil fuel-based backup generation, leading to measurable carbon emissions reductions that can be monetized as carbon credits.

In some cases, the implementation of SSSCs can reduce the carbon intensity of wind power by enhancing the grid's ability to accommodate fluctuations in wind generation. By improving the performance of the transmission system, SSSCs enable more wind energy to be transmitted over longer distances without the need for additional backup generation, contributing to the reduction of carbon emissions across the power grid.

3.3. Synergy Between Policy and Technology

To bridge the gap between technical innovation and economic incentives, carbon trading mechanisms like the EU ETS are essential. These policies provide the financial foundation to support advanced grid technologies such as SSSC, which optimize wind energy integration by reducing transmission losses and stabilizing power flow. Yet, the effectiveness of such mechanisms varies significantly across regions, depending on the regulatory environment and levels of technological adoption. Policies governing carbon markets and wind energy integration differ depending on the local economic context, regulatory frameworks, and levels of wind energy penetration. The deployment of SSSC technology, supported by carbon market incentives, creates a synergistic effect that enhances wind energy integration. For example, carbon pricing revenues can help offset the costs of SSSC deployment, driving further investments in grid stability solutions. This alignment between policy mechanisms and technological advancements ensures reduced transmission losses, improved wind energy utilization, and consistent carbon credit generation.

$$F_C(P_{g_i}) = \sum_{j \in g_i}^{n_g} A_i P_{g_i}^2 + B_i P_{g_i} + C_i \tag{3}$$

The CSCOPF model addresses these challenges by optimizing power generation costs while maintaining grid reliability. The objective function F_C minimizes the total generation cost across all units, where P_{gi} is the real power output and A_i, B_i, and C_i are cost coefficients.

For instance, countries in Europe have established robust carbon pricing mechanisms, whereas many developing countries are still in the early stages of adopting carbon trading systems. These regional differences impact how wind energy can be integrated into power systems and how carbon markets can incentivize this integration [44,45].

In China, the national carbon market that launched in 2021 is still in the process of developing, with a focus on the power sector. Although it covers over 1700 power plants (approximately 40% of the country's emissions), the price of carbon allowances has remained relatively low, around USD 7 per ton. This price is too low to drive substantial investments in renewable energy, which highlights the need for policy refinement [46]. Conversely, in California, a more mature carbon market has successfully driven investments in renewable energy projects, with wind energy capacity increasing by 25% over the last five years, largely due to favorable carbon credit policies [47]. Regions such as Taiwan have demonstrated the potential of combining SSSC technology with carbon trading policies to optimize grid efficiency. By leveraging international experiences like the EU ETS and California's cap-and-trade program, emerging markets can refine their carbon pricing frameworks to encourage the deployment of advanced grid technologies, ensuring a stable and low-carbon energy transition.

Case Study: Taiwan's carbon market and wind energy integration

A case study of Taiwan provides valuable insights into the potential for integrating wind energy into emerging carbon markets. Taiwan has made significant strides in adopting renewable energy, particularly wind power, and is exploring ways to link its wind energy projects with carbon markets. Taiwan's government has introduced various incentives for wind energy developers, including financial subsidies and tax credits. However, there are still challenges in harmonizing the country's wind energy projects with its carbon pricing mechanisms. The lack of a well-established carbon market infrastructure and the nascent stage of renewable energy policies in Taiwan mean that there is still substantial room for policy optimization.

Through international collaboration and policy dialogue, regions like Taiwan can learn from established carbon markets like the EU ETS and integrate carbon pricing mechanisms more effectively. Collaborative efforts between countries, particularly those with high wind potential, will be crucial in achieving global climate goals [48,49].

4. Synergy Between SSSC Technology and Carbon Market Mechanisms for Wind Power Integration

4.1. SSSC Technology for Wind Power Integration: Opportunities and Benefits

SSSC is a critical component of FACTS designed to improve power flow control, stabilize voltage, and reduce line congestion in transmission systems. In the context of high wind energy penetration, SSSC offers significant technical benefits by addressing challenges such as voltage fluctuations, reactive power management, and system instability [9,16,50].

Several studies have shown that integrating SSSC technology into wind-dominated grids can reduce transmission losses by approximately 10–12%, while enhancing system efficiency by up to 15% [51,52]. These benefits are particularly pronounced in regions with intermittent wind generation, where traditional transmission networks face significant strain due to variable power outputs. Furthermore, the integration of SSSC technology not only enhances grid efficiency but also aligns with carbon market incentives. By reducing line losses and improving system stability, SSSC enables wind farms to generate additional carbon credits, providing a direct economic benefit within active carbon trading frameworks such as the EU ETS or the California cap-and-trade program.

Despite the documented technical advantages, the existing literature rarely considers how SSSC technology aligns with carbon market mechanisms to generate additional value. Ref. [23] introduced a framework that integrates SSSC technology with carbon trading to achieve carbon reduction. As shown in Figure 5, the test results highlight the effectiveness of SSSC technology in improving system efficiency and reducing emissions, with carbon credits being generated as part of this process.

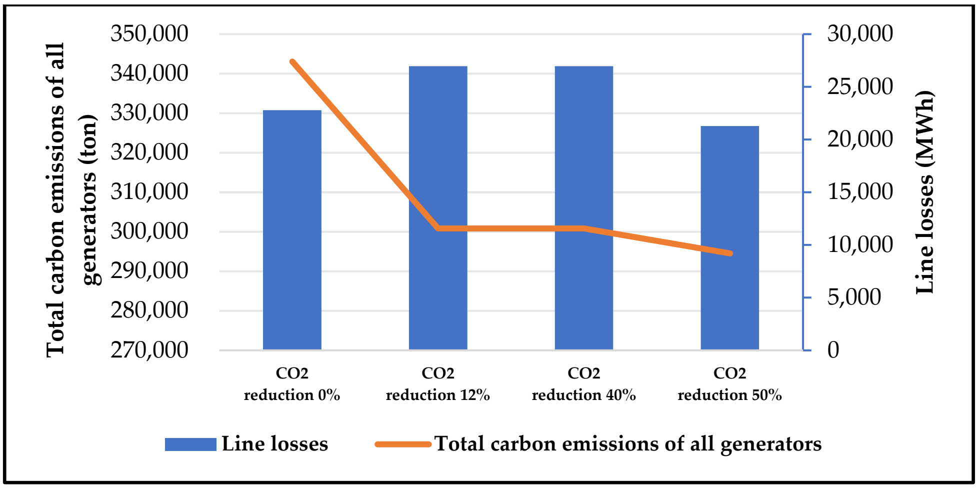

Figure 5. Impact of CO_2 reduction targets on line losses and carbon emissions [23].

As shown in Figure 5, integrating SSSC technology into carbon trading mechanisms results in significant carbon reductions and improved system efficiency. Specifically, a 50% carbon reduction is achievable with SSSC technology, while carbon trading mechanisms alone can only achieve up to 40%. These results are based on real data from the Taiwan power grid, where SSSC plays a crucial role in enhancing transmission efficiency and further reducing emissions.

While [23] demonstrates the integration of SSSC and carbon trading, it does not address the potential of wind power integration. This study highlights that combining wind power with SSSC could maximize carbon credit generation and provide a more effective solution for carbon reduction.

4.2. Carbon Market Mechanisms and Their Role in Wind Energy Projects

Carbon markets, such as the EU Emissions Trading System (EU ETS) and California's cap-and-trade program, have become critical instruments in the global effort to reduce greenhouse gas emissions. By putting a price on carbon, these mechanisms encourage industries to transition to low-carbon technologies, including wind energy, which plays a pivotal role in mitigating the effects of fossil fuel-based power generation [53]. Wind power, being inherently low in emissions, is well positioned to generate tradable carbon credits, thus financially incentivizing further investments in renewable energy technologies.

While the positive impact of carbon markets on renewable energy adoption is well documented, the interaction between advanced transmission technologies like SSSC and carbon market incentives remains underexplored. For example, studies conducted in Taiwan demonstrate that integrating SSSC technology into wind-dominated power grids can lead to a significant reduction in carbon intensity, with measurable improvements in grid efficiency. These reductions translate directly into carbon credits, which, when traded in established carbon markets, provide financial incentives that offset the initial deployment costs of SSSC technology [23]. This synergy highlights the potential for aligning technical innovation with economic mechanisms to accelerate wind energy integration. Most studies focus on how carbon markets can encourage the deployment of wind energy, but they rarely quantify the additional benefits of integrating technologies that improve the delivery efficiency of wind power, such as FACTS devices [6]. FACTS technology enhances the transmission system by reducing curtailment rates and improving power transfer capacity, which in turn allows for more efficient integration of wind power into the grid [54].

The integration of FACTS technology into wind power systems can substantially increase the amount of carbon credits that wind farms generate, thereby boosting the economic viability of renewable energy projects. The benefits of FACTS technology, such as reduced transmission losses and improved grid stability, directly correlate with increased carbon credit generation. This additional financial incentive further enhances the attractiveness of wind projects in regions with well-established carbon markets.

Recent studies have highlighted the role of carbon reduction revenue in driving investments in wind power projects. For example, Wang et al. (2023) demonstrated that carbon revenues play a significant role in improving the economic viability of distributed wind power investments, as seen in Shanghai's renewable energy initiatives [55]. Similarly, the hybridization of wind farms with integrated technologies, such as solar energy, power-to-gas, and power-to-liquid systems, presents further opportunities for circular business models to enhance both technical and economic performance (Mendoza and Ibarra, 2023) [56].

However, while carbon markets have been effective in promoting renewable energy adoption, their synergy with advanced transmission technologies such as FACTS remains an emerging area of research. As wind energy projects scale up, their integration with technologies that optimize power delivery and grid efficiency becomes more critical. Without these technologies, the full potential of carbon markets to incentivize large-scale renewable energy projects, particularly in regions with high wind penetration, may not be realized. Therefore, the future of wind energy integration into carbon market frameworks hinges on the combination of technological innovation and market incentives.

4.3. Synergistic Effects: Combining SSSC with Carbon Market Mechanisms

The combination of SSSC technology with carbon market mechanisms offers a powerful synergy that enhances both the technical performance and economic viability of wind energy projects. SSSC is an essential component in improving power transmission efficiency, particularly in grids with high levels of renewable energy penetration. By improving power flow, stabilizing voltage, and mitigating transmission losses, SSSC enables a more reliable and efficient integration of wind power into the grid. Additionally, carbon markets, such as the EU ETS and California's cap-and-trade program, incentivize the generation of carbon credits, which further supports the financial viability of renewable energy projects.

Integrating SSSC technology into wind-dominated grids not only improves system performance but also contributes to the generation of carbon credits, which can be traded in established carbon markets. As wind power is inherently low in emissions, wind farms that deploy SSSC technology can increase their carbon credit generation by reducing transmission losses and improving overall grid stability. This creates an additional financial benefit for developers, making wind energy projects even more attractive in markets with active carbon trading systems.

Research demonstrates that SSSC technology plays a key role in improving power transfer efficiency and stabilizing grids in high-wind penetration scenarios [26,28]. These technical advancements, when aligned with carbon market incentives, enable wind farms to generate additional carbon credits by reducing transmission losses and improving grid stability. This synergy offers both economic and environmental benefits, accelerating the adoption of renewable energy. These improvements directly contribute to the creation of additional carbon credits, which can be sold in carbon markets, generating new revenue streams for wind farm operators. In Taiwan, for example, the application of FACTS devices like SSSC has proven to be effective in improving grid integration and reducing curtailment while generating substantial carbon credits for wind projects [23,24].

However, despite these advantages, the full potential of SSSC technology combined with carbon market mechanisms is still not fully realized in many regions. While carbon markets have successfully driven the adoption of renewable energy technologies, their synergy with advanced transmission technologies like SSSC remains an emerging area of research. For wind energy projects to scale up effectively, their integration with technologies that optimize power delivery is becoming increasingly crucial. The full benefits of carbon markets in incentivizing large-scale renewable energy projects cannot be realized without the integration of SSSC technology, which enhances grid efficiency and supports the smooth integration of intermittent renewable energy sources [28].

The future of wind energy integration into carbon market frameworks depends on the combination of innovative transmission technologies like SSSC and evolving market mechanisms that provide financial incentives for large-scale wind energy projects. As wind energy projects continue to grow, policymakers and regulators will need to address the barriers that hinder the widespread adoption of SSSC technology. This includes improving access to financial incentives, supporting the development of more sophisticated carbon trading systems, and ensuring that SSSC technologies are deployed where they can have the greatest impact on grid stability and carbon reduction.

Ultimately, the combination of SSSC technology and carbon market mechanisms represents a unique opportunity to accelerate the transition to a low-carbon energy system, supporting both the technical and economic dimensions of wind power integration. By fostering the development of a more integrated and efficient energy grid, these synergies can play a pivotal role in achieving global decarbonization goals.

5. Wind Energy Integration with SSSC and Carbon Markets: Case Studies and Practical Implementation

5.1. Case Study: Optimal Power Flow of Wind Energy Integrated Systems Considering Costs and Emissions

In this section, this paper reviews the optimization of wind energy integration into power systems, specifically focusing on the optimal power flow (OPF) problem [27,29,30]. The integration of wind energy, while reducing reliance on fossil fuels, introduces challenges due to the intermittent and variable nature of wind generation. A recent case study on the IEEE 118-bus system revealed that OPF implementation, combined with SSSC technology, reduced overall system losses by 8% and improved grid stability under variable wind penetration conditions [24]. These improvements not only enhance operational efficiency but also translate into measurable emission reductions, enabling wind farm operators to earn additional carbon credits [25]. This dual benefit aligns economic gains with environmental goals, further incentivizing participation in carbon trading markets.

The applicability of the proposed optimization approach extends globally to high wind penetration grids. For instance, in regions such as Northern Europe and the Midwest United States, where wind energy constitutes a significant share of power generation, similar optimization techniques have been employed to manage transmission congestion and stabilize voltage profiles under variable wind conditions. These implementations have demonstrated reductions in system losses by up to 12% and emission reductions exceeding 15%, aligning with regional decarbonization policies. Such practical outcomes highlight the potential for scaling the proposed algorithm to real-world systems, reinforcing its value as a tool for achieving operational efficiency and environmental sustainability.

This demonstrates the practical effectiveness of OPF solutions in optimizing power flow and aligning economic benefits with emission reduction goals. The OPF problem is crucial in these systems as it seeks to determine the most cost-effective and environmentally friendly operation of the power system while meeting demand and ensuring grid stability. In comparison with traditional OPF models, the integration of SSSC into wind-dominated systems reduces line congestion and improves overall grid efficiency. The resulting operational cost savings further align with carbon credit generation goals, highlighting the dual economic and environmental benefits achievable through this synergistic approach. The following section explores the role of SSSC in enhancing wind power delivery efficiency and its contributions to carbon market participation.

For example, in systems with high wind penetration, implementing OPF solutions has been shown to significantly reduce transmission losses while enhancing grid stability and cost efficiency [27]. These improvements allow wind energy operators to optimize power dispatch, minimize reliance on fossil fuel-based backup generation, and maximize participation in carbon trading markets, achieving both economic and environmental goals. While the presented case study uses the IEEE 118-bus system for illustrative purposes, future research will focus on pilot projects utilizing real-time operational data from high wind penetration grids. For example, data-driven simulations in coastal regions with offshore wind farms could validate the algorithm dynamic performance under varying wind conditions and load demands. Additionally, integrating this optimization approach with active carbon trading systems could provide direct insights into economic incentives for wind farm operators, further substantiating the dual objectives of cost minimization and emission reduction in practical applications.

The optimization process also takes into account carbon market participation, where wind energy's reduced emissions enable power producers to generate carbon credits. This introduces a dual optimization objective: economic performance (cost minimization) and environmental performance (emission reduction). Several studies have examined the economic benefits of carbon credit generation in conjunction with OPF, finding that carbon pricing can significantly impact generator dispatch decisions and enhance the overall cost-efficiency of wind-integrated systems. Figure 6, derived from these studies, illustrates the optimization results for various objectives such as cost, power loss, and voltage deviation. It highlights the trade-offs between these factors and visually demonstrates how wind energy integration influences both the economic and technical performance of the power system, reinforcing the dual objectives of cost minimization and emission reduction discussed in the literature.

Figure 6 highlights the trade-offs between these objectives. For instance, the minimum cost scenario achieves the lowest fuel cost (USD 800.48/h) but results in higher power losses (9.02 MW) and emissions (0.366 t/h). In contrast, the minimum power loss scenario significantly reduces power losses to 4.56 MW and emissions to 0.2292 t/h but incurs a higher fuel cost (USD 859/h). Similarly, the minimum bus voltage deviation scenario balances these objectives, achieving moderate fuel cost (USD 803.81/h), power losses (9.88 MW), and emissions (0.36 t/h).

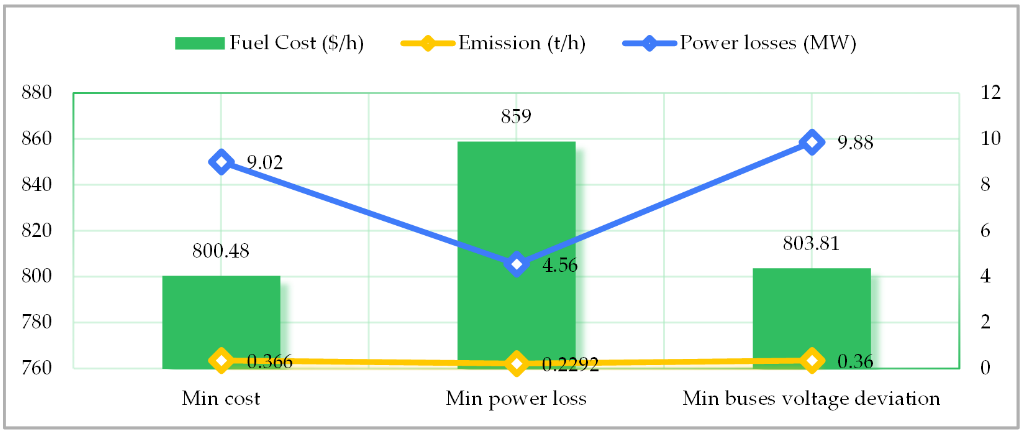

Figure 6. Optimization results of different objectives: cost, power loss, voltage deviation.

This figure visually demonstrates how optimizing for one objective can impact the others, illustrating the inherent trade-offs in power system optimization. These results underscore the importance of a balanced approach in wind energy integration to simultaneously achieve economic efficiency, grid stability, and emission reduction. By explicitly addressing these trade-offs, this study reinforces the dual objectives of cost minimization and environmental sustainability discussed in the literature.

5.2. Enhancing Wind Power Flow and Carbon Credit Potential Through SSSC Technology: Opportunities and Challenges

In Section 5.1, this paper highlights how different optimization objectives, such as minimizing transmission losses, can lead to lower carbon emissions and improved system efficiency, as shown in Figure 5. When minimizing line losses is the primary goal, the system achieves the lowest carbon emissions, as reducing losses reduces the need for backup fossil fuel-based generation. This directly contributes to carbon credit generation. It is in this context that advanced technologies like FACTS devices, particularly SSSC technology, can play a pivotal role in optimizing wind energy flow, further enhancing carbon credit generation.

SSSC technology has demonstrated clear potential in improving power transfer efficiency and stabilizing voltage profiles under fluctuating wind conditions. By mitigating reactive power imbalances and enhancing power flow control, SSSC minimizes energy losses and supports carbon credit generation, particularly in wind-intensive regions with active carbon trading systems [29,30]. This synergy highlights SSSC's economic and environmental contributions in modern power systems. This highlights its role as a complementary solution in wind energy projects seeking to align technical performance with carbon market incentives. By optimizing the flow of wind power, SSSC technology improves power transfer efficiency, stabilizes voltage, and reduces reactive power imbalances, which are critical in areas with high wind energy penetration. These improvements can help reduce transmission losses and reliance on fossil fuel generation, both of which lead to significant reductions in carbon emissions. As a result, wind farms using SSSC technology can produce more carbon credits by offsetting emissions that would otherwise be generated by conventional power sources.

The potential for SSSC technology to enhance wind power flow and increase carbon credit generation represents a significant opportunity for wind energy projects to generate additional revenue streams. However, while optimizing wind power flow through SSSC can maximize carbon credit potential, the stability of wind energy integration into the grid remains a key concern, particularly during grid disturbances or faults.

In regions with high wind penetration, wind generation can fluctuate significantly, making grid stability a critical issue [57–59]. SSSC technology plays an important role in maintaining stability by regulating power flow and ensuring that wind energy remains integrated into the grid. However, during fault conditions, it is essential to ensure that wind farms do not disconnect from the grid and can continue to operate, ensuring that they can still participate in carbon markets and continue generating carbon credits.

Thus, while SSSC technology can enhance carbon credit generation, ensuring the stability of wind power integration during fault conditions is an essential area for further research. The ability of SSSC to improve both wind power flow and grid stability [60,61] will be crucial for maximizing the economic and environmental benefits of wind energy in the context of carbon markets.

5.3. Enhancing Grid Stability and Carbon Credit Continuity Through CSCOPF

In a case study of a wind-integrated power system, CSCOPF solutions successfully optimized power dispatch during fault conditions, ensuring uninterrupted wind power delivery and minimizing voltage deviations [24,62]. By maintaining grid stability during faults, CSCOPF prevents wind power curtailment, ensuring continuous carbon credit accumulation. This capability reinforces the economic feasibility of wind energy projects, particularly in regions with stringent carbon emission targets. This capability safeguards wind farms' participation in carbon trading markets, offering stable economic returns while supporting grid reliability under dynamic operational scenarios. By incorporating preventive security constraints, CSCOPF optimizes power flow, mitigates voltage deviations, and reduces the risk of system instability. This optimization is particularly critical for wind power systems, where intermittent generation often challenges grid resilience.

CSCOPF in wind-integrated systems: case study and validation [24]

To evaluate the effectiveness of CSCOPF in renewable-dominated grids, Figure 6 compares the voltage stability performance between the traditional OPF and CSCOPF under fault conditions using the IEEE 118-bus system. The results demonstrate that CSCOPF significantly reduces voltage deviations, maintaining grid stability and ensuring continued wind power delivery during contingencies (Figure 7).

Further validation of CSCOPF's capabilities is presented in Figure 8, which illustrates the power distribution patterns under both normal operation and the most severe contingency. The figure highlights three key aspects: the upper power flow limit, the power flow under normal conditions, and the power flow during a severe contingency.

As shown, the CSCOPF model efficiently redistributes power flows during contingencies, preventing line overloads and ensuring that the system operates within the defined limits. For instance, under the most severe contingency, the power flow (gray line) approaches the upper limit in some lines but remains within acceptable bounds due to the optimization provided by the CSCOPF model. This demonstrates the model's effectiveness in mitigating overloads and maintaining grid reliability, even in highly stressed scenarios.

These results highlight CSCOPF's role in enabling wind farms to remain operational during grid disturbances, ensuring uninterrupted power delivery and contributing to the consistent generation of carbon credits.

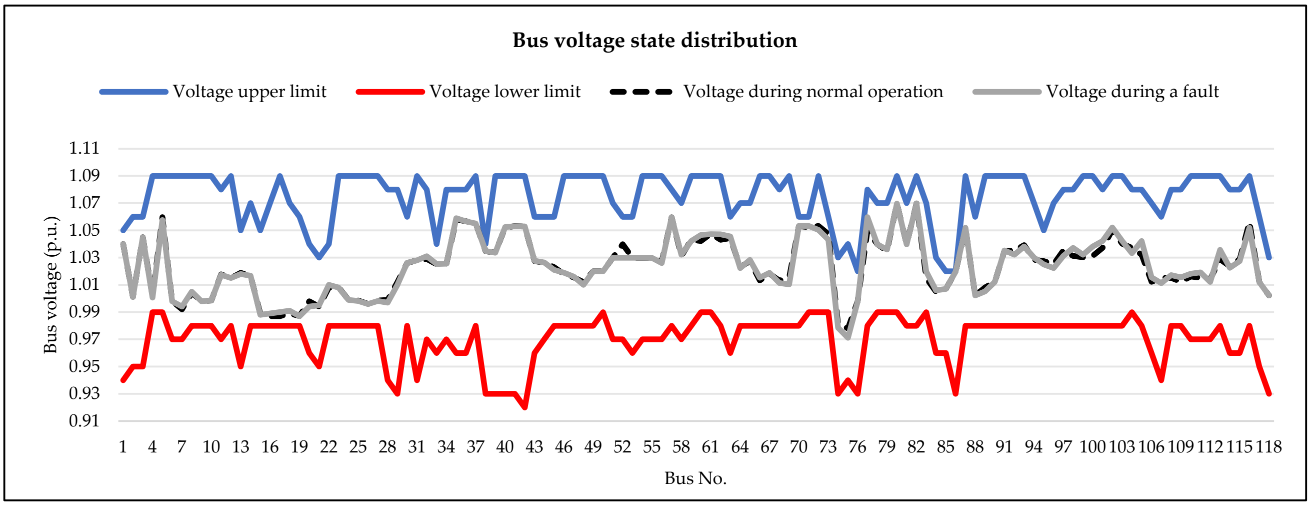

Figure 7. Voltage stability comparison between traditional OPF and CSCOPF under fault conditions [24].

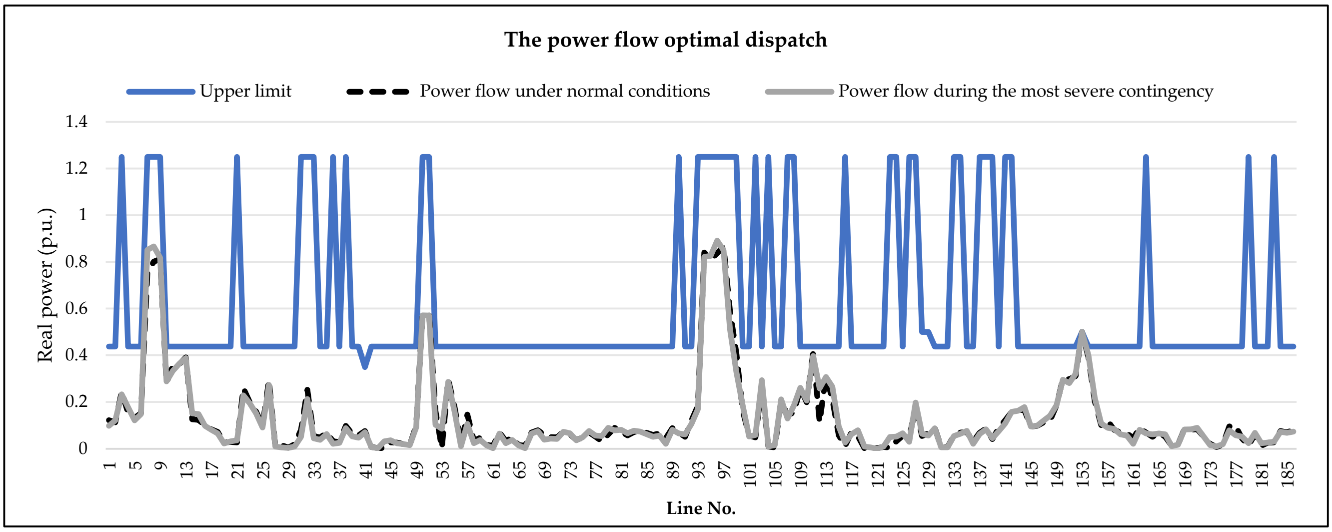

Figure 8. CSCOPF distribution under normal operation and the most severe contingency for the IEEE 118-bus system [24].

While CSCOPF effectively enhances fault resilience and optimizes grid performance, its combination with SSSC technology offers additional benefits for wind-integrated power systems as follows:

(1) Power flow optimization: SSSC dynamically regulates line impedance and improves reactive power compensation, complementing CSCOPF's optimization of power dispatch.
(2) Reduced transmission losses: the combined implementation minimizes energy losses, ensuring that more wind energy reaches the grid efficiently.
(3) Enhanced voltage stability: by mitigating voltage fluctuations caused by wind variability, SSSC strengthens the stability improvements achieved by CSCOPF.

The synergy between CSCOPF and SSSC ensures that wind farms can operate reliably during grid contingencies, maximizing both technical performance and economic benefits.

The integration of CSCOPF and SSSC technologies plays a vital role in helping various stakeholders participate effectively in carbon trading markets, thereby contributing to broader decarbonization goals as follows:

(1) Transmission system operators (TSOs): by reducing line losses and ensuring fault resilience, TSOs can improve grid efficiency and reliability, supporting the seamless integration of renewable energy into the system.
(2) Wind farm operators: maintaining grid connection during fault conditions ensures uninterrupted power delivery, enabling wind farms to continuously generate carbon credits, thus improving financial returns in carbon trading markets.
(3) Other renewable energy stakeholders: solar and other renewable energy operators can benefit from the CSCOPF-SSSC framework to address grid challenges, enhancing their ability to participate in carbon trading while reducing operational emissions.

By ensuring grid stability and minimizing disruptions, CSCOPF and SSSC enable these stakeholders to maximize their contributions to carbon reduction targets while capitalizing on economic incentives offered by carbon markets.

The integration of CSCOPF and SSSC technologies addresses critical challenges in wind-integrated power systems, including grid stability, power loss reduction, and fault resilience. By enabling uninterrupted renewable energy delivery, these solutions empower transmission operators, wind farm operators, and other renewable energy stakeholders to participate effectively in carbon trading markets, achieving both economic benefits and significant carbon reduction effects.

6. Conclusions and Future Perspectives

6.1. Summary of Key Findings

This review highlights the synergistic integration of SSSC technology, CSCOPF strategies, and carbon trading mechanisms as a comprehensive solution to grid stability and emission reduction challenges. By reducing line losses, improving grid reliability, and supporting continuous carbon credit generation, these approaches provide a sustainable and economically viable pathway for large-scale wind energy integration. By reducing transmission losses, stabilizing voltage, and maintaining wind farm operations under contingencies, these solutions contribute collectively to decarbonization objectives. Through a comprehensive analysis of the existing research, the synergistic potential of combining SSSC technology, CSCOPF models, and carbon market mechanisms has been identified as a promising approach to address these challenges.

The key findings of this review are as follows:

(1) SSSC technology enhances grid performance by reducing line losses, stabilizing voltage, and improving power flow, enabling wind farms to maximize energy output.
(2) CSCOPF models provide robust solutions for grid stability, ensuring optimized power dispatch and secure operation under normal and contingency conditions.
(3) Carbon market participation offers economic incentives for wind and other renewable energy operators, encouraging emission reductions through efficient grid operations.

6.2. Conceptual Contribution: A Synergistic Framework

The primary contribution of this work lies in proposing a synergistic concept that combines the following:

(1) Wind energy as a clean and intermittent renewable source.
(2) SSSC technology for power flow optimization and transmission efficiency.
(3) CSCOPF models for grid stability and fault resilience.
(4) Carbon trading markets as a platform to incentivize emission reduction.

This framework ensures the following:

(1) For transmission operators: line losses are minimized, and power transfer capacity is maximized through the deployment of SSSC devices, enhancing grid performance under high renewable penetration.
(2) For wind energy operators: grid stability is maintained even during faults, preventing disconnection and enabling uninterrupted power generation, which ensures continuous carbon credit accumulation.
(3) For carbon market stakeholders: the combined use of CSCOPF and SSSC technologies supports greater emission reductions by optimizing renewable energy utilization and reducing reliance on fossil fuel-based generation.

6.3. Future Directions

Future studies should prioritize pilot implementations of the proposed framework in high wind penetration regions to validate its technical and economic feasibility. Additionally, developing integrated models that combine SSSC, CSCOPF, and hybrid renewable systems (e.g., wind–solar) will further enhance grid resilience and emission reductions. Research should also focus on creating policy-driven financial incentives to promote the large-scale adoption of these technologies, ensuring alignment with global decarbonization targets.

(1) Practical implementation: develop real-world case studies that validate the combined application of CSCOPF and SSSC in renewable-dominated grids.
(2) Economic impact analysis: quantify the financial benefits of improved grid stability and continuous carbon credit generation for renewable energy operators.
(3) Scalability and integration: explore the integration of other renewable energy sources, such as solar and hybrid systems, within the proposed framework to create a unified low-carbon energy system.
(4) Regulatory and policy support: establish policies and incentives that promote the deployment of advanced grid control technologies while facilitating carbon market participation.

Future work should include large-scale pilot projects to evaluate the practical deployment of SSSC and CSCOPF technologies under real-world grid conditions. Additionally, comprehensive cost benefit analyses are needed to quantify the financial advantages of carbon credit generation for transmission and wind farm operators. Developing stochastic models that incorporate wind variability and fault dynamics will further enhance the robustness of power flow optimization strategies, ensuring scalability in diverse energy systems.

6.4. Final Remarks

By combining wind energy, SSSC technology, CSCOPF models, and carbon market mechanisms, this synergistic framework provides a pathway to address current challenges in renewable energy integration. It not only enhances grid stability and operational efficiency but also ensures uninterrupted renewable power delivery, enabling consistent carbon credit generation. This contribution supports the global transition to a sustainable low-carbon energy future and provides practical insights for industry stakeholders, policymakers, and researchers.

Author Contributions: K.-H.L. made substantial contributions to defining the research direction and designing the overall framework, including setting research objectives and outlining the core methodology. K.-H.L. also played a pivotal role in integrating team efforts, ensuring the study maintained clarity and addressed critical issues in the field. C.-M.H. focused on the technical aspects of this study, including data processing, modeling, and conducting system performance analyses. C.-M.H. contributed significantly to interpreting results and providing insights into the implications of the findings within the context of wind energy integration and grid stability. J.L. was responsible

for conducting a comprehensive literature review, establishing a strong theoretical background for this research. F.-S.C. performed detailed result validation, created visual representations of key findings, and ensured data accuracy to enhance this manuscript's presentation quality. All authors have read and agreed to the published version of the manuscript.

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Nomenclature

SSSC	Static Synchronous Series Compensator
CSCOPF	Security-Constrained Optimal Power Flow
FACTS	Flexible AC Transmission System
EU ETS	European Union Emissions Trading System
OPF	Optimal Power Flow
VSC	Voltage Source Converter
PWM	Pulse Width Modulation
EU ETS	European Union Emissions Trading System
CO_2	Carbon Dioxide
RES	Renewable Energy Sources
ECI	Equivalent Current Injection
CDM	Clean Development Mechanism
FDI	Foreign Direct Investment
CBAM	Carbon Border Adjustment Mechanism
PTC	Renewable Energy Production Tax Credit

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