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Keywords

Energiewende, RES, transmission networks, congestion, loop flows, ELMOD, Central Europe

JEL Classification

L94, Q21, Q48, C61

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1 Introduction

This paper investigates a contradiction between two important energy policy directions of EU: on one side creating a unified energy market, on the other side promoting renewable energy, where the problems with accommodation of renewable electricity in electricity transmission networks provide strong policy incentives to close the national networks and to refuse the transfer of electricity from other countries during high-production events (Huppmann & Egerer 2015). In order to address this problem we use the non-linear optimization model ELMOD, which maximizes social welfare under a number of constraints We analyse the impacts of increased renewable energy feed-in and nuclear phase-out on cross-border grid congestion in Central Europe (CE) and on volatility growth in transmission networks in CE. The important contribution of this paper is that, unlike many others, it focuses on the whole region of CE in the same detail as Germany and particularly elaborates on the influence of individual components of German Energiewende policy (i.e. renewable energy promotion and nuclear phase-out) on the whole area. Also, this paper stresses the importance of the German - Austrian bidding zone which was mostly neglected in the previous research. This paper uses a "critical scenario approach". This means that the results must be interpreted in the context of what would be the impact of electricity flows on the grid if nothing was changed in the grid development.

On the renewable energy side of our investigated policy conflict there are EU 20-20-20 targets (European Commission 2009) and even more ambitious targets of 2030 climate energy framework (at least 40% cuts in greenhouse gas emissions (from 1990 levels) and at least 27% share for renewable energy and at least 27% improvement in energy efficiency) (European Commission 2014). On the market integration side of the controversy there is the effort to create a European Energy Union, officially launched in 2015 European Commission (2015). The development of variable renewable energy sources (VRES) in Germany caused severe problems with transmission network in CE region, defined as Germany, Czech Republic, Slovak Republic, Poland and Austria in this paper. Excess production in the north has to be transported to the consumption centres in the south of Germany, to Austria and other energy deficient countries in southern Europe. The existing German grid is not able to accommodate such a big feed-in of intermittent renewable energy and, therefore, exhibits congestion. As a result, electricity flows through the systems of adjacent countries, Poland and the Czech Republic, and this causes severe problems in their grids as well. These problems are exacerbated by the market integration, in particular by the existence of German-Austrian bidding zone which enables these two countries to trade electricity disregarding the physical grid constraints as illustrated in figure 1. While this single bidding zone also includes Luxembourg, we refer to it as German-Austrian zone because of the Central European focus of this paper.

Figure 1: Stylized map of situation in CE

Source: Authors, based on maps from ENTSOE (2016)

Czech and Polish transmission system operators (TSOs) react to this by the requirement of splitting up the German-Austrian bidding zone (ČEPS *et al.* 2012), which was also supported by the Agency for the Cooperation of Energy Regulators (ACER) (ACER 2015), or even for splitting up Germany in more zones. TSOs also attempt to solve this problem by installing phase-shifting transformers that should be able to stop the physical electricity flows in case of emergency. Nevertheless, in January 2016, the Director of DG Energy declared that European Commission is against the split of the biding zone as it considers this step to be "meaningless" (Kamparth 2016).

While many academicians conducted research on the topic of the influence of renewables on spot and forward market prices of electricity (Traber & Kemfert (2009); Cludius *et al.* (2014); Ketterer (2014); Meyer & Luther (2004)), public budgets and consumer prices (Janda *et al.* (2014); Průša *et al.* (2013)) or power system in general (Blesl *et al.* (2007); Havlíčková *et al.* (2011); Rečka & Ščasný (2016; 2013); Ščasný *et al.* (2009)), less attention has been drawn to equally important transmission networks issues. The majority of the literature assesses the transmission network issues only in the context of Germany (Burstedde (2012); Kunz (2013); Kunz & Zerrahn (2015); Schroeder *et al.* (2013); Egerer *et al.* (2014); Weigt *et al.* (2010); Dietrich *et al.* (2010)).

For the transmission network analysis in this paper we use the most suitable state-of-the-art model ELMOD. Since its first publication in Leuthold *et al.* (2008), this model has been applied most frequently to the analysis of market design (Neuhoff *et al.* (2013); Egerer *et al.* (2016b)), the influence of renewables on transmission networks (Egerer *et al.* (2009); Schroeder *et al.* (2013)) including grid and power plant investment decisions (Leuthold *et al.* (2009); Weigt *et al.* (2010); Dietrich *et al.* (2010); Egerer *et al.* (2016a)), uncertainty and stochastic effects (Abrell & Kunz (2012)) and congestion management issues (Kunz (2013); Kunz & Zerrahn (2015; 2016)).

The literature on transmission networks and grid in CE is significantly less extensive. Apart from the above-mentioned ELMOD literature, there are several other articles which mostly deal with optimal grid extension or integration of renewables into the grids. Nevertheless, these focus on Germany (Winkler *et al.* 2016; Singh *et al.* 2015) or Europe as a whole (Fürsch *et al.* 2013; Majchrzak *et al.* 2013; Schaber *et al.* 2012a;b). The grid related literature in Poland examined most often possibilities of phase-shifting transformers (Korab & Owczarek 2016; Kocot *et al.* 2013).

The literature paying pure attention to the region of CE is very sparse. A few examples are very recent articles from Singh *et al.* (2016), analysing the impact of unplanned power flows on transmission networks, Eser *et al.* (2015), assessing the impact of increased renewable penetration under network development and Kunz & Zerrahn (2016) focusing on cross-border congestion management.

The rest of this paper is structured in the following way: Section 2 provides an overview of power and transmission systems in CE. Section 3 explains the ELMOD model and the following section 4 describes the data. Section 5 introduces our base scenario and two development policy scenarios, section 6 presents and interprets the results and the last, section 7, concludes.

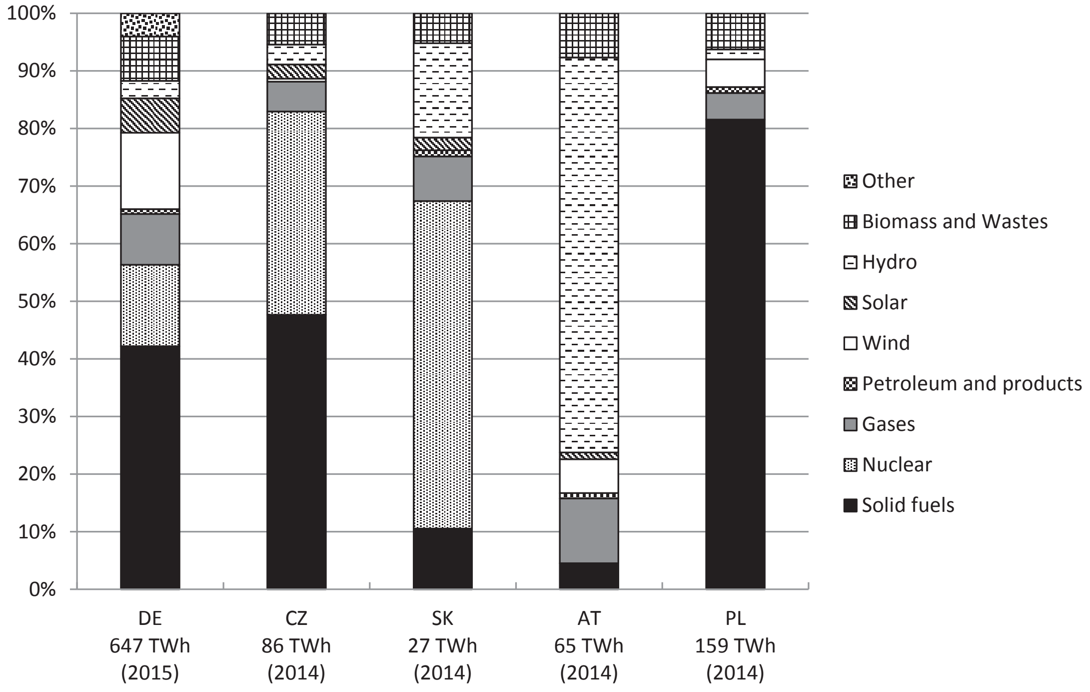
2 Overview of power and transmission systems in Central Europe

2.1 Electricity production

Electricity production in CE is heterogeneous and reflects energy reserves, potentials and policies in each country of this region. Figure 2 illustrates the differences in the generation structure among the CE countries in 2014 (2015 in case of Germany).

Out of 651.6 TWh of electricity produced in Germany during 2015 (BMWi 2016) the share of solid fuels is 42% and renewables account for 30 %. The most

Figure 2: Electricity production by fuel type in CE countries

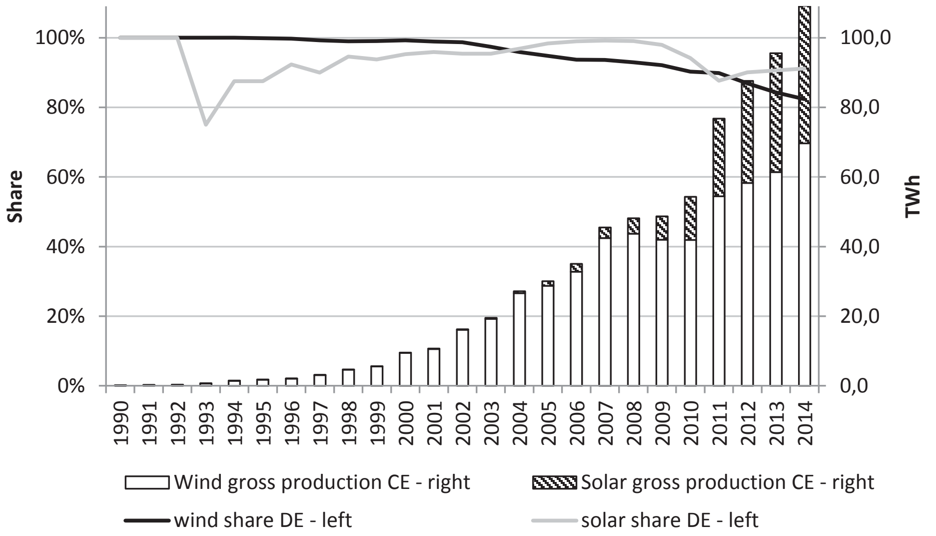


Source: European Commission, DG Energy (2016a)

important German renewable sources are on shore wind turbines, biomass and solar power plants. At the end of 2014, 46.72% of total installed capacity can be assigned to renewable energy sources (RES). This is a second highest number after Austria in the CE region. Germany is a net electricity exporter since 2003 and it exported 50.1 TWh of electricity in 2015 (BMWi 2016). Due to its size, the German energy system is dominant in CE region. Thus, policies implemented in Germany affect the whole region fundamentally. This is particularly true for wind and solar production, as illustrated by the figure 3.

Out of 86.3 TWh of electricity generated in the Czech Republic during 2014 (Energy Regulatory Office 2015) the biggest contributors were solid fuels (48%) and nuclear power plants (35%). At the same time, the net balance with foreign countries accounted for 16300 GWh of export which made the Czech Republic the third largest exporter of electricity in Europe (Energy Regulatory Office 2015). Moreover, the balance with other countries has not dropped under 11 TWh since 2002.

Figure 3: Wind and solar production in CE* and share of Germany



*This includes CZ, SK, AT, DE, PL

Source: Own, data European Commission, DG Energy (2016a)

With 83 % share of RES of total electricity generation (65.4 TWh in 2014), Austria is a leading nation in CE in ecological production. Austria is a net importer since 2001 with net electricity import of 9.275 TWh in 2014 which corresponded to 13.46% of its 2014 inland consumption (European Commission, DG Energy 2016a; E-CONTROL 2016). 2871 MW of intermittent installed capacities (wind and solar) as of 2014 corresponded to 12% of total installed capacity. It is important to note that majority of the Austrian hydro power are pumped storage power plants (7969 MW or 58.73 % of installed hydro) (E-CONTROL 2016).

Slovak electricity production (27.4 TWh in 2014) as well as consumption is the lowest in the CE region. The greatest share (57%) came from nuclear power plants and hydro power plants (16%). Similarly to Austria, Slovakia has low share of fossil fuels on total electricity production (20%). Slovakia is a net electricity importer since 2006 when it had to shut down part of Jaslovske Bohunice nuclear power plant. In 2014, imports accounted for 1.1 TWh which represents 3.9% of Slovak consumption. The amount of imports between different years substantially varies (European Commission, DG Energy 2016a; Ministersvo hospodárstva

Slovenskej republiky 2015).

Out of 159.3 TWh produced in Poland in 2014, 81 % was generated by coal fired power plants, where hard coal power plants supplied 80.24 TWh and lignite power plants 54.2 TWh (PSE 2015b). The second most utilized source were then biomass and wind power plants (6% and 5% respectively). Especially the wind power plant installed capacity growth was significant in past years which can be mainly attributed to the fact that Baltic sea and surrounding regions offer suitable conditions for wind production. Poland is structurally an electricity exporter. Nevertheless, in 2014 we can observe imports of 2.16 TWh which accounted for 1.36% of annual consumption in 2014 (PSE 2015b).

2.2 Transmission systems and grid development

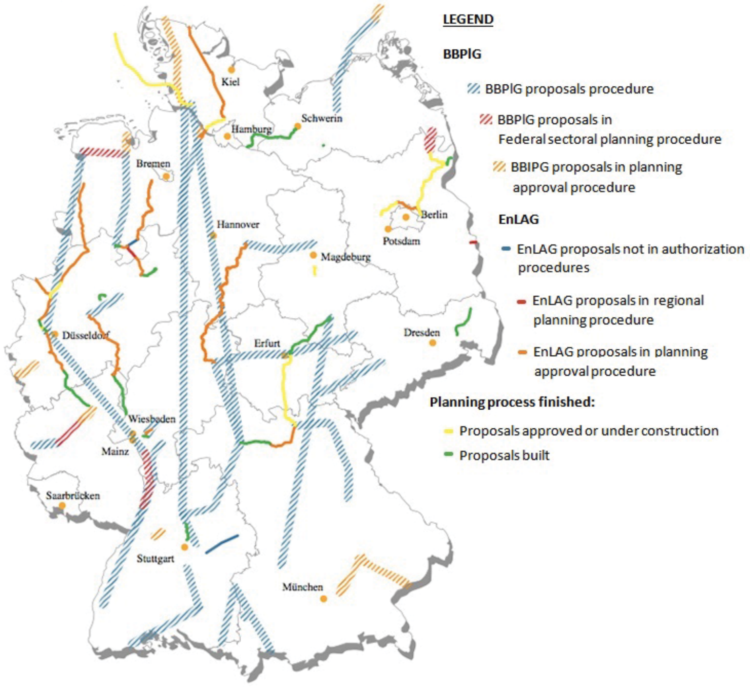
The German transmission grid is divided between four TSOs: TenneT, Amprion, 50Hertz Transmission and TransnetBW. The TSOs are supervised and regulated by the German federal network agency, Bundesnetzagentur (BnetzA) which ensures discrimination free grid access. Since 2011, it has also played an essential role in implementing the grid expansion codified in the Grid Expansion Acceleration Act (NABEG).

The German transmission grid faces severe congestion problems. In the past, electricity generation was based on two criteria: Availability of resources in proximity and close location to the demand. The boom of renewables has, however, changed the situation dramatically. In Germany, centres of electricity consumption are situated mostly in the south and west of Germany but regions suitable for most economic production VRES being located in the north. The electricity generated there must therefore be transported over long distances to the consumers in north-south way. In the process, the existing network is frequently reaching its capacity limits (Bundesnetzagentur 2015). This embodies clear challenge for old, supply-adjustment based grid model. More dynamic and agile set-ups including demand balancing, electricity storage devices installation and re-dispatching will be necessary to handle the situation successfully (Pollitt & Anaya 2016).

The planned nuclear phaseout furthermore contributes to the north-south grid pressures. Nuclear power plants are mostly located in southern regions, Bavaria and Baden-Wurttemberg. 8386 MW of nuclear installed capacity in these two states should be disconnected from the grid by 2022. The loss of capacity is not expected to be fully offset by new installed capacities, which is the result of limited RES potential in the area (Flechter & Bolay 2015).

The need to strengthen the infrastructure in north-south direction is therefore unquestionable which is also a stance of both, German authorities (BMWi 2015a) and especially neighboring TSOs as described bellow. The grid expansion agenda is backed by two German laws - Power Grid Expansion Act (EnLAG) from 2009 and Federal Requirements Plan Act (BBPlG) from 2013.

Figure 4: Future extension of German transmission lines



Source: BMWi (2015c)

Nevertheless, the volume of the infrastructure extension as well as the realization itself seem to be a matter of controversy and this contributes to prolongation of problems. EnLAG legislature specified 23 mostly north-south transmission lines in the length of 1876 km that need to be urgently built to preserve the stability of the system in the environment of increasing RES production. The construction should have been finished by the end of 2015 (Flechter & Bolay 2015). Nonetheless, in the second quarter of 2015, only 8 kilometers of lines were built which provides 487 km with previous construction. Estimates now calculate with 40% being built till the end of 2016 (Bundesnetzagentur 2016). BBPlG, which came into effect in July 2013, added another 36 planned extension lines out of which 16 are considered of cross-regional or cross-border importance. Corridors of future networks are now determined and a public discussion about the exact tracing is in progress (BMWi 2015c). Mainly EnLAG activities suffer major project delays which can be ascribed to the negative public opinion and resistance which accompanies the network construction. The general public refuses the grid construction in the vicinity of their places of living and requires mostly the underground cable solutions.This is estimated to be up to 5 times more expensive than ordinary lines since kilometre of lines costs 1.2 Mio EUR whilst kilometre of cable costs 6 Mio EUR (Rapp 2012). As a result, it barely seems that fast short term improvement with the 40% target is foreseeable.

The Czech transmission system still reflects the design at the time of completion in the 1980s. Investments to the grid enhancement and reinforcement need to be done so that the grid is able to cope with upcoming challenges (ČEPS 2016).

Extreme growth of installed capacity of Czech solar power plants between 2008 and 2012 caused itself problems in Czech grid. In this period, the Czech cumulative solar capacity grew little more than 50 times and only during 2009 and 2010, applicants asked the distribution companies to connect up to 8000 MW (Vrba *et al.* 2015) which resulted in the request of Czech transmission system operator, the company CEPS, to temporarily stop the approvals of new capacities (ČEPS 2010). Thus network security was endangered already in 2010 (1727

MW of solar and 213 MW of wind installed)(EGÚ Brno 2010) because of Czech domestic reasons. As a result, feed-in tariffs were decreased up to 50% and later were completely abolished for most RES built after 2014 (Vrba *et al.* 2015). After that, approvals for connections to the grid were allowed again in January 2012 (Klos 2012).

The process of planning the further development of Czech grid is mostly driven by the "Ten-year investment plan for the development of the transmission system" that works with the time scope of 2015-2024 and its main goals are expansion and upgrade of existing substations, construction of second circuits on selected lines as well as building of several new ones. Installation of phase-shifting transformers at Czech-German interconnectors should be finished till the end of 2016 with approximate cost of 74 mil EUR (ČEPS 2015). The total volume of investments during this development plan is estimated to reach 1.66 bn EUR (ČEPS 2015).

The Austrian transmission network, operated by the company APG, plays a key role in Central Europe as it is a crucial cross-road for transport of electricity from the Czech Republic and Germany to south-eastern European countries. Since 2015 the new Austrian "Ten year Network development plan" focused on grid reinforcement and expansion measures, upgrade of existing lines to higher voltage levels, construction of substation and transformers as well as 370 km of new transmission lines (APG 2015).

The Slovak transmission network, like the Czech one, was for a very long time part of common Czechoslovakian system which was developed together as one fully integrated system. This explains the absence of bottlenecks on the Czech-Slovak border and extraordinarily high level of interconnection of 61 %. The Slovak grid is important in the international context as Czech exports to Slovakia are almost fully passed further to Hungary (In 2014, 9392 GWh of electricity was imported from the Czech Republic and 9356 was exported to Hungary (Ministersvo hospodárstva Slovenskej republiky 2015)). Also the Slovak grid will be subject to reinforcements and upgrades. In 2014, SEPS issued a "Ten year development plan for the years 2015-2024". In this plan, investments reaching 564 mil EUR are outlined. They concern mostly internal advancement of infrastructure as well as expansion of cross-border transmission lines, particularly on Slovak-Hungarian borders. All other border profiles are not included in projected investment plans as their capacity is sufficient (SEPS 2014).

Polish transmission network suffers from very low density in northern and western areas as well as very low interconnection level of only 2% which entails severe problem when transmission of electricity is considered. Very often, congestion and hitting up of limits of the lines occur. The most critical situations appear on Polish-German border where only 4 interconnectors on the voltage level 220 kV are present. The contemporary "Development Plan for meeting the current and future electricity demand for 2016-2025" reacts to this and the existing interconnectors are planned to be upgraded to 400 kV levels. Moreover, after the grid in western Poland is reinforced by 2020, new interconnector is projected after 2025. PSE also plans major infrastructure enhancement within whole Poland which is the precondition for successful connection of new expected power plants, including mostly wind, gas and coal ones. Outlays in the first half of the period should reach 1.59 bn EUR, in the second half then 1.43 bn EUR (PSE 2015a).

2.3 Market design description and cooperation setup

Market design is another important factor that influences power and transmission systems in CE. Under current levels of technology, possibilities of electricity storing are extremely limited when economic viability is taken into account. Consequently, flawless grid operation requires equality of supply and demand at particular time and place. TSOs are responsible for ensuring such equilibrium by forecasting demand, scheduling supply and balancing the deviations.

The design of bidding zones is an important parameter of the electricity market. Bidding zones are frequently set to correspond to national borders which reflects the nature of the infrastructure development. Setting up cross-zonal bidding areas has several advantages as well as disadvantages. The main benefits are the equality of the price of wholesale electricity in the bidding zone, higher liquidity, effectiveness and transparency of the market as well as implicit capacity allocation (ACER 2015). This is based on the fundamental assumption of sufficient transmission capacity being present within the bidding zone. The main drawback is embodied by the fact that the cross-border internal flows in a huge bidding zone cannot be controlled which implies that the flows also have an impact on adjacent bidding areas (ČEPS *et al.* 2012). The usual reaction of responsible TSOs is a decline of cross-zonal tradable transmission capacity (Net Transfer capacity (NTC) which is the main determinant of free cross-border commercial transmission capacities between particular zones). As such, proper bidding zone delineation is crucial for efficient functioning of the system; otherwise, such zone can represent an artificial bottleneck in the electricity market.

Austria, Germany and Luxemburg are one of the single-country bidding zone exemptions and has formed a major bidding zone in Central Europe since the year 2005. The formation was merely unilateral with no attention paid to the side-effects imposed on the adjacent countries, the Czech Republic and Poland Bemš *et al.* (2016). So even though the zone guarantees unrestricted trading and common electricity prices to all participating countries, lack of internal transmission capacity causes significant negative overflows to the transmission systems of neighbouring countries. Mostly for these reasons, there are attempts to split the German-Austrian bidding zone or even to split Germany into two zones to terminate the source of artificial bottleneck in the grid.

3 Methodology

This study applies the state-of-the-art DC load flow model called ELMOD also used in Leuthold *et al.* (2012) and Egerer *et al.* (2014). The mathematical formulation can be found in the Appendix and is based on an optimization problem that maximizes social welfare after taking into account the technical and physical peculiarities connected to electricity. The maximization problem is solved for the whole area at once which is equivalent to the assumption of one TSO operating entire area. The model is solved in GAMS (General Algebraic Modeling System) using the CONOPT solver.

The model applies a welfare maximizing approach with a target function maximizing consumer and producer surplus (see eq.1 in the Appendix A). The model is constrained by a nodal energy balance which states that the difference between generation and demand at a specific node, net of storage, demand shifting and load in- or outflow, must be zero (eq.3). A generation capacity constraint incorporates technical generation limits of each plant type at each node and time (eq.4). Line flow restrictions are taken into account (eq. 5)-(eq.7).

Electricity inputs include total generation from conventional power plants $\sum_c g_{nct}$, wind generation G_{nt}^{wind}, solar generation G_{nt}^{solar} and storage power plant release PSP_{nt}^{out}. Moreover, the parameter on maximum thermal limit of transmission line inherently incorporates the system security criterion by allowing for some reliability margin. The flows over particular line in a given time are modelled (eq. 5) and the phase angle for an arbitrary slack node is set to zero (eq. 7) to ensure the uniqueness of solutions (Egerer *et al.* 2014).

This application of ELMOD model uses a simplification of AC load flow to DC load flow model which is an approach commonly found in numerous ELMOD applications. Overbye *et al.* (2004) discusses the actual differences between the AC and DC flow applications and concludes that the loss of accuracy is very small and that DC results match pretty well AC load flow solutions. To simplify the flow calculations, ELMOD model follows the work of Schweppe *et al.* (1988) and Stigler & Todem (2005) where reactive power flows and transmission lines losses are neglected, angle differences are assumed to be small and voltages are standardized to per unit levels (see Purchala *et al.* (2005) for applicability of these assumptions).

As a result, DC load flow deals only with two variables - voltage angle and active power injections (eq. 8). The net input into a DC line is determined by the line flows of the DC lines multiplied by their factor in the incidence matrix.

4 Data description

Our dataset is based on Egerer *et al.* (2014) in which several adjustments and updates are made. The transmission network system, power plant units and their technical characteristics are completely taken from Egerer *et al.* (2014) and resemble thus the state of the year 2012. Similarly to the application of Kunz & Zerrahn (2016), the rest of the dataset related to electricity is updated to 2015. Data for load, solar, wind, pump-storage plant generation and pump-storage plant pumping are obtained from the ENTSOE Transparency platform (ENTSOE 2016) or from the pages of individual TSOs in case of unavailability in the Transparency platform. Prices of electricity to calculate demand are obtained from (European Commission, DG Energy 2016c). Power plant fuels prices are collected from several resources as shown in the table 1. Prices of CO_2 allowances are retrieved from the database of European Energy Exchange (EEX) in Leipzig. Data on cross-country price differences in gas and oil are collected from (European Commission, DG Energy 2016d) and (European Commission, DG Energy 2016b), respectively.

4.1 Grid

The underlying grid data consist of nodes (transformer stations) which are connected by transmission lines (individual circuits). In several cases, auxiliary nodes are added on the intersection of lines (Egerer *et al.* 2014). Our dataset consists of 593 nodes, 10 country-specific nodes and 981 lines.

Each transmission line is characterized by several parameters necessary for conduction of a DC load flow model – number of circuits, length, resistance, reactance, voltage level and thermal limit.

There are two levels of detail in our data. First, the transmission systems of CE countries are reflected to a most possible level of detail. This means structural nature of the network is modelled by taking into account actual lines and substations which are operated by the TSOs. The exact form of the transmission system can be found in Egerer *et al.* (2014, p.56). The second level is more aggregate. Following Leuthold (2009), adjacent countries (all states with interconnections to the CE region: Netherlands, Luxembourg, France, Switzerland, Italy, Slovenia, Hungary, Denmark, Sweden) are represented by country-specific single nodes which are interconnected with the CE region as well as between each other. The number and properties of interconnectors between the countries are unaffected.

This distinguishes the paper from most of the research works which focus primarily on Germany and model only German network in such a detail. Another benefit is that incorporation of aggregated neighbouring states as single nodes prevents the occurrence of severe biases in resulting flows which would be the consequence of absent transit and loop flows of electricity between CE and adjacent areas. The transit flows can be illustrated on Italy, the biggest importer of electricity in Europe. Italy has terrestrial interconnections to France, Switzerland, Austria and Slovenia which supply all the imported electricity. Neglecting this would lead to inappropriate flows in the grid. Nevertheless, the applied model could be extended by at least a Balkan node as discussed in section 6.1.

The final dimension of the grid data regards security which the TSO has to take into account. In real life, this is captured by the "N-1" security criterion which is a basic criterion of power system stability. It requires that the system is able to operate and supply electricity provided a sudden outage of one system element occurs (Neuhoff *et al.* 2005). In the model, this security constraint is introduced by a 20% reliability margin in the thermal limit of each line (Leuthold *et al.* 2008, p.13).

4.2 Generation

Based on the approach in Egerer *et al.* (2014), generation capacities are divided between conventional and renewable sources which are treated accordingly. For conventional generation, individual units or power plants are considered separately (only units above 10 MW are considered). Each unit is allocated into one of 20 technological clusters according to fuel that is being consumed and technology that is utilized by the generation unit. Exact overview and definition can be found in Egerer *et al.* (2014, p.57).

The 607 generation units in the CE region are assigned to specific nodes by the method of shortest distance. In the remaining single node countries, all generation units are summed up over the production technology and allocated to that single node. Due to lack of data availability, all power plants data are taken from Egerer *et al.* (2014). The cost of this approach is that the generation dataset reflects the state in the year 2012. Thus an assumption about time-invariant development of generation capacities had to be made for the years 2013 to 2015. The only exception is the German nuclear phase-out which is fully reflected in the dataset for the particular period.

Actual generation from individual plants is subject to model optimization after taking technical parameters of the plants into account. These include fuel cost, generation efficiency and availability of production units. Fuel and emission prices have to be introduced as these represent the short-term variable costs of producing one MWh. This applies to conventional power plants whereas RES are considered at the zero production cost. For both types, operation and maintenance costs as well as unit commitment costs are not considered (Egerer *et al.* 2014). Input prices for particular inputs are given in the table 1 together with the respective data sources. All prices are updated to 2015 values except the price for coal where only 2014 values are available.

Following Egerer *et al.* (2014, pp.62, 64) and Leuthold (2009), solar and wind power plants are aggregated regionally with respect to individual nodes. As a result, the weights of individual nodes on the total solar and wind generation are obtained. The renewable generation enters the model as a parameter and for this reason, aggregate data on 2015 hourly generation for the country level are obtained from ENTSOE transparency platform. These are then allocated to individual nodes in accordance with the aforementioned approach.

Table 1: Fuel prices

Fuel	Price [EUR/MWh$_{th}$], [EUR/t(CO$_2$)]	Source
Uranium	3	Assumption of Egerer et al. (2014)
Lignite	3,48	Own calculation
Hard Coal	6,96	BP: Northwestern Europe coal price 2014
Gas	22,28	EC: Quarterly reports on European gas markets
Oil	28,42	Bloomberg: Brent oil price
Biomass	7,2	Assumption of Egerer et al. (2014)
Hydro	0	
Wind	0	
Sun	0	
Waste	7,2	Assumption of Egerer et al.
Carbon	7,59	EEX: Median CO2 EUA settlement prices

Table 2 shows the technology-specific efficiencies with respect to time and technology.

Table 2: Efficiency of conventional generation technologies (in %)

	1950	1960	1970	1980	1990	2000	2010
Nuclear	33	33	33	33	33	33	33
Lignite	29	32	35	38	41	44	47
Coal	29,6	32,8	35,9	39,1	42,3	45,5	48,7
CCGT and CCOT	20	26,7	33,3	40	46,7	53,3	60
Gas Steam and Oil Steam	30,6	33,8	36,9	40,1	43,3	46,5	49,7
OCGT and OCOT	24,7	27,3	29,9	32,5	35,1	37,7	40,3
Source	(Egerer *et al.* 2014, p.70)						

Availability parameter can be found in the table 3. Availability of wind, solar and pump storage power plants is set to one as corresponding data enter the model as external parameters.

Table 3: Availability of conventional generation technologies

Type	Nuclear	Lignite	Coal	CCGT, CCOT	OCGT, OCOT	Gas Steam, Oil Steam	Reservoir, RoR	Hydro
Availability	0,84	0,9	0,87	0,91	0,9	0,89	0,62	0,32
Source:	Egerer *et al.* (2014, p.70) and Schröder *et al.* (2013)							

4.3 Load and electricity price

ENTSOE database is the source of hourly data for all included countries for the year 2015. Primary need for the load data is based on the necessity to have the counterpart to the generation on nodal basis in CE region and national basis in the rest of countries. However, the load values are available on national level only which is not satisfactory for the purposes of the model. Egerer *et al.* (2014) suggests to use GDP and population as proxies for industrial and residential demand respectively (GDP assumes 60% weight whereas population assumes 40%). All data are taken on the NUTS 3 level, for which the data are available in all cases (Egerer *et al.* 2014). Exact allocation procedure is described in detail in Egerer *et al.* (2014) and Leuthold *et al.* (2012).

Secondary utilization of the load data occurs in the optimization problem where the welfare function is maximized. At each node, reference demand, reference price and elasticity are estimated in order to identify demand via a linear demand function (Leuthold *et al.* 2012). In here, as Leuthold suggests, the hourly load is assigned to the nodes according to the node's share described earlier. This, subsequently, yields a reference demand per node. Table 4 shows the prices for relevant countries.

Table 4: Electricity reference prices, [EUR/MWh]

Country	AT	CH	CZ	DE	DK	FR	HU	IT	LU	NL	PL	SI	SK	SE
Price	32,33	36,80	32,53	32,08	25,63	38,75	41,45	53,80	32,08	41,73	41,48	41,93	33,50	18,51
Source:	European Commission, DG Energy (2016c)													

Demand elasticity is taken as -0.25 based on Green (2007).

4.4 Simplification of the full year model

Due to computational limitations resulting from complex structure of the model, four representative weeks with the different combinations of extreme values of RES production are used and investigated in detail. Similarly to Schroeder *et al.* (2013), four weeks (we use English-type weeks, i.e. the week starts by Sunday) with different values of wind and solar production are chosen. In particular, we speak about two base weeks, week 4 (penultimate week in January - from 18th January to 24th January) and week 14 (last week in March - from 29th March to 4th April), where the cumulative production from wind and sun is lowest or highest in CE, respectively. The two other weeks, 27 (last week in June from 28th June to 4th July) and 49 (last week in November from 29th November to 5th December), were considered only as a robustness check for our results as they mirror the opposite extremes in production. Thus, week 27 mirrors the situation provided there is a high production from sun and low production from wind and week 49 reflects the opposite.

In the figures 5 and 6, the aggregate load-generation profiles for CE countries during the base weeks are shown on the real data for 2015. Load, residual load, where *Residual load = Load - Sun generation - Wind generation*, sun and wind generations are depicted during the respective hours of the week.

Figure 5: Week 4 profile

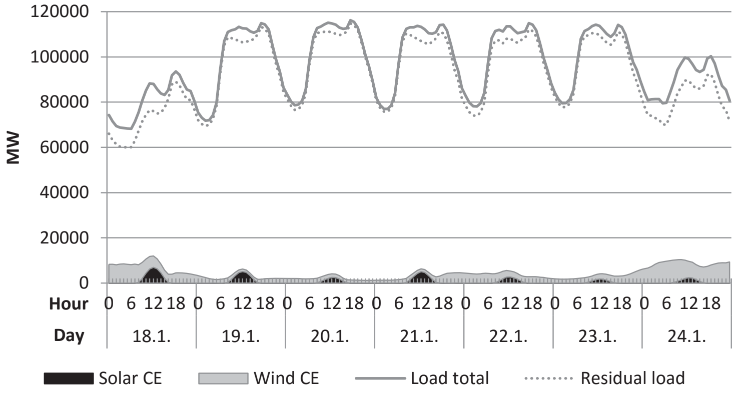
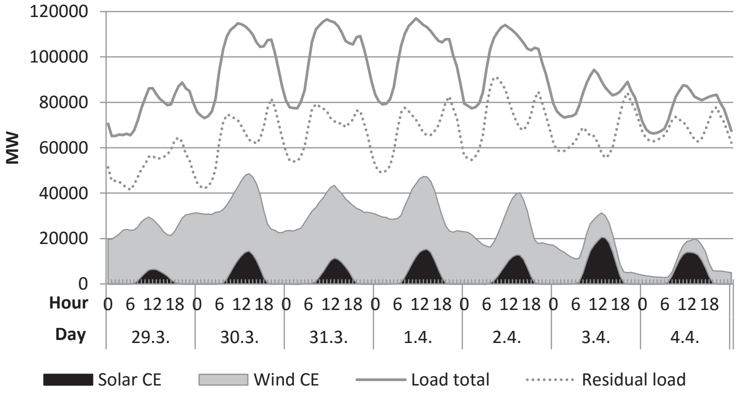


Figure 6: Week 14 profile



Source: Own, based on ENTSOE (2016) data

5 Scenarios

To measure exactly the impacts of grid bottlenecks between southern and northern Germany and Energiewende policy on the transmission grid, electricity flows over the individual lines within the network are obtained. Afterwards, they are compared in the context of three scenarios.

Reference scenario, called *base*, models the current situation in the power sector based on the data as specified in section 4.

Scenario *full* assesses full range of the impacts of increase of VRES production and nuclear phase-out in CE context. It is derived from the *base* scenario by taking into account the aims of German energy policy for the year 2025. Parameters reflecting the VRES production are multiplied by coefficients (table 5) and nuclear power plants are phased-out. Everything else in Germany as well as in remaining countries, including grids, reflect the state of 2015 or other years as specified in the section 4. From the nature of construction the results must be read in the context of worst possible outcome if nothing was done in network development.

All relevant electricity-related Energiewende goals are defined as a percentage of electricity consumption as compared to the year 2008. According to

AGEB (2015), 618.2 TWh of electricity was consumed in Germany in 2008. Energiewende goals require the electricity consumption to be reduced by 10% until 2020 and by 25% until 2050 (BMWi 2015b). Linear approximation leads to 12.5% reduction in 2025 which accounts for 541 TWh. This comprises 90.61% of the 2015 consumption.

Shares of solar and wind electricity generation are based on the scenario "2025 A" from "Netzentwicklungsplan" (Feix *et al.* 2015) where installed capacities are projected. Actual generation is obtained by multiplying these figures by utilization factors of individual power plant types extracted from AGEB data. This approach yields the renewable/consumption ratio of 45.91%, pretty close to 42.5% which is the result of linear approximation for year 2025 using BMWi scenarios (BMWi 2015b). Table 5 summarizes the calculations concisely.

Table 5: Parameters of *full* scenario model

TYPE	Installed capacity 2013 (MW) (1)	Development coefficient (2)	Installed capacity 2025 (MW) (3)	Full load hours (4)	Generation 2025 (TWh) (5)	Generation 2015 TWh (6)	Generation coefficient (7)
Solar	36340,00	1,490	54159,61	969,77	52,52	38,50	**1,364**
Wind onshore	33310,00	1,568	52231,66	1900,46	99,26		
Wind offshore	620,00	14,355	8900,00	3118,28	27,75		
Wind	33930,00		61131,66		127,02	86,00	**1,477**
Biomass	8380,00	1,032	8650,32	5000,00	43,25	44,30	
Water	5590,00	1,000	5590,00	3494,62	19,53	19,50	
Other					6,00	5,70	
Source:	Feix *et al.* (2015)	Feix *et al.* (2015)	(1)*(2)	Own, data BMWi (2015b)	(3)*(4)	AGEB (2015)	(5)/(6)

Values given in the column "Generation coefficients" are then that ones, by which original data for wind and solar production are multiplied. Finally, BMWi scenario was selected because it is highly probable that policy makers will stick to it and will thus follow time-consistent development based on this scenario. This assumption is based on two findings: first, the BMWi scenario exhibits extraordinarily high social acceptance when compared to other development scenarios (Schubert *et al.* 2015b), and, second, it focuses highly on economic viability and emission reduction (up to 80 % as of 1990 (Keles *et al.* 2011)) which are both factors playing major role in German public's opinion on Energiewende (Schubert *et al.* 2015a).

Scenario *res* inspects one particular part of Energiewende policy – the nuclear phase-out or, from the other point of view, isolated impact of renewables on transmission networks without the nuclear phase-out. It is based on *full*, except the fact that German nuclear power plants are considered to be still in operation even after 2022.

6 Results

The results are presented for the two base weeks with low and high VRES production. There are 30 interconnectors between the countries of Central Europe, 29 interconnectors between the German TSOs, another 39 interconnectors between the Central Europe and adjacent states and hundred of lines within the particular countries. Commentary on each individual line would not contribute to a lucid and clear interpretation of results. Hence, resulting modelled flows are reported and interpreted on "border profiles" as in Egerer *et al.* (2014). (Full access to aggregated results is provided in supplemental materials available upon request).

There are three kinds of border profiles considered in this paper: border profiles between countries, border profiles between TSOs within Germany, and border profile between northern and southern Germany. This northern-southern Germany border profile is employed for the examination of the electricity exchanges with respect to the bottlenecks within Germany as described in the section 2. This border profile is created similarly to the study of Egerer *et al.* (2016b).

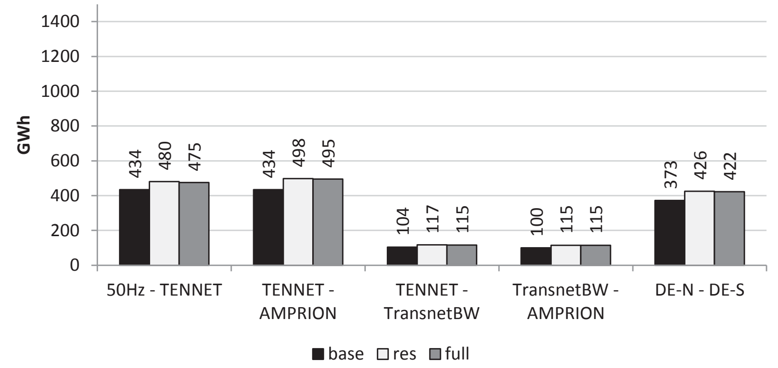
Detailed commentaries are made only for the weeks 14 and 4 where peak and bottom of cumulative VRES production occurred, respectively. We do not report the results for the weeks 27 and 49 as they quantitatively confirm he results for weeks 4 and 14. From the qualitative perspective, these results match the reality pretty well. Brief overview of these results can be found in supplementary materials. Eventually, *res* and *full* scenarios are compared with the *base* scenario.

Percentage changes in transmission (sum of absolute values of import and export over the interconnector) and absolute value of changes of balances (difference between import and export keeping the flow direction) and transmission are presented together in table 6. Table 7 gives then an overview of extreme loads which are defined as a number of times the flow over particular line exceeds 75% thermal limit of the line. Each line is subject to a 20 % margin representing the "N-1" criterion of security. Thus, if the line exceeds 75%, it could be considered as critical event.

6.1 Week 4 - low VRES production

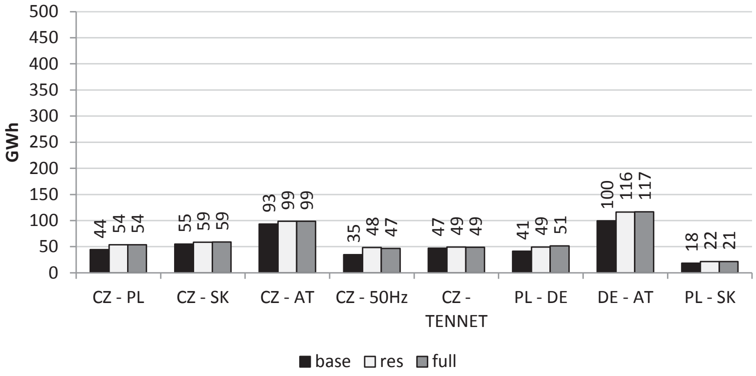
The general effect of low VRES production is the low international balance as well as total transmission of electricity (fig. 7 - 8).

Figure 7: Transmission DE, W4



The *base* scenario results for exchange balance fit the actually observed ones, except the case of Czech-Slovak and Polish-German borders. Despite this fact, week 4 results exhibit quite a poor performance in predictions of amounts. Table 6, column 1, summarizes the proportional deviation from real balances. The opposite flow directions in the cases of Czech-Slovak and Polish-German borders are represented by the values lower than -100%. Reversed flow on Czech-Slovak border is structural in the model due to the fact that electricity flows from the

Figure 8: Transmission CE, W4



Czech Republic through Slovakia to Hungary and further to Balkan countries in the reality. In the model, the Balkan countries are not modelled which results in above mentioned consequence. Problem could be solved in future by adding up Balkan countries as one additional importing node.

The poor model prediction performance in this particular week with low load might be linked to the single TSO's area nature of the model. As low share of zero-marginal cost renewable production enters the model, non-zero cost conventional production has to take place to meet the demand. Because of the single TSO in the model, all area is optimized at once. Therefore, conventional power plants produce at the most possible local level and the necessity for cross-zonal transport of electricity is limited. Furthermore, similar predictive power of the model was found also in other studies, e.g. in Egerer *et al.* (2014).

Comparison of the scenarios *res* and *full* does not confirm the anticipated negative impacts on the grid of nuclear phase-out in the sense of exacerbating the overloading of grids in the north-south direction in Germany and in sense of greater loop flows through Poland and the Czech Republic (table 6, figures 7 and 8). Average utilization of cross border-interconnectors is very low (below 20 %) as a result of low amount of transport as explained in previous paragraphs. Even though some increase of utilization can be observed on all but three lines, the increase is very modest. The maximal rise of 6,56% is measured over the line

Krajnik (PL)-Vierraden (DE).

The results also confirm that VRES induce growth of volatility of transmission and, consequently, contribute to the system destabilization. All but three lines evince standard deviation increment and thus more fluctuating flows can be observed. Unlike in the previous case with the average load, the degree of volatility differs between *res* and *full* scenarios. In both cases, the higher degree of volatility can be observed, but nuclear phase-out in *full* scenarios further aggravates it.

Within the scope of week 4, only one critical event, when the flow on the particular line exceeds 75% thermal limit of the line, occurs on the line Krajnik-Vierraden (table 7). This is due to the fact that the general load is very low in this week.

6.2 Week 14 - high VRES production

The qualitative nature of the results for this week is essentially the same as for week 4. Nevertheless, the magnitudes and strengths of effects are notably larger. Actual total transmission average rose 2.54 times, maximal relative one increased about 3.41 times (CZ-Tennet profile) and maximal absolute one grew by 670.3 GWh (50Hz -Tennet profile).

Figure 9: Transmission DE, W14

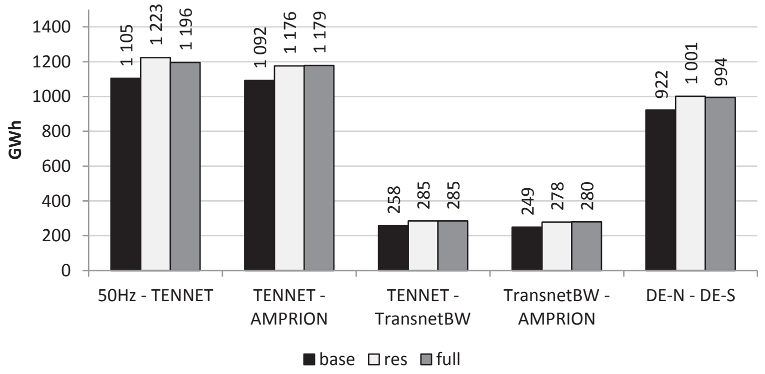
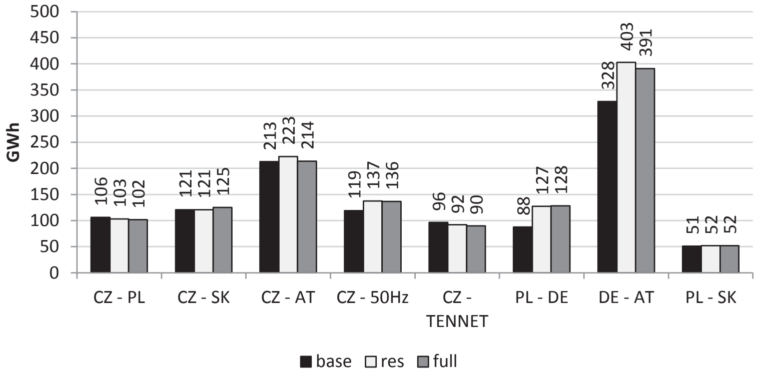


Figure 10: Transmission CE, W14



The comparison of real balances to the modelled ones yields much more satisfactory results as can be seen in table 6.

Scenarios *res* and *full* yield both higher exchanges and larger amount of transmitted electricity as compared to *base* but again the influence of nuclear phase-out, i.e. the difference between *res* and *full* flows, is counter-intuitive. Flows in *full* are actually almost the same or lower than in the case of *res* but they were originally expected to be much higher. It is very likely that the answer to this question is hidden in the merit order effect. When base-load and cheaply operating nuclear power plants are shut down, electricity supply curve shifts to the left resulting in higher price. This incentivizes more flexible but more expensively operating hard-coal, gas or even oil power plants to produce and supply locally and flexibly the electricity which can smooth the VRES volatile production. These amounts cannot be naturally enough to equilibrate all the increase in volatile production but they can significantly milder it. The exact effect of the smoothing (and consequently the amount of electricity transport) depends on the magnitude of the merit order shift and on the increase of the production from mentioned conventional power units. These merit order price-related effects are not exactly measured in this paper as they exemplify completely independent research question.

Within the scope of the week 14, roughly 10% increase occurs on profiles in Germany (fig. 9) in scenarios *res* and *full* compared to *base* scenario. The other profiles exhibit various behaviour, ranging from slight decreases to immense growths (fig. 10). German-Austrian and German-Polish border profiles face 46.5 % and 19.2% transmission increase, respectively, when *full* scenario is considered. Also the average load on particular lines on these profiles rose (Krajnik-Vierraden even by 18.2%). Intuitively, this is also accompanied by the upturn in critical events growing cumulatively by 16 on all 13 DE-AT lines and by 27 on only two 50Hz-PL lines as compared to the *base* situation (table 7).

Growth of standard deviation can be observed on the *base-res* basis as well as on the *base-full* basis on all but two border lines. Also the *res-full* comparison shows rise in volatility on majority of lines. In all three cases, particularly interconnectors between Germany and Austria are under the biggest volatility pressure; highest values achieve 50% increase.

Table 6: Weekly changes

	Model vs. real bal. deviation*	Balance increse GWh		Transmis. increase from the base, GWh		Transmis. increase from the base, %		Model vs. real bal. deviation*	Balance increse GWh		Transmis. increase from the base, GWh		Transmis. increase from the base, %	
	w4							**w14**						
Border profile:		res	full	res	full	res	full		res	full	res	full	res	full
CZ - PL	-82,4%	-5,37	-6,97	9,31	9,34	21,0%	21,1%	-24,5%	-6,51	-7,36	-2,91	-4,40	-2,7%	-4,1%
CZ - SK	-111,6%	-1,33	-3,08	3,48	4,03	6,3%	7,3%	-119,0%	-12,58	-18,37	-0,10	4,42	-0,1%	3,7%
CZ - AT	-81,8%	2,31	-1,06	5,42	5,52	5,8%	5,9%	42,6%	9,12	-0,27	9,97	1,17	4,7%	0,6%
CZ - 50Hz	-30,5%	7,81	7,77	13,61	12,06	39,1%	34,7%	70,3%	19,52	18,63	18,33	17,41	15,4%	14,6%
CZ - TENNET	-86,2%	-1,63	-3,04	1,96	1,66	4,1%	3,5%	3,8%	-7,04	-10,95	-4,44	-6,28	-4,6%	-6,5%
PL - DE	-100,4%	21,63	25,38	8,29	10,12	20,1%	24,6%	-77,0%	66,88	65,90	39,84	40,68	45,5%	46,5%
DE - AT	-78,1%	13,56	10,77	16,44	17,28	16,5%	17,3%	20,2%	72,47	62,33	74,91	62,87	22,8%	19,2%
PL - SK	-89,4%	-2,80	-3,88	3,44	3,15	18,8%	17,3%	-34,1%	-1,10	-0,54	0,67	0,89	1,3%	1,7%
50Hz - TENNET	-	19,56	14,62	45,95	40,47	10,6%	9,3%	-	4,13	-13,42	118,59	90,79	10,7%	8,2%
TENNET - AMPRION	-	14,44	4,86	63,48	60,55	14,6%	14,0%	-	85,20	79,87	84,52	87,03	7,7%	8,0%
TENNET - TransnetBW	-	6,42	3,75	12,75	11,44	12,3%	11,0%	-	27,83	26,35	27,37	26,57	10,6%	10,3%
TransnetBW - AMPRION	-	3,48	0,30	15,38	15,21	15,4%	15,2%	-	25,58	28,08	29,25	31,03	11,7%	12,5%
DE-N - DE-S	-	0,50	-7,41	53,24	49,41	14,3%	13,3%	-	-11,63	-14,57	79,38	72,33	8,6%	7,8%
*	% of base flow; - stands for underestimation, + stands for overestimation													

6.3 North-Western Europe

Despite the fact that North-Western Europe is not the area of our particular interest, it is very important to mention that the impact of above mentioned high VRES feed-in together with the scenarios have much more striking impact on this area than on the area of CE, specially in week 14 (fig. 8). Whilst the increases in flows of electrical current are still in manageable terms in CE, different effect can be measured on the borders of Germany and Netherlands and Germany

Table 7: Extreme load overview

		# extremes					
		w4	w4	w4	w14	w14	w14
Interconnector	Substations	base	res	full	base	res	full
PL ⟹ CZ	Bujakow-Liskovec	-	-	-	-	1	-
CZ ⟹ PL	Liskovec-Kopanina	-	-	-	-	-	-
PL ⟹ CZ	Wielopole-Nosovice	-	-	-	-	-	-
CZ ⟹ PL	Albrechtice-Dobrzen	-	-	-	-	-	-
SK ⟹ CZ	Varin-Nosovice	-	-	-	-	-	-
CZ ⟹ AT	Slavetice-Durnrohr	-	-	-	-	-	-
CZ ⟹ SK	Sokolnice-Stupava	-	-	-	-	-	-
CZ ⟹ SK	Sokolnice-Krizovany	-	-	-	-	-	-
CZ ⟹ AT	Sokolnice-Bisamberg	-	-	-	-	-	-
SK ⟹ CZ	Povazska Bystrica-Liskovec	-	-	-	-	-	-
SK ⟹ CZ	Senica-sokolnice	-	-	-	-	-	-
CZ ⟹ Tennet	Hradec II-Etzenricht	-	-	-	-	-	-
CZ ⟹ 50Hertz	Hradec I-Rohrsdorf	-	-	-	-	-	-
CZ ⟹ Tennet	Prestice-Etzenricht	-	-	-	-	-	-
PL ⟹ SK	Lemesany-Krosno Iskrzynia	-	-	-	-	-	-
DE ⟹ AT	Aux-Oberbayern-Burs	-	-	-	-	3	8
DE ⟹ AT	Vohringen West-Burs	-	-	-	-	-	-
AT ⟹ DE	Burs-Obermorrweiler	-	-	-	-	-	-
DE ⟹ AT	Obermorrweiler-Burs	-	-	-	-	-	-
DE ⟹ AT	Pirach-Sankt Peter	-	-	-	-	-	-
DE ⟹ AT	Altheim-Sankt Peter	-	-	-	-	-	-
DE ⟹ AT	Simbach-Sankt Peter	-	-	-	1	3	3
DE ⟹ AT	Pleinting-Sankt Peter	-	-	-	-	6	3
DE ⟹ AT	Leupolz-Westtirol	-	-	-	-	-	-
DE ⟹ AT	Leupolz-Westtirol	-	-	-	-	-	-
AT ⟹ DE	Burs-Grunkraut	-	-	-	-	-	-
DE ⟹ AT	Pleinting-Sankt Peter	-	-	-	-	6	3
AT ⟹ DE	Sankt Peter-Pirach	-	-	-	-	-	-
PL ⟹ DE	Mikulowa-Neuerbau	-	-	-	-	1	3
PL ⟹ DE	Krajnik-Vierraden	1	-	-	13	46	40
Source:	Own						

and France for example. Especially in the former case, the lines are hitting their limits almost continuously. Altogether 4 interconnectors connect Netherlands and Germany. These lines are subject to very high average load ranging from 57% to 75.5%. Also, 257 critical events occurred in the *base* scenario which increased about another 49 when *full* scenario is considered. Slightly better situation can be seen in the latter case of German-French borders. After all, these amounts represent very critical values for the system manageability and stability.

7 Conclusion

The overall novelty of this paper lies in the enrichment of current literature on transmission networks in Central Europe which is generally very sparse. According to our knowledge, this paper is the first to conduct the detailed load flow analysis for CE region using the ELMOD model, in which the same degree of detail of the grid was modelled not only for Germany but also for remaining CE countries. Additionally, the result that nuclear phase-out does not exacerbate the grid overloading is of great importance as it goes against widely accepted conventional knowledge.

The paper thoroughly examined power and transmission systems in Central Europe. Three key issues were identified: i) the capacity of the grid in Germany does not correspond to the needs emerging from Energiewende which creates grid bottlenecks between northern and southern Germany, ii) this induces the electricity to flow through the energy systems of neighbouring states and iii) current market design in the form of German-Austrian bidding zone further exacerbates the problems.

Our analysis revealed several important findings. First of all, the higher is the feed-in of solar and wind power plants, the higher is the exchange balance and total transport of electricity between TSO areas. This holds for international cross-border profiles as well as for inner-Germany's ones. The rise in flows leads also to increase in number of critical events which directly endanger grid stability. Furthermore, model results fit the real values much better under the peak VRES production. This is important feature of the model as the high amounts of volatile inflows are of substantial importance when examining transmission grids. Additional analysis found that while the situation remains manageable in CE, the North-Western Europe should be concerned about this issue much more.

Two scenario developments, *full* and *res*, were examined. The first one attempted to measure the *ceteris paribus* effect of German Energiewende on the transmission networks, especially in the context of CE. The latter one dropped out nuclear phase-out and thus assessed isolated *ceteris paribus* impact of increased solar and wind power production.

In the case of *res*, all expectation were met. Amount of cross- border transmission grew both on intra-national lines as well as on the cross-zonal ones; so did the average load on majority of particular lines. Moreover, significant rise in volatility of flows was observed.

Our case of *full* scenario revealed that nuclear phase-out does not significantly contribute to the amount of transmission as well as to the average load on lines; instead, these remain almost unchanged or slightly decrease. Reasoning for this behaviour lies presumably in the merit order effect. On the other hand, our results suggest that volatility grows as nuclear plants are shut down. This is in accordance with intuition as the nuclear power plants supply stable base-load output.

Finally, focusing on separate peaks in solar and wind production showed that the combination of high solar and low wind feed-in induces greater volatility and cross-border flows on the Czech-Austrian and German-Austrian borders. This finding is critical as it is predicted that solar power will be economically viable without subsidies within the 30 years horizon (Torani *et al.* 2016). A sky-rocketing increase in installed capacity can thus be expected.

On the contrary, low solar and high wind production leads to the highest observed flows within Germany as well as on transnational lines, except the ones on German-Austrian borders. Thus, electricity loop flows through other CE countries take up on intensity.

Our results also indicate new questions for further research. The ceteris paribus changes could be replaced by incorporation of parameters and variables according to the energy conceptions of all relevant countries, perfect competition and one TSO assumption could be replaced by oligopolistic structures backed by game theoretic approach and external social planner could be replaced by political institutions.

8 Appendix A. Mathematical formulation

The objective function of the model maximizes social welfare

$$\underset{g,q}{max} \quad \sum_{T}\sum_{N}\Big((A_{nt}q_{nt}+\frac{1}{2}D_{nt}q_{nt}^{2})-\sum_{C}g_{nct}M_{nc}\Big) \tag{1}$$

where A_{nt} is non-negative intercept and D_{nt} is negative slope coefficient which are used to estimate the linear inverse demand function:

$$\pi_{nt}(q_{nt}) = A_{nt} + D_{nt} q_{nt}. \tag{2}$$

Supply function is also linearized. The marginal cost function $m_{nct}(g_{nct})$ is replaced by the coefficient M_{nc} determining the time-invariant marginal cost of generation for each individual power plant unit c at node n based on the model data.

When solving Eq. 1 several energy balance constraints have to be accounted for. The nodal balance constraint has to be true for any node at any point in time:

$$\sum_c g_{nct} + G_{nt}^{wind} + G_{nt}^{solar} + PSP_{nt}^{out} - PSP_{nt}^{in} + \sum_{nn} \theta_{nn,t} B_{n,nn} - q_{nt} = 0 \quad \forall n, t. \tag{3}$$

The electricity production from power plant is bounded by the installed capacity of given production unit and cannot exceed this value:

$$g_{nct} \leq G_{ct}^{max} \quad \forall n, c, t. \tag{4}$$

Electricity flows are modeled by

$$p_{lt} = \sum_n H_{ln} \theta_{nt} \quad \forall l, t. \tag{5}$$

Inequality (6) takes into account the capacity limits of individual transmission lines and restricts the modelled flow to respect these upper and lower bounds respectively.

$$|p_{lt}| \leq \overline{P}_l \quad \forall l, t. \tag{6}$$

The equation (7) sets the voltage angle of an arbitrary node, called slack node, to be zero which is important because uniqueness of solution of the system is thus guaranteed. Due to the setting of the voltage angle of one variable, all other angle values are relative to this specific one.

$$\theta_{n't} = 0 \quad \forall n, t. \tag{7}$$

$$P_{jk} = B_{jk}\theta_{jk}. \tag{8}$$

Last steps in obtaining desired result in form of particular line flow incorporate the identification of nodes *n,nn* and mapping to the lines. For this purpose, Leuthold *et al.* (2012) uses a special matrix, incidence matrix I_{ln}, which is defined followingly:

$$I_{ln} = \begin{cases} 1 & \text{if } n = j \\ -1 & \text{if } n = k \\ 0 & \text{else.} \end{cases}$$

With the help of series line susceptance B_{ln}, final line power flow (5) can be obtained:

$$H_{ln} = B_{ln}I_{ln} \tag{9}$$

$$p_{lt} = \sum_{n} H_{ln}\theta_{nt}.$$

Referring to the previous text on net input, technical description is added. Net input variable is determined by network susceptance matrix and voltage angles $\nu_{nt} = \sum_{nn} B_{n,nn}\theta_{nn,t}$. Mathematical derivation of the first parameter, the susceptance matrix $B_{n,nn}$, is based on above mentioned flow definitions (Leuthold *et al.* 2012).

$$B_{n,nn} = \sum_{l} I_{ln}H_{ln} \tag{10}$$

Sets and indices:

L	set of all lines
N	set of all nodes
C	set of all conventional plants
T	set of all time periods
$l \in L$	line within the network
$n, nn \in N$	nodes within the network
$n' \in N$	slack node(s) within the network
$c \in C$	conventional power plant unit
$t \in T$	time periods

Parameters:

G_{nt}^{wind}	wind input at node n in time t
G_{nt}^{solar}	solar input at node n in time t
PSP_{nt}^{out}	pump storage plant release at node n in time t
PSP_{nt}^{in}	pump storage loading at node n in time t
G_{ct}^{max}	maximal generation of generation unit c in time t
$\overline{P}_{lt}$	maximal available capacity limit of line l in time t
H_{ln}	network transfer matrix
$B_{n,nn}$	network susceptance matrix
A_{nt}	intercept coefficient at node n in time t
D_{nt}	slope coefficient at node n in time t
M_{nc}	marginal cost coefficient of power plant unit c at node n

Variables:

w	welfare function
$\pi_{nt}(q_{nt})$	inverse demand function at node n in time t
$m_{nct}(g_{nct})$	marginal cost of generation of plant c at node n in time t
g_{nct}	generation of generation unit c at node n in time t
q_{nt}	demand at node n in time t
ν_{nt}	net input to node n in time t
p_{lt}	power flow over line l in time t
$\theta_{nt}, \theta_{nn,t}, \theta_{n't}$	flow angle at node n in time t

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