Flow-Based Market Coupling and Renewable Energy Integration in Nordic

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***Abstract*—The study investigates how renewable energy affects electricity markets and their development. The research addresses Nordic electricity market analysis, based on the first lessons learned and findings implementing a new model for Nordic power system balancing. We estimate the effect of transitioning from Coordinated Net Transfer Capacity (CNTC) mechanisms for capacity estimations and market efficiency to Flow-Based Market Coupling (FBMC) considering the economic and operational consequences. Insights from this work will contribute to ongoing activities addressing the economic impacts of renewable-dominated energy grids, targeting electricity prices stabilization in the context of global decarbonization and climate goals**.

***Index Terms*—Balancing Model, Market Efficiency, Flow-Based Market coupling (FBMC).**

I. Introduction

The use of renewable energy sources (RES) has many potential benefits, including a reduction in greenhouse gas emissions, the diversification of energy supplies and a reduced dependency on fossil fuel markets (in particular, oil and gas). In 2023, RES represented 24.5% of energy consumed in the EU, up from 23.0% in 2022. The share of energy from renewable sources used in transport in the EU reached 10.8% in 2023, up from 9.6% in 2022 [1]. The transition towards RES, such as wind and solar, has significantly transformed global electricity markets, introducing both opportunities and challenges. Renewable energy's low marginal costs and decreasing production costs have the potential to lower electricity prices [2]. However, their high intermittency and unpredictable supply contribute to price volatility, creating unique economic challenges for energy market participants, policymakers, and consumers.

This study focuses on the Nordic electricity market development, which has a new model for power system balancing and is transitioning to a system predominantly reliant on renewable energy, to explore the economic implications of renewable integration. It is apparent that market design is a difficult task. Many competing objectives must be met, including short-term and long-term perspectives such as price stability improvement, more efficient electricity trading, balancing market interventions and RES integration.

The research question raised in this paper is: how does FBMC improve the Nordic electricity market and support RES integration, and what are the economic and operational consequences of transitioning from CNTC in terms of capacity estimations and market efficiency?

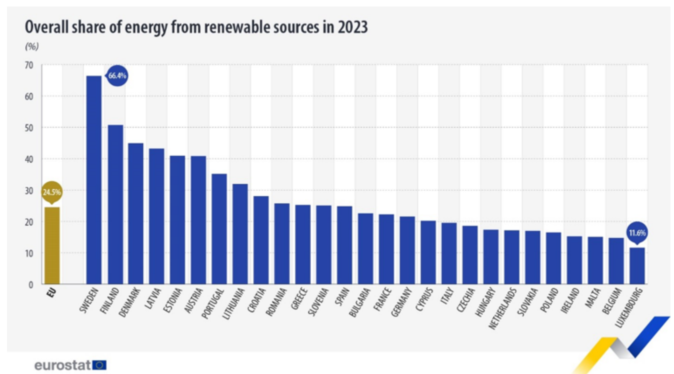

Figure 1. Overall share of energy from renewable sources in 2023 [1].

The paper is organized as follows: Chapter 2 presents electricity market models and balancing market structure. Chapter 3 discusses RES integration in terms of market efficiency and demonstrates the effect of the FBMC method by use of an example. The results are analyzed in Chapter 4. Finally, the main conclusions of the study are summarized in Chapter 5.

II. Electricity Market Models and Balancing Markets

The electricity market consists of different timeframes. The **Forward market**, operating in the long-term, is the traditional platform for almost 90% of energy exchanges across and within European countries; the short-term markets are playing an increasingly relevant role in the electricity sector. The **Spot Market** consists of the Day-Ahead (DA), where 80% electricity is traded, and Intraday markets (ID), where 20% electricity is traded. The **Balancing markets**, which is concerned with close-to-real-time power exchanges to equilibrate the network with largely smaller volumes of exchange than the spot market, see Figure 2, adopted from [3].

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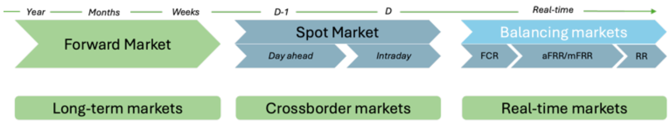

Figure 2. Electricity market structure. Adapted from Sia-Partners [3].

Key components of each market are its main actors: producers, TSOs, suppliers, consumers and marketplaces. Power exchanges are responsible for the wholesale electricity market exchanges. They consist of an online trading platform collecting orders from all market players, processing clearing prices and volumes, and a clearing house to ensure its transactions. They mainly operate in the spot market for day-ahead and intraday exchanges. In some cases, power exchanges have the license of Nominated Electricity Market Operators (NEMO): they are responsible for operating market coupling for a given bidding zone.

A. *Nordic Electricity Market organization*

With an increasing share of renewables in the energy mix and the development of interconnection capacities, the creation of a competitive market for power exchanges is bringing many benefits to all market players: multiple offers are now available within the same bidding zone, opening the door for many opportunities. In 2019, NordPool launched day-ahead markets in Austria, Belgium, France, Germany/Luxembourg, and the Netherlands. In 2020, 3580 GWh of day-ahead orders were also sold in France through the NordPool platform. Bidding zones within a NordPool platform are shown in Figure 3.

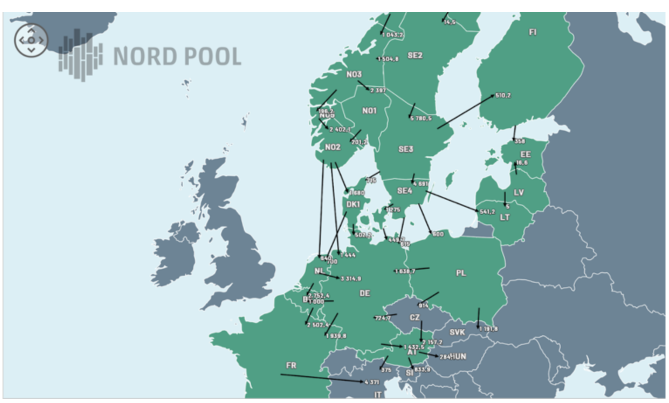

Figure 3. Bidding zones. Retrieved from NordPool. [4].

The increased traded volume on day-ahead and intraday European electricity markets results in better liquidity of the market, with a price signal relevant and robust.

In 2017, Nordic TSOs submitted a proposal for using a new Capacity Calculation Methodology (CCM) [4]. Capacity calculation translates physical transmission limits in the power system to commercial trade limits based on the market design and operational security. The capacity calculation in the Nordic CCR was recently based on a CNTC, which assumes that power can be directly transferred from one zone to another. Since electricity flows in the grid follows the laws of physics, this assumption does not apply in a meshed grid. The new CCM is proposed instead and is based on FBMC.

FBMC considers a linearized contribution from each zone on each critical line in the system. By using FBMC instead of CNTC the available grid should be utilized to a higher degree, which should lead to more frequent price convergence between zones and a higher total social surplus. The proposed change was implemented (tested) during 2021, demonstrating promising results and was preceded by a period of running the FBMC in parallel so that the actors in the market have time to adjust. The Nordic Regional Security Coordinator (Nordic RSC) is responsible for making capacity calculations for the Nordic region, with local input from the TSOs. As a part of the preparation for using a CCM based on FBMC, TSOs have done simulations based on historical weeks, comparing FBMC methodology with the current CNTC methodology [4].

FBMC aims to contribute to the Nordic Market development and support high-RES utilization in power supply. The day-ahead Nordic FBMC project successfully began in 2024, when the first trading day for delivery was 30th October 2024. The Nordic FMC is the result of the close cooperation between all involved NEMOs, TSOs, Nordic RCC and regulatory authorities [5].

B. *Common Nordic Capacity Market*

The Common Nordic Capacity Market is an important aspect in the electric power system and electricity market organization. Capacity Markets are used by TSOs to keep the power grid stable and secure every second of power system operation. Procurement of capacity is organized through the aFRR (automatic Frequency Restoration Reserves) and mFFR (manual Frequency Restoration Reserves) procurements. To support Nordic Capacity Market development process, the roadmap considering all Nordic countries involving TSOs from Denmark, Sweden Norway, Finland, as a high-level plan with specific building blocks of the new balancing model, is developed and illustrated, see Figure 4 below.

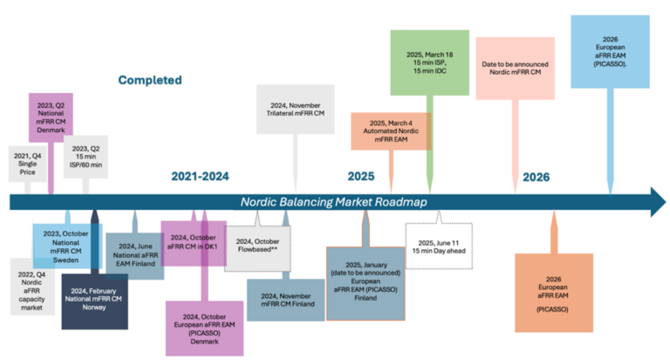

Figure 4. Nordic Balancing Market Roadmap. Adapted from Nordic Balancing Market Model. [5].

The roadmap presents the whole process with the key milestones for each building block, including its progress monitoring in line with the roadmap and reporting to the stakeholders, involved NEMOs, TSOs, Nordic RCC and regulatory authorities.

C. How Market Coupling Works and Why is CNTC being replaced?

Market coupling optimizes electricity trade across regions by ensuring electricity flows efficiently between markets. It integrates multiple bidding zones into a single market, allowing electricity to be sold where demand is highest at the most competitive price. [6]. This improves market liquidity and stabilizes electricity prices. Historically, CNTC determined cross-border electricity flows using fixed capacity limits set in advance. However, CNTC's rigid approach often led to inefficient grid usage, preventing electricity from flowing through the most optimal paths. [7]. This limitation, combined with increasing renewable energy production, has driven the need for a more flexible approach. FBMC replaces CNTC by dynamically allocating transmission capacity based on actual grid conditions. It considers how electricity naturally flows across the network rather than treating interconnections as isolated transactions. This ensures that transmission capacity is used efficiently, reducing congestion costs and improving cross-border trade. By continuously adjusting capacity, FBMC better accommodates renewable energy fluctuations and enhances overall market efficiency. Its adoption ensures a more integrated and resilient power system, reducing artificial price differences and improving economic outcomes for all market participants.

III. TARGETING MARKET EFFICIENCY

There is a challenge with RES integration, such as a need for a fine-tuned balance between consumption and production every second of the day so as keeping stability of the power system. Currently RES are balanced mostly by burning gas (or coal), one of the most expensive energy sources, used to adjust supply and demand. However, the energy crisis of 2022 marked a significant shift in consumption, causing a dramatic spike in gas prices. For instance, on 26 August 2022, gas prices soared from a historical average of €10-20 per MW to €339 – a 20-fold increase; this surge had a profound impact on power prices across Europe [1].

There is a diversity of market designs existing at European level in general targeting RES and Distributed Energy Resources (DER) facilitation within the energy transition. The definition of the problem can be grouped around four fundamental topics of EU energy policy:

- Massive integration of RES
- Balancing market’s re-structure to support power system in change
- Market distortions and multiple timescales
- Importance of security of supply

In many rapidly developing economies, policy debates centre on whether and how to support and speed up the process of energy transition to better meet rapidly growing demand, improve reliability, achieve better economic efficiency, and accelerate the integration of variable renewable energy [8]. Moving to a net zero future, European society aims to balance production and demand through renewable energy – nuclear, hydro, storage and flexible demand. Significant developments have been made, with 100 TWh of new wind and solar production added in 2022 and an additional 200 TWh in 2023. These developments demonstrate that the price signals reflecting surplus or deficit balances serve as an investment incentive for more renewable energy projects and initiatives. *“It has never been more profitable to invest in new renewable production capacity. Policymakers need to create the legislative frameworks to reduce lead times for renewable energy projects.”* [8].

The Norwegian government’s primary focus regarding RES is to expand and optimize its renewable energy infrastructure to meet growing energy demands while supporting climate goals. The emphasis is on leveraging Norway’s abundant hydropower resources, which remain the cornerstone of its energy system, alongside accelerating the development of onshore and offshore wind power, particularly floating offshore wind farms. This includes ambitious plans, such as awarding areas for offshore wind projects to achieve a capacity of 30 GW by 2040. [9]. Additionally, the government is prioritizing energy efficiency measures to reduce consumption and maximize existing resources, all while maintaining a sustainable balance between energy production, environmental protection, and social equity. These initiatives are integral to Norway’s broader climate strategy, aiming to transition to a low-emission society and foster green industrial growth.

A. FBMC and ATC comparison

To demonstrate the effect of the new method, this subchapter contains the FBMC calculation example, with the aim to compare the FBMC methodology and the CNTC methodology. The capacity and FBMC simulations are done based on simplified three node models, Figure 5, and historical weekly data, comparing FBMC methodology with the current CNTC methodology, defining Available Transfer Capacity (ATC) in operational terms.

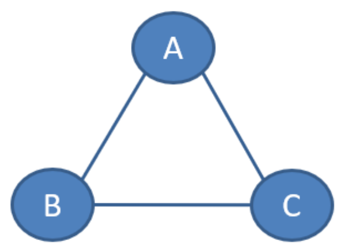

Figure 5. Three Node Model.

The power network consists of three nodes: A, B and C, connected to each other in a triangular layout. The network includes three transmission lines: A-B, B-C and A-C, Figure 5. The grid characteristics table shows important technical limits for each line, see Figure 6. Each line is assumed to have an equal electrical “length” of 1 unit, representing the relative impedance of the connection. This uniform value simplifies the system structure and allows for symmetrical modeling of the power flow. Additionally, every line is constrained by the same flow limits: a maximum forward flow of +1000 units and a minimum flow of -1000 units. These limits represent the operational capacity of lines and are critical for maintaining safe and reliable operation during load transfers and disturbances. To understand how electricity flows through this network, one analyzes it using several key grid characteristics table, and the Power Transfer Distribution Factors (PTDFs). PTDFs describe how a transfer of power between two buses impacts the power flow of each transmission.

Grid characteristics

Line	Line "length"	Max flow	Min flow
A->B	1	1000	-1000
B->C	1	1000	-1000
A->C	1	1000	-1000

PTDFs

	A	B	C
A->B	33 %	-33 %	0 %
B->C	33 %	67 %	0 %
A->C	67 %	33 %	0 %

Figure 6. Technical limits for each line and PTDF matrix

PTDF values are given as percentages and indicate the proportion of the transferred power that will flow through each line. These factors are essential for operational planning, congestion analysis, and market-based power flow control, as they help predict the effect of injections and withdrawals on the line usage across the system. Following the FBMC analysis, the next step presents the optimal market clearing solution under the ATC model. Unlike the FBMC approach, which dynamically adapts to system constraints, the ATC model operates under predefined bilateral capacity limits, leading to a more conservative, but operationally simpler allocation of transmission capacity. In the ATC-based solution, the resulting market prices differ slightly from the FBMC case, due to the limited trading flexibility.

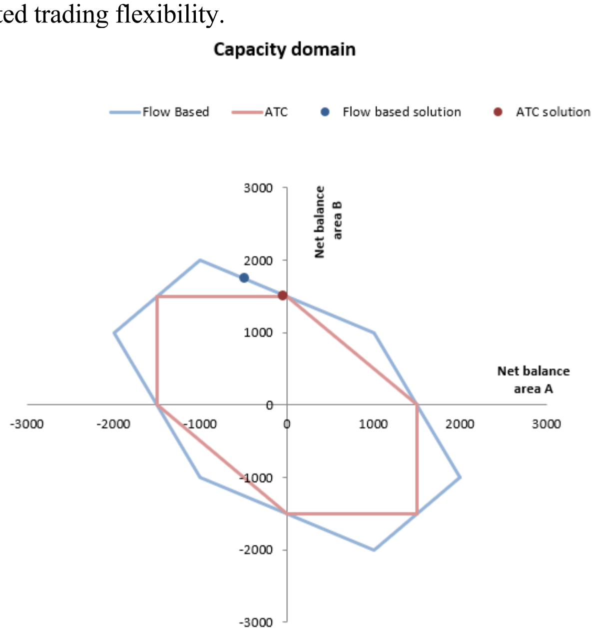

Figure 7. Capacity domain differences in FBMC and ATC models.

The capacity domain diagram in Figure 7 visually captures the key distinction between the FBMC and ATC methods. The blue polygon represents the full secure capacity domain under the FBMC model, while the red polygon shows the restricted ATC domain. The FBMC solution (blue dot) is located outside the ATC domain, indicating that it allows economically beneficial exchanges that would have been blocked under ATC due to simplified bilateral limits. The FBMC method enables more flexible and welfare-enhancing dispatch decisions.

B. *FBMC role in RES Integration*

Considering the previous chapter, FBMC demonstrates crucial potential in integrating renewable energy by ensuring that electricity flows efficiently across borders. Unlike CNTC, which imposes fixed transmission limits, FBMC dynamically adjusts capacity based on real-time conditions. [10]. This flexibility is essential for handling the variability of wind and solar generation, allowing surplus renewable electricity to be exported to regions with higher demand rather than being curtailed. By reducing curtailment, FBMC maximizes the use of renewable energy while improving price stability. When renewables generate excess electricity, FBMC enables efficient cross-border trading, reducing price volatility and ensuring a fairer market. Additionally, FBMC enhances grid stability by optimizing power flows, preventing congestion, and ensuring that electricity is distributed in the most efficient manner. The adoption of FBMC is one of the key elements to achieve a more sustainable energy system. By dynamically managing transmission capacity, it facilitates RES penetration, reduces inefficiencies, and strengthens market integration. This makes it a crucial component in transitioning toward a low-carbon and reliable electricity market.

IV. *Analysis and Discussion*

To facilitate renewable energy integration and target efficiency of the Nordic electricity market, the FBMC method was implemented, transitioning from CNTC for capacity estimations approach. Updating the Nordic balancing process with FBMC will facilitate increased volumes of RES in the system, European market integration and improve balancing market efficiency, maintaining operational security in the most cost-effective manner. This complex project has several great challenges to be resolved, including changing and automating critical system operation processes, applying real-time power flow to account for the physics of the system targeting cross-border electricity trading optimization.

A. *Capacity Estimation in CNTC vs FBMC*

The way available transmission capacity is estimated differs significantly between CNTC and FBMC. CNTC relies on predefined capacity limits set for each cross-border connection, while FBMC dynamically calculates available transmission capacity based on real-time grid conditions. This difference has a major impact on how efficiently electricity markets operate and how well the transmission system is utilized. [11].

Under CNTC, TSOs set transfer limits between bidding zones in advance based on historical grid conditions and expected system constraints. This approach does not account for real-time fluctuations in electricity generation and demand. As a result, CNTC can lead to inefficient use of available capacity, as some transmission lines may be underutilized while others become congested. Moreover, since CNTC treats each interconnection separately, it fails to optimize electricity flows across the entire network, leading to high electricity prices in some areas.

FBMC, on the other hand, uses a dynamic approach by considering the entire transmission network holistically. Instead of predefined limits, it calculates available capacity using Power Transfer Distribution Factors (PTDFs), which determine how electricity injected at one point affects flows across multiple transmission lines. This enables the system to optimize power flows dynamically, reducing bottlenecks and ensuring that the available infrastructure is used efficiently. By continuously adjusting capacity, FBMC leads to more effective cross-border electricity trading, improved price convergence, and lower congestion costs.

A key reason FBMC improves capacity calculations is that it reflects the actual physical constraints of the grid in real time. By incorporating the impact of all transactions into the calculation, FBMC avoids artificial constraints that limit electricity trade under CNTC. This allows the market to operate more efficiently and ensures that electricity is delivered where it is needed most at the lowest cost.

B. The New Balancing Market

The first lesson observed in the new Balancing Market platform is based on the analysis and findings on capacity market integration and the interaction of policy mechanisms with market prices. After a few months of operation and the testing of the new Balancing Market platform, some challenges and observation can already be formulated, as the main change is related to a bid selection in the existing regulating power market.

FBMC provides an efficient allocation mechanism in which all exchanges that are subject to the allocation mechanism compete with one another for the use of the scarce capacity. Therefore, the advantages of the FBMC approach can be summarized as follows:

- In FBMC capacity split is not a choice of the TSO, but is market driven (at the time of allocation), which leads to a more efficient and flexible use of the grid
- FBMC offers more trading opportunities with the same level of security of supply
- More price convergence / smaller price differences
- Higher social welfare and income redistribution.

There are several changes from the existing bid selection done by the TSOs prior to the go-live automated operation, and with expected consequences summarized in Table 1.

With the new capacity market principles, all connected TSOs ensure that sufficient frequency restoration reserve is/will be available at any given time to maintain the power system balance between production and consumption, and to ensure security of supply for Nordic power systems. With this, balancing capacity for the market is provided by various reserve suppliers, including opportunities for connected RES and DER owners. To secure the continuity of the day ahead coupling, consideration and contributions of all market participants, NEMOs and TSOs are important.

Table 1. Analyzing the new balancing market effect.

	Changes	Economic and operational consequences
1	Automatic bid selection and shorter intervals each 15 minutes, instead of manual bid selection	FBMC enables more efficient electricity trading
2	Support for new bid attributes, to make automatic bid selection possible	Process automatization is important, bid structure and packaging should support grid real-time operation
3	Market-based capacity through FBMC	Creates more opportunities for RES participation. Reduces the Need for Expensive Balancing Market Interventions.
4	Impact on the market price	More precise price information, capturing power system dynamics. Reduces market volatility and improves price stability.
Planned impact		Increase the social welfare

In the long-term perspective, the results should indicate an increase in Nordic socio-economic welfare. Insights from this work will contribute to ongoing debates about managing the economic impacts of renewable-dominated energy grids, providing practical recommendations for stabilizing electricity prices in the context of global decarbonization and climate goals.

V. Conclusion and Further Work

The study investigates how renewable energy can be efficiently integrated into electricity markets while maintaining system stability and optimizing market mechanisms. It highlights the role of various instruments supporting renewable integration, with a particular focus on the Nordic TSOs and NEMOs within the Nordic Balancing Model initiative. Through this framework, FBMC emerges as a key enabler for the future of European electricity markets, offering a more dynamic and efficient allocation of transmission capacity that enhances cross-border electricity trading and system flexibility.

FBMC optimizes price convergence, reduces congestion costs, and facilitates higher renewable energy penetration, leading to a more efficient electricity market. Unlike the traditional CNTC model, FBMC dynamically adjusts capacity based on real-time grid conditions, ensuring more accurate price signals and minimizing inefficiencies in power flows. The Nordic electricity market has already observed benefits, including reduced price volatility, enhanced market liquidity, and improved balancing market efficiency, as TSOs rely less on costly redispatch measures.

The study also emphasizes the interplay between RES and power system dynamics, particularly in balancing market operations. To maximize the benefits of RES and DER integration, new tools and mechanisms are required. This includes enhanced bid selection principles in the Nordic Energy Activation Market, improved market algorithms, and further development of mFRR automated operations to accommodate system technical constraints.

A. Policy and Market Recommendations

To stabilize electricity prices and enhance market efficiency in the context of global decarbonization and climate goals, the study provides the following key recommendations:

- RES significantly affects power system operations and should be fully integrated into market mechanisms.
- System operators and renewable generation owners must leverage RES as a key balancing tool.
- New tools and mechanisms are essential to maximize the benefits of RES and DER integration.
- Regulatory Authorities must play an active role in shaping the Nordic market platform and mFRR balancing market conditions, ensuring supportive decisions that facilitate massive RES integration.
- Continuity in analyzing and estimating the impact of RES participation in the balancing market is necessary to fine-tune mechanisms and support the transition toward a fully decarbonized society.
- Further work should focus on evaluating the price zone effects of RES participation, ensuring that market structures and price signals support investment in renewable technologies.

B. Final outlook

The shift to FBMC is a critical step towards a more efficient, sustainable, and market-driven electricity system in Europe. It not only ensures better price stability and grid utilization but also plays a vital role in enabling higher shares of renewable energy without compromising system reliability. As electricity markets continue evolving, the integration of automation in balancing markets, improved bid selection strategies, and further enhancements to market coupling will shape the future of European energy markets. With these efforts, the Nordic electricity market can continue leading Europe's transition to a fully decarbonized and market-efficient power sector.

Acknowledgment

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