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Abstract

The impacts of renewable energy production and German nuclear phase-out on the electricity transmission systems in Central Europe is investigated with focus on the disparity between the growth of renewable production and the pace at which new electricity transmission lines have been built, especially in Germany. This imbalance endangers the system stability and reliability in the whole region. The assessment of these impacts on the transmission grid is analysed by the direct current load flow model ELMOD. Two scenarios for the year 2025 are evaluated from different perspectives. The distribution of loads in the grids is shown. Hourly patterns are analysed. Geographical decomposition is made, and problematic regions are identified. The high solar or wind power generation decrease the periods of very low transmission load and increase the mid- and high load on the transmission lines. High solar feed-in has less detrimental impacts on the transmission grid than high wind feed-in. High wind feed-in burdens the transmission lines in the north-south direction in Germany and water-pump-storage areas in Austria.

Keywords

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

JEL Classification

L94, Q21, Q48, C61

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Impact of German Energiewende on Transmission Lines in the Central European Region*

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The impacts of renewable energy production and German nuclear phase-out on the electricity transmission systems in Central Europe is investigated with focus on the disparity between the growth of renewable production and the pace at which new electricity transmission lines have been built, especially in Germany. This imbalance endangers the system stability and reliability in the whole region. The assessment of these impacts on the transmission grid is analysed by the direct current load flow model ELMOD. Two scenarios for the year 2025 are evaluated from different perspectives. The distribution of loads in the grids is shown. Hourly patterns are analysed. Geographical decomposition is made, and problematic regions are identified. The high solar or wind power generation decrease the periods of very low transmission load and increase the mid- and high load on the transmission lines. High solar feed-in has less detrimental impacts on the transmission grid than high wind feed-in. High wind feed-in burdens the transmission lines in the north-south direction in Germany and water-pump-storage areas in Austria.

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1 Introduction

German governments have accepted an energy policy that supports the development of renewable energies, the reduction of greenhouse gas emissions, the improvement of energy efficiency and the phase out of nuclear power ('Energiewende'). As a result, generation from variable renewable energy sources (VRES) in Germany has experienced a considerable uptake in recent years (mainly due to the German Renewable Energy Sources Act (Erneuerbare Energien Gesetz, EEG)) which has led not only to lower electricity spot market prices but also to many challenges for the stability and security of electricity supply (Fischer *et al.* 2016). As Germany is the largest economy in the EU and represents the majority of wind and solar power generation in the Central Europe (CE) (80% and 90% of wind and solar power generation in CE in 2014, respectively), its energy policy influences energy systems in neighbouring countries not only in terms of power market prices (Mulder & Scholtens 2016) but also in terms of stability, congestion and volatility of transmission grid (Janda *et al.* (2017); Kunz & Zerrahn (2015)).

German centres of electricity consumption are situated mostly in the south and west but regions suitable for most economic VRES production are located in the north. The electricity generated by VRES must therefore be transported over long distances to the end-consumers in the north-south direction. As a result, the existing network is frequently reaching its capacity limits (Bundesnetzagentur 2015). The planned German phase-out of 8386 MW of installed nuclear capacity by 2022 furthermore contributes to the north-south grid pressures since nuclear power plants are mostly located in southern regions, Bavaria and Baden-Wurttemberg. The loss of nuclear 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). This embodies even larger pressure on the transmission grid and a need to strengthen the infrastructure in German north-south direction, as confirmed by German authorities (BMWi 2015a) and especially neighbouring transmission system operators (TSO) 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.

The grid expansion proceeds slower than expected, since the volume of the infrastructure extension as well as the realization itself seem to be a matter of controversy. EnLAG legislature specified 23 mostly north-south transmission lines with the cumulative 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 first quarter of 2017, 35 kilometres of lines were built which gives around 700 km with previous construction (40% of planned length). Estimates now calculate with 45% being built till the end of 2017 (Bundesnetzagentur 2017). BBPlG, which came into effect in July 2013, added another 43 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). As of first quarter of 2017, 14 km were built. Together with previous construction, 150 km of lines were realized and 450 km were approved (Bundesnetzagentur 2017). 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 a kilometre of line costs 1.2 Mio EUR whilst a kilometre of cable costs 6 Mio EUR (Rapp 2012). As a result, it is implausible that fast short term improvement with the 45% target is foreseeable.

The Czech TSO installed two phase-shifting transformers at one of the two CEPS - 50 Hertz interconnectors to manage the overflows from Germany in January 2017 and another two at the second interconnector in July 2017 with an approximate total cost of 74 mil EUR (ČEPS 2015a; 2017). The total volume of investments during current Czech development plan is estimated to reach 1.66 bn EUR by 2024 (ČEPS 2015b). Austrian and Polish development plans assume investment of 2.4 and 3 bn EUR by 2025, respectively (APG 2015; PSE 2015).

Existing literature extensively focused on the influence of VRES 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)). However much less attention has been drawn to transmission networks issues that are connected to the security of electricity supply and become increasingly crucial as the share of VRES rises. The majority of the transmission networks related research is focused only on Germany (Burstedde 2012; Kunz 2013; Kunz & Zerrahn 2015; Schroeder *et al.* 2013; Egerer *et al.* 2014; Weigt *et al.* 2010; Dietrich *et al.* 2010; Winkler *et al.* 2016; Singh *et al.* 2015) or Europe as a whole (Neuhoff *et al.* 2013; Fürsch *et al.* 2013; Majchrzak *et al.* 2013; Schaber *et al.* 2012a;b). Polish researches examine mainly the possibilities of phase-shifting transformers on German cross-border profiles (Korab & Owczarek 2016; Kocot *et al.* 2013).

There are only a few papers paying attention to the region of Central Europe (CE: Austria, Czech Republic, Germany, Poland and Slovakia). Singh *et al.* (2016) assess the impact of unplanned power flows on transmission networks. Eser *et al.* (2015) analyse the impact of increased renewable penetration under network development. Kunz & Zerrahn (2016) focus on cross-border congestion management. Finally, Janda *et al.* (2017) analyse the impacts of increased renewable generation and nuclear phase-out in Germany on border-crossing profiles in the Czech Republic and other CE countries.

This paper fills the gap in the literature and contributes to the analysis of the impact of increasing wind and solar power generation and nuclear phase-out in the region of Central Europe (CE). Unlike other papers, we focus on the whole

CE at the same level of detail as Germany and analyse the impacts of increased German VRES feed-in and nuclear phase-out on hourly grid load and volatility in transmission networks. Since Janda *et al.* (2017) focus on the cross-border profiles only, we assess here the impact on individual transmission lines in the CE region. We use the non-linear optimization model ELMOD (Leuthold *et al.* 2008), which maximizes social welfare under a number of constraints. We use 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.

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

2 Model

This study applies the state-of-the-art DC load flow model ELMOD also used in Leuthold *et al.* (2012), Egerer *et al.* (2014) and Janda *et al.* (2017). The mathematical formulation can be found in the Appendix and is based on an optimization problem that maximizes social welfare after taking the technical and physical characteristics of electricity into account. The model looks for a solution that satisfies a given electricity demand at the least cost. The hourly resolution of demand load allows the merit order of the power sources. The modelling of physical flows of power enables that the final solution takes into account constraints of the grid and does not jeopardize its stability. This is the main advantage compared to models that do not include load flow modelling like MARKAL or TIMES model and that could reach a solution that could overload the grid dangerously. The maximization problem is solved for the whole area at once which is equivalent to the assumption of one TSO operating entire area.

Electricity inputs include total generation from conventional power plants $\sum_c g_{nct}$, wind generation G_{nt}^{wind}, solar generation G_{nt}^{solar} and pumped-storage power plant release PSP_{nt}^{out}. The outputs include pumping of pumped-storage power plants PSP_{nt}^{in} and consumption (demand) q_{nt}.

The demand enters in hourly intervals as an external parameter as it is based on the real data. Thus, it can be considered as fixed for every node in every hour. Consequently, price adjusts to clear the demand and supply.

The model is merit-order based which implies that the plants with the cheapest production supply electricity first. However, the production from solar and wind plants has an absolute priority as it enters the model as an exogeneous parameter (see section 3). This set-up of the model therefore resembles reality very closely.

The flows over particular line in a given time period are modelled (eq. 5 in the appendix) and the phase angle for an arbitrary slack node is set to zero (eq. 7 in the appendix) to ensure the uniqueness of solutions (Egerer *et al.* 2014).

The ELMOD model uses a simplification of AC load flow to DC load flow model. Overbye *et al.* (2004) discusses the actual differences between the AC and DC flow applications and concludes that the loss of accuracy is small and that DC results match well AC load flow solutions. To simplify the flow calculations, ELMOD 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.

3 Data description

We use the same dataset as in Janda *et al.* (2017). It is based on Egerer *et al.* (2014) with several adjustments and updates. The transmission network system, power plant units and their technical characteristics are 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. Hourly 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 (2016b). 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 (2016c) and European Commission, DG Energy (2016a), respectively.

The underlying grid data consist of nodes (transformer stations) which are connected by transmission lines. Our dataset consists of 593 nodes, 10 country-specific nodes and 982 lines. Each transmission line is characterized by several parameters necessary to run 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 the 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.

This distinguishes our paper and Janda *et al.* (2017) from most of other research that focus primarily on Germany and model only German network in such a detail. Another benefit is that incorporating aggregated neighbouring countries as nodal entities 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 transmission grid has to fulfil 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).

The 607 power 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 a respective single nodes. Due to the data availability issues, all power plants data are taken from Egerer *et al.* (2014). The limitation of this approach is that the generation capacities 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 in the case of phase-out scenario.

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 of fuels are given in the table 1 together with the respective data sources. All prices are updated to 2015 values except the price of coal for which only 2014 values are available.

Tab. 1: Fuel prices

Fuel	Price	Unit	Source
Uranium	3	EUR/MWh	Assumption of Egerer et al. (2014)
Lignite	3.48	EUR/MWh	Own calculation
Hard Coal	6.96	EUR/MWh	BP: Northwestern Europe coal price 2014
Gas	22.28	EUR/MWh	EC: Quarterly reports on European gas markets
Oil	28.42	EUR/MWh	Bloomberg: Brent oil price
Biomass	7.2	EUR/MWh	Assumption of Egerer et al. (2014)
Hydro	0	EUR/MWh	
Wind	0	EUR/MWh	
Sun	0	EUR/MWh	
Waste	7.2	EUR/MWh	Assumption of Egerer et al. (2014)
Carbon	7.59	EUR/tCO_2	EEX: Median CO_2 EUA settlement prices

ENTSOE database is the national level source of hourly load data for all included countries for the year 2015. National level values are disaggregated to NUTS2 level according to Egerer *et al.* (2014) and Leuthold *et al.* (2012) (GDP 60% weight, population 40%).

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). For a more detailed description of the data see Janda *et al.* (2017).

Similarly to Schroeder *et al.* (2013) and Janda *et al.* (2017) three representative weeks with the different combinations of extreme values of RES production are used and investigated in detail (we use English-type weeks, i.e. the week starts on Sunday). In contrast to Janda *et al.* (2017), who analyse week 4 and week 14, we focus on week 14 (last week in March - from 29th March to 4th April, 2015) when the highest cumulative production from wind and sun occurs in CE;

week 27 (last week in June from 28th June to 4th July, 2015); and week 49 (last week in November from 29th November to 5th December, 2015). This allows to capture the effects of individual VRES. Week 27 represents the situation when the solar feed-in is high and wind feed-in is low. Week 49 mirrors exactly the opposite. Figures 1-3 depict the situation during each of the considered weeks.

4 Scenarios

To measure the influence of the increased installed capacity of VRES over time and space, electricity flows over the individual lines within the network are obtained for each hour of the week. The results are then compared in the context of three scenarios: *base*, *res-only* and *phase-out*.

The *base* is our reference scenario that models the current situation in the power sector in CE based on data specified in section 3.

Scenario *phase-out* assesses the impacts of increase of VRES production in Germany and German 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 appropriate coefficients (table 2) and nuclear power plants are phased-out. Everything else in Germany as well as in the other countries, including grids, reflects the state of 2015 or other years as specified in the section 3. By construction, the results must be interpreted in the context of the worst possible outcome if nothing is 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 is equivalent to 90.61% of

Fig. 1: High wind and high solar production profile (Week 14)

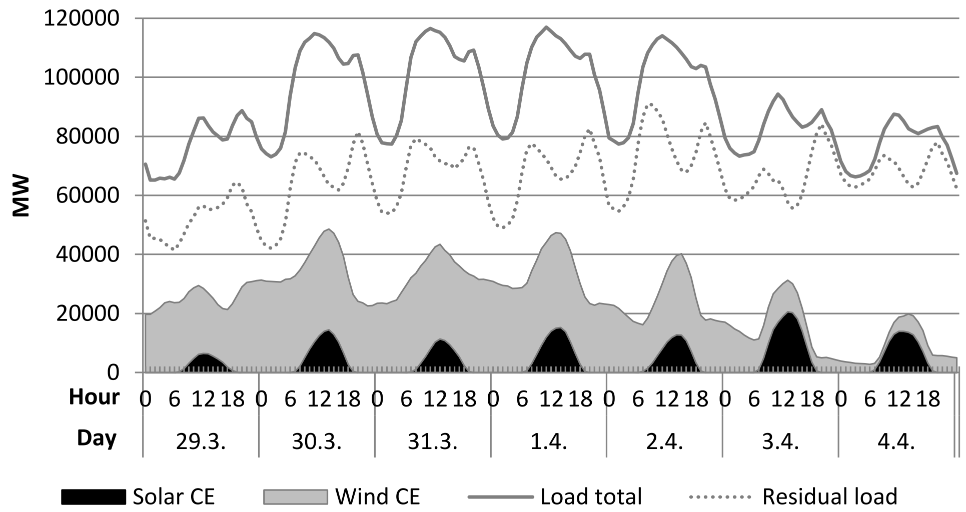


Fig. 2: Low wind and high solar production profile (Week 27)

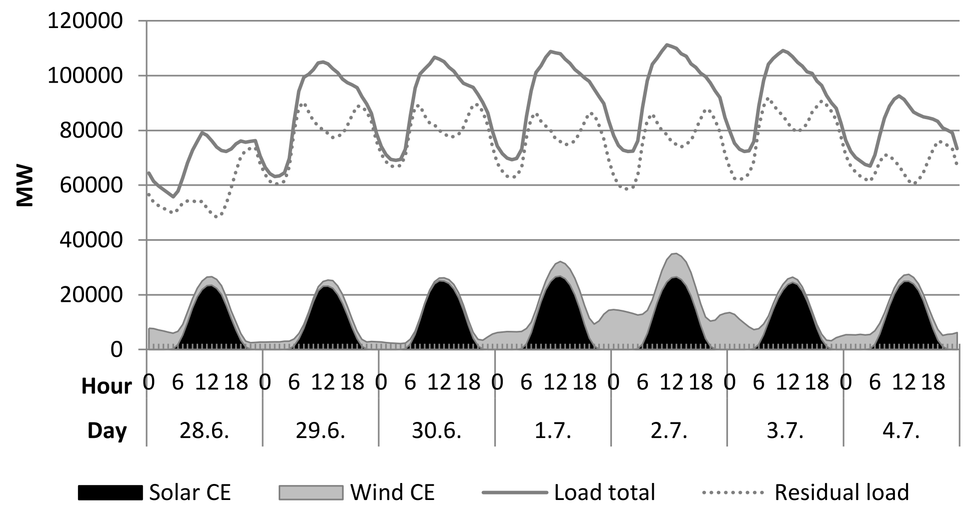
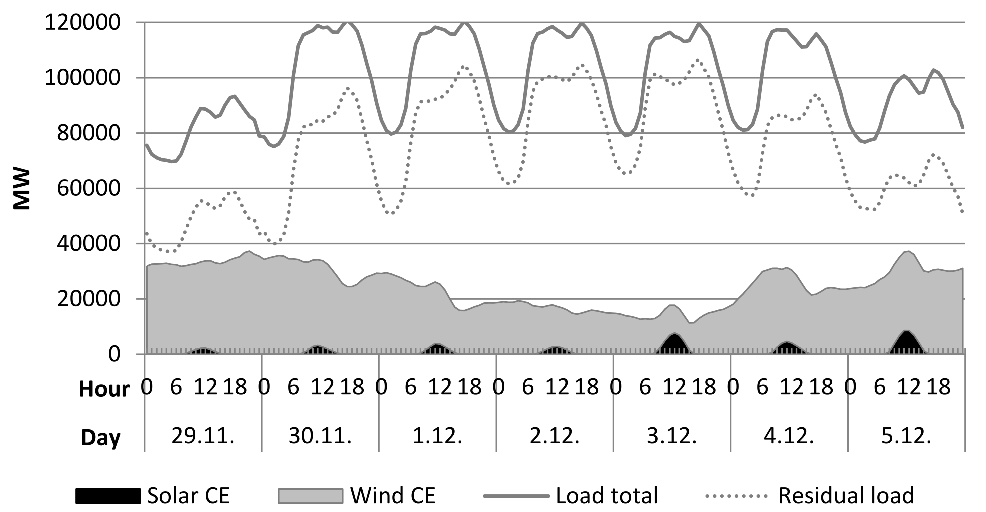


Fig. 3: High wind and low solar production profile (Week 49)



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%, close to 42.5% which is the result of linear approximation for year 2025 using BMWi scenarios (BMWi 2015b). The derivations are shown in the table 2.

Tab. 2: Parameters of *phase-out* 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	1.490	54159.61	969.77	52.52	38.50	**1.364**
Wind onshore	33310	1.568	52231.66	1900.46	99.26		
Wind offshore	620	14.355	8900.00	3118.28	27.75		
Wind	33930		61131.66		127.02	86.00	**1.477**
Source:	Feix *et al.* (2015)	Feix *et al.* (2015)	(1)*(2)	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, the BMWi scenario was selected because it is very likely that policy makers will stick to it and will therefore follow time-consistent development based on this scenario. This surmise is based on two pieces of evidence: 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-only* considers the same set-up as in the *phase-out* case with the exception of German nuclear power plants which are considered to be still in operation even after the planned shut down in 2022. This allows us to isolate the impact of shutting down the nuclear power plants on the grid by comparing the *phase-out* and *res-only* scenarios.

5 Results

The results are presented for each of the mentioned weeks so that the different situations can be easily distinguished. Moreover, we first present the aggregate impacts and then focus on time and geographic dimensions separately.

5.1 Impact of renewables and nuclear phase-out on transmission lines congestion

Table 3 depicts the distributions of 'load' of transmission lines in all representative weeks in the scenario *base* and percentage changes from the *base* in scenarios *res-only* and *phase-out*. The inputs in the table are "number of observations in given interval of the line 'load' ". These individual observations of load values are independent of line mapping. For example, first column and first line in the table 3 tell us that there were 94472 observations in the lowest 'load' decile in the week 14 in *base* scenario. By this approach, we assess the impact of the above mentioned scenarios on the distribution of system load within the particular week as a whole. The ex-ante hypotheses are that when renewable inflow increases then the distribution should be shift towards the high-'load' values as we expect more congestion in the network.

Both *res-only* and *phase-out* scenarios are associated with a decline in the number of observations in the lowest 'load' decile from 4 to 7 percent as compared to *base* in all three representative weeks. The second and third 'load' deciles differ across the weeks in term of direction of impact of *res-only* and *phase-out* scenarios. In week 14, with high solar and wind generation the number of observations (lines and hours) in the second 'load' decile remains of the same level as in scenario *base* in both alternative scenarios. However, there are 4 and 5 percentage increases in the *res-only* and *phase-out* scenarios in the third 'load' decile, respectively. Both the *res-only* and *phase-out* scenarios induce increase of observations in the fourth and higher 'load' deciles by 9 to 41 percent. Since summer week 27 with

Tab. 3: Load distribution in scenario base and percentage difference of scenario res only and phase-out

Load [%]	w14 - high sun and wind			w27 - high sun and low wind			w47 - low sun and high wind		
	base [obs.]	res-only [% change]	phase-out [% change]	base [obs.]	res-only [% change]	phase-out [% change]	base [obs.]	res-only [% change]	phase-out [% change]
0-10	94472	-4.5	-4.7	117121	-4.9	-7.1	90679	-4.7	-3.9
11-20	30703	-0.3	0.3	24008	6.9	13.1	33496	-1.6	-1.7
21-30	16540	3.6	5.0	10815	11.9	17.4	18813	0.0	-1.2
31-40	10466	9.5	8.9	6212	11.7	15.6	10482	19.2	17.5
41-50	4917	20.4	20.5	3262	28.4	29.5	4749	19.7	18.6
51-60	2999	23.7	21.2	1573	31.0	41.1	2976	20.2	16.0
61-70	1602	36.2	32.5	813	34.9	29.4	1565	38.1	37.6
71-80	2295	21.8	19.3	1172	33.5	39.0	2216	27.6	26.0
80	1529	21.5	19.8	833	32.8	36.4	1432	27.0	26.2

NOTE: The 'load' is defined as a ratio of a flow over particular line in every hour and the capacity of the line, multiplied by 100. The inputs are hourly flows over each of the 982 model lines and capacities of the lines. There are 163 994 observations for the week 14 (982 lines times 167 hours) and 164 976 observations for the weeks 27 and 49 (982 lines times 168 hours) in each particular scenario. It is noteworthy that the highest values of the load is 80% as this embodies the highest admissible value because of the 'N-1' criterion. The 'load' measure is introduced to enable the mutual comparison of the results as the absolute value of the flow does not reflect different capacities of the lines.

high solar and low wind generation has the lowest grid load, the relative increase of observations in fifth to seventh 'load' decile is the highest in this week but the absolute 'load' of transmission lines is the lowest in *res-only* and *phase-out* scenarios in this week.

The last line in table 3 depicts observations of the 80% 'load' of transmission lines when the load encounters the model constraint reflecting the N-1 rule and the lines are congested at critical level. As such, this load can be interpreted as critical because if some line breaks down, the grid fulfils the N-1 rule no longer. Development of VRES increases the number of observations in this critical 'load' significantly in all weeks and scenarios - at least by 20 percent in week 14 in *phase-out* scenario. At the same time the lowest relative increase in observations of 80% 'load' in week 14 leads to the highest number of observations among all weeks, due to the fact that winter week 14 has high grid load and the highest number of observations in 80% 'load' also in the *base* scenario (1,529). The *res-only* scenario in week 14 induces the highest number of observations of 80% 'load' - out of 163,994 combination of 982 lines and 167 hours in week 14 there are 1,858 observations of 80% 'load', which yields more than 1 percent. This could be interpreted as if almost 10 lines of 982 would be at the limit of their capacity constantly during the whole week.

To briefly summarize, this analysis shed light on the changes in the distribution of load in the transmission system from the perspective of each of the mentioned week as a whole. We can conclude that the data are in line with our hypothesis that increase in renewable feed-in causes higher occurrence of observations in higher deciles, including the critical values of 80%, of the grid 'load' and lower occurrence in the lowest deciles. This pattern holds universally across weeks.

The net impact of the nuclear phase-out in the context of Energiewende is isolated as a difference between *res-only* and *phase-out* scenarios. Table 4 depicts the difference between *res-only* and *phase-out* scenarios in number of observations in each load decile. The percentage change then indicates the relative magnitude of the change related to the *base* scenario's load.

Tab. 4: Effect of nuclear phase out down on distribution of grid load (phase-out – res-only)

Load [%]	w14 - high sun and high wind		w27 - high sun and low wind		w47 - low sun and high wind	
	[obs.]	[% change relative to *base*]	[obs.]	[% change relative to *base*]	[obs.]	[% change relative to *base*]
0-10	-157	-0.2	-2529	-2	686	0.8
11-20	175	0.6	1477	6	-57	-0.2
21-30	235	1.4	599	6	-224	-1.2
31-40	-65	-0.6	238	4	-181	-1.7
41-50	4	0.1	36	1	-56	-1.2
51-60	-76	-2.5	160	10	-125	-4.2
61-70	-59	-3.7	-45	-6	-8	-0.5
71-80	-57	-2.5	64	5	-35	-1.6
80	-27	-1.8	30	4	-11	-0.8

It can be observed that the phase-out itself slightly helps to loosen the 'load' in weeks 14 and 49 as the number of observations increases in the lower range and decreases in the upper range of the spectrum compared with the *res-only* where German nuclear power stations are in operation. The impact of nuclear phase-out in week 27 is different. We can observe growth in number of observations in all 'load' deciles but the first and seventh decile. Even the critical 80% 'load' is increased by 4 percent of the *base* 'load' in *phase-out* scenario compared to *res-only* scenario. We should keep in mind that the week 27 has the lowest grid load among our representative weeks, which could be one of the reasons the nuclear phase-out has different impact in this week.

The isolated impact of the nuclear phase-out can be summed up in a following manner. If there is a high production from wind power plants or wind and solar power plants together at the same time, the phase-out slightly helps to reduce the load in the grid. However, if there is just a bit of wind production and strong solar feed-in combined with low grid load, the effect partly reverses.

5.2 Hourly patterns during the week

We can approach the previous issue also from a different perspective. In this section, we examine the behaviour of the flows over the scope of a particular week and we do not treat the individual hourly observations independently anymore, i.e. we continue to map the flows to particular lines.

In the figures 4-6, we identify congestion patterns throughout time. Each of the figures mirrors one week of our interest. X-axis shows the hours of the day in 24 hour formate. Y-axis shows the number of lines where the flows exceed 50% or 75% of the line's capacity in given hour respectively. The number of lines did not exceed 73 in any case, which is about 7.4% of all lines. One figure depicts all three scenarios in a given week. Gray bars stand for *base* scenario, yellow and red lines stand for *phase-out* and black and green lines stand for *res-only* scenario. This allows to compare visually all relevant combinations of outputs - not only between weeks but also between scenarios.

The general result suggests that the occurrence of high loads follows similar trend as the amount of renewable feed-in (compare to figures 1-3). Also, as the VRES installed capacity grows, number of lines with loads higher than both 50 and 75 % rises as well. More specifically, in the week 14/27/49 there are just 30/25/21 hours in the *res-only* scenario and 35/18/21 hours in the *phase-out* scenario, where the number of lines is below the baseline case respectively. Another noteworthy observation is that behaviour of the flows in both development sce-

Fig. 4: No. of lines with loads higher than 50 % during week 14 - high sun and wind

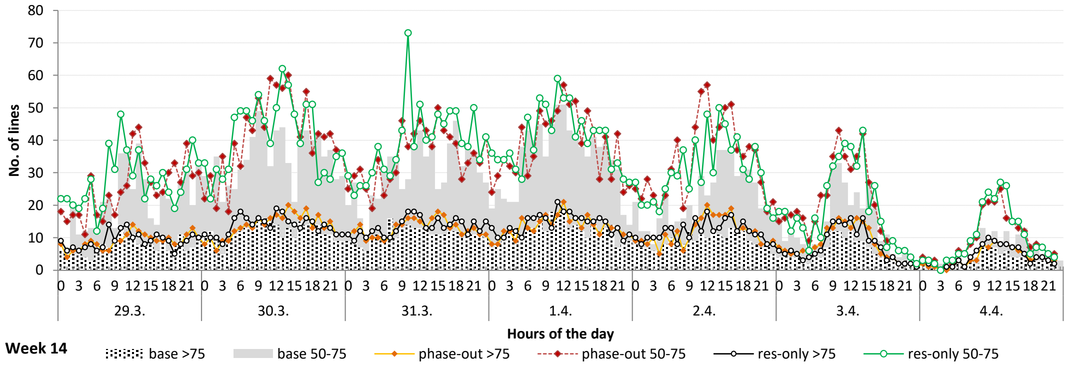


Fig. 5: No. of lines with loads higher than 50 % during week 27 - high sun and low wind

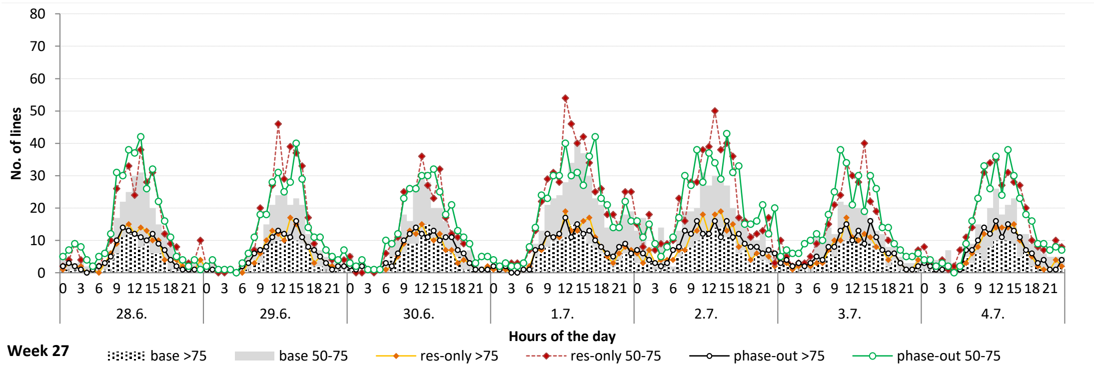
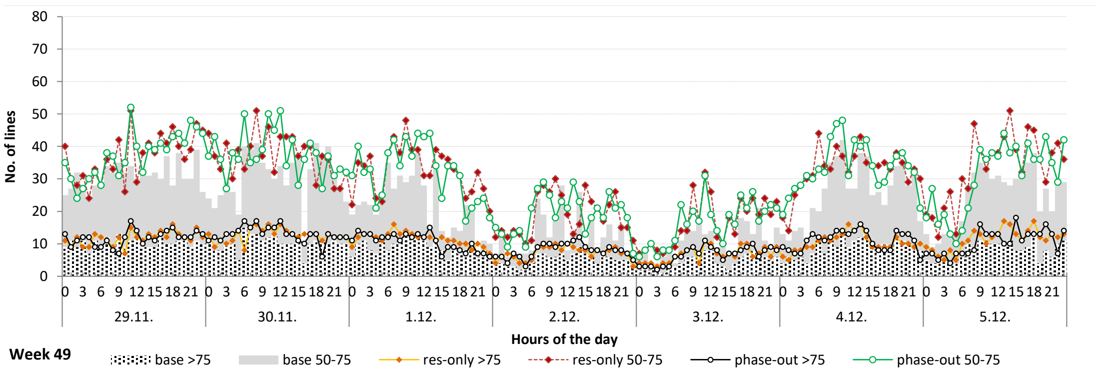


Fig. 6: No. of lines with loads higher than 50 % during week 49 - low sun and high wind



Source: Authors

narios *res-only* and *phase-out* follows very similar trend over time. Nevertheless, there is different dynamics indicating differences in volatility of flows between scenarios. It is also clear that the number of congested lines (load above 75%) fluctuates less than the number of upper-middle loads in the range of 50-75%. Statements about the magnitude and significance of variances in particular cases would require separate analysis though.

5.3 Geographical occurrence of highly loaded transmission lines

The load is not distributed equally across regions as shown in figures 7-9, where a number of transmission lines during the given week is depicted. We include the lines that evince systematic load over 50% and where also critical events occur frequently. Such lines are concentrated mainly in the centres of wind generation, on the pathway from north of Germany to Austria and in Austria where water pump storage plants are located. This supports our concern about the insufficient pace of new line construction, as stated in the introductory section.

The distribution of load reflects not only the wind and solar generation but also the overall grid load. In the week 27 with the lowest load there are 15 regions with highly-loaded lines in at least one scenario (1 in Poland, 10 in Germany and 4 in Austria), but there are 25 and 29 regions in week 14 and 49, respectively. The highest grid load combined with high wind and low solar power generation in week 49 involves congestions in at least one scenario in all regions in the north of Germany and Poland, regions in Germany on the pathway to Austria and 5 regions in Austria as depicted in figure 9. The high solar and wind feed-in in week 14 involves congestions in at least one scenario in fewer regions than in week 49 - only in one region in Poland, in 18 regions in Germany and 6 regions in Austria. The number of congested lines remains the same or increases in almost all regions in both *res-only* and *phase-out* scenarios. Just one line (in one German region) in week 14 and three lines (in one German and two Austrian regions) in week 27 are less loaded in the *res-ony* scenario than in *base*. The *res-ony* scenario induces critical load on 20, 6 and 17 transmission lines more than in *base* scenario in weeek 14, 27 and 17, respectively. The *phase-out* scenario induces critical load on 16, 10 and 16 transmission lines more than in *base* scenarion in weeek 14, 27 and 17, respectively.

5.4 Policy implications

We thus identified regions that authorities responsible for the stability of the grid should pay attention to. All scenarios identify roughly the same regions as problematic - from north of Germany to Austria and Austrian regions - only the number of lines changes. The credibility of our results is supported by the fact that regions identified by our model do follow a general pattern of the Ten Year Network Development Plan, as published by (ENTSOE 2017).

In the context of the problematic regions identified above, the table 5 gives an overview of the occurrences of extra high load on the border profiles. The figures represent average values over the lines on the particular profile. Such a presentation of results is chosen due to mutual comparability of the profiles. Extra high load is a value of the load if it lies between 75% and 80% of the line's capacity within a particular hour. Loads higher than 80 % do not occur in the model (restriction of the model) as such values would violate the "N-1" security criterion.

The highest values of average extreme load per each line of the border profile occur especially in the centre of the German wind production - in the control area of 50 Hertz. The highest value of the average 23.5 hours of the extreme load over each interconnector between Poland and Germany illustrates the seriousness of the situation on that border and the reason why Poland installed phase-shift transformers in the Mikulova-Neuerbau substation (ACER 2016). Another profiles with extreme load include the profiles within Germany (50 Hertz - TenneT; Amprion - TenneT), but the frequency of extreme loading there is low.

The German-Austria cross-border profile is subject to the largest congestion

Fig. 7: Regions with most congested lines in the week 14

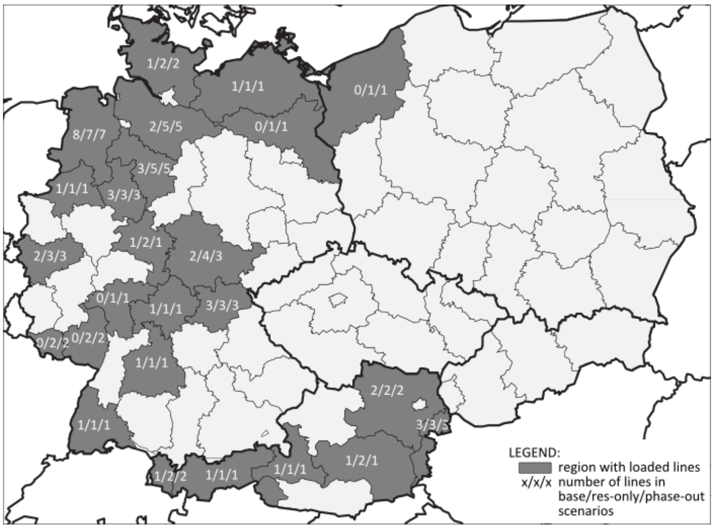


Fig. 8: Regions with most congested lines in the week 27

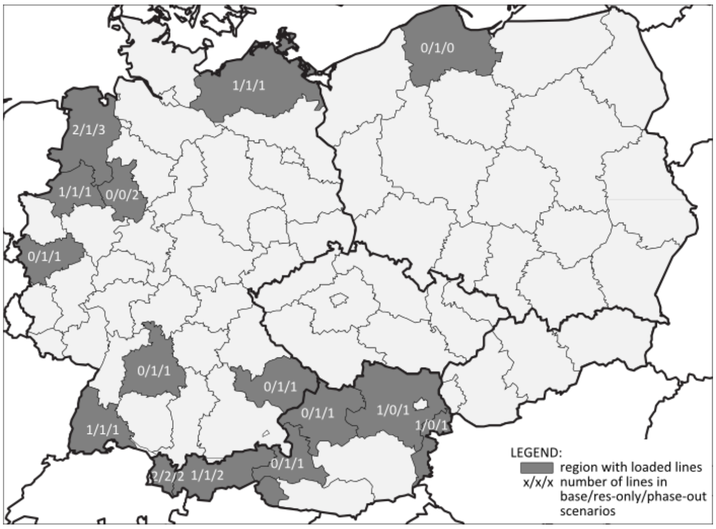
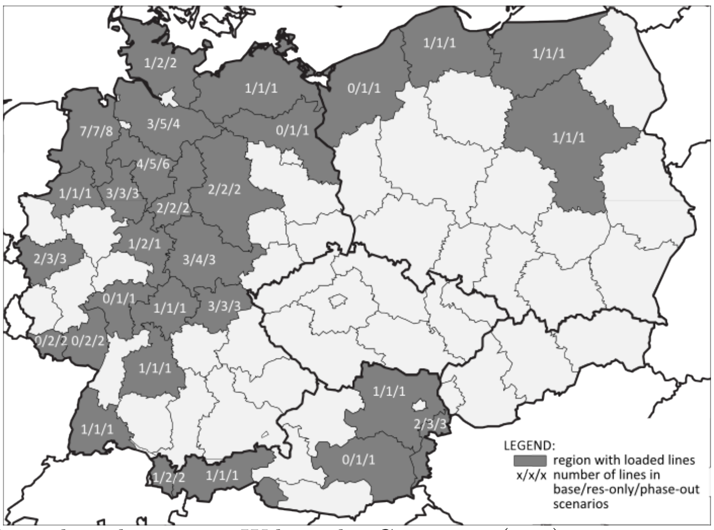


Fig. 9: Regions with most congested lines in the week 49



Source: Authors, based on maps Wikimedia Commons (n.a.)

Tab. 5: Extreme load (75-80%), average weekly hours of extreme load per cross-border line by profile

	high sun. high wind (w14)			high sun. low wind (w27)			low sun. high wind (w49)		
	base	res-only	phase-out	base	res-only	phase-out	base	res-only	phase-out
50Hertz-PSE	6.50	23.50	20.00	0	1.50	2.50	8.50	18.50	24.50
50Hertz-Tennet	1.00	3.13	3.13	0	0	0	1.75	4.88	4.00
Amprion-APG	0	0	0	0	0	0	0	0	0
Amprion-Tennet	2.70	5.40	5.60	0.20	0.70	0.20	2.00	2.90	2.40
Amprion-TransnetBW	0	0	0	0	0	0	0	0	0
APG-Tennet	0.14	2.57	2.43	3.86	8.86	11.71	0	0	0
APG-TransnetBW	0	0	0	0	0	0	0	0	0
CEPS-50Hertz	0	0	0	0	0	0	0	0	0
CEPS-APG	0	0	0	0	0	0	0	0	0
CEPS-PSE	0	0.25	0	0	0	0	0	0	0
CEPS-SEPS	0	0	0	0	0	0	0	0	0
CEPS-Tennet	0	0	0	0	0	0	0	0	0
PSE-SEPS	0	0	0	0	0	0	0	0	0
Tennet-TransnetBW	0	0	0	0	0	0	0	0	0

if solar production is high and wind production is low. In particular, this profile exhibits congestion which is disproportionately higher that on the other profiles where it almost does not occur at all. It can be deduced that since the existence of German-Austrian bidding zone allows unlimited electricity trading between Germany and Austria, the market and regulatory framework does not create any incentives to limit the congestion at German-Austrian cross-borders profiles and the connected transmission lines. The results indicate that a profound effort should be dedicated to the development of transmission lines from the north to the south of Germany and to the construction cross-border interconnections. On the other hand, the example of German-Austrian bidding zone shows, that also the regulatory framework matters. One part of the solution could therefore be to change the regulatory framework in such a way that it would bring undistorted price signals to all energy market participants, from the producers to the consumers, as proposed in the Energy Winter Package (European Commission 2017).

6 Conclusion

This paper provides an analysis of the impacts of two major developments in the Central European energy sector - the wind and solar power generation and nuclear phase-out in Germany - on the transmission lines in the region. The reference scenario *base* and two policy scenarios *res-only* and *phase-out* are created to analyse the impacts of the Energiewende as a whole and the net impacts of nuclear phase-out, respectively. The *base* scenario reflects the year 2015. Scenario *res-only* reflects the development of German renewables' production according to the Energiewende targets in 2025 and the *phase-out* scenario adds the nuclear phase-out too. The non-linear optimization model ELMOD is applied to analyse these impacts during three representative weeks in hourly resolution.

The analysis examining the changes in the distribution of load in the transmission system from the perspective of each of the mentioned week as a whole gives us the following conclusion: The data are in line with our hypothesis that increases in renewable feed-in cause higher occurrence of observations in higher load deciles, including the critical values of 80%, of the grid 'load' and lower occurrence in the lowest deciles. This pattern holds universally across weeks.

Under high grid load, the nuclear phase-out has a slightly positive impact on the transmission lines load and congestion. On the other hand, if there is just a bit of wind production and strong solar feed-in combined with low grid load, the effect partly reverses. This supports our expectation that nuclear power is poorly compatible with high shares of renewables.

Our results confirm that increase of German wind and solar electricity generation increase the congestion not only in Germany but also in Austria and Poland. Although the solar power generation is less predictable than wind generation, the results indicate that the increased high solar feed-in has less detrimental impacts on the transmission grid than high wind feed-in. This is given by two circumstances. First, the solar power plants are located closer to the power demand and are not so concentrated in only a few regions in the north of Germany as the wind power plants and second, high solar feed-in occurs in summer when the grid load is lower. Wind feed-in is more correlated with network load than solar feed-in. This helps to satisfy the electricity demand by renewable sources, but due to the fact the wind generation is concentrated in the north of Germany, it induces higher load of transmission lines and even congestions. High wind feed-in burdens the transmission lines in the north-south direction in Germany. This implies that any delay in transmission grid development plan (Bundesnetzagentur 2017) could involve a serious problem in the grid.

7 Appendix A. Mathematical formulation

The objective function of the model (for more details see Leuthold *et al.* (2012)) maximizes social welfare

$$\max_{g_{nct},q_{nt}} \left\{ w = \sum_{n,t} \left(\int_0^{q_{nt}} \pi_{nt}(q_{nt}) dq_{nt} - \sum_c g_{nct} M_{nc} \right) \right\} \tag{1}$$

where π_{nt} is linear inverse demand function with non-negative intercept A_{nt} and negative slope coefficient D_{nt}:

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

The coefficient M_{nc} is time-invariant marginal cost of generation for each individual power plant unit c at node n determined based on the model data.

In this paper the ELMOD runs as cost minimization model as the reference demand values at each node q_{nt} are fixed.

When solving Eq. 1 several energy balance constraints have to be accounted for. The nodal balance constraint (sum of all inflows equals sum of all outflows) has to be true for any node at any point in time:

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

Electricity inflows include total generation from conventional power plants $\sum_c g_{nct}$, wind generation G_{nt}^{wind}, solar generation G_{nt}^{solar} and pumped-power plant release PSP_{nt}^{out}. Electricity outflows include pumping of pumped-storage power plants PSP_{nt}^{in} and consumption q_{nt}. The term $\sum_{nn} \theta_{nn,t} B_{n,nn}$ is specific to the technical characteristics of electricity and is responsible for balancing the remaining small deviations of the constraint.

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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