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ANALYSIS OF THE NORDLINK PROJECT: COUPLING GERMANY AND NORWAY

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INTRODUCTION

NordLink is the first interconnector that directly connects Norwegian and German energy markets, running from Tonstad in southern Norway to Wilster in northern Germany. The subsea bi-pole high voltage, direct current (HVDC) interconnector will have the capacity to transmit 1.4 gigawatts of power, is scheduled to go into commercial operation in 2020 and is predicted to cost between 1500 and 2000 million Euro.

"With its capacity of 1.400 megawatts, the interconnector can provide renewable energy for more than 3.6 million German households and will be able to export for example wind generated by approximately 466 wind turbines of 3 megawatts. This is comparable to the capacity of a large conventional power plant (Tennet)."

The NordLink project has been developed by the Norwegian TSO Statnett in cooperation with the national electricity transmission system operator of the Netherlands TenneT and German government owned development bank KfW. Statnett will own a 50 percent stake in the transmission line project. German investment bank KfW Group and the grid company TenneT each will hold 25 percent shares. The investment decision for the project was taken on February 10th 2015, and the goal is to complete the project by 2019, followed by trial operations and commercial operations in 2020. Orders for the construction and installation of the German section of the HVDC-cable and the two converter stations has won a Swedish-Swiss multinational corporation ABB Ltd.

Reasons for cooperation in electricity exchange are for example the increase of domestic energy security and minimizing of electricity short falls. In economic view it is also seen as a larger market which could lead to cheaper electricity prices for consumers and gives the producers more potential customers. The possibility of access to more renewable energies is a reason as seen from an environmental point of view (Gullberg et al. 2014, p. 217). In the case of NordLink the focus is clearly on the bidirectional access to renewable energy resources. Germany on one hand has a remarkable amount of photovoltaic und wind generation. Norway on the other hand is has a significant percentage of hydro power generation.

By investigating the connection of different electricity systems it is shown that the increase of transmission capacity leads to lower cost for the whole system, because expensive generation would be replaced by cheaper electricity imports. Through increased generation on the exporting side the price is likely to increase while on the other side the price will decrease (Egerer et al. 2012, p. 29).

Valeri (2009) also found out, by modelling the connection between Ireland and Great Britain, that one side gained profits while the other side loses through the interconnection. A price drop in Ireland is accompanied by massive profits for the Irish consumer while the Irish producers are losing. On the other side there are lower impacts on the price but it is shown that British producers are winning and British consumers would lose. Summarized it was investigated that social welfare on both side increased (Valeri 2009, P.4682f).

Besides, it could be expected that the total costs of the two markets will decrease due to the interconnection by NordLink. It is shown that investments in interconnectors are likely to reduce total costs of the system where renewable energies are included in power generation (Lynch et al. 2012, p. 612).

The expansion of the electricity transmission between northern and central Europe is seen as profitable and necessary. By balancing surplus areas and load centers on this way it is expected that the electricity price will orientate on the Northern Europe power system. That could lead to an average price reduction of 5% in the whole system (Jaehnert et al. 2013, p. 138)

In the present research paper, we introduce a comprehensive analysis of the NordLink project. Considering real installed capacities and demand profiles, we will investigate effects and synergies of coupling Norwegian and German electricity systems and find optimal dispatch decision by means of The General Algebraic Modeling System (GAMS). Furthermore, by changing some key parameters, we are going to build up a couple of possible future scenarios in order to analyze how the power exchange will affect the markets under modified conditions

DATA

The first step of the project is to collect actual data for the model. These are

Data	Source	Year
installed generation capacity in Germany including wind and PV capacities	Agora's Report on the German power system; Umweltbundesamt, eigene Zusammenstellung 2016 (data for steam gas)	2015
technologies' variable costs	the European Electricity Market Model (EMMA) by Lion Hirth (*Wiki Workspace of the openmod initiative*)	2010
minimum capacity for each technology	the European Electricity Market Model (EMMA) by Lion Hirth (*Wiki Workspace of the openmod initiative*)	2010
hourly load profiles for Germany and Norway	databank of the European Network of Transmission System Operators (ENTSO-E)	2015
hourly patterns for wind and solar infeed	the European Electricity Market Model (EMMA) by Lion Hirth (*Wiki Workspace of the openmod initiative*)	2010

Other indispensable for the modelling information (Norwegian reservoir capacity, startup costs, technology availability) has been initially given. All data have been collected in the Excel File Input_NordLink.xlsx, which the program will use as a data input for modelling.

MODELLING

Equations are an important part for our GAMS model. The following equations have been created in order to build necessary relationships between various parameters:

Objective Function	
obj..	COST =E= SUM((n,i,t), vc(i)*GEN(n,i,t) + sc(i)*SU(n,i,t))
	Total costs = Total variable costs + Start up costs
Market Clearing Condition (with network flow)	
res_dem(t,n)..	demand(t,n) =E= SUM(i, GEN(n,i,t)) + StGen(t,n)* eta_PSP - StLoad(t,n) + ReGen(t,n)* eta_Reservoir + RES_Gen(t,n) + sum(nn, Imp(t,n,nn)) - sum(nn, Exp(t,n,nn))
	Demand = Total generation of conventional technologies + Generation by PSP * Efficiency of storage power plants – Power used for loading the PSP + Generation by reservoirs * Efficiency of reservoir turbines + Generation by RES technologies + Total Import – Total Export
res_im_ex(t,n,nn)..	Imp(t,n,nn) =E= Exp(t,nn,n)
	The import to one country at each hour = The export from the other country at each hour
Reservoir Activities	
res_ReserLevel(t,n)..	ReserLevel(t,n) =E= ReserLevel(t-1,n) - ReGen(t,n)
	Level of reservoir at each hour = The level of reservoir one hour before - Generation by reservoirs at that hour
res_reservoirCap(t,n)..	ReGen(t,n) =L= ReserLevel(t,n)
	Reservoir capacity ≤ Charging level of reservoirs
res_maximum_ reservoir(t,n)..	ReGen(t,n) =L= power_reservoir(n) * a_reservoir
	Maximum generation by reservoirs at any given time period ≤ Turbine capacity for reservoirs * Availability factor hydro reservoirs
res_reservoirCap_first..	ReserLevel(tfirst,n) =E= cap_Reservoir(n)
	The initial condition of reservoir level = Total capacity of reservoirs

Network Restrictions	
res_Imp(t,n,nn)..	Imp(t,n,nn) =L= inter_cap
	Import ≤ Interconnector capacity
res_Exp(t,n,nn)..	Exp(t,n,nn) =L= inter_cap
	Export capacity ≤ Interconnector capacity

The conventional power plant constraints, RES generation constraints, and storage activities are already defined in the given model.

RESULTS

Markets without interconnector

In our model, six conventional technologies operate on the German power market. These are nuclear, lignite, hard coal, CCGT, OCGT and gas steam. Apart from this, there are three CO2-free sources: run of the river, solar power and wind. Additionally, 12 GW of pump storage capacity secure system flexibility. RoR, Nuclear, Lignite and Hard Coal cover base load operating at least 87% of time during the simulated year. The rest of demand is covered by CCGT operating 10% of time, gas steam – running 10 hours per year – and OCGT that is needed merely for two hours out of 8760. 505 TWh of electricity are consumed in Germany with a maximum load of 77,5 GW. Intermittent renewables cover 29% of German demand. The model shows the highest electricity prices appearing in hours with high demand and low RES-infeed, which reflects reality. The average price on the German market without interconnector is 47,13 €/MWh.

The Norwegian market is characterized by large amount of zero-variable-cost reservoirs that can cover demand during 99,3% of time. In rare cases of demand exceeding available reservoirs' capacity, OCGTs provide missing power. No wonder that Norwegians have a very low average electricity price of 1,40 €/MWh. Norwegian annual power consumption is 128,6 TWh, with peak demand of 22,5 GW.

Markets with interconnector

After introduction of 1.400 MW transfer capacity between two markets, Norway receives the opportunity to export annually 12.029,75 GWh of its reservoirs' generation to Germany. The transmission occurs every hour when there is a surplus of power in Norway, replacing generation from German fossil-fuel power stations by zero-variable-cost, CO2-free hydropower. Conversely, during the rare hours of high demand – when expensive open cycle gas turbines are in operation – Norway can import cheaper electricity from Germany. According to our simulation, annual German power export to Norway makes up 22,18 GWh.

This results in reduction of peak capacity generation:

- Gas steam: from 7.830 MWh before connection to 1.390 MWh;
- OCGT: from 1.775 MWh to 0;
- CCGT: from 5.049.565 MWh to 3.966.680 MWh;

and significant drop of CO2 intensive base capacity generation in Germany:

- Hard Coal: 95.399.452 MWh – 86.230.424 MWh (10,6%)
- Lignite: from 148.967.066 MWh to 147.247.035 MWh (1,2%)
- Nuclear: by 0,05%

The consequence of NordLink for the Norwegian market is even more straightforward. The model shows that there will be no need of high-variable-cost OCGT after the markets are connected.

Thus, the lion's share of generation that will be replaced by hydropower accounts for CO2-intensive lignite and hard coal (Figure 1). The simulation has proven that the power exchange between Germany and Norway will contribute to the achievement of climate goals in Europe.

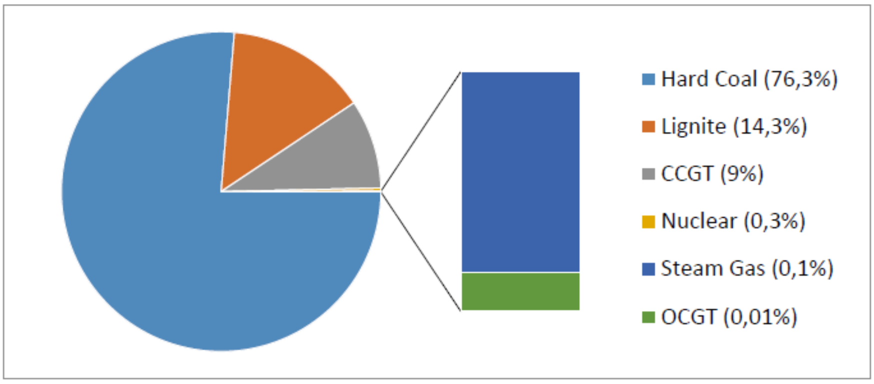

Figure 1. Share of German fossil fuel generation replaced by import (Source: own research)

Apart from the overall reduction of power generation from conventional sources, the connection of two markets must also result in less different price levels. We observe this effect in our model. As already mentioned above, the average electricity price in Germany without interconnector was 47,13 €/MWh. The power exchange reduces it down to 45,98 €/MWh. We also observe the lower standard deviation (12,39% instead of 13,03%), which means more stable prices in the system with connection. The opposite situation occurs on the other side of the cable. Norwegians must now bear with the higher price level: 1,88 €/MWh instead of 1,40 €/MWh. However, with a standard deviation dropping from 16,45% down to 10,51%, they also have more stable electricity prices. As expected, we behold price convergence restricted by the interconnector capacity.

Apparently, there are both gainers and losers in such situation. German consumers now relish lower electricity prices, which results in increase of consumer surplus. On the other hand, the producers' surplus in Germany is now decreased. The same reasoning can be used in respect of the Norwegian market. Producers get the opportunity to convert power surplus into cash on the German market, whereas consumers have to accept higher price level.

The overall gain in social welfare can be analyzed by comparison of the total system cost before and after the introduction of power trade. Total Cost of the simulated system without connection is 11.016.080.828,50 €, which is 560.458.861,45 € more than the cost of the system with interconnector. This means that the connected markets provide the more efficient utilization of resources covering the same demand volume by less expensive generation.

ALTERNATIVE SCENARIOS

1st Scenario: increased Interconnector Capacity

In the first alternative scenario, we would like to investigate how the system will change if we increase the interconnector capacity up to 3 GW.

The amount of transferred power will more than double from 12.000 GWh to 25.000 GWh. Expectedly, the increment occurs owing to the Norwegian export, while the export from Germany stays the same. The model shows, that the lion's share of the transferred electricity replaces hard coal and lignite power plants' generation, which again can be estimated as a beneficial outcome for the environment.

We observe a 2,5% decrease in German price level (45,98 €/MWh – 44,85 €/MWh) along with insignificant raise of price volatility (from 12,39 % to 12,83 %). The Norwegian consumers, however, suffer from much higher (7,14 €/MWh) and less stable (19,35%) electricity prices, which makes the expansion of interconnector capacity undesirable in this country.

As for the total system cost, the simulation predicts appreciable improvement from 10.455.621.967 € to 9.880.618.027,8 € due to less expensive energy production and gains from trade. However, such a project does not seem feasible from the political standpoint, due to significant decrease in consumers' surplus in Norway.

2nd Scenario: Energy System without Coal

In the second alternative scenario, a system without coal-fired power plants is simulated. 47 GW of German lignite and hard coal capacities are replaced by CO_2-free nuclear (34 GW) and additional wind (60 GW) and solar (75 GW) capacities. We also assume more CCGT in such system (22 GW), more energy storage (30 GW) with higher efficiency (80%) and 6% less consumption in Germany reflecting an increase in energy efficiency. The interconnector capacity is 1,4 GW. The point is to learn how much an environment-friendly energy system would have cost the society.

According to simulation, 475 TWh of demand are covered mainly by renewables and nuclear in such an energy system. Various electricity storage technologies (e.g. PSH, lithium-based batteries, compressed air storage, flywheel, etc.), CCGT and import from Norway secure system flexibility being responsible for about 10% of power generation (Figure 2). German export has expectedly grown up to 378 GWh (compared with 22 GWh) since much more hours with excess renewable electricity generation occur.

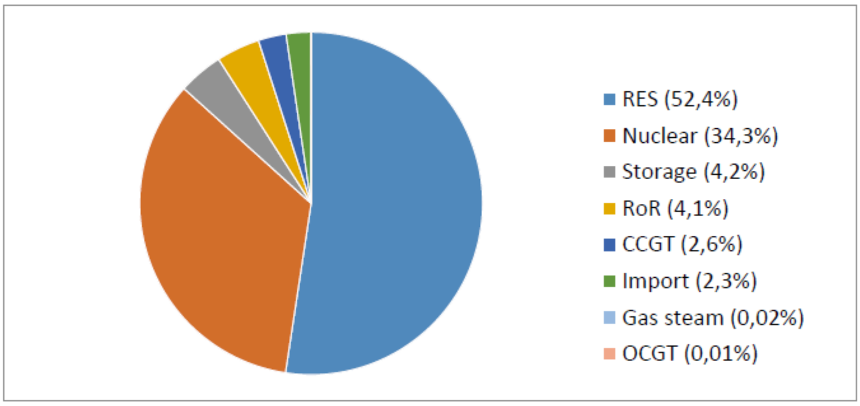

Figure 2. Share of electricity production in Germany (Source: own research)

The average electricity price in the German market falls down to 25,39 €/MWh. Yet the consumers must now accept high price volatility of more than 25%. In Norway, we observe lower and more stable prices (1,14 €/MWh, standard deviation 8%).

The model shows profoundly lower total cost of our no-coal energy system – 3.033.786.853,4 €. However, it does not take into consideration a number of important factors of influence, such as:

- Lasting RES and energy storage subsidies
- High investment costs of nuclear power stations
- Potential environmental risk of fusion power
- Higher price volatility
- Decay of coal industry

The Third Scenario: Nuclear Phase Out; RES expansion

The aim of the third scenario is to simulate the approximate energy system that Germany is about to have in 2022. The two pillars of it are the announced nuclear phase out and substantially increased share of renewables in electricity production.

According to the forecast of Federal Network Agency, there must be about 100 GW of wind and PV capacity in Germany in 2022. We assume 46 GW installed wind capacity and 52 GW of photovoltaic, which represents a growth of 25 GW renewable energy capacities if compared to the original model. More CCGT capacity (21.842 GW) along with 16.080 GW of more advanced and efficient electricity storage will provide the new system with flexibility. Expecting the development in energy efficiency technologies (e.g. smart buildings, smart metering and load management systems), we decreased the German demand data by 6%. No changes in the Norwegian market are assumed. The interconnector capacity stays at its initial level.

As expected, there is a large share of RES in German electricity production – 41,2%. Lignite, hard coal and hydroelectric generation plants cover base load, providing combined more than 50% of power. Yet now there are 60 hours during the year when these capacities do not run. In these hours, RES-infeed exceeds demand and we observe very low or even zero prices (Figure 3). However, the average price In Germany will marginally grow up to 46,29 €/MWh, whereas Norwegians can expect lower electricity price level (1,75 €/MWh) due to increased import of renewable energy.

The model predicts the no-nuclear-system to be more efficient in terms of total system cost: 9.800.720.164 € instead of 10.455.621.967 €. This proves again that RES-intensive interconnected systems can increase the social welfare in the long run.

Figure 3. Relationship between Price, Load and RES infeed (Source: own research)

CONCLUSION

Our model has shown that connecting Norwegian and German electricity systems provides benefits for both countries. The exchange of power enabled by NordLink results in lower power generation from fossil fuels. German coal-fired power stations suffer especially dramatic decrease. Thus, the connection contributes to CO2 emissions decline and provides grid flexibility to handle increasing flows of renewable energy, which makes NordLink a key link for realization of the energy transition (Energiewende) in Germany. According to the simulation, power trade with Germany allows Norwegians to refuse generation from high-variable-cost, inefficient open cycle gas turbines, which leads to more stable electricity prices in the country.

Furthermore, the interconnected markets proved to have less different price levels, just as it must be in theory. German consumers benefit from lower electricity prices, whereas Norwegian suppliers gain, selling a surplus of power on the German market. Conversely, Norwegian consumers and German suppliers can be considered as losers in such situation. However, the comparison of the system's total costs before and after connection proves that the interconnected markets result in more efficient use of resources. We observe a gain of € 560 million. This means that the overall surplus exceeds the overall loss. Saved funds could be reallocated by the states so that every party is satisfied (e.g. grid improvements or lower grid fees).

By modeling different alternative scenarios, we learned that interconnected systems with greater share of renewables in electricity generation are more efficient in terms of total costs (at least with parameters we used). Thus, the support of RES and adjacent technologies will pay off in the long term, increasing the overall social welfare in such systems. Besides, connecting of markets contributes to the mitigation of market power by enlarging market, which again can be considered as a benefit for the society.

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