Energy Economics 37 (2013) 114–127

Contents lists available at SciVerse ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneco

# Evaluating interconnector investments in the north European electricity system considering fluctuating wind power penetration

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ARTICLE INFO

*Article history:*
Received 17 June 2012
Received in revised form 21 January 2013
Accepted 26 January 2013
Available online 13 February 2013

*JEL classification:*
C61
L94
Q43

*Keywords:*
Electricity grid planning
Power system economics
Stochastic optimization
Wind power generation

ABSTRACT

With increasing amounts of power generation from intermittent sources like wind, transmission planning has not only to account for the expected load curve but also for the stochasticity of volatile power infeeds. Moreover investments in power generation are no longer centrally planned in deregulated power markets but rather decided on competitive grounds by individual power companies. This poses particular challenges when it comes to evaluating the benefits of increased interconnection capacities in large-scale systems like the European transmission system.

Within this article an approach is presented which allows assessing the benefits of interconnector investments in the presence of stochastic power infeed and endogenous power plant investments. This model uses typical days and hours as well as recombining trees to represent both load and infeed fluctuations. An application is presented covering 30 European countries and simultaneously optimizing generation investments and dispatch as well as utilization of transmission lines. The model is used to evaluate the benefits of further line extensions between the European mainland and northern European countries. We compute welfare gains and the distribution of these gains within a business as usual scenario up to 2030.



## 1. Introduction

In recent years, liberalization has played an important role in the European energy policy and also in the energy policy of many member states. Besides the introduction of the EU certificate trading scheme power markets in Europe have been liberalized and competition has been introduced into the wholesale markets. In this context existing interconnectors and related trade have led to an increased integration of the national markets (cf. Jamasb and Politt, 2006). Thereby dispatch and exchanges are organized in a cost minimizing way under the assumption of a functioning, integrated European market. Price differences between interconnected zones allude to potential welfare gains through increased grid capacities connecting neighboring zones. Realizing them may help to reduce overall electricity generation cost (cf. Turvey, 2006).

Along with far-reaching policies and measures large amounts of intermittent generation capacities, most notably wind turbines, have been installed in numerous European countries over the last years. They have impact on the power plant system because of their stochastic behavior and their limited capacity credit compared to conventional generation technologies. In the short run power plant dispatch becomes more difficult and in the long investment planning in power systems is influenced (cf. Swider and Weber, 2007; Tuohy et al., 2009).

Tuohy et al. (2009) have shown that it is not sufficient to use deterministic planning tools as they were established previously in order to consider the impact of wind stochastics. Here volatile generation is not considered properly. In the last years several models have been developed for short-term optimization, namely determination of unit commitment und dispatch, taking into account the stochastic behavior of wind infeeds (cf. Barth et al., 2006; Garcia-Gonzalez et al., 2008; Matevosyanand and Söder, 2006; Pappala et al., 2009; Ruiz et al., 2009). Yet, for long-term analysis with endogenous investment this behavior is often neglected.

Various approaches have been proposed for transmission expansion planning in the past, especially optimization techniques. Here often linear programming (cf. Garver, 1970; Villasana et al., 1985) and mixed integer programming (cf. Alguacil et al., 2003; Bahiense et al., 2001) have been used. But also heuristic approaches (cf. Latorre-Bayona and Perez-Arriaga, 1994; Sanchez et al., 2005), real options (cf. Martzoukos and Teplitz-Sembitzky, 1992) and methods derived from artificial intelligence research such as genetic algorithms and particle swarm optimization (cf. Escobar et al., 2004; Ren et al., 2005; Sepasian et al., 2009) have been applied. An overview can also be found in cf. Lee et al. (2006). The applicability of these approaches to large-scale systems with high wind penetration like the European transmission system is, however, limited by two factors: 1) the size of the system and 2) the dependency of transmission

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http://dx.doi.org/10.1016/j.eneco.2013.01.012

expansion plans on multiple factors including notably political support. In this context, an evaluation of prespecified, feasible interconnector extensions is needed. For a realistic evaluation, moreover the dynamic changes in power markets have to be taken into account, which result on the one hand from the increased (politically supported) wind power penetration and on the other hand from new, commercially driven investments in conventional generation.

Within this article a stochastic power system market model is presented that takes the intermittent characteristics of wind into account. To evaluate investment decisions which have impact on the entire system the whole European power market is taken into account. In this case study a potential increase in European interconnector capacities, mostly between the northern European countries and the European mainland is analyzed. Possible interconnectors were chosen according to proposals in literature (e.g. Boyle, 2007) and in-depth discussions with European TSOs (EWIS, 2010). Finally, distributional effects on transmission system operators (TSOs), producers and consumers of electricity in the countries under consideration are determined.

Section 2 of this article first describes the applied methodology, including the economic valuation of interconnector capacities and how they are influenced by increased shares of wind power. Also a description of the applied model is given and the analyzed case study and scenarios are reviewed in Section 3. In Section 4 model results are presented and their implications are discussed. The article ends with brief conclusions on the presented results and the policy implications. Furthermore a full model description is provided in the Appendix A.

## 2. Methodology

### 2.1. Interconnector economics with wind

Transmission capacities between regions have several positive effects, of which the most important are (cf. Turvey, 2006):

- Decrease in generation cost
- Decrease in generation investment
- Increase of system security
- Reduction of potential market power

The first three issues are important in a pure techno-economic perspective that is of high relevance in a functioning competitive electricity market. However, increased grid connection has also the advantage that it reduces potential market power of large incumbent generators who might withhold capacities or might bid above their marginal generation cost in order to increase price levels and revenues. With strengthened transmission lines, generators from neighboring countries can export more and more frequently electricity into the incumbent's market, bringing price levels to a lower if not competitive level. However, a detailed estimation of increased welfare benefits from boosted competition is beyond the scope of this article. In case of market power, the applied methodology delivers only a lower bound of the welfare improvements from increased interconnection.

On the example of a stylized two country model, the general benefits of increased interconnection may be highlighted and how these benefits are distributed among the relevant stakeholders.

On the abscissa we draw the total demand of two countries in one particular situation (cf. Fig. 1). Supply is represented by the merit order curves $C^A$ and $C^B$ that are different in shape. Actual demand levels $D^A$ and $D^B$ deviate from each other as well. If both countries serve their own load, significant differences in (marginal) generation cost arise ($P^{A0}$ and $P^{B0}$). On the other hand, if the two countries could exchange electricity without any limitation a homogenous price in both zones $P^*$ would be established. Of course this can only occur when there is sufficient transport capacity for transmitting electricity, so that no congestion occurs. In the situation described above we presume no transmission capacity (TC0), the demand in each country being covered by domestic supply. Here potential beneficial exchanges of electricity are excluded.

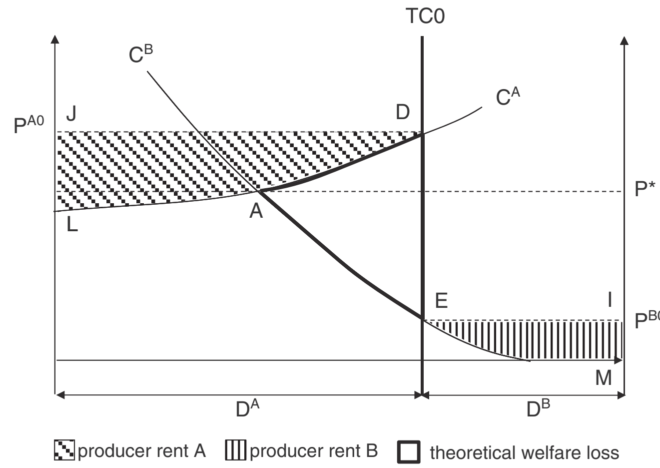


**Fig. 1.** Welfare implications of interconnection.

Therefore we have different prices $P^{A0}$ and $P^{B0}$ and the optimal situation with a uniform price level is not reached. This situation leads to a theoretical welfare loss in height of the area ADE, because overall generation costs are higher than they theoretically could be.

If the interconnector capacity is increased to the level TC1 the optimal price level is still not met, but the welfare loss is significantly reduced to the Area ABC, resulting in a welfare gain in height of CBDE (Fig. 2). For the stakeholders different effects occur, even within one country. While total welfare is increasing in both countries, producers and consumers are affected differently. Increasing imports decrease the price level in country A which leads to lower costs for consumers (DGJK). Conversely, profits of producers are reduced due to lower production and lower prices (BDJK). For country B the opposite occurs. Costs for consumers are increasing (EFHI) in line with the profits of producers (CEHI).

When looking at these results, one has to keep in mind that the increase of interconnection is rather expensive. As the marginal welfare gain decreases with increasing capacity the optimal transmission capacity is not the one that avoids all welfare losses of congestion, but the one where avoided welfare losses equal the investment cost of newly built transmission lines. In a more complicated setting with more than two countries as described later on, it might also happen

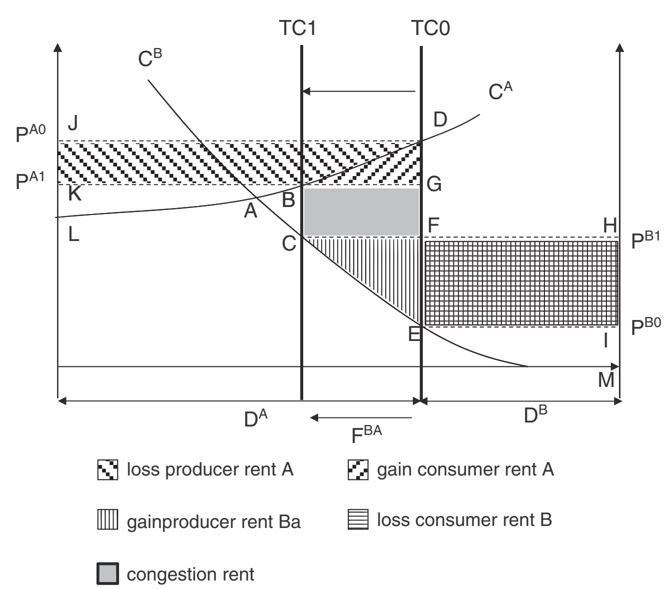


**Fig. 2.** Welfare implications of line investment on different stakeholders.