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Generation and Transmission Expansion under Aspects of Cooperation: Insights from Offshore Wind Integration in Baltic Region

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INTRODUCTION AND MOTIVATION

The rapid expansion of offshore wind generation and the growing need for cross-border electricity exchange in Europe have intensified interest in integrated offshore grids—shared infrastructures that combine wind power collection with interconnection capacity. The Baltic Sea, with its shallow waters, favorable wind conditions, and central location, stands out as one of the most promising regions for large-scale integrated offshore wind development. This research work investigates the techno-economic and market coordination challenges of developing such hybrid interconnectors in the Baltic Sea region through optimization and equilibrium modeling.

The framework considers Germany (DE), Denmark (DK), and Sweden (SE) connected through both onshore and offshore hybrid interconnectors. Despite the promising potential of integrated offshore grids, a key challenge lies in aligning the incentives of multiple national stakeholders who differ in their cost structures, regulatory environments, and welfare outcomes. This asymmetry gives rise to coordination failures and underinvestment, as rational players may refrain from committing to shared infrastructure if the distribution of benefits is perceived as unfair or uncertain. To mitigate welfare asymmetry, incentive mechanisms are proposed that redistribute the congestion rents generated by interconnectors. The research includes Financial Transmission Rights (FTRs) as an instrument to hedge against unfavorable welfare differences while modeling the investment behavior of market zones in hybrid interconnector projects.

METHODOLOGY

This research work addresses market integration challenges caused by hybrid projects by proposing and evaluating four market designs to ensure net revenue neutrality and/or overall social welfare gains within integrated offshore projects:

(i) In the base case, a single decision-maker determines investment and dispatch decisions so as to maximize overall social welfare (fully centralized decision-making).

(ii) As the second market design scenario, the research work formulates a novel Cournot competition market model where each market zone acts as a strategic player (fully decentralized decision-making). Two further variations of the decentralized equilibrium scenario are developed by introducing cooperation and mutual incentive mechanisms in decentralized decision-making.

(iii) Explicit allocation of Financial Transmission Rights (FTRs) to participants negatively affected by market coupling.

(iv) Market-based trading of FTRs among all stakeholders.

Both FTR-based approaches provide financial instruments that enable participants to hedge against congestion-related redistributions, thereby improving investment incentives and promoting equitable cost-sharing.

RESULTS

Results are first analyzed for 2023 to identify key patterns across scenarios. The analysis is then extended to 2030, reflecting higher demand and greater renewable penetration in each market zone to provide a forward-looking perspective. Scenarios with and without Sweden as an additional low-price, highly renewable market zone are considered to assess its impact on market behavior, investment coordination, and welfare outcomes. Overall, four market designs combined with two years (2023 and 2030) and two participant configurations (with and without Sweden) yield 16 scenarios for evaluating the proposed methods.

The comparative analysis suggests that the proposed implementations in the FTR Trade and Explicit FTR Allocation scenarios increase the participation (investment) of market zones in shared offshore infrastructure.

The comparative analysis of the scenarios is highlighted below:
1. While the optimal outcome in the base centralized scenario is assumed to be not achievable in reality, this remains the reference for globally optimal allocation, achieving the highest price convergence across all scenarios.
2. Equilibrium without FTR compensation (decentralized decision-making) results in overinvestment and less effective price convergence.
3. Explicit FTR allocation overcompensates, leading to excessive investment but slightly lower efficiency.
4. Market-based FTR trading achieves the best balance between price convergence, net revenue neutrality, and investment efficiency.
5. The inclusion of Sweden stabilizes market outcomes and increases total welfare, but at the cost of increased heterogeneous investment by market participants.
Combining the flow, welfare, and investment analyses indicates that economic coordination and shared investment planning can promote alignment among market zones only under relatively balanced price conditions. When price differentials are large, cooperative investments tend to exacerbate disparities rather than resolve them. The proposed mechanisms targeting revenue neutrality through FTR trading effectively compress welfare disparities but shift investment burdens toward selected participants, highlighting a key trade-off in cooperative offshore grid development. This observation underscores the importance of market design measures that reduce initial price divergence—through improved congestion management and enhanced intra-zonal interconnection capacity—before expecting shared infrastructure mechanisms to yield equitable outcomes.
Overall, coordinated planning of offshore hybrid interconnectors can deliver significant welfare gains, but without mechanisms to balance cost and benefit distribution, investment incentives remain uneven and coordination falters. The adoption of financial instruments such as FTRs offers a promising means of enabling decentralized yet equitable participation in cross-border energy infrastructure. These findings, when combined with a detailed representation of uncertainty and strategic behavior (market power), could support the design of regulatory frameworks that balance economic efficiency with political feasibility in Europe's evolving offshore energy landscape.

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