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Impact of Germany's energy transition on the Nordic power market – A market-based multi-region energy system model

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ABSTRACT

The EU energy policy aims at creating a single European electricity market through market couplings and grid expansions. To analyse the implications of such power market couplings, we propose a market-based multi-region energy system model. The model simulates a multi-region power market (by applying market optimization and network theory), with detailed representation of each region as an energy system (by simulation of both heat and power sectors). We examine the impact of further integration of variable renewable energy (VRE) in Germany on the Nordic power market. The results indicate that the average electricity price slightly grows in the Nordic power market after Germany's Energy Transition (Energiewende). Hence, the economic surplus of Nordic consumers diminishes while Nordic producers improve their gain under new market conditions. Considering the gird congestion income, the overall system-level benefits (social welfare) will improve in the Nordic region after Germany's Energiewende. However, this gain is not equally distributed among different Nordic countries and across different stakeholders. Furthermore, the Energiewende slightly increases carbon emissions from power and district heating (DH) sectors, and reduces the flexibility in integration of VRE in some Nordic countries like Denmark. The direct interconnection of Norway and Germany through NordLink will contribute to the flexibility in wind integration in other Nordic countries, such as Denmark and Finland.

1. Introduction

The EU energy policy seeks to integrate national/regional power markets to create a single European power market. The objective is to enhance the security of supply, to achieve an optimal use of energy resources, and to offer competitive electricity prices across Europe [1]. An EU-wide power market is also deemed a solution for the efficient use of power production and transmission capacity across national borders [2], which can potentially reduce grid congestions and investment requirements for the provision of backup capacity [3]. Moreover, the expansion of power markets to wider geographical areas with various patterns of power supply and demand can act as a flexibility measure to facilitate high-level integration of variable renewable energy (VRE) [4].

In 2014–15, the Nordic power market exchange (Nord Pool Spot) together with six other power exchanges launched the Price Coupling of Regions (PCR) project. Under this initiative, a common calculation algorithm will determine the day-ahead electricity prices in a wide area from Portugal to Finland [5], corresponding to 85% of electricity consumption in the EU. Accordingly, all cross-border interconnectors will be optimally allocated through implicit auctioning to allow the transmission of electricity from areas with cheaper electricity to more expensive regions [6].

However, these market couplings and grid expansions have complex implications for interconnected countries. For example, the energy transition in Germany (Energiewende) and the dramatic

Abbreviations: CHP, combined heat and power; DH, district heating; HDH, heating degree hours; NWE, Northern-West Europe (power market); PES, primary energy supply; PCR, price coupling of regions; TSO, transmission system operator; VRE, variable renewable energy.

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growth in the installed capacity of VRE has introduced new opportunities and challenges that may affect the power markets coupled with Germany. The increased fluctuations in power flow has complicated the issue of transmission planning and investment in reserve capacity [7]. Higher price volatility [8,9] and greater power balancing requirements [10] are among other implications of the Germany's energy transition for the interconnected regions. The Nordic power market is linked with Germany through several transmission lines. Therefore, the future VRE scenarios in Germany can potentially affect the Nordic energy systems, especially under further market couplings. In this regard, the hydro reservoirs in the Nordic region have been long considered a potential solution for balancing VRE in Germany and other countries [11]. This has led to several plans to expand the interconnection capacity, e.g., between Norway and the UK (North Sea Link, NSL), and between Norway and Germany (NordLink) [12].

These north-south grid expansions and market couplings have attracted a wide range of studies (e.g., see a review of such studies in Ref. [13]). Jaehnert and Doorman [14] employ an operation optimization model to simulate the state of the North-West Europe (NWE) power system in 2010 and 2020. They consider the case of market couplings by nearly doubling of interconnection capacity between the Nordic region and continental Europe to monitor the possibility of balancing VRE with the Norwegian hydropower. They conclude that market coupling will result in higher price volatility in Norway, greater power exchange within the areas, and lower operation of thermal power plants in the whole system. Farahmand et al. [15] assess the challenges of offshore wind power variability in the North and Baltic Seas. They quantify the transmission grid required for harvesting wind and for the optimal use of hydropower flexibility by applying a long-term cost-benefit analysis. In Ref. [16], the economic impact of an HVDC line between Norway and Great Britain is examined, highlighting an increase in the social welfare[2] in different case studies depending on market conditions. In the above-mentioned and other similar studies [18–20], the impact of market couplings and transmission expansions are investigated by using power market and/or grid expansion models, mainly focusing on the power sector (i.e., power production mix, hydropower reservoirs, transmission networks, etc.).

However, the capability of energy systems in absorbing VRE is not limited to the power sector. Heat and power sectors are interconnected inside most of the Nordic countries, through combined heat and power (CHP) production, electric boilers, and electric heat pumps connected to the district heating (DH) systems. In 2014, CHP plants were responsible for 30% of domestic power production and two-thirds of DH supply in Finland [21]. Many small and regional CHP plants operate based on the respective heat demand, which means they are shut down during summertime leading to the loss of respective power capacity in the power market. The situation in Denmark is even more intensive: half of the electricity comes from CHP plants. Moreover, in future renewable energy scenarios developed for the Nordic region, like many other regions in the world, the electrification of the heating sector [22–26] and electric transportation [27] will grow in importance. Accordingly, future energy systems witness increasingly integrated heat, power, transport and other sectors [28], to absorb a high share of VRE [29,30]. Thus, different sectors of an energy system will be further linked to the power sector and power prices, and consequently, to the cross-border power exchange in an EU-wide expanded grid.

Considering the above, we propose a new modelling paradigm for the study of the intersection of energy transitions in a group of countries with a common power market. The proposed approach seeks to (i) model several national-level energy systems (with possible integration of different sectors inside a country), and (ii) analyse power exchange possibilities among interconnected countries on a market-based scheme. We employ a simulation-based method for hourly modelling of the energy system inside each region. Then, we apply an optimization-based approach for the modelling of the common power market and inter-regional power exchange. This paves the way to model a so-called *complex energy system*, comprising an agent-based computational econometrics model, simulation-based bottom-up model, and application of network theory (see Bale et al. [31] for more details). Therefore the proposed model is, inter alia, capable to compare the flexibility solutions inside a region, e.g., energy storage, with the possibility of cross-border power exchange for balancing VRE.

As a case study, we examine the impact of the energy transition in Germany on the Nordic power market. We investigate this impact on each Nordic country separately (i.e., Norway, Denmark, Sweden, and Finland), which is not yet discussed in a comparative format in the reviewed literature. The aim is to capture the dynamics of both power and heat sectors in the Nordic region when dealing with the power market coupling with Germany. We model future prospective scenarios for VRE and interconnection capacity in the region up to 2030 for analyzing the impact of such market couplings.

The remaining part of this article is structured as follows. In Section 2, we describe the method in more details. Section 3 deals with the input data and assumptions, the validation and limitations of the proposed model, and the examined future VRE scenarios in the region. Section 4 presents the results and discussion, followed by concluding remarks in Section 5.

2. Methods

2.1. A market-based multi-region energy system model (Enerallt)

Multi-area or multi-region[3] energy models are suitable tools for informing energy policy when dealing with a group of networked countries/regions. In this Section, we explain the modelling paradigm proposed in this study and highlight its position compared with similar tools and models.

Among existing multi-region energy models, MESSAGE [32] (long-term systems engineering and optimization model), TIMES (The Integrated MARKAL-EFOM System) family models [33] and OSEMOSYS (open-source energy modelling system) [34] offer capabilities for long-term investment planning by considering selective time slices per year. These models commonly reflect the viewpoint of a central planner who seeks to optimize the capacity expansion in the whole multi-region energy system over a time horizon of several decades.

On the other hand, optimal dispatch models are capable of representing short-term variability in load, VRE, and power plant operations in restructured power markets. To name a few, EMPS [35] (multi-area power market simulator), WILMAR [36] (short-term stochastic model), and Balmorel [37] (partial equilibrium energy system model) are among the modelling tools employed for analyses related to the Nordic region. EMPS has the capability of

[2] In this study, the term *social welfare* (or so-called *gain of trade*) refers to its use in microeconomics, which is the sum of the economic surplus of market participants after the trade in a given market [17]. We further discuss this in Section 4.2.

[3] In this study, the terms *region* and *area* have been used interchangeably, referring to an energy system with distinguishable borders from neighbouring energy systems, and linked through power transmission lines. The term *area* is more often used in power market terminology. For example, Denmark is presented with two eastern and western *regions/areas*, resembling the two respective price areas in the Nordic power market.

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