ANGUS II Scenario Description

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Background

The ANGUS scenarios and their assumptions have been developed to model a pathway towards 100% renewable energy system in Germany. The assessed system aims to adhere with the COP Paris agreement, i.e. providing a CO2-neutral energy supply in Germany by 2050. The developed scenarios are based on the TYNDP2018, the NEP2019, the e-Highway 100%-RES scenario and the UBA RESCUE scenarios. Their main purpose is to generate storage operation profiles (power, energy) to assess underground storage technologies with regard to techno-ecnomic indicators. Therefore, the shadow prices of the developed techno-economic energy system model play an important role as an economic signal for the storage dispatch and the model coupling (see ANGUS Case Studies). Hence, high priority is given to sensitivities that have a major effect on the storage dispatch and requirements of the future German energy system.

Existing Scenarios

The scientific foundation for the ANGUS scenarios is provided by an alignment wit prominent scenarios from literature. For the mid-term perspective, the *Netzentwicklungsplan (NEP)* in combination with the Ten Year Netwok Development Plan (TYNDP) are considered. In addition, the e-Highway2050 scenarios are used as a starting point for the long-term (2050) system.

The NEP is developed by the German transmission system operator (TSOs) to plan the transmission grid in Germany. It is based on a broad public consultation phase to enable high acceptance of planned grid expansion. Similarly, TYNDP is developed by the European TSOs with regard to the European grid. The processes of the national NEP and the TYNDP are coordinated to ensure coherent national and international planning. Both of these scenarios are updated every two years. Hence, the projects reflect current and expected socio-economic developments as well as recent relevant policy decisions. Due to the public consultation and their prominent nature, these scenarios constitute import visions for the future European energy system. Another important project in the Eurpean context are the EUCO scenarios. Their data has been used as input data for the TNYDP2018. Thus, in the ANGUS project the focus will be given to the TNYDP2018 scenarios for modelling the electrical neigbouring countries of Germany in the mid-term future.

The NEP as well as the TYNDP are focussing on the short to mid-term perspective. Hence, within the ANGUS project another prominent scenario development project, the e-Highway2050 project, is used as a foundation for the scenario frame. The project has been funded by the European Commission and aimed to develop a plan for the European transmission network from 2020 to 2050. One important part of this study is the support of EU's overall policy objectives with regard to energy. The study builds upon the TYNDP2016 and includes scenarios for 100% renewable energy supply in 2050.

The scenarios projects have been chose as the major guideline for the ANGUS project. However other additional national scenarios are considered with respect to the scenario development. These include the BMWI Langfristszenarien for Germany developed by the Fraunhofer ISI and the UBA RESUCE [@katja_purr_wege_2019] scenarios.

System with high shares of RE

In literature different scenarios for up to 100% renewable energy systems can found. Figure 1 shows installed capacities of renewable energies in Germany for systems with high share of renewables. One important factor for the required capacity / energy is the future electricity demand including the electrification of heat and transport sectors. In addition, capacity factors and biomass potentials are crucial aspects. While PV capacity factors lie within a small range of values, onshore and offshore capacity factors can vary strongly with major impacts on results. While in the BMWI Reference scenario onshore wind fullloadhours (flh) are 3527 (capacity factor of 0.403), the onshore wind production in e-Highway 100% RES scenario is modelled with 2102 flh (average capacitiy factor of 0.24). However, the avaible biomass potential can be considered to be even more imporant, as it constitutes the only dispatchable renewable energy source. The role of biomass for 100% long-term scenarios has been discussed for example by [@szarka_interpreting_2017].

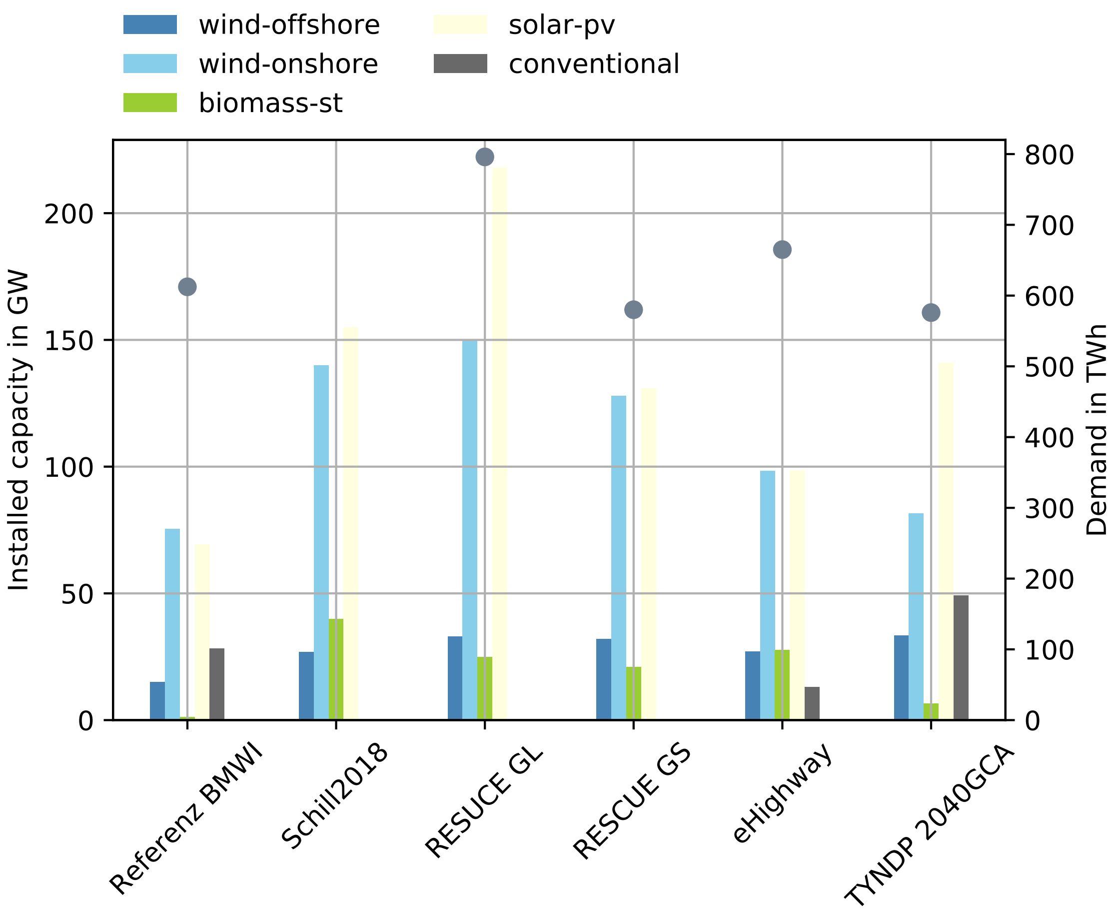

Figure 1: Installed renewable capacities in scenarios from literature.

The lowest capacities are found in the BMWI Reference scenario. However, capacity factors for wind in the scenario are significantly higher compared to the other scenarios. In addition, this scenario only comes with a share of approx. 82% RE. The highest capacities of wind and pv are obtained in the RESCUE GL scenario. Here the 100% RE, no import and the higher demand of 796 TWh are the driving factors. Within the set of scenarios, the wind and pv capacities of e-Highway scenario are rather located at the lower end of the range. The main reason is the high biomass potential, increasing hydro capacities (in particular in Norway) and higher offshore wind capacities. This results in significant imports in Germany, but also lower in installed capacities of onshore wind and pv. In addtion to the before mentioned factors, system flexibility is another important determinate. Here grid infrastructure (spatial flexibility) and storages (temporal flexbiliy) have to be considered.

Mathematical Model

Subsequently a mathematical description of the linear programming least cost optimisation model is given. Total operational cost of the system are minimised with subject to system constraints. The equations for the mathematical model are provided for the different types of the oemof-tabular components. Subsequently, endogenous model variables are denoted with x, while exogenous parameters are denoted with c. The full set of equations for oemof-tabular components can be found in the online documentation of the software.

Component overview

The table shows the carrier and technologies present in the scenarios and their corresponding type (i.e. oemof tabular class) and set.

carrier	tech	type	set name	index
wind	onshore	volatile	V	v
wind	offshore	volatile	V	v
other	res	dispatchable	D	d
hydro	ror	volatile	V	v
biomass	st	conversion	C	c
solar	pv	volatile	V	v
gas	ccgt	dispatchable	D	d
gas	ocgt	dispatchable	D	d
coal	st	dispatchable	D	d
lignite	st	dispatchable	D	d
uranium	st	dispatchable	D	d
oil	ocgt	dispatchable	D	d
mixed	st	dispatchable	D	d
waste	st	dispatchable	D	d
lithium	battery	storage	S	s
hydrogen	storage	storage	S	s
redox	battery	storage	S	s
cavern	acaes	storage	S	s
hydro	phs	storage	S	s
hydro	reservoir	reservoir	R	r
electricity	load	load	L	l
electricity	line	link	n	N

ANGUS Scenario Assumptions

Spatial and temporal resolution

The scenarios model the Western European energy system with one node per country. Countries modelled are:

AT, BE, CH, CZ, DE, DK, FR, IT, LU, NL, NO, PL, SE.

The model simulates the system on an hourly basis for one year using a perfect foresight approach with the years 2030 and 2050. Due to the regional focus of this study the German energy system is modelled with greater detail compared to the neigbouring countries.

Implications & Limitations: Intra-country grid constraints are not reflected by the model. Hence, renewable energy curtailment and/or storage demand may be underestimated.

Grid

The grid for 2030 and 2040 is based on the TYNDP2018 (see Annex), while the grid for 2050 is based on the e-Highway 100% RES scenario. Figure 2 shows the installed transmission capacities of the 2050 electricity system. The transmission system is modelled with a transshipment approach assuming a loss of 0.03 on the lines.

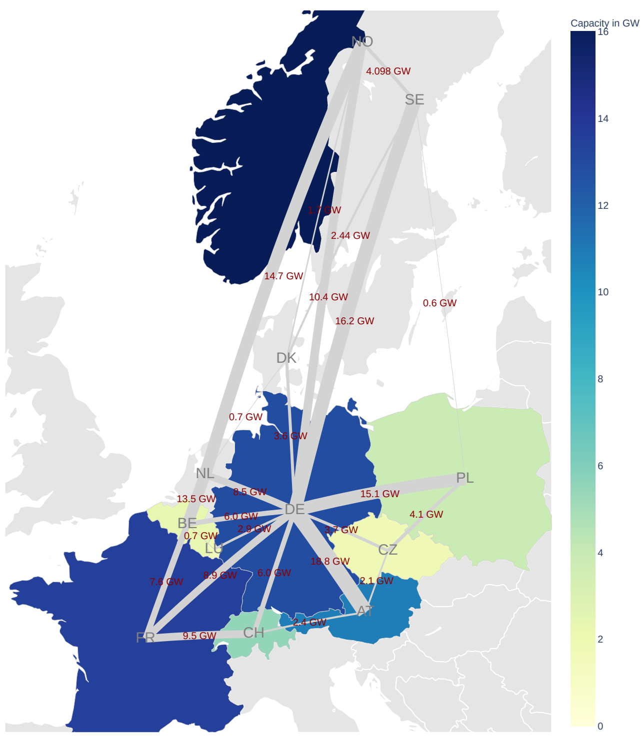

Figure 2: Installed transmission capacities in 2050.

Demand

Conventional electricity demand

The German goals regarding efficiency aim to reduce the electricity demand by 10% until 2020 and 25% by 2050 compared to 2008 levels (403.8 TWh). The development of future electricity demand strongly depends on demographic and economic development as well as implemented efficiency measures. In literature, different values can be found. Assumptions regarding the electricity demand are an important driving factor for the energy system. At the same time, these values come with a high degree of uncertainty (Result of the ANGUS Scenario Workshop). While for example the conventional electricity demand within the *Reference Scenario* of the German *BMWI Langfristszenarien* accounts for 441.2 TWh in 2030 and 417.2 TWh in 2050 respectively, the demand in the NEP2019 scenarios for 2030 is slightly higher (477 TWh). Hence, depending on assumptions (demographics, efficiency and rebound effects, economic activity) the amount of conventional electricity applications can vary.

Sector coupling

Despite a decreasing demand due to efficiency measures, the electrification of other sectors (heat, transport) will create an additional demand for electricity. Currently the heat demand for residential heating accounts for 122.4 TWh hot water and 678.5 TWh space heating (2017). The German government set a goal of 60-80% reduction for this sector 2050. These values are very ambitious, as current values of insulation are lacking behind necessary rates. Heat demand for hot water and space heating in the RESCUE scenarios ranges from 436.8 TWh (green late scenario: GL) to 246.2 TWh (green supreme scenario: GS). These amounts correspond to a reduction of approx. 72 % to 50 % compared to 2008 (889 TWh). The supply for this heat demand is heavily based on electricity (heatpumps) with 74.6 % (GS) and 65 % (GL). The remaining energy is provided by district heating (62.4 TWh, GS) and in the case of the GL also by additional local gas boilers.

In the NEP2019 2030C scenario, additional 29 TWh electricity from heatpumps in residential heating and 25 TWh additional demand for electric vehicles are consumed. In contrast, within the BMWI scenarios, 17.8 TWh electricity for heatpumps is consumed. These values are in the range with the RESCUE green late (GL) and green supreme (GS) scenarios with 57 TWh_th and 95 TWh_th respectively (assuming an coefficienct of performance of approximately 3). For the 2030NEPC a heat demand covered by heat pumps of 87 TWh is assumed.

The electricity demand (excluding electricity for decentral heat pumps) for the different scenarios is given in the Table below.

	2030DG	2030NEPC	2040DG	2040GCA	2050REF
AT	80.7	76.55	91.34	80.5	84.82
BE	88.71	88.78	92.27	91.52	121.25
CH	58.07	58.28	62.98	57.93	77.33
CZ	75.87	70.86	86.57	76.43	71.76
DE	571	547	601	601	613
DK	50.21	46.96	57.88	53.78	42.67
FR	474.66	466.74	493.5	468.62	649.45
LU	11.07	11.05	11.59	8.26	7.38
NL	129.79	118.53	147.85	136.61	160.72
NO	150.66	149.93	153.63	148.09	102.02
PL	219.3	206.68	234.79	251.3	172.22
SE	140.38	143.04	137.34	145.84	131.56

The heat demand covered by heat pumps for each scenario is given in the Table below.

Scenario	Amount in TWh
2050REF	284
2040DG	195
2030DG	57
2030NEPC	87
2040GCA	195

Demand profiles are calculated from the OPSD dataset of the ENTSOE timeseries for the selected weather year (2011).

Implications & Limitations:

- Due to the historic demand profiles, future flexibilities like smart operation of certain applications and industry processes are not modelled.
- The model only covers the residential hot water and space heating demand.
- Electric vehicles are modelled without specific profile for charging / discharging but only with a constant additional base load.

Generation capacity

The different scenarios are based on the NEP2019, TYNDP2018 and the e-Highway project.

- NEP2030C: Installed capacities in Germany are based on the NEP2019 scenario 2030C. The capacities of neighbouring countries are based on the TYNDP2018-2030ST vision. The renewable share of produced energy in Germany in this scenario is approx. 68 %.
- 2040GCA: This scenario is based on the TYNDP2018-GCA vision. Similary the *DG* scenarios are based on the TYNDP2018-DG scenario.
- 2050REF: The base for this scenario is the e-Highway 100 % RES scenario. It scenario strongly depends on hydro capacity expansion in Norway. The biomass potential has been reduced and the PV and wind capacities have been increased to match with the demand values of the RESCUE GL scenario.

The installed capacities in Germany are shown in the Figure 3 below.

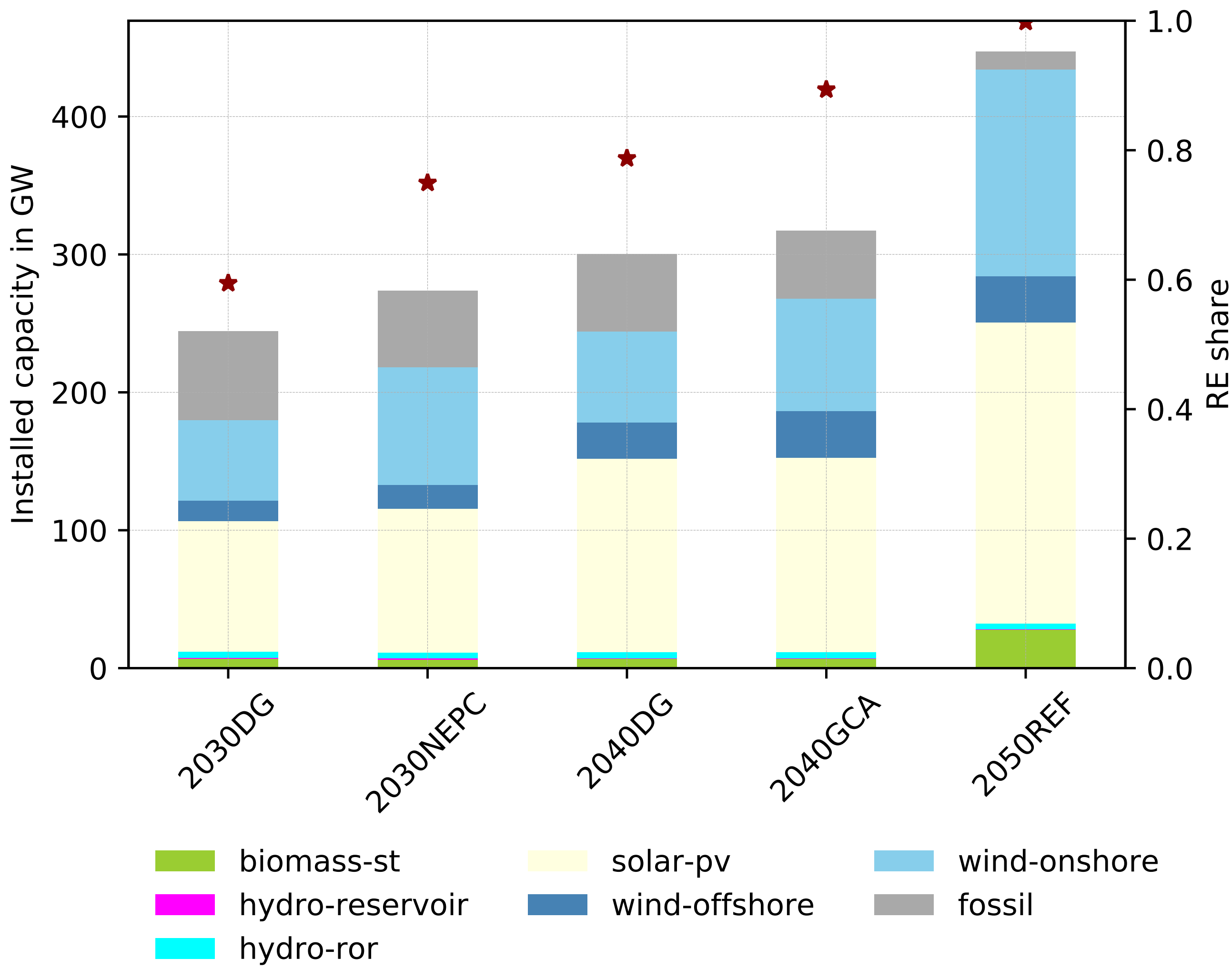

Figure 3: Installed generation capacity in Germany from 2030 to 2050 with different shares of renewables in 2050.

Storage Capacities

PHS storage capacity has been fixed to values from the TYNDP2018 and the e-Highway2050 scenario. For the short-term (lithium) and long-term (hydrogen) storages the results are shown in the table below in GW installed capacity. It can be seen that only for the 100% scenario in 2050 long-term storage is required. For 2030 no additional storage is invested. Note, that the storage demand due to grid constraints not modelled inside the countries might be higher.

	2030DG	2030NEPC	2040DG	2040GCA	2050REF
Lithium (GW)	0	0	3225.55	4528.6	6075.72
Hydrogen (GW)	0	0	0	0	5089.42

Renewable Energies

Wind and PV

Onshore wind and pv timeseries are based on renewables ninja for each country. The offshore profiles are taken from the Vernetzen-project and adapted with a correction factor of 0.8 which has been derived from the energy production in the e-Highway scenarios.

country	offshore	onshore	pv	ror
AT	-	1507	1291	3058
BE	3939	2406	1135	1335
CH	-	1354	1416	3832
CZ	-	1875	1226	1974
DE	3976	1951	1151	4043
DK	4224	2670	977	-
FR	3295	2040	1265	2722
LU	-	2917	1192	2644
NL	4025	1921	1095	1518
NO	4341	3562	811	2028
PL	3964	1834	1113	1493
SE	3792	2654	862	2161

Biomass potential

The maximum biomass potential per country is derived from the hotmaps project [@hotmaps_hotmaps_2019] and is equal for all scenarios in the ANGUS project. The potential does not cover waste but only agriculture and forestry residues. The potential for Germany has been reduced to match with the RESCUE scenarios. This limit does only apply for the year 2050. For previous years no limit on biomass potential is given. With an efficiency of 0.487 for biomass to electricity conversion the potential in Germany is approx. 21.9 TWh{_el}.

Biomass potential:

	Amount in TWh
AT	23.6111
BE	8.08333
CH	0
CZ	32.7778
DE	150.167
DK	13.5556
FR	45
LU	0.611111

	Amount in TWh
NL	2.80556
NO	0
PL	71.3611
SE	86.75

Hydro

For 2030 and 2040 hydro data has been calculated based on the TYNDP2018. The reservoir (rsv) capacity is calculated by subtracting the column *hydro-pump* from column *hydro turbine* in the original data source. Therefore, it is assumed, that each pumped hydro storage (phs) has equal pump/turbine capacities. For 2050 e-Highway database is used as a source. The storage energy capacity (max-hours) for pumped hydro is based on [@geth_overview_2015]. For the rsv capacity the Restore2050 data is used where storage capacities are provided in addition to the installed capacity.

The inflow in run of river and reservoirs is modelled with the inflow timeseries of the Restore2050 project. The total hydro inflow from the Restore2050 project is split by the ror-share for each scenario year. For Norway and Sweden the reservoir inflow has been scaled up to match with the e-Highway results. Similary, the run of river units for all countries except Sweden and Norway have been scaled by a factor of 1.6. The resulting fullloadhours are show in the Table below.

Annex

Hydro data

country	year	phs	phs-max-hours	ror	ror-share	rsv	rsv-factor	rsv-max-hours
AT	2015	2971.1	33	5542.7	0.6515	2964.9	1	857
AT	2030	6055.33	33	4671.9	0.493889	4787.52	1.61473	857
AT	2040	6055.33	33	4671.9	0.493889	4787.52	1.61473	857
AT	2050	10733	33	7401.16	0.565961	5676	1.9144	857
BE	2015	1308	4	114.56	1	0	1	500
BE	2030	1150	4	117	0.425455	158	1	500
BE	2040	1908	4	117	0.425455	158	1	500
BE	2050	2308	4	331.972	1	0	0	500
CH	2015	3940	136	190	0.0381388	4791.8	1	906
CH	2030	4593	136	4139	0.315328	8987	1.8755	906
CH	2040	6722	136	4139	0.315328	8987	1.8755	906
CH	2050	5443	136	4122.7	0.336473	8130	1.69665	906
CZ	2015	1175	5	440	0.40367	650	1	1111
CZ	2030	1000	5	365	0.879518	50	0.0769231	1111
CZ	2040	1145	5	365	0.879518	50	0.0769231	1111
CZ	2050	1787	5	454.846	0.357065	819	1.26	1111
DE	2015	8699	6	3988.62	0.724332	1518	1	592
DE	2030	9791.6	6	4329	0.812973	995.9	0.656061	592
DE	2040	10244	6	4329	0.874722	620	0.408432	592
DE	2050	12799	6	4233	0.872244	620	0.408432	592
DK	2015	0	6	9	1	0	1	
DK	2030	0	6	6.6082	1	0	0	
DK	2040	0	6	6.6082	1	0	0	
DK	2050	0	6	13.3102	1	0	0	
FR	2015	4965	15	10314	0.556671	8214	1	1201
FR	2030	5500	15	13797	0.627307	8197	0.99793	1201
FR	2040	5500	15	13600	0.62963	8000	0.973947	1201
FR	2050	13420	15	10318.6	0.36182	18200	2.21573	1201
LU	2015	0	4	25	0.694444	11	1	2840
LU	2030	1026	4	34	0.106918	284	25.8182	2840
LU	2040	1026	4	34	0.106918	284	25.8182	2840
LU	2050	1650.68	4	149.203	1	0	0	2840
NL	2015	0	6	38	1	0	1	
NL	2030	0	6	38	1	0	0	
NL	2040	2500	6	38	1	0	0	
NL	2050	0	6	104.435	1	0	0	
NO	2015	0	314	1351.8	0.0478322	26909.5	1	3139
NO	2030	1114.71	314	0	0	34702.2	1.28959	3139
NO	2040	1114.71	314	0	0	34702.2	1.28959	3139
NO	2050	17291	314	28141	0.398518	42473	1.57836	3139
PL	2015	1770.12	5	377.84	0.707552	156.17	1	5477
PL	2030	1488	5	1033	1	0	0	5477
PL	2040	2292	5	1033	1	0	0	5477
PL	2050	3790	5	2078.8	1	0	0	5477
SE	2015	0	793	0	0	15956	1	3456
SE	2030	0	793	0	0	16184	1.01429	3456
SE	2040	0	793	0	0	16184	1.01429	3456
SE	2050	0	793	10775.2	0.335066	21383.3	1.34014	3456

Carrier cost

scenario	carrier	source	unit	value
2030DG	biomass	HeatRoadMap	EUR/MWh	30.32
2030DG	co2	TYNDP2018	EUR/t	50
2030DG	coal	TYNDP2018	EUR/MWh	9.72
2030DG	gas	TYNDP2018	EUR/MWh	31.68
2030DG	lignite	TYNDP2018	EUR/MWh	3.96
2030DG	mixed	Own Assumption	EUR/MWh	6.7
2030DG	oil	TYNDP2018	EUR/MWh	78.48
2030DG	uranium	TYNDP2018	EUR/MWh	1.692
2030DG	waste	Own Assumption	EUR/MWh	6.7
2030NEPC	biomass	Own Assumption	EUR/MWh	5
2030NEPC	co2	NEP2019	EUR/t	29.4
2030NEPC	coal	NEP2019	EUR/MWh	8.4
2030NEPC	gas	NEP2019	EUR/MWh	26.4
2030NEPC	lignite	NEP2019	EUR/MWh	5.6
2030NEPC	mixed	Own Assumption	EUR/MWh	6.7
2030NEPC	oil	NEP2019	EUR/MWh	48.3
2030NEPC	uranium	TYNDP2018	EUR/MWh	1.692
2030NEPC	waste	IRENA2015	EUR/MWh	6.7
2040DG	biomass	HeatRoadMap	EUR/MWh	30.32
2040DG	co2	TYNDP2018	EUR/t	80
2040DG	coal	TYNDP2018	EUR/MWh	10.08
2040DG	gas	TYNDP2018	EUR/MWh	35.28
2040DG	lignite	TYNDP2018	EUR/MWh	3.96
2040DG	mixed	Own Assumption	EUR/MWh	6.7
2040DG	oil	TYNDP2018	EUR/MWh	87.84
2040DG	uranium	TYNDP2018	EUR/MWh	1.692
2040DG	waste	Own Assumption	EUR/MWh	6.7
2040GCA	biomass	HeatRoadMap	EUR/MWh	30.32
2040GCA	co2	TYNDP2018	EUR/t	126
2040GCA	coal	TYNDP2018	EUR/MWh	6.48
2040GCA	gas	TYNDP2018	EUR/MWh	30.24
2040GCA	lignite	TYNDP2018	EUR/MWh	3.96
2040GCA	mixed	Own Assumption	EUR/MWh	6.7
2040GCA	oil	TYNDP2018	EUR/MWh	50.22
2040GCA	uranium	TYNDP2018	EUR/MWh	1.692
2040GCA	waste	Own Assumption	EUR/MWh	6.7
2050REF	biomass	HeatRoadMap	EUR/MWh	34.89
2050REF	co2	Own Assumption	EUR/t	150
2050REF	coal	HeatRoadMap	EUR/MWh	7.97
2050REF	gas	HeatRoadMap	EUR/MWh	43.72
2050REF	lignite	Own Assumption	EUR/MWh	6
2050REF	mixed	Own Assumption	EUR/MWh	6.7
2050REF	oil	HeatRoadMap	EUR/MWh	47.63
2050REF	uranium	Own Assumption	EUR/MWh	1.692
2050REF	waste	Own Assumption	EUR/MWh	30

Technical parameters

year	parameter	carrier	tech	source	unit	value
2030	capex	gas	ccgt	DIW	Euro/kW	800
2030	capex	gas	ocgt	DIW	Euro/kW	400
2030	capex	lithium	battery	IWES	Euro/kW	785
2030	capex	solar	pv	DIW	Euro/kW	600
2030	capex	wind	offshore	DIW	Euro/kW	2506
2030	capex	wind	onshore	DIW	Euro/kW	1182
2030	capex_energy	cavern	acaes	IWES	Euro/kWh	40
2030	capex_energy	hydrogen	storage	IWES	Euro/kWh	0.2
2030	capex_energy	lithium	battery	IWES	Euro/kWh	300
2030	capex_energy	redox	battery	IWES	Euro/kWh	150
2030	capex_power	cavern	acaes	IWES	Euro/kW	825
2030	capex_power	hydrogen	storage	IWES	Euro/kW	1550
2030	capex_power	lithium	battery	IWES	Euro/kW	65
2030	capex_power	redox	battery	IWES	Euro/kW	1000
2030	efficiency	biomass	st	DIW	per unit	0.35
2030	efficiency	cavern	acaes	IWES	per unit	0.7
2030	efficiency	coal	st	TYNDP2018	per unit	0.4
2030	efficiency	gas	ccgt	TYNDP2018	per unit	0.5
2030	efficiency	gas	ocgt	TYNDP2018	per unit	0.38
2030	efficiency	hydro	phs	roundtrip; DIW	per unit	0.75
2030	efficiency	hydro	ror	DIW	per unit	0.9
2030	efficiency	hydro	rsv	DIW	per unit	0.9
2030	efficiency	hydrogen	storage	IWES	per unit	0.32
2030	efficiency	lignite	st	TYNDP2018	per unit	0.4
2030	efficiency	lithium	battery	IWES	per unit	0.9
2030	efficiency	mixed	st	Own assumption	per unit	0.26
2030	efficiency	oil	ocgt	TYNDP2018	per unit	0.35
2030	efficiency	porous	acaes	Own assumption (2050)	per unit	0.5
2030	efficiency	redox	battery	IWES	per unit	0.74
2030	efficiency	uranium	st	TYNDP2018	per unit	0.33
2030	efficiency	waste	st	Own assumption	per unit	0.26
2030	fom	cavern	acaes	Own assumption (2050)	Euro/kWha	10
2030	fom	hydrogen	storage	Own assumption (2050)	Euro/kWha	10
2030	fom	lithium	battery	Own assumption (2050)	Euro/kWha	10
2030	fom	redox	battery	Own assumption (2050)	Euro/kWha	10
2030	lifetime	cavern	acaes	IWES	a	30
2030	lifetime	hydrogen	storage	Own assumption	a	22.5
2030	lifetime	lithium	battery	IWES	a	12
2030	lifetime	redox	battery	IWES	a	25
2030	max_hours	cavern	acaes	Own assumption (2050)	h	7
2030	max_hours	hydro	phs	Own assumption (2050)	h	8
2030	max_hours	hydrogen	storage	Own assumption (2050)	h	168
2030	max_hours	lithium	battery	Own assumption (2050)	h	6.5
2030	max_hours	porous	acaes	Own assumption (2050)	h	300
2030	max_hours	redox	battery	Own assumption (2050)	h	3.3
2030	vom	cavern	acaes	Own assumption (2050)	Euro/Mwh	1
2030	vom	hydrogen	storage	Own assumption (2050)	Euro/Mwh	1
2030	vom	lithium	battery	Own assumption (2050)	Euro/Mwh	1
2030	vom	redox	battery	Own assumption (2050)	Euro/Mwh	1
2040	capex_energy	cavern	acaes	Own assumption (2050)	Euro/kWh	40
2040	capex_energy	hydrogen	storage	Own assumption (2050)	Euro/kWh	0.2
2040	capex_energy	lithium	battery	Own assumption (2050)	Euro/kWh	187
2040	capex_energy	redox	battery	Own assumption (2050)	Euro/kWh	70

year	parameter	carrier	tech	source	unit	value
2040	capex_power	cavern	acaes	Own assumption (2050)	Euro/kW	750
2040	capex_power	hydrogen	storage	IWES 2050	Euro/kW	1400
2040	capex_power	lithium	battery	Own assumption (2050)	Euro/kWh	35
2040	capex_power	redox	battery	Own assumption (2050)	Euro/kW	600
2040	efficiency	biomass	st	Own assumption	per unit	0.4185
2040	efficiency	cavern	acaes	Own assumption (2050)	per unit	0.73
2040	efficiency	coal	st	Own assumption	per unit	0.425
2040	efficiency	gas	ccgt	Own assumption	per unit	0.53475
2040	efficiency	gas	ocgt	Own assumption	per unit	0.373
2040	efficiency	hydro	phs	roundtrip; DIW	per unit	0.75
2040	efficiency	hydro	ror	DIW	per unit	0.9
2040	efficiency	hydro	rsv	DIW	per unit	0.9
2040	efficiency	hydrogen	storage	Own assumption (2050)	per unit	0.46
2040	efficiency	lignite	st	Own assumption	per unit	0.4
2040	efficiency	lithium	battery	Own assumption (2050)	per unit	0.92
2040	efficiency	mixed	st	Own assumption	per unit	0.28
2040	efficiency	oil	ocgt	Own assumption	per unit	0.373
2040	efficiency	porous	acaes	Own assumption (2050)	per unit	0.56
2040	efficiency	redox	battery	Own assumption (2050)	per unit	0.8
2040	efficiency	uranium	st	Own assumption	per unit	0.335
2040	efficiency	waste	st	Own assumption	per unit	0.26
2040	fom	cavern	acaes	Own assumption (2050)	Euro/kWha	10
2040	fom	hydrogen	storage	Own assumption (2050)	Euro/kWha	10
2040	fom	lithium	battery	Own assumption (2050)	Euro/kWha	10
2040	fom	redox	battery	Own assumption (2050)	Euro/kWha	10
2040	lifetime	cavern	acaes	Own assumption (2050)	a	30
2040	lifetime	hydrogen	storage	Own assumption (2050)	a	22.5
2040	lifetime	lithium	battery	Own assumption (2050)	a	20
2040	lifetime	redox	battery	Own assumption (2050)	a	25
2040	max_hours	cavern	acaes	Own assumption (2050)	h	7
2040	max_hours	hydro	phs	Own assumption (2050)	h	8
2040	max_hours	hydrogen	storage	Own assumption (2050)	h	168
2040	max_hours	lithium	battery	Own assumption (2050)	h	6.5
2040	max_hours	porous	acaes	Own assumption (2050)	h	300
2040	max_hours	redox	battery	Own assumption (2050)	h	3.3
2040	vom	cavern	acaes	Own assumption (2050)	Euro/Mwh	1
2040	vom	hydrogen	storage	Own assumption (2050)	Euro/Mwh	1
2040	vom	lithium	battery	Own assumption (2050)	Euro/Mwh	1
2040	vom	redox	battery	Own assumption (2050)	Euro/Mwh	1
2050	avf	biomass	st	Own assumption	per unit	0.9
2050	avf	coal	st	PRIMES	per unit	0.85
2050	avf	gas	ccgt	PRIMES	per unit	0.85
2050	avf	gas	ocgt	PRIMES	per unit	0.96
2050	avf	hydro	phs	Own assumption	per unit	1
2050	avf	hydro	ror	Own assumption	per unit	1
2050	avf	hydro	rsv	Own assumption	per unit	1
2050	avf	lignite	st	PRIMES	per unit	0.85
2050	avf	lithium	battery	Own assumption	per unit	1
2050	avf	mixed	st	Own assumption	per unit	0.9
2050	avf	oil	ocgt	PRIMES	per unit	0.9
2050	avf	porous	acaes	Own assumption	per unit	1
2050	avf	solar	pv	Own assumption	per unit	1
2050	avf	uranium	st	Own assumption	per unit	0.9
2050	avf	waste	st	Own assumption	per unit	0.9
2050	avf	wind	offshore	Own assumption	per unit	1

year	parameter	carrier	tech	source	unit	value
2050	avf	wind	onshore	Own assumption	per unit	1
2050	capex	biomass	st	DIW, p. 75	Euro/kW	1951
2050	capex	coal	st	DIW, p. 75	Euro/kW	1300
2050	capex	gas	ccgt	DIW, p. 75	Euro/kW	800
2050	capex	gas	ocgt	DIW, p. 75	Euro/kW	400
2050	capex	hydro	phs	DIW, p. 75	Euro/kW	2000
2050	capex	hydro	ror	DIW, p. 75	Euro/kW	3000
2050	capex	hydro	rsv	DIW, p. 75	Euro/kW	2000
2050	capex	lignite	st	DIW, p. 75	Euro/kW	1500
2050	capex	oil	ocgt	DIW, p. 75	Euro/kW	400
2050	capex	solar	pv	DIW, p. 75	Euro/kW	425
2050	capex	wind	offshore	DIW, p. 75	Euro/kW	2093
2050	capex	wind	onshore	DIW, p. 75	Euro/kW	1075
2050	capex_energy	cavern	acaes	Schill2018	Euro/kWh	40
2050	capex_energy	hydrogen	storage	Schill2018	Euro/kWh	0.2
2050	capex_energy	lithium	battery	Schill2018	Euro/kWh	187
2050	capex_energy	redox	battery	Schill2018	Euro/kWh	70
2050	capex_power	cavern	acaes	Schill2018	Euro/kW	750
2050	capex_power	hydrogen	storage	Schill2018	Euro/kW	1000
2050	capex_power	lithium	battery	Schill2018	Euro/kWh	35
2050	capex_power	redox	battery	Schill2018	Euro/kW	600
2050	efficiency	biomass	st	DIW	per unit	0.487
2050	efficiency	cavern	acaes	roundtrip;Schill2018	per unit	0.73
2050	efficiency	coal	st	DIW	per unit	0.45
2050	efficiency	gas	ccgt	Avg; DIW	per unit	0.5695
2050	efficiency	gas	ocgt	Avg; DIW	per unit	0.366
2050	efficiency	hydro	phs	roundtrip; DIW	per unit	0.75
2050	efficiency	hydro	ror	DIW	per unit	0.9
2050	efficiency	hydro	rsv	DIW	per unit	0.9
2050	efficiency	hydrogen	storage	roundtrip;Schill2018	per unit	0.46
2050	efficiency	lignite	st	Avg; DIW	per unit	0.4
2050	efficiency	lithium	battery	roundtrip; Schill2018	per unit	0.92
2050	efficiency	mixed	st	Own assumption	per unit	0.3
2050	efficiency	oil	ocgt	DIW	per unit	0.396
2050	efficiency	porous	acaes	Own assumption	per unit	0.56
2050	efficiency	redox	battery	roundtrip;Schill2018	per unit	0.8
2050	efficiency	uranium	st	DIW	per unit	0.34
2050	efficiency	waste	st	Own assumption	per unit	0.26
2050	fom	biomass	st	DIW, p.78	Euro/kWa	100
2050	fom	cavern	acaes	Schill2018	Euro/kWha	10
2050	fom	coal	st	DIW, p.78	Euro/kWa	25
2050	fom	gas	ccgt	DIW, p.78	Euro/kWa	20
2050	fom	gas	ocgt	DIW, p.78	Euro/kWa	15
2050	fom	hydro	phs	DIW, p.78	Euro/kWa	20
2050	fom	hydro	ror	DIW, p.78	Euro/kWa	60
2050	fom	hydro	rsv	DIW, p.78	Euro/kWa	20
2050	fom	hydrogen	storage	Schill2018	Euro/kWha	10
2050	fom	lignite	st	DIW, p.78	Euro/kWa	30
2050	fom	lithium	battery	Schill2018	Euro/kWha	10
2050	fom	oil	ocgt	DIW, p.78	Euro/kWa	6
2050	fom	redox	battery	Schill2018	Euro/kWha	10
2050	fom	solar	pv	DIW, p.78	Euro/kWa	25
2050	fom	wind	offshore	DIW, p.78	Euro/kWa	80
2050	fom	wind	onshore	DIW, p.78	Euro/kWa	35
2050	lifetime	biomass	st	DIW, p. 72	a	30

year	parameter	carrier	tech	source	unit	value
2050	lifetime	cavern	acaes	Schill2018	a	30
2050	lifetime	coal	st	DIW, p. 72	a	40
2050	lifetime	gas	ccgt	DIW, p. 72	a	30
2050	lifetime	gas	ocgt	DIW, p. 72	a	30
2050	lifetime	hydro	phs	DIW, p. 72	a	50
2050	lifetime	hydro	ror	DIW, p. 72	a	50
2050	lifetime	hydro	rsv	DIW, p. 72	a	50
2050	lifetime	hydrogen	storage	Schill2018	a	22.5
2050	lifetime	lignite	st	DIW, p. 72	a	40
2050	lifetime	lithium	battery	Schill2018	a	20
2050	lifetime	oil	ocgt	DIW, p. 72	a	40
2050	lifetime	redox	battery	Schill2018	a	25
2050	lifetime	solar	pv	DIW, p. 72	a	25
2050	lifetime	wind	offshore	DIW, p. 72	a	25
2050	lifetime	wind	onshore	DIW, p. 72	a	25
2050	max_hours	cavern	acaes	Wolf2011	h	7
2050	max_hours	hydro	phs	Plessmann, p. 90	h	8
2050	max_hours	hydrogen	storage	eGo	h	168
2050	max_hours	lithium	battery	Plessmann, p. 90	h	6.5
2050	max_hours	porous	acaes	Own assumption	h	300
2050	max_hours	redox	battery	ZNES	h	3.3
2050	vom	biomass	st	Own assumption	Euro/Mwh	10
2050	vom	cavern	acaes	Schill2018	Euro/Mwh	1
2050	vom	coal	st	DIW, p. 78	Euro/Mwh	6
2050	vom	gas	ccgt	DIW, p. 78	Euro/Mwh	4
2050	vom	gas	ocgt	DIW, p. 78	Euro/Mwh	3
2050	vom	hydro	phs	DIW, p. 78	Euro/Mwh	0
2050	vom	hydro	ror	DIW, p. 78	Euro/Mwh	0
2050	vom	hydro	rsv	DIW, p. 78	Euro/Mwh	0
2050	vom	hydrogen	storage	Schill2018	Euro/Mwh	1
2050	vom	lignite	st	DIW, p. 78	Euro/Mwh	7
2050	vom	lithium	battery	Schill2018	Euro/Mwh	1
2050	vom	mixed	st	Own assumption	Euro/Mwh	5
2050	vom	oil	ocgt	DIW, p. 78	Euro/Mwh	3
2050	vom	redox	battery	Schill2018	Euro/Mwh	1
2050	vom	solar	pv	Plessmann	Euro/Mwh	0
2050	vom	uranium	st	DIW, p. 78, AVG	Euro/Mwh	8.5
2050	vom	waste	st	Own assumption	Euro/Mwh	10
2050	vom	wind	offshore	Plessmann	Euro/Mwh	0
2050	vom	wind	onshore	Plessmann	Euro/Mwh	0

Installed capacities

The table show the installed grid capacities for path towards 100% renewable energy supply from 2030 to 2050. For the 2030NEPC scenario, the 2030DG Grid has been applied.

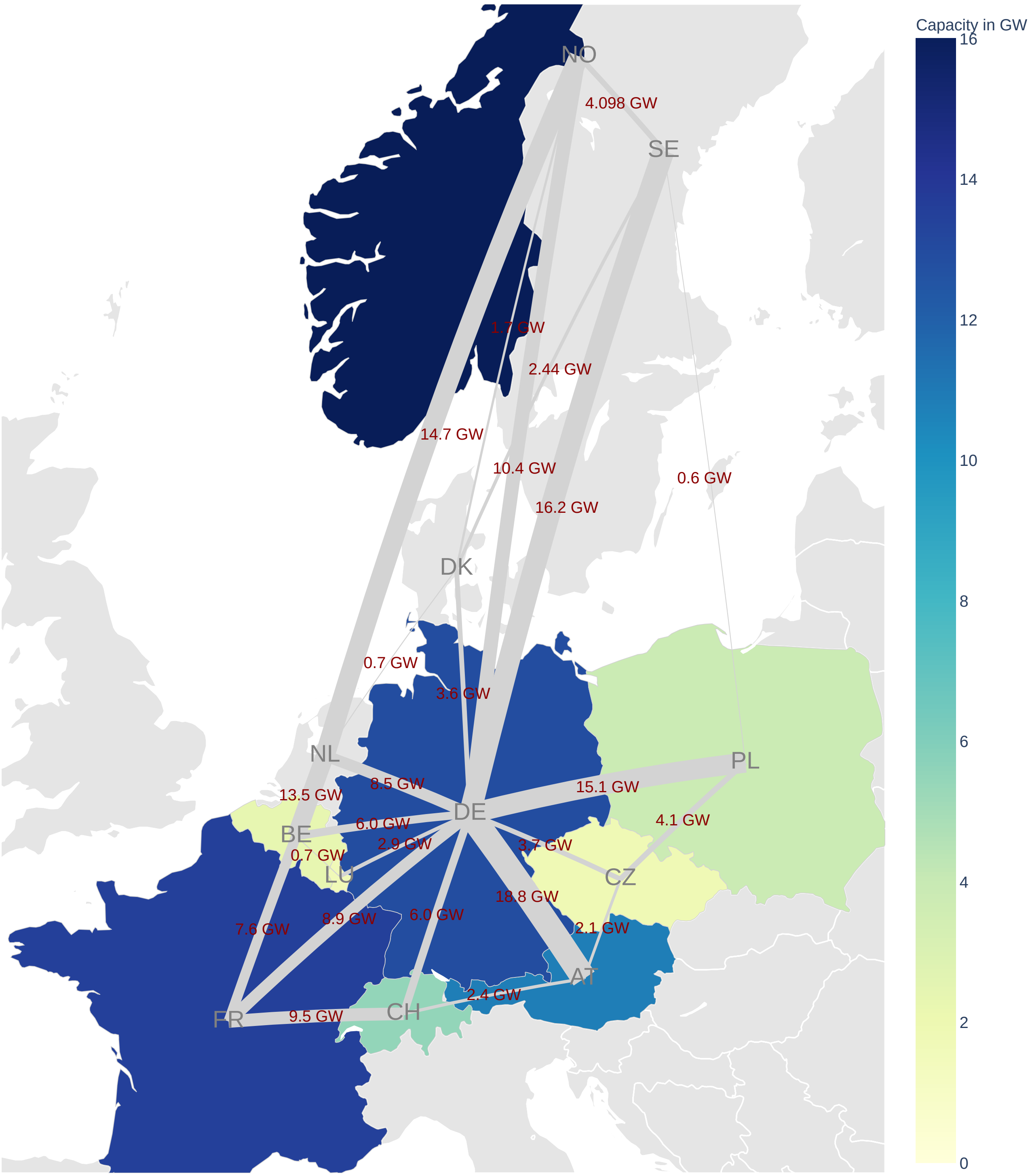

Figure 4: Installed transmission capacities in 2050

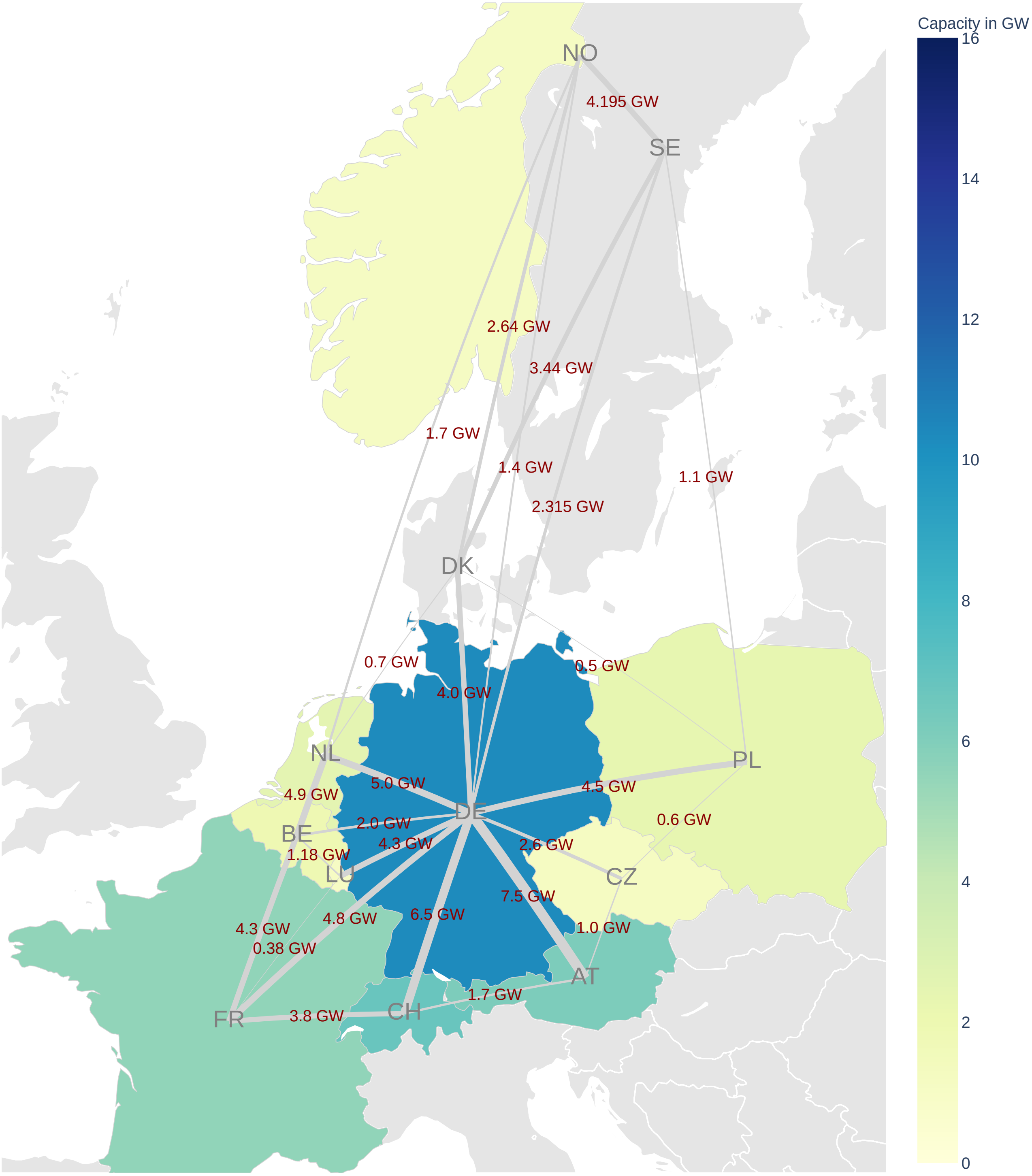

Figure 5: Installed transmission capacities in 2040

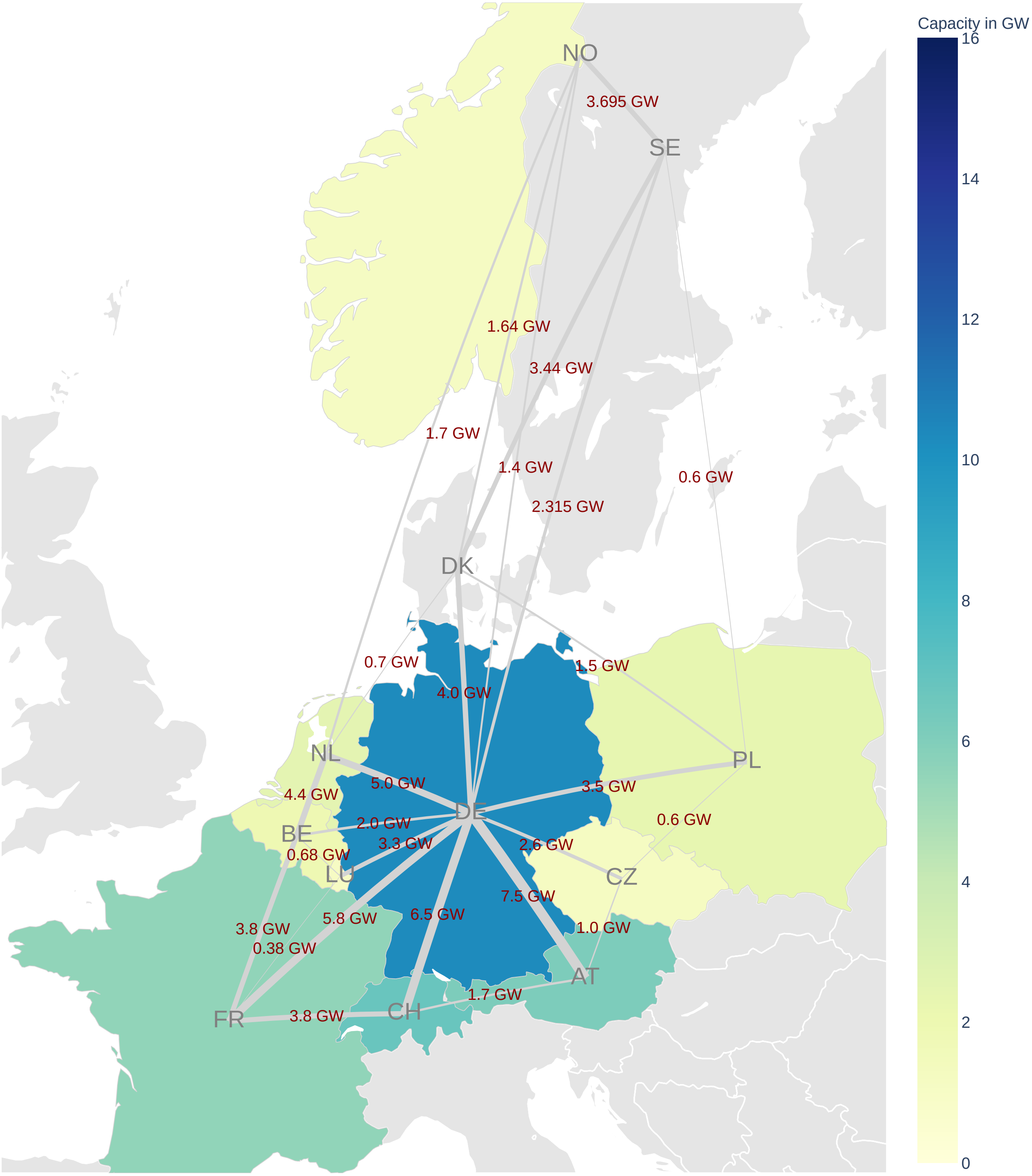

Figure 6: Installed transmission capacities in 2040

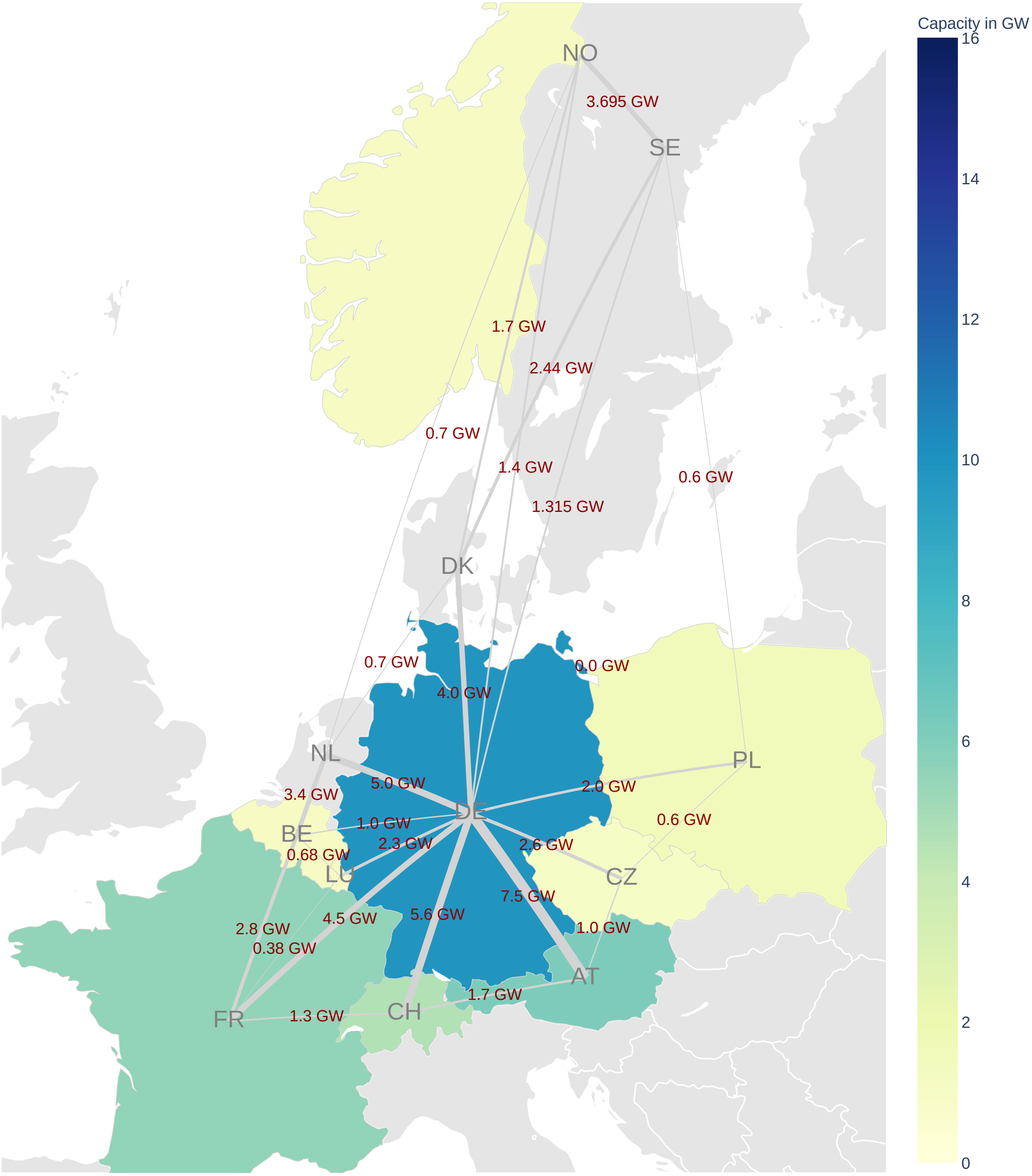

Figure 7: Installed transmission capacities in 2030

Data Sources

All relevant raw input data can be found in:

- https://github.com/ZNES-datapackages/angus-input-data
- https://github.com/ZNES-datapackages/technology-potential
- https://zenodo.org/record/3549531

The scenario datapackages with python scripts and the model is located on github:

- https://github.com/znes/angus-scenarios

Links

- ehighway website
- TYNDP2018a data
- TYNDP2018b data
- NinjaWind data
- NinjaPV data
- OPSD demand data
- OPSD powerplant data
- OPSD heat data
- NEP2019a
- NEP2019 powerplant data
- Restore2050 hydro data
- Brown2018 sector coupling data
- hotmaps biomass data

References