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 ANGUSII 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 et al. 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 et al. 2017).

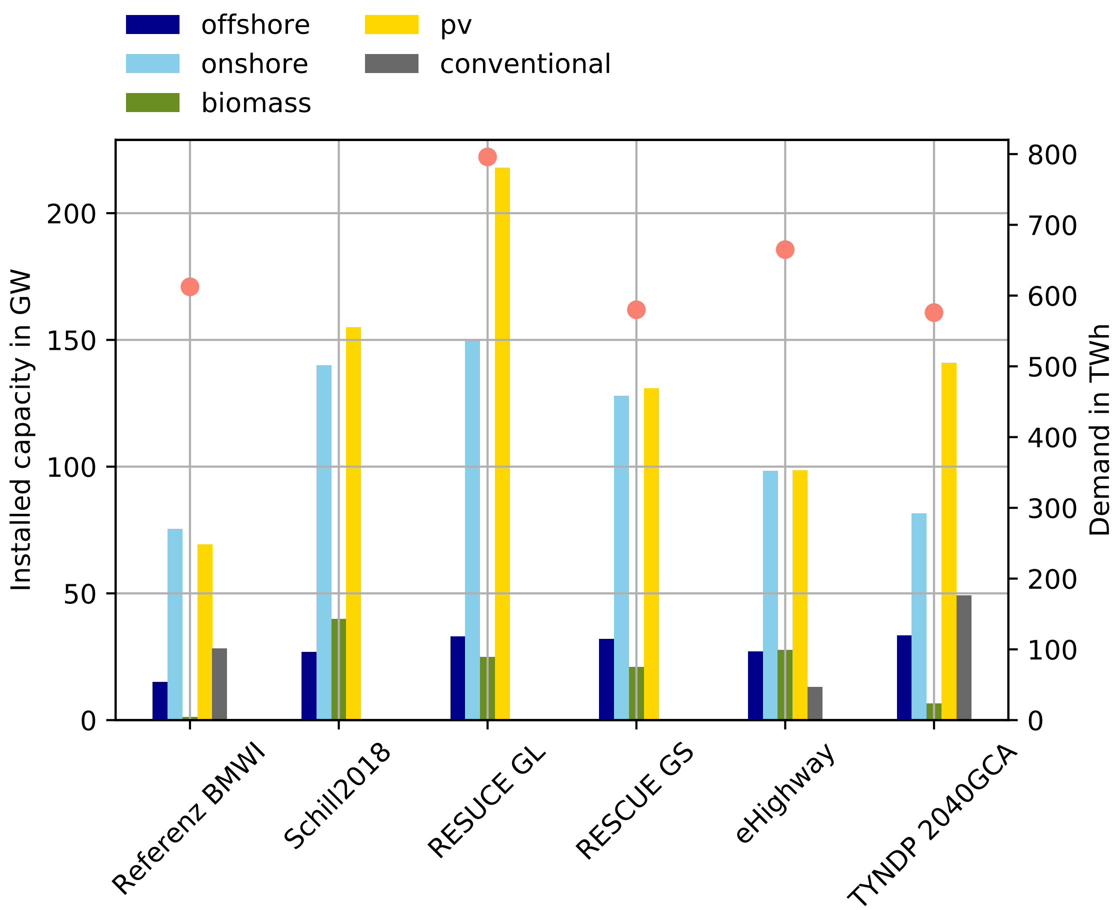

Figure 1: Installed renewable capacities in scenarios from literature.

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.

Objective function

The objective function will minimise all operating costs.

$$\text{min:} \sum_g \sum_t \overbrace{c_g^{marginal\_cost} \cdot x_g^{flow}(t)}^{\text{operating cost}}$$

Energy Balances (Buses)

With the set of all Buses B all inputs $x_{i(b),b}^{flow}$ to a bus b must equal all its outputs $x_{b,o(b)}^{flow}$

$$\sum_i x_{i(b),b}^{flow}(t) - \sum_o x_{b,o(b)}^{flow}(t) = 0 \qquad \forall t \in T, \forall b \in B$$

Loads

For the set of all loads denoted with $l \in L$ the load x_l at timestep t equals the exogenously defined profile value $c_l^{profile}$ multiplied by the amount of this load c_l^{amount}

$$x_l^{flow}(t) = c_l^{profile}(t) \cdot c_l^{amount} \qquad \forall t \in T, \forall l \in L$$

Dispatchable Supply

For the set of all dispatchable generators $d \in D$ the flow from the component to the connected bus is limited by the defined capacity:.

$$x_d^{flow}(t) \leq c_d^{capacity} \qquad \forall t \in T, \forall d \in D$$

Volatile Supply

In contrast to dispatchble components, for all volatile components denoted with $v \in V$ the flow is fixed to a specific value.

$$x_v^{flow}(t) = c_v^{profile}(t) \cdot c_v^{capacity} \qquad \forall t \in T, \forall v \in V$$

The set of all volatile components includes all *wind-onshore*, *wind-offshore*, *solar-pv* and *hydro-ror*

Commodities

Commodities are modelled with an upper limit on the aggregated flow of the component:

$$\sum_t x^{flow} k(t) \leq c_k^{amount}, \qquad \forall k \in K$$

Conversion Processes

Biomass units are modelled with a conversion process with the following equation:

$$x_{c,to}^{flow}(t) = c_c^{efficiencty} \cdot x_{c,from}^{flow}(t), \qquad \forall c \in C, \forall t \in T$$

In combination with the commodity components, their supply can be limited.

Reservoirs

The reservoir is modelled as a storage with a constant inflow:

$$x_r^{level}(t) = x_r^{level}(t-1) \cdot (1 - c_r^{loss\_rate}(t)) + x_r^{profile}(t) - \frac{x_r^{flow,out}(t)}{c^{efficiency}(t)} \qquad \forall t \in T, \forall r \in R$$
$$x_r^{level}(0) = c_r^{initial\_storage\_level} \cdot c_r^{capacity}$$

The inflow is bounded by the exogenous inflow profile. Thus, if the inflow exceeds the maximum capacity of the storage, spillage is possible by setting $x_r^{profile}(t)$ to lower values.

$$0 \leq x_r^{profile}(t) \leq c_r^{profile}(t) \qquad \forall t \in T, \qquad \forall r \in R$$

The spillage of the reservoir is therefore defined by $c_r^{profile}(t) - x_r^{profile}(t)$. Additional constraints apply that have been omitted but can be retrieved from the oemof documentation.

Storages

The mathematical representation of the storage for all storages $s \in S$ will include the flow into the storage, out of the storage and a storage level.

Intertemporal energy balance of the storage:

$$x_s^{level}(t) = \eta^{loss\_rate} x_s^{level}(t) + \eta x_{s,in}^{flow} - \eta x_{s,out}^{flow}(t) \qquad \forall t \in T, \forall s \in S$$

Bounds of the storage level variable $x_s^{level}(t)$:

$$x_s^{level}(t) \leq c_s^{storagecapacity} \qquad \forall t \in T, \forall s \in S$$

$$x_s^{level}(1) = x_s^{level}(t_e) = 0.5 \cdot c_s^{storagecapacity} \qquad \forall t \in T, \forall s \in S$$

Of course, in addition the inflow/outflow of the storage also needs to be within the limit of the minimum and maximum power.

$$-c_s^{capacity} \leq x_s^{flow}(t) \leq c_s^{capacity} \qquad \forall t \in T, \forall s \in S$$

The loss rate for the storage can be obtained by a time constant $loss\_rate = 1 - \exp^{-\frac{1}{24 \cdot d}}$, where d denotes the time constant in days.

Transmission lines

Transmission lines are modelled with a transhipment approach.

$$x_{from,n}^{flow}(t) = c_n^{loss} \cdot x_{n,to}^{flow}(t), \qquad \forall n \in N, \forall t \in T$$

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
hydor	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

ANGUSII 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.

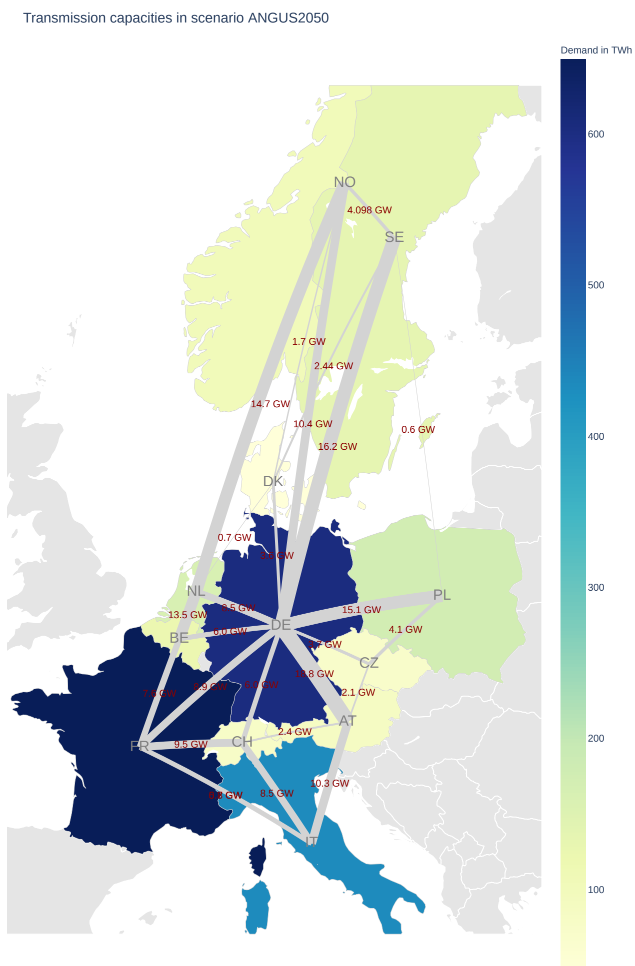

Figure 2: Installed transmission capacities in 2050.

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). Therefore, for 2050
both scenarios are used as a basis for additional electricity demand due to space heating.

The total electricity demand for the different scenarios is given in the Table below.

	2030NEPC	2040GCA	2050ANGUS	2050ANGUS-nb	2050ZNES
AT	76.55	80.5	84.82	84.82	84.82
BE	88.78	91.52	121.25	121.25	121.25
CH	58.28	57.93	77.33	77.33	77.33
CZ	70.86	76.43	71.76	71.76	71.76
DE	547	575.86	665.7	665.7	665.7
DK	46.96	53.78	42.67	42.67	42.67
FR	466.74	468.62	649.45	649.45	649.45
LU	11.05	8.26	7.38	7.38	7.38
NL	118.53	136.61	160.72	160.72	160.72
NO	149.93	148.09	102.02	102.02	102.02
PL	206.68	251.3	172.22	172.22	172.22
SE	143.04	145.84	131.56	131.56	131.56

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.
- 2050ZNES: The base scenario is the e-Highway 100 % RES scenario. This scenario strongly depends on hydro capacity expansion in Norway and also substantial biomass capacity/energy. Based on the input data, this scenario has an renewable energy supply share of approx. 95 % .
- 2050ANGUS: Therefore, an adapted ANGUS scenario has been developed to model 100% renewable energy scenarios with different sensitivities such as the no-biomass (nb).

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

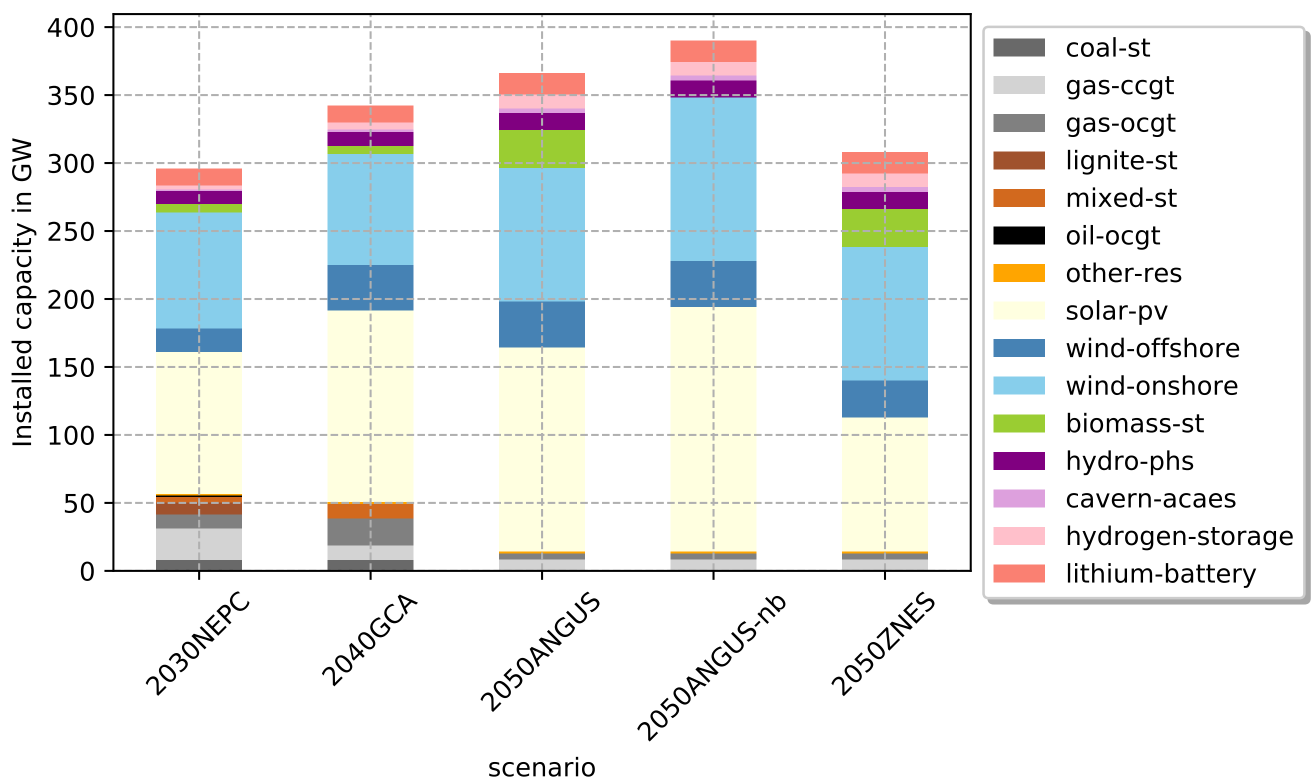

Figure 3: Installed generation capacity in Germany from 2030 to 2050 with different shares of renewables in 2050. The 2050ZNES scenario has a RE-share of 95% and 2050ANGUS scenario 100% RE-share of supply in Germany. Hydro capacities are not shown.

Note that only the scenarios 2030NEPC, 2040GCA, 2050ANGUS-(nb) depict a path towards 100% renewable energy supply.

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 an correction factor of 0.8 which has been derived from the energy production in the e-Highway scenarios.

country	offshore	onshore	pv	ror
AT	nan	1507	1291	3058
BE	3939	2406	1135	1335
CH	nan	1354	1416	3832
CZ	nan	1875	1226	1974
DE	3976	1951	1151	4043
DK	4224	2670	977	0
FR	3295	2040	1265	2722
LU	nan	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 2019) and is equal for all scenarios in the ANGUS project. The potential does not cover waste but only agriculture and forestry residues. With an efficiency of 0.487 for biomass to electricity conversion the potential in Germany is approx. 73 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	149.556
LU	0.611111
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 et al. 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

Energy Balances

Figure 4 shows the energy supply and demand for each scenario.

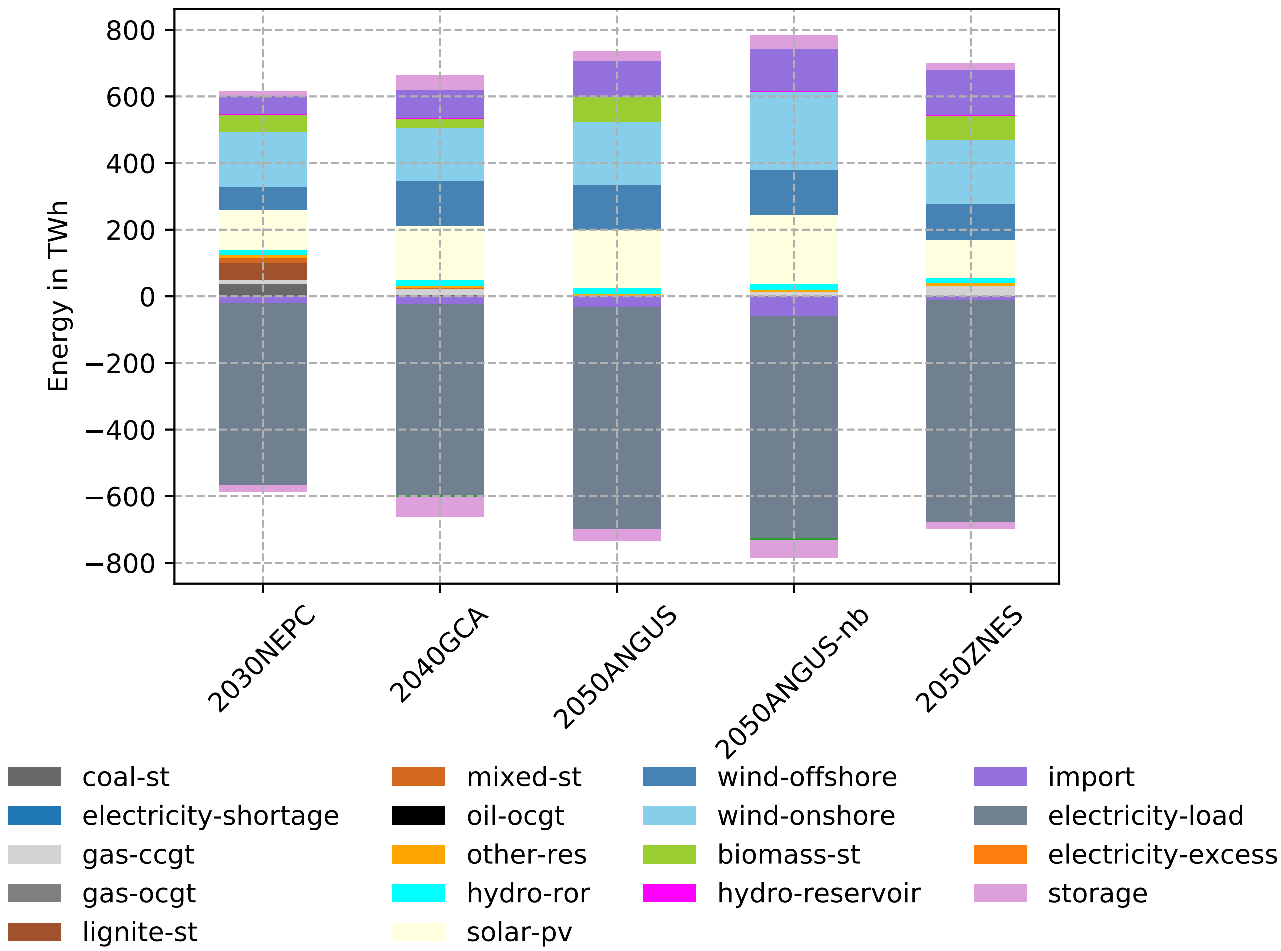

Figure 4: Energy supply and demand for all scenarios. Storage capacities have been aggregated.

Hydro data

country	year	rsv	phs	ror	ror-share	phs-max-hours	rsv-max-hours
AT	2030	4787.52	6055.33	4671.9	0.493889	33	857
AT	2040	4787.52	6055.33	4671.9	0.493889	33	857
AT	2050	5676	10733	7401.16	0.565961	33	857
BE	2030	158	1150	117	0.425455	4	500
BE	2040	158	1908	117	0.425455	4	500
BE	2050	0	2308	331.972	1	4	500
CH	2030	8987	4593	4139	0.315328	136	906
CH	2040	8987	6722	4139	0.315328	136	906
CH	2050	8130	5443	4122.7	0.336473	136	906
CZ	2030	50	1000	365	0.879518	5	1111
CZ	2040	50	1145	365	0.879518	5	1111
CZ	2050	819	1787	454.846	0.357065	5	1111
DE	2030	995.9	9791.6	4329	0.812973	6	592
DE	2040	620	10244	4329	0.874722	6	592
DE	2050	620	12799	4233	0.872244	6	592
DK	2030	0	0	6.6082	1	6	
DK	2040	0	0	6.6082	1	6	
DK	2050	0	0	13.3102	1	6	
FR	2030	8197	5500	13797	0.627307	15	1201
FR	2040	8000	5500	13600	0.62963	15	1201
FR	2050	18200	13420	10318.6	0.36182	15	1201
LU	2030	284	1026	34	0.106918	4	2840
LU	2040	284	1026	34	0.106918	4	2840
LU	2050	0	1650.68	149.203	1	4	2840
NL	2030	0	0	38	1	6	
NL	2040	0	2500	38	1	6	
NL	2050	0	0	104.435	1	6	
NO	2030	34702.2	1114.71	0	0	314	3139
NO	2040	34702.2	1114.71	0	0	314	3139
NO	2050	42473	17291	28141	0.398518	314	3139
PL	2030	0	1488	1033	1	5	5477
PL	2040	0	2292	1033	1	5	5477
PL	2050	0	3790	2078.8	1	5	5477
SE	2030	16184	0	0	0	793	3456
SE	2040	16184	0	0	0	793	3456
SE	2050	21383.3	0	10775.2	0.335066	793	3456

Carrier cost

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

Technical parameters

year	parameter	carrier	tech	value	unit	source
2030	capex	gas	ccgt	800	Euro/kW	DIW
2030	capex	gas	ocgt	400	Euro/kW	DIW
2030	capex	lithium	battery	785	Euro/kW	IWES
2030	capex	solar	pv	600	Euro/kW	DIW
2030	capex	wind	offshore	2506	Euro/kW	DIW
2030	capex	wind	onshore	1182	Euro/kW	DIW
2030	efficiency	biomass	st	0.35	per unit	DIW
2030	efficiency	cavern	acaes	0.7	per unit	roundtrip;ZNES
2030	efficiency	coal	st	0.4	per unit	TYNDP2018
2030	efficiency	gas	ccgt	0.5	per unit	TYNDP2018
2030	efficiency	gas	ocgt	0.38	per unit	TYNDP2018
2030	efficiency	hydro	phs	0.75	per unit	roundtrip; DIW
2030	efficiency	hydro	ror	0.9	per unit	DIW
2030	efficiency	hydro	rsv	0.9	per unit	DIW
2030	efficiency	hydrogen	storage	0.4	per unit	roundtrip;ZNES
2030	efficiency	lignite	st	0.4	per unit	TYNDP2018
2030	efficiency	lithium	battery	0.85	per unit	roundtrip;Own assumption
2030	efficiency	mixed	st	0.26	per unit	Own assumption
2030	efficiency	oil	ocgt	0.35	per unit	TYNDP2018
2030	efficiency	uranium	st	0.33	per unit	TYNDP2018
2030	efficiency	waste	st	0.26	per unit	Own assumption
2030	max_hours	cavern	acaes	3	h	ZNES
2030	max_hours	hydro	phs	8	h	Plessmann
2030	max_hours	hydrogen	storage	168	h	eGo
2030	max_hours	lithium	battery	6.5	h	Plessmann
2030	max_hours	porous	acaes	300	h	Own assumption
2040	efficiency	biomass	st	0.4185	per unit	Own assumption
2040	efficiency	cavern	acaes	0.7	per unit	roundtrip; ZNES
2040	efficiency	coal	st	0.425	per unit	Own assumption
2040	efficiency	gas	ccgt	0.53475	per unit	Own assumption
2040	efficiency	gas	ocgt	0.373	per unit	Own assumption
2040	efficiency	hydro	phs	0.75	per unit	roundtrip; DIW
2040	efficiency	hydro	ror	0.9	per unit	DIW
2040	efficiency	hydro	rsv	0.9	per unit	DIW
2040	efficiency	hydrogen	storage	0.4	per unit	roundtrip;ZNES
2040	efficiency	lignite	st	0.4	per unit	Own assumption
2040	efficiency	lithium	battery	0.885	per unit	Own assumption
2040	efficiency	mixed	st	0.28	per unit	Own assumption
2040	efficiency	oil	ocgt	0.373	per unit	Own assumption
2040	efficiency	porous	acaes	0.57	per unit	roundtrip; Own assumption
2040	efficiency	uranium	st	0.335	per unit	Own assumption
2040	efficiency	waste	st	0.26	per unit	Own assumption
2040	max_hours	cavern	acaes	3	h	ZNES
2040	max_hours	hydro	phs	8	h	Plessmann
2040	max_hours	hydrogen	storage	168	h	eGo
2040	max_hours	lithium	battery	6.5	h	Plessmann
2040	max_hours	porous	acaes	300	h	Own assumption
2050	avf	biomass	st	0.9	per unit	Own assumption
2050	avf	coal	st	0.85	per unit	PRIMES
2050	avf	gas	ccgt	0.85	per unit	PRIMES
2050	avf	gas	ocgt	0.96	per unit	PRIMES
2050	avf	hydro	phs	1	per unit	Own assumption
2050	avf	hydro	ror	1	per unit	Own assumption

year	parameter	carrier	tech	value	unit	source
2050	avf	hydro	rsv	1	per unit	Own assumption
2050	avf	lignite	st	0.85	per unit	PRIMES
2050	avf	lithium	battery	1	per unit	Own assumption
2050	avf	mixed	st	0.9	per unit	Own assumption
2050	avf	oil	ocgt	0.9	per unit	PRIMES
2050	avf	porous	acaes	1	per unit	Own assumption
2050	avf	solar	pv	1	per unit	Own assumption
2050	avf	uranium	st	0.9	per unit	Own assumption
2050	avf	waste	st	0.9	per unit	Own assumption
2050	avf	wind	offshore	1	per unit	Own assumption
2050	avf	wind	onshore	1	per unit	Own assumption
2050	capex	biomass	st	1951	Euro/kW	DIW, p. 75
2050	capex	coal	st	1300	Euro/kW	DIW, p. 75
2050	capex	gas	ccgt	800	Euro/kW	DIW, p. 75
2050	capex	gas	ocgt	400	Euro/kW	DIW, p. 75
2050	capex	hydro	phs	2000	Euro/kW	DIW, p. 75
2050	capex	hydro	ror	3000	Euro/kW	DIW, p. 75
2050	capex	hydro	rsv	2000	Euro/kW	DIW, p. 75
2050	capex	lignite	st	1500	Euro/kW	DIW, p. 75
2050	capex	oil	ocgt	400	Euro/kW	DIW, p. 75
2050	capex	solar	pv	425	Euro/kW	DIW, p. 75
2050	capex	wind	offshore	2093	Euro/kW	DIW, p. 75
2050	capex	wind	onshore	1075	Euro/kW	DIW, p. 75
2050	capex_energy	cavern	acaes	40	Euro/kWh	Schill2018
2050	capex_energy	hydrogen	storage	0.2	Euro/kWh	Schill2018
2050	capex_energy	lithium	battery	187	Euro/kWh	Schill2018
2050	capex_energy	redox	battery	70	Euro/kWh	Schill2018
2050	capex_power	cavern	acaes	750	Euro/kW	Schill2018
2050	capex_power	hydrogen	storage	1000	Euro/kW	Schill2018
2050	capex_power	lithium	battery	35	Euro/kWh	Schill2018
2050	capex_power	redox	battery	600	Euro/kW	Schill2018
2050	efficiency	biomass	st	0.487	per unit	DIW
2050	efficiency	cavern	acaes	0.7	per unit	roundtrip;ZNES
2050	efficiency	coal	st	0.45	per unit	DIW
2050	efficiency	gas	ccgt	0.5695	per unit	Avg; DIW
2050	efficiency	gas	ocgt	0.366	per unit	Avg; DIW
2050	efficiency	hydro	phs	0.75	per unit	roundtrip; DIW
2050	efficiency	hydro	ror	0.9	per unit	DIW
2050	efficiency	hydro	rsv	0.9	per unit	DIW
2050	efficiency	hydrogen	storage	0.4	per unit	roundtrip;ZNES
2050	efficiency	lignite	st	0.4	per unit	Avg; DIW
2050	efficiency	lithium	battery	0.92	per unit	roundtrip; IWES
2050	efficiency	mixed	st	0.3	per unit	Own assumption
2050	efficiency	oil	ocgt	0.396	per unit	DIW
2050	efficiency	porous	acaes	0.57	per unit	roundtrip; Own assumption
2050	efficiency	redox	battery	0.75	per unit	roundtrip;ZNES
2050	efficiency	uranium	st	0.34	per unit	DIW
2050	efficiency	waste	st	0.26	per unit	Own assumption
2050	fom	biomass	st	100	Euro/kWa	DIW, p.78
2050	fom	cavern	acaes	10	Euro/kWha	Schill2018
2050	fom	coal	st	25	Euro/kWa	DIW, p.78
2050	fom	gas	ccgt	20	Euro/kWa	DIW, p.78
2050	fom	gas	ocgt	15	Euro/kWa	DIW, p.78
2050	fom	hydro	phs	20	Euro/kWa	DIW, p.78
2050	fom	hydro	ror	60	Euro/kWa	DIW, p.78

year	parameter	carrier	tech	value	unit	source
2050	fom	hydro	rsv	20	Euro/kWa	DIW, p.78
2050	fom	hydrogen	storage	10	Euro/kWha	Schill2018
2050	fom	lignite	st	30	Euro/kWa	DIW, p.78
2050	fom	lithium	battery	10	Euro/kWha	Schill2018
2050	fom	oil	ocgt	6	Euro/kWa	DIW, p.78
2050	fom	redox	battery	10	Euro/kWha	Schill2018
2050	fom	solar	pv	25	Euro/kWa	DIW, p.78
2050	fom	wind	offshore	80	Euro/kWa	DIW, p.78
2050	fom	wind	onshore	35	Euro/kWa	DIW, p.78
2050	lifetime	biomass	st	30	a	DIW, p. 72
2050	lifetime	cavern	acaes	30	a	Schill2018
2050	lifetime	coal	st	40	a	DIW, p. 72
2050	lifetime	gas	ccgt	30	a	DIW, p. 72
2050	lifetime	gas	ocgt	30	a	DIW, p. 72
2050	lifetime	hydro	phs	50	a	DIW, p. 72
2050	lifetime	hydro	ror	50	a	DIW, p. 72
2050	lifetime	hydro	rsv	50	a	DIW, p. 72
2050	lifetime	hydrogen	storage	22.5	a	Schill2018
2050	lifetime	lignite	st	40	a	DIW, p. 72
2050	lifetime	lithium	battery	10	a	Plessmann, p. 90
2050	lifetime	oil	ocgt	40	a	DIW, p. 72
2050	lifetime	redox	battery	25	a	Schill2018
2050	lifetime	solar	pv	25	a	DIW, p. 72
2050	lifetime	wind	offshore	25	a	DIW, p. 72
2050	lifetime	wind	onshore	25	a	DIW, p. 72
2050	max_hours	cavern	acaes	3	h	ZNES
2050	max_hours	hydro	phs	8	h	Plessmann, p. 90
2050	max_hours	hydrogen	storage	168	h	eGo
2050	max_hours	lithium	battery	6.5	h	Plessmann, p. 90
2050	max_hours	porous	acaes	300	h	Own assumption
2050	max_hours	redox	battery	3.3	h	ZNES
2050	vom	biomass	st	10	Euro/Mwh	Own assumption
2050	vom	cavern	acaes	1	Euro/Mwh	Schill2018
2050	vom	coal	st	6	Euro/Mwh	DIW, p. 78
2050	vom	gas	ccgt	4	Euro/Mwh	DIW, p. 78
2050	vom	gas	ocgt	3	Euro/Mwh	DIW, p. 78
2050	vom	hydro	phs	0	Euro/Mwh	DIW, p. 78
2050	vom	hydro	ror	0	Euro/Mwh	DIW, p. 78
2050	vom	hydro	rsv	0	Euro/Mwh	DIW, p. 78
2050	vom	hydrogen	storage	1	Euro/Mwh	Schill2018
2050	vom	lignite	st	7	Euro/Mwh	DIW, p. 78
2050	vom	lithium	battery	0	Euro/Mwh	Plessmann, p. 90
2050	vom	mixed	st	5	Euro/Mwh	Own assumption
2050	vom	oil	ocgt	3	Euro/Mwh	DIW, p. 78
2050	vom	redox	battery	1	Euro/Mwh	Schill2018
2050	vom	solar	pv	0	Euro/Mwh	Plessmann
2050	vom	uranium	st	8.5	Euro/Mwh	DIW, p. 78, AVG
2050	vom	waste	st	10	Euro/Mwh	Own assumption
2050	vom	wind	offshore	0	Euro/Mwh	Plessmann
2050	vom	wind	onshore	0	Euro/Mwh	Plessmann

Installed capacities

The table show the installed capacities for path towards 100% renewable energy supply fomr 2030 to 2050.

scenario	name	AT	BE	CH	CZ	DE	DK	FR	LU	NL	NO	PL	SE
2030NEPC	biomass-st	0.6	1.3	1.3	1.2	6.0	1.9	3.6	0.1	0.5	0.1	1.8	4.5
2030NEPC	lithium-battery	-	-	-	-	12.5	-	-	-	-	-	-	-
2030NEPC	hydrogen-storage	-	-	-	-	3.0	-	-	-	-	-	-	-
2030NEPC	wind-offshore	-	2.3	-	-	17.0	2.9	7.0	-	11.5	-	2.2	0.2
2030NEPC	hydro-phs	6.1	1.2	4.6	1.0	9.8	-	5.5	1.0	-	1.1	1.5	-
2030NEPC	mixed-st	1.0	1.2	1.0	1.5	4.1	0.1	-	0.1	3.5	-	7.3	0.4
2030NEPC	gas-ocgt	1.4	2.2	-	0.5	10.0	0.1	3.9	-	2.6	0.1	2.0	-
2030NEPC	lignite-st	-	-	-	4.8	9.0	-	-	-	-	-	7.4	-
2030NEPC	gas-ccgt	2.7	4.2	-	0.9	23.4	0.3	7.6	-	5.0	0.3	3.8	-
2030NEPC	wind-onshore	5.0	3.3	0.4	1.0	85.5	5.6	36.3	0.2	6.7	3.3	9.2	10.8
2030NEPC	uranium-st	-	-	1.2	4.1	-	-	37.6	-	0.5	-	3.0	6.9
2030NEPC	oil-ocgt	0.2	-	-	-	0.9	0.8	1.5	-	-	-	-	-
2030NEPC	coal-st	-	-	-	0.3	8.1	0.4	-	-	4.6	-	13.8	0.1
2030NEPC	solar-pv	4.5	5.1	5.6	3.5	104.5	2.9	31.5	0.2	11.4	0.4	2.4	1.7
2030NEPC	other-res	-	-	-	-	1.3	-	-	-	-	-	-	-
2030NEPC	cavern-acaes	-	-	-	-	1.0	-	-	-	-	-	-	-
2040GCA	gas-ccgt	2.0	3.3	-	0.7	10.4	-	5.9	-	5.0	-	1.8	-
2040GCA	wind-offshore	-	8.3	-	-	33.5	7.8	20.0	-	23.4	0.4	7.0	1.3
2040GCA	biomass-st	0.6	1.3	1.3	1.2	6.0	1.9	3.6	0.1	0.5	0.1	1.8	4.3
2040GCA	solar-pv	5.6	22.0	12.6	5.2	141.0	7.5	60.0	1.1	46.0	3.0	42.5	6.7
2040GCA	hydrogen-storage	-	-	-	-	5.0	-	-	-	-	-	-	-
2040GCA	lithium-battery	-	-	-	-	12.5	-	-	-	-	-	-	-
2040GCA	wind-onshore	5.5	7.7	2.6	1.3	81.6	7.2	49.0	0.2	7.4	10.0	32.9	17.4
2040GCA	coal-st	-	-	-	0.3	8.3	-	-	-	3.4	-	8.3	-
2040GCA	hydro-phs	6.1	1.9	6.7	1.1	10.2	-	5.5	1.0	2.5	1.1	2.3	-
2040GCA	gas-ocgt	1.0	1.7	-	0.3	20.1	-	3.0	-	2.6	-	0.9	-
2040GCA	cavern-acaes	-	-	-	-	2.0	-	-	-	-	-	-	-
2040GCA	uranium-st	-	-	-	3.3	-	-	37.6	-	-	-	7.5	3.7
2040GCA	other-res	-	-	-	-	1.3	-	-	-	-	-	-	-
2040GCA	oil-ocgt	0.2	-	-	0.2	0.2	0.3	1.0	-	-	-	3.9	-
2040GCA	mixed-st	1.0	1.7	1.0	1.5	10.3	0.1	-	0.1	3.5	-	7.3	0.4
2040GCA	lignite-st	-	-	-	1.3	-	-	-	-	-	-	1.9	-
2050ANGUS	other-res	-	-	-	-	1.3	-	-	-	-	-	-	-
2050ANGUS	mixed-st	-	-	-	-	-	-	-	-	-	-	-	-
2050ANGUS	redox-battery	-	-	-	-	-	0.1	0.1	-	-	-	-	-
2050ANGUS	lithium-battery	0.2	0.3	0.3	2.5	15.6	0.9	3.4	0.1	1.3	-	4.5	3.2
2050ANGUS	oil-ocgt	-	-	-	-	-	-	-	-	-	-	-	-
2050ANGUS	hydrogen-storage	-	1.8	-	0.2	10.1	5.0	26.0	0.6	7.6	-	0.3	-
2050ANGUS	gas-ccgt	1.0	1.6	1.3	1.2	8.6	0.7	10.6	0.2	2.0	-	2.0	-
2050ANGUS	biomass-st	3.5	4.8	1.2	5.0	27.8	3.8	28.2	-	4.0	0.5	14.2	5.5
2050ANGUS	wind-onshore	6.9	10.9	1.4	10.2	98.3	18.7	124.2	0.7	15.0	12.2	81.9	24.2
2050ANGUS	cavern-acaes	-	0.4	-	0.9	3.4	0.2	0.2	0.1	1.7	-	1.7	-
2050ANGUS	coal-st	-	-	-	-	-	-	-	-	-	-	-	-
2050ANGUS	lignite-st	-	-	-	-	-	-	-	-	-	-	-	-
2050ANGUS	gas-ocgt	0.5	0.8	0.7	0.6	4.4	0.3	5.4	0.1	1.0	-	1.0	-
2050ANGUS	solar-pv	12.1	24.1	15.0	13.0	150.0	2.0	103.1	1.0	22.2	5.4	24.2	8.9
2050ANGUS	hydro-phs	10.7	2.3	5.4	1.8	12.8	-	13.4	1.7	-	17.3	3.8	-
2050ANGUS	wind-offshore	-	3.0	-	-	33.8	25.6	-	-	15.9	3.0	-	3.0
2050ZNES	solar-pv	12.1	24.1	15.0	13.0	98.6	2.0	103.1	1.0	22.2	5.4	24.2	8.9
2050ZNES	wind-offshore	-	3.0	-	-	27.2	25.6	-	-	15.9	3.0	-	3.0
2050ZNES	lignite-st	-	-	-	-	-	-	-	-	-	-	-	-

scenario	name	AT	BE	CH	CZ	DE	DK	FR	LU	NL	NO	PL	SE
2050ZNES	other-res	-	-	-	-	1.3	-	-	-	-	-	-	-
2050ZNES	oil-ocgt	-	-	-	-	-	-	-	-	-	-	-	-
2050ZNES	mixed-st	-	-	-	-	-	-	-	-	-	-	-	-
2050ZNES	lithium-battery	0.2	0.3	0.3	2.5	15.6	0.9	3.4	0.1	1.3	-	4.5	3.2
2050ZNES	hydrogen-storage	-	1.8	-	0.2	10.1	5.0	26.0	0.6	7.6	-	0.3	-
2050ZNES	hydro-phs	10.7	2.3	5.4	1.8	12.8	-	13.4	1.7	-	17.3	3.8	-
2050ZNES	gas-ocgt	0.5	0.8	0.7	0.6	4.4	0.3	5.4	0.1	1.0	-	1.0	-
2050ZNES	gas-ccgt	1.0	1.6	1.3	1.2	8.6	0.7	10.6	0.2	2.0	-	2.0	-
2050ZNES	coal-st	-	-	-	-	-	-	-	-	-	-	-	-
2050ZNES	cavern-acaes	-	0.4	-	0.9	3.4	0.2	0.2	0.1	1.7	-	1.7	-
2050ZNES	biomass-st	3.5	4.8	1.2	5.0	27.8	3.8	28.2	-	4.0	0.5	14.2	5.5
2050ZNES	redox-battery	-	-	-	-	-	0.1	0.1	-	-	-	-	-
2050ZNES	wind-onshore	6.9	10.9	1.4	10.2	98.3	18.7	124.2	0.7	15.0	12.2	81.9	24.2

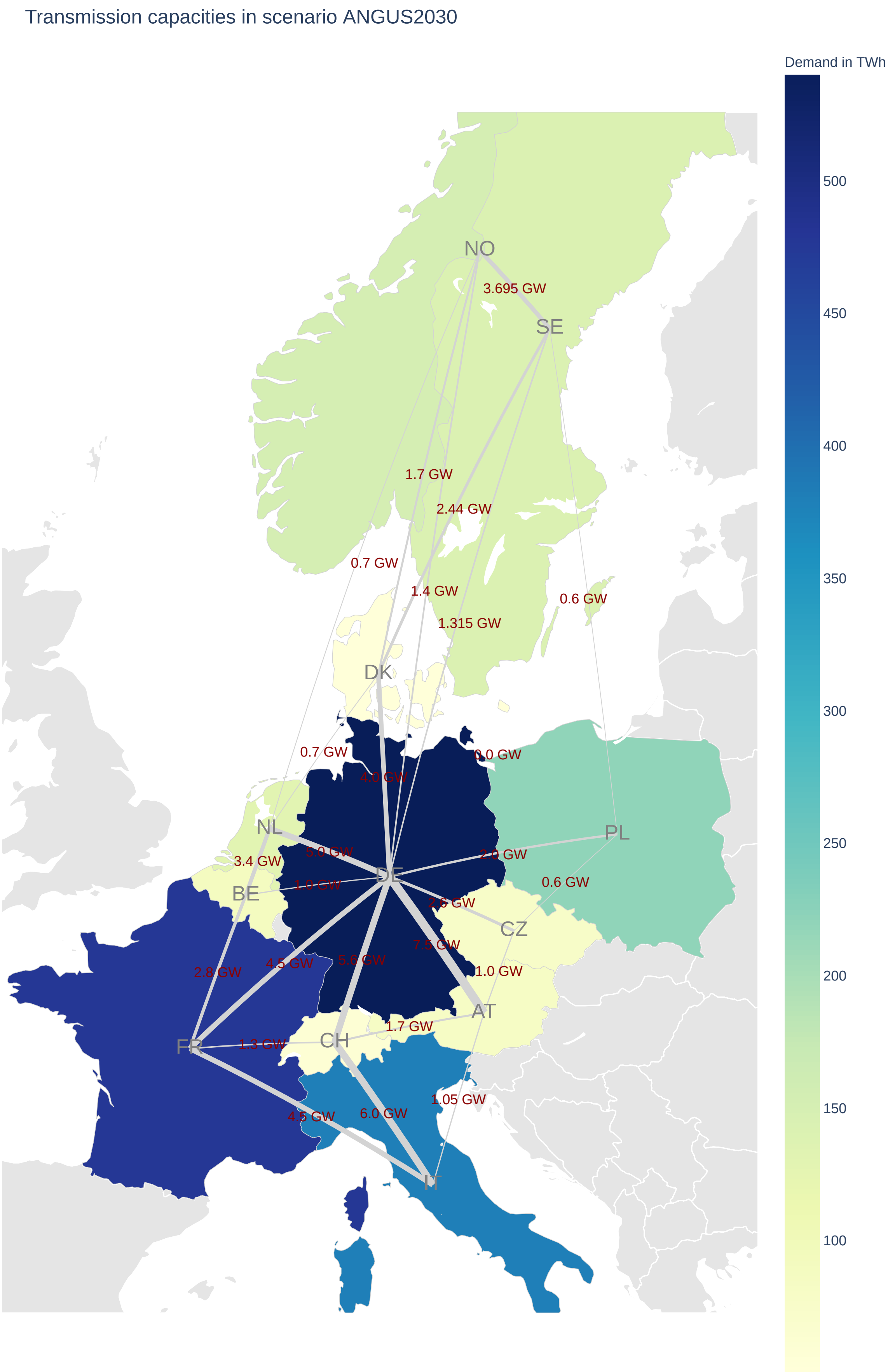

Figure 5: Installed transmission capacities in 2030

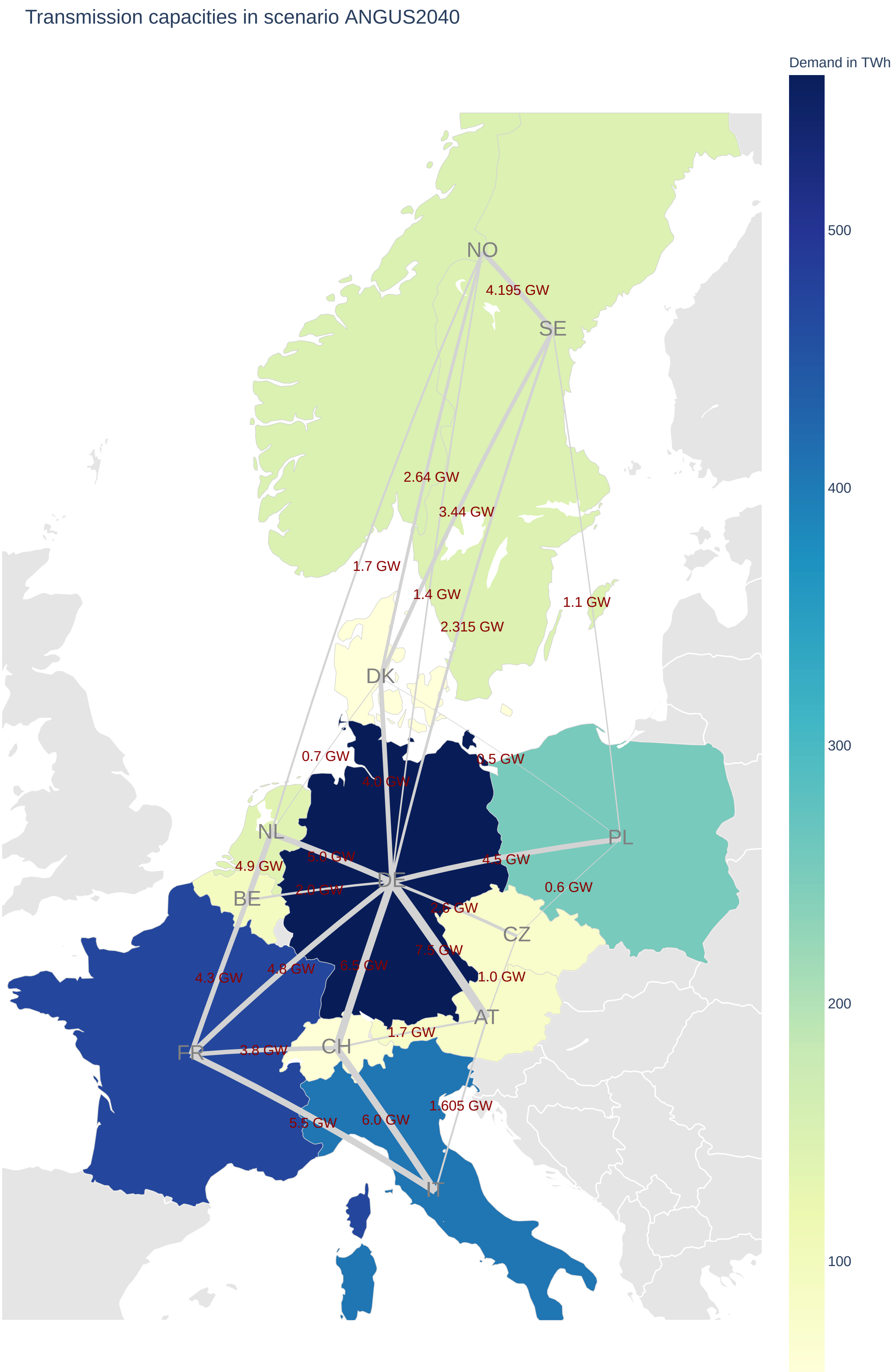

Figure 6: Installed transmission capacities in 2040

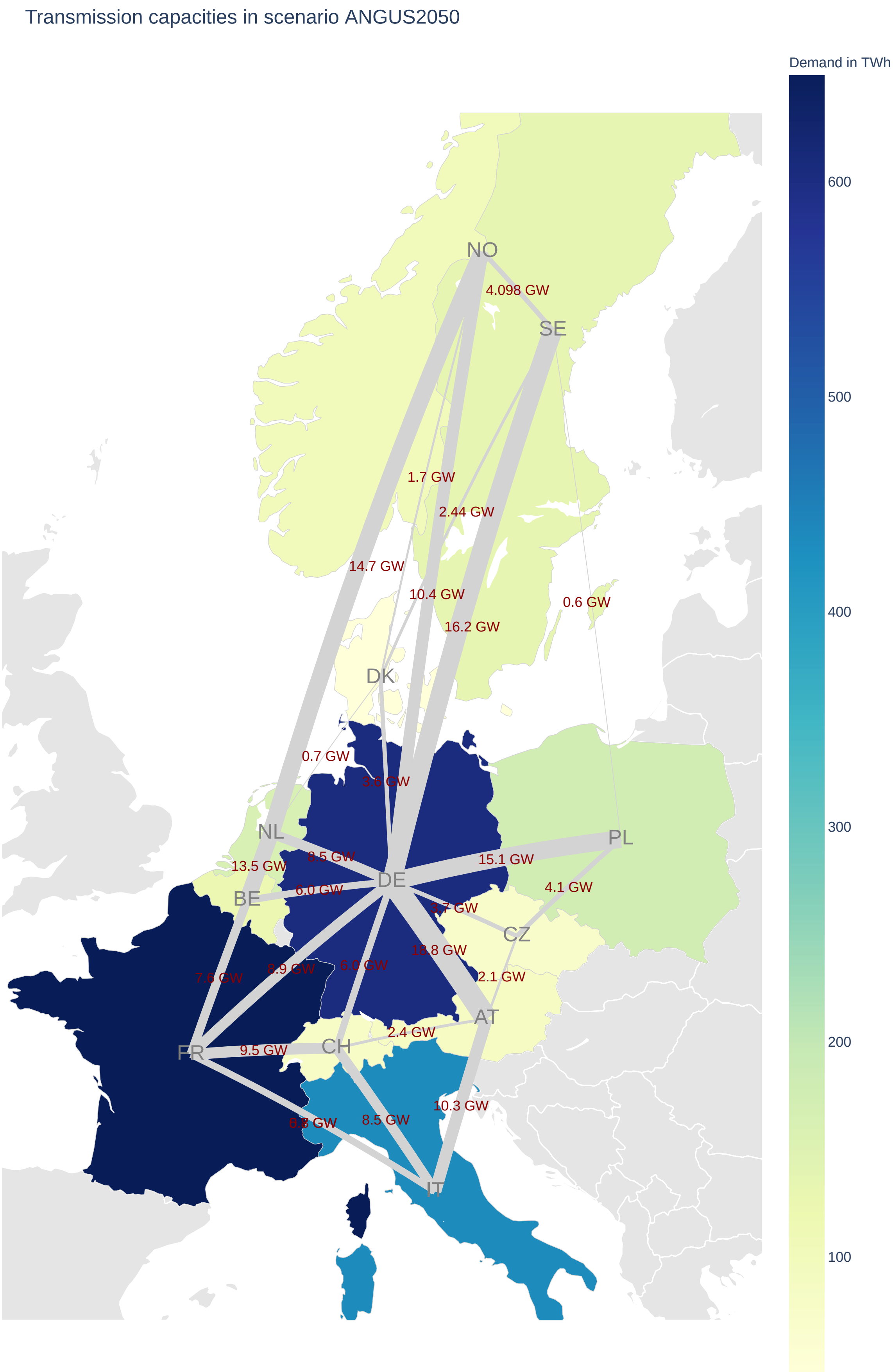

Figure 7: Installed transmission capacities in 2050

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

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