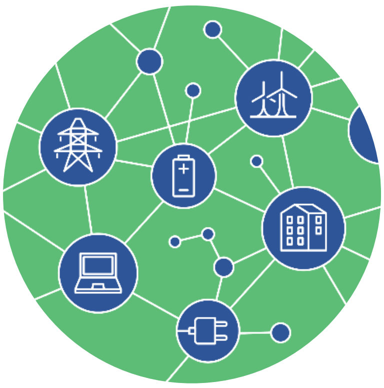
OSMOSE

OPTIMAL SYSTEM-MIX OF FLEXIBILITY SOLUTIONS FOR EUROPEAN ELECTRICITY

European Long-Term Scenarios Description

D1.1



Contact: www.osmose-h2020.eu

The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773406

Document properties

Project Information

Programme	**O**ptimal **S**ystem-**M**ix **O**f Flexibility **S**olutions For **E**uropean Electricity
Project acronym	OSMOSE
Grant agreement number	773406
Number of the Deliverable	D1.1
WP/Task related	WP1/Task 1.1.1

Document information

Document Name	Report: European Long-Term Scenarios Description
Date of delivery	May 17, 2019
Status and Version	Final, v1.0
Number of pages	33

Responsible

Document Responsible	Jens Weibezahn
Author(s)	Leonard Göke (TUB), Jens Weibezahn (TUB)
Reviewer(s)	Luca Orrù (TERNA)
Approver	Nathalie Grisey (RTE)

Dissemination Level

Type (distribution level)	☒ PU, Public ☐ CO – full consortium, Confidential, only for members of the consortium (including the Commission Services) ☐ CO – some partners, Confidential, only for some partners (list of partners to be defined)

Review History

Version	Date	Reviewer	Comment
V0.1	31.03.2019		Initial Version
V0.2	26.04.2019		Update after Review
V0.3	30.04.2019		Update after Review
V1.0	17.05.2019		Final Version

Table of content

List of figures

List of tables

0 Executive summary

This report maps out the long-term development of the European power system and aims to provide a basis for subsequent studies on the arising need for flexibility in the OSMOSE project. For this purpose, three scenarios named “Current Goals Achieved” (CGA), “Accelerated Transformation” (AT), and “Neglected Climate Action” (NCA) are introduced. Model calculations determine, for each scenario, the development of the overall energy system and, in greater detail, that of power system supply and demand.

The three scenarios differ in terms of what climate protection efforts are successfully undertaken within the EU. In practical terms, varying levels of final energy demand and carbon emissions are set. Reducing carbon emissions implies shifting the supply of electricity, heat, and mobility from fossil fuels (coal, gas, oil, ...) to renewables (wind, solar, biomass, ...). With the exception of biomass, where the sustainable potential is limited, renewable energies cannot directly substitute fossil fuels in the heat and mobility sectors. Therefore, heat pumps, synthetic fuels, electric vehicles, or any other technology that allow the use of renewable electricity in these sectors will result in a growing electricity demand. As a result, the power system, at the centre of this process, is increasingly shaped by the heat and mobility sectors.

To reflect these interdependencies within the calculation process, first each scenario’s energy system is modelled. Then, results from the energy system model, such as total electricity demand, serve as inputs to a more detailed power system model. In contrast to existing scenarios, this top-down methodology allows a high-resolution analysis of the power system while also capturing its interaction with other sectors of the energy system, especially with respect to final electricity demand.

Results show that both electricity total demand and load profile greatly depend on decarbonisation efforts taken in the heat and mobility sectors. The same applies to the supply side. For example, investment in seasonal storage systems in the power system (e.g. Power-to-Gas) is highly dependent on demand from electric heating appliances.

1 List of acronyms and abbreviations

You can find in the table below the list of the acronyms and abbreviations used in this document.

Acronym	Meaning
AA-CAES	advanced adiabatic compressed air energy storage
AT	Scenario “Accelerated Transformation”
CCS	carbon capture and storage
CGA	Scenario “Climate Goals Achieved”
CHP	combined heat and power
DSM	demand side management
GHG	greenhouse gases
NCA	Scenario “Neglected Climate Action”
TYNDP	Ten-Year Network Development Plan
PTDF	power transfer distribution factors
OPSD	Open Power System Data

2 Introduction

The OSMOSE project aims to investigate the need for flexibility and how it can be covered in a future energy system characterized by high shares of variable renewables and low carbon emissions. Flexibility can generally be defined as a power system's ability to cope with variability and uncertainty in demand and generation.

Power generation from variable renewables is only predictable to a certain extent and cannot be dispatched freely: operators can curtail generation, but not increase it (with the exception of biomass). These characteristics create a need for different temporal kinds of flexibility within the energy system. The need for long-term flexibility is largely independent from forecasts and forecast errors (See Figure 1. It is due to fundamental mismatches between demand and renewable supply patterns. Solar power generation during the summer and winter peak load is an example of such a mismatch. Over the medium term (from hours to weeks), dispatchable generators adjust to forecasts in advance to keep deviations small in the first place. Finally, in the short term, demand/supply deviations stemming from forecast errors have to be balanced out by ancillary services almost immediately to ensure grid stability.

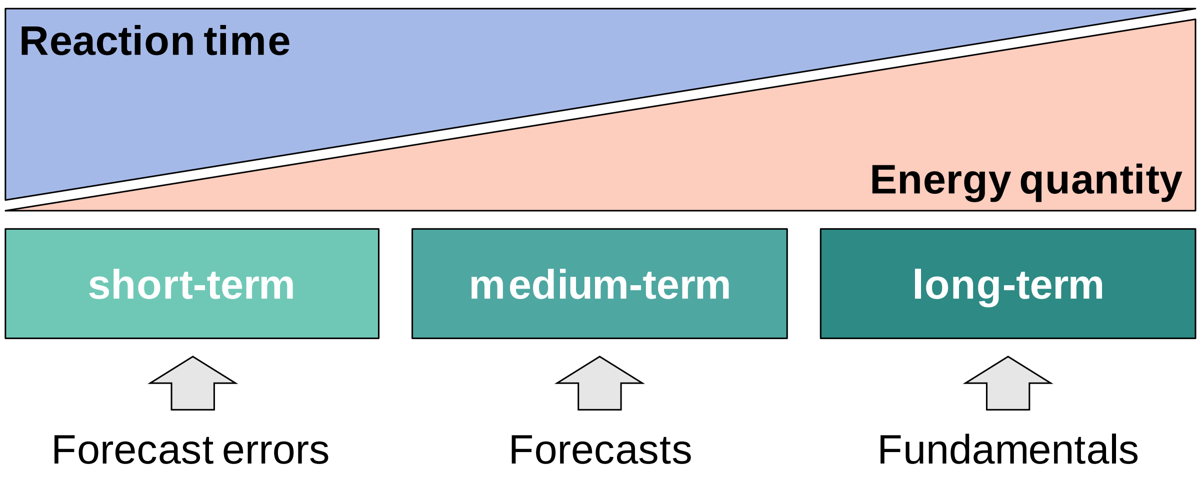


Figure 1: Typology of flexibility requirements

Future needs and sources for flexibility do not solely depend on the power system, but on developments in the heat and mobility sector. Since the sustainable potential of biomass is limited, there are few renewable energy sources available to use directly in these sectors. Consequently, decarbonization in the heat and mobility sector implies increasing reliance on renewable electricity as an energy carrier. This can be achieved by either converting electricity into synthetic fuels or direct use of electricity in electric cars or heat pumps. However, both options result in major sectoral interdependencies and, thus, the integration of the energy system. Scenarios in this report aim to quantify the conceivable range of needs and sources for flexibility arising from these interdependencies. This will enable follow-up studies on investigating the cost-efficient mix of flexibility in future energy systems characterized by variable renewables.

3 Scenarios

3.1 Review of existing scenarios

Scenario-building and modelling are common tools to assess future developments of the energy system. To place this report in the context of other work, as a first step pre-existing scenarios covering the European energy system are reviewed.

The European Commission published their latest EU Reference scenario in 2016. These scenarios range until 2050 and are developed to support policy design and assessment by the commission [1]. As a result, these scenarios are *“not designed as a forecast of what is likely to happen in the future”,* but as a *“benchmark against which new policy proposals can be assessed”* [2]. For example, the baseline for the 27% energy efficiency target of the European Union is based on a reference scenario from 2007 [3]. Nevertheless, these scenarios also tend to be applied within other research to represent the future development of the energy system, presumably due to their high recognition and extensive documentation of results [4]. The European Commission also provides scenarios that comply with current or even more ambitious climate and environmental targets, but these are limited to the time span of 2030. All scenarios provided by the European Commission and discussed above rely at their core on the energy system model PRIMES. This model closely captures demand for energy services across Europe and how this demand is covered with great sectoral and technological detail on a country level [5].

Other well-known scenarios are included in ENTSO-Es biennial Ten-Year Network Development Plan (TYNDP), which is used to evaluate grid expansion over the next ten years. Since this purpose is very different from providing a benchmark for energy policy, methodology and scope of these scenario greatly differ from the scenarios provided by the European Commission. Most importantly, scenarios are much more focussed on the power system rather than the entire energy system. Consequently, final electricity demand is exogenously assumed instead of endogenously computed as in PRIMES, but the power grid is modelled in greater detail, also below the country-level. Scenarios explicitly aim to capture the conceivable range of future developments and, as the name suggests, mostly cover the next ten years. The most recent TYNDP also includes scenarios until 2040. Scenarios until 2030 have a bottom-up approach, which means installed generation capacities are based on TSOs assumptions, even if this leads to results which are inconsistent with European energy policy goals. Only scenarios for 2040 (and one scenario for 2030) are orientated towards long-term policy goals and installed generation capacities on a country level are computed in accordance [6, 7, 7].

Scenarios created within the E-Highways2050 project extend scenarios from the TYNDP 2016 until 2050 using a top-down approach [8]. For each scenario, demand for electricity and deployment of generation technologies are exogenously assumed and then distributed across countries and later below country level. Within this process, the application of power system models is limited to ensuring the technical feasibility (or system adequacy) of results or ensuring the installed capacities comply with a predefined generation mix. Consequently, within this methodology GHG emissions are not an input, but a result.

The scope of the OSMOSE project requires scenarios that capture the conceivable range of future developments within the whole energy system, because otherwise the impact of decarbonization in the heat and mobility sector on flexibility needs and potential sources cannot be investigated. Of the above mentioned, only the methodology of the European Commission scenarios meets these criteria. Unfortunately, these scenarios either explicitly chose not to model likely future developments or only cover the time span until 2030. Furthermore, the level of reported detail is insufficient for the purpose of this project.

3.2 Scenarios selection

The goal of the OSMOSE project is to study the optimal mix of flexibility for the European electricity system. Given all the uncertainties related to such prospective work, a scenario approach has been chosen to catch different possible futures of the power system.

The key driver identified is the total carbon emissions within the EU. These will greatly impact the power sector in two ways:

- The generation portfolio: different emission levels imply different renewable system penetrations. This impacts the need for flexibility as well as potential flexibility sources.
- The electricity demand: reducing energy sector emissions will likely imply electrification of some energy uses. This impacts the annual electricity demand as well as its profile and flexibility capability.

So, referring to the definition of “top-down” and “bottom-up” scenarios as used in ENTSO-E's TYNDP, the developed scenarios are mostly “bottom-up”: constraints relating to European policy targets are externally set; demand, generation mix and installed capacities are computed accordingly. However, scenarios also include a “top-down” element to ensure consistency with scenarios of the TYNDP and current projections of transmission grid operators in general: for 2030, lower and upper bounds on installed renewable capacities and total demand per countries are included, based on the Sustainable Transition scenario of the TYNDP 2018.

As a result, three contrasted scenarios regarding emissions are selected for future work:

- Neglected Climate Action (NCA)
- Current Goals Achieved (CGA)
- Accelerated Transformation (AT)

Other drivers could also greatly impact the future needs and sources of flexibility in Europe. One could for example think of:

- technological and cost evolution of some key technologies like batteries
- social acceptance of grid development
- social acceptance of certain generation technologies (nuclear, wind farms)
- social acceptance of demand side management
- political or social ambitions for energy self-sufficiency

These elements will be considered in further stages of the project to deepen the analysis.

3.3 Main assumptions for the scenarios

3.3.1 Emissions in the energy sector

The three scenarios *Current Goals Achieved (CGA)*, *Accelerated Transformation (AT)*, and *Neglected Climate Action (NCA)* aim to cover the range of conceivable developments in the European energy sector. The most important driver within these scenarios is the total carbon emissions within the EU, shown in Figure 2. *Current Goals Achieved* is based on the current framework that aims to comply with the 2°C target. This corresponds to a 40% reduction until 2030 and 80% until 2050 compared to 1990 levels [9]. The *Accelerated Transformation* scenario climate objectives are more ambitious, aiming for a 55% reduction by 2030 and 98% by 2050.[1] Lastly, in the *Neglected Climate Action* scenario, even current goals are not achieved. The 2030 target is missed by 5% and the 2050 one by 10%.

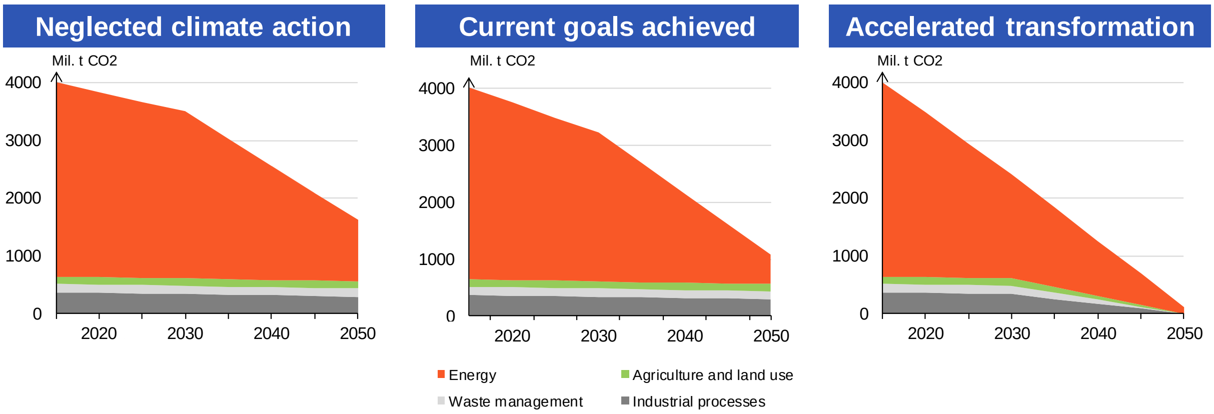


Figure 2: Emissions across scenarios

To obtain the emission limit for the energy sector, which is the only relevant sector for further calculations, emissions in agriculture, land use, waste management, and industrial processes are subtracted from the total budget. For *Neglected Climate Action* and *Current Goals Achieved,* the current trend in these sectors was extrapolated, which only leads to minor reductions by 2050. In *Accelerated Transformation*, current trends are continued until 2030 and zero emissions are assumed for 2050 [10]. Figure 3 shows cumulated emissions resulting from these assumptions, from 2015 to 2050.

[1] These numbers reflect a current resolution by the European Parliament. LINK

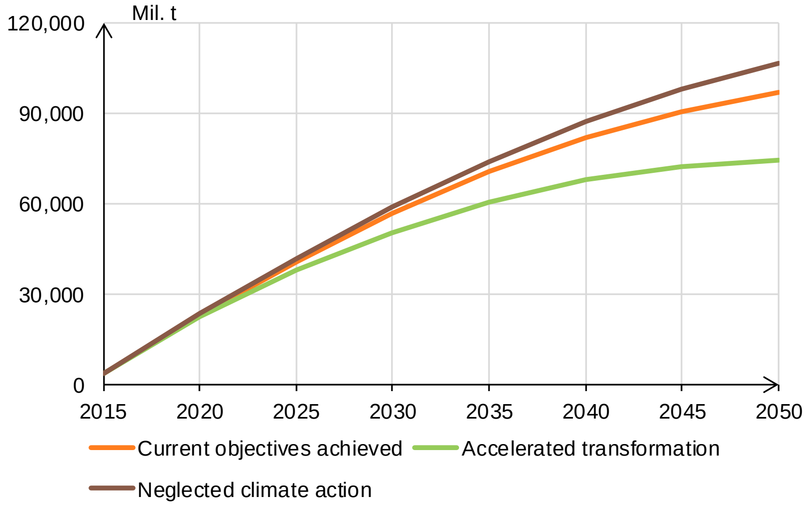


Figure 3: Total cumulative emissions across scenarios

In addition to emission limits, each scenario assumes a different date for a coal and lignite phase-out. In *Current Goals Achieved* this date is the year 2040, in *Accelerated Transformation* and *Neglected Climate Action* 2035 and 2045, respectively.

3.3.2 Final energy demand

Besides yearly emission limits, scenarios vary in terms of final energy demand. Final energy demand refers to energy services demanded by consumers and is not to be confused with primary energy demand. Primary energy demand additionally includes losses from conversion and transmission. The EU efficiency target of 27% for example refers to primary energy, which is why it is not applicable here.

Within our energy sector model, final energy is subdivided into original electricity, heat demand below 100 degrees, and heat demand above 100 degrees. Original electricity demand only includes electricity that is not used within the heat or mobility sector.[2] For example, electricity used by an electric heat pump would not qualify as original electricity, but the provided heat would qualify as final energy demand. Final energy demand for all sectors and groups across scenarios is displayed in Figure 4.

It is apparent that significant reductions in final energy demand from low temperature heat can only be achieved through enforced building insulation. Values for heat, both low and high temperature, in the *Current Goals Achieved* and *Neglected Climate Action* scenarios are based on data from the Heat Roadmap Europe project, where *Current Goals Achieved* corresponds to the Baseline scenario [11]. *Neglected Climate Action* reflects a scenario where only 50% of insulation efforts of the Baseline scenario are realized. Assumptions regarding heat demand for *Accelerated Transformation* are the same as for *Current Goals Achieved* in 2030 and 5% below for 2050.

---

[2] Consequently, electricity used for cooling is included.

Original electricity demand is assumed to be constant until 2050 in *Current Goals Achieved* and until 2030 in *Neglected Climate Action* and *Accelerated Transformation.* In these scenarios demand is assumed to increase or decreases by 5%, respectively until 2050 to create some conceivable deviations across scenarios More elaborate assumptions would require an in-depth analysis, because literature does not provide sufficient numbers on potential efficiency gains limited to the use of electricity.

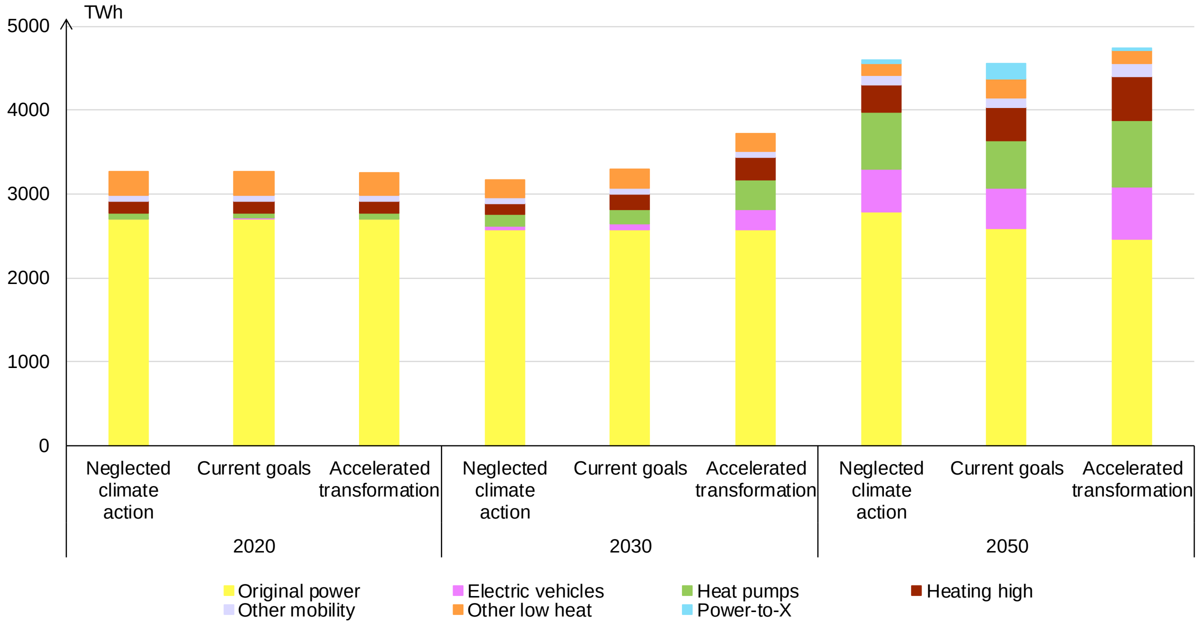


Figure 4: Final energy demand across scenarios

Mobility demand is treated analogously to final energy demand within the calculation process, but assumptions for all scenarios are the same and based on PRIMES scenarios [12]. This means demand, which is provided in passenger-kilometre for passenger transport and tonne-kilometre for freight, is subdivided by modal splits that allocate total demand to the types of transportation (see Figure 5). The model then decides on technologies to cover each type of demand, for example vehicles fuelled by oil, hydrogen, or electricity in case of passenger road transport.

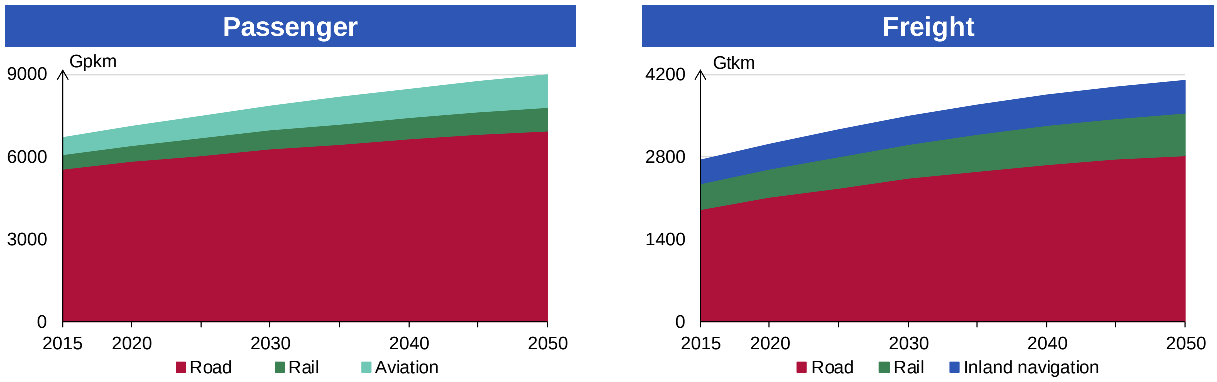


Figure 5: Transport demand by modal split [12]

3.3.3 Fuel prices

Lastly, the three considered scenarios vary in terms of fuel prices. As shown in Figure 6, fuel prices are based on the corresponding scenarios of the World Energy Outlook 2017 until 2040 and held constant afterwards [13]. In general, the impact of fuel prices on results is limited, because as soon as strict emission limits are introduced, the use of fuels is mostly determined by specific carbon emissions rather than price.

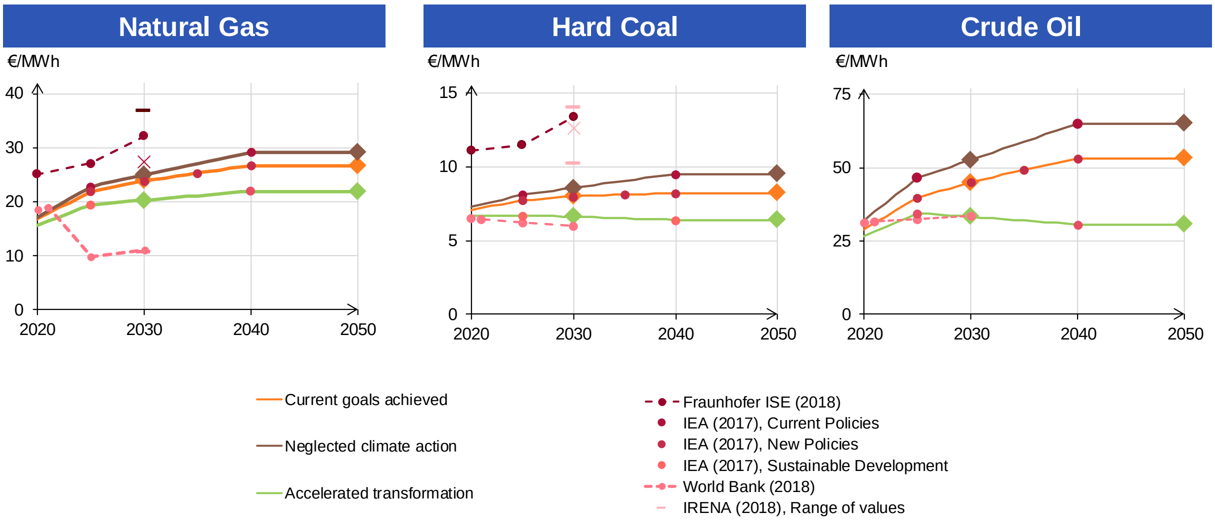


Figure 6: Fuel prices across scenarios

4 Methodology

So far, the three scenarios only provide some basic quantitative assumptions, but no comprehensive picture of the energy system and the emerging need for flexibility. The methodology to obtain these is presented next.

First, the two models applied for this purpose, an energy and an electricity system model, are briefly presented. The following paragraph describes with greater detail how these two models are linked to provide the final results. The section concludes with a discussion of the method's shortcomings and how they could be addressed by further model developments.

4.1 Energy system model

The used energy system model GENeSYS-MOD is an application of the open-source energy modelling system (OSeMOSYS) [14, 15]. It is a cost minimizing optimization problem, determining dispatch and investment decisions to cover a fixed demand for a set of consecutive years and different macro regions. The macro regions considered in this application are displayed in Figure 9.

The model can be formulated as a network flow problem. Nodes of the network correspond to technologies that either produce or convert at least one fuel. Fuels can be interpreted as edges of the network and might refer to actual fuels, but also more abstract entities like available rooftop space. The model covers final demand for electricity, heat (low temperature and high temperature) and transportation (freight and passenger, further decomposed according to

Figure 5). Low temperature heat is defined to be below 100°C and thus covers space and water heating demand, high temperature heat demand is above 100°C and dominated by industrial processes. Figure 7 provides an overview of the considered technologies and their interrelation.

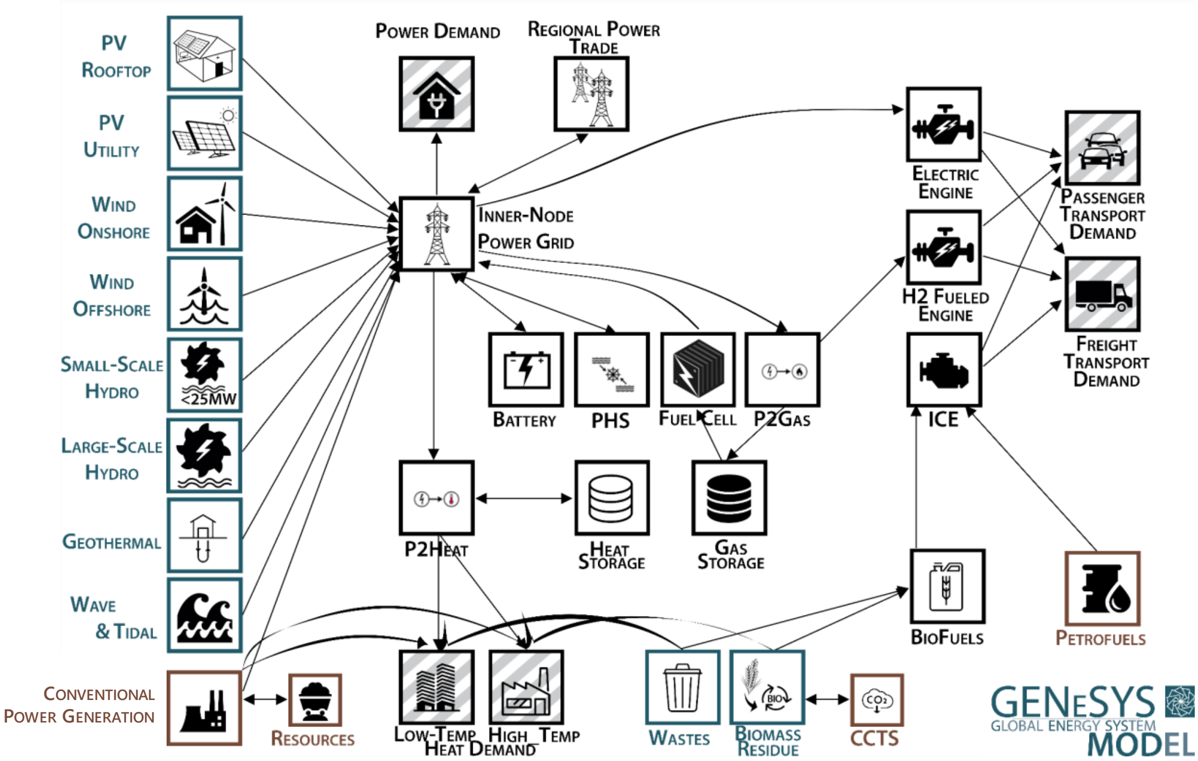


Figure 7: Model structure of GENeSYS-MOD

The model is subject to further constraints, most importantly on the emission of greenhouse gases (GHG) per macro region, per time step or over the entire scope of the model. Abstracting from complex flows in the real power grid, exchange of electricity between countries is modelled as a simple transport problem with expandable capacities. Furthermore, it is possible to limit the net share of imports on demand of any fuel and define caps on the yearly expansion of technologies.

4.2 Power system model

The applied electricity system model dynELMOD is, like GENeSYS-MOD, a cost minimizing optimization problem, determining dispatch and investment decisions to cover demand for a fixed set of consecutive years [16]. But, since it focusses only on the electricity system, it allows for a much greater level of detail. A list of included technologies can be found in Annex 9.1. Unlike GENeSYS-MOD, it includes ramping and must-run constraints, stemming from combined heat and power (CHP) production or provision of balancing reserves, from thermal power plants as well as reservoir inflows and demand side management technologies. The model relies on an abstracted power grid with a reduced number of nodes, but is also able to approximate complex power flows via a DC load flow approach if the underlying power transfer distribution factors (PTDF) are available. The abstracted grid and regions considered in this application are displayed in Figure 9. Just like GENeSYS-MOD, the model can limit the share of net imports in a region or a group of regions (e.g. a country) and the yearly expansion of technologies.

The calculation procedure in dynELMOD is a two-step process. It first determines investment decisions based on a reduced time-set created with a special reduction technique, consisting of 351 steps by default. Then, all hours of a year are considered, but investment is fixed to the values computed in the previous step. As a result, the model provides both an accurate impression of power plant dispatch and investment decisions over a long period of time. To increase the level of system adequacy, additional investment in peak-load technologies can be enabled in the last step.

In addition to conventional electricity demand, which is provided by a fixed load profile, the model allows the user to set a yearly demand that can be freely distributed and is only restricted by a set capacity limit. This feature is used to include electricity demand for the creation of synthetic fuels into the model, since, compared to electricity, fuels can be stored and transported rather easily. Any other flexibility on the demand side can be included as a demand side management technology within the model.

4.3 Model linking

Final results with a high degree of detail are obtained by transferring outputs of the energy system model to the electricity system model as inputs. In previous research, a similar practice has been referred to as “soft-linking” [17].

4.3.1 Sectoral coupling

The stylized energy flow diagram in Figure 8 can be used to explain the applied process in more depth. First of all, the diagram is arranged according to the process sequence (or work flow) from left to right. As a result, the flow of energy is opposed, which is against common practice. Final consumption is exogenously assumed within the scenarios and storylines discussed in Section 3.3 and displayed on the very left of the diagram.

Compliance with climate objectives implies fossil fuels replacement by bio fuels or variable renewables (like solar, wind, or hydro) as a source of primary energy. However, there are many conceivable options to achieve this. In the transport sector, for example, cars could be powered by renewable electricity (directly or indirectly by synthetic fuels generated from electricity) or bio fuels. The same applies for the heat sector.

The energy system model determines the extent to which these options and technologies are used to cover final energy demand. This corresponds to secondary energy demand (synthetic fuels and electricity) in the middle and primary energy on the very right of the diagram.

From the key role electricity plays in most concepts to decarbonize the heat and mobility sector, it is apparent that how demand is covered in these sectors will greatly impact the electricity system. Therefore, the electricity model “zooms in” on the part of the energy flow diagram dedicated to electricity as a secondary energy carrier to achieve a more detailed view. On a practical level, this is implemented by setting the electricity demand and certain capacities in the electricity system model to values computed by the energy system model.

In the heat sector, electricity demand of low-temperature heat pumps, electric boilers, and geothermal systems as well as high-temperature electric furnace systems are determined within the energy system model. These demands are then transferred to the electricity system model as an input. The same applies for demand from electric vehicles (passenger and freight including overhead lines). Load profiles for electric boilers and electric furnaces are based on the underlying demand for low and high temperature heat and the shape of these curves remains unchanged over the entire modelling period. Profiles for low-temperature heat, which corresponds to space and water heating, are obtained by applying a methodology developed for residential gas demand for heating purpose [18]. Based on an intensive statistical evaluation of actual data, a sigmoidal-shaped function is introduced to describe the relation between heat demand and outside temperature and parameters for this function are supplied. Applying this approach to low-temperature heat demand was suggested in former research [19]. For electric vehicles standard load profiles are used. The load profiles were obtained by analysing public statistics on road use, which are inverted to give the hourly profile of vehicles being plugged in for loading.[3] Hourly profiles vary by business or non-business day and by season [20].

Furthermore, electricity used for hydrogen or methane production is included, but is not subject to a fixed load profile. Since synthetic fuels can be stored comparatively easily, only the upper limit of hourly demand is set according to the installed capacities.

Also, installed capacities of heat-pumps, heat storage systems, and electric vehicles are transferred into the electricity system model. These technologies are able to flexibly interact with the electricity system but are also subject to restrictions arising from the final energy services (heat or mobility) they provide. When soft linking the two models however, any information about these restrictions cannot be transferred. Therefore, these technologies are only implemented as measures of demand side management (DSM), which can temporarily shift demand quantities.[4] Installed capacities of CHP power plants in the electricity system model are also set according to the energy system model. In the electricity system model they are subject to temperature dependent must-run constraints.

[3] If according to statistics x% of the vehicle fleet are on the road at a given hour, vice versa 100% minus x% are assumed to be plugged into a charging station.
[4] The numerical constraints of demand shifting is based on previous technology assessments and discussed in Section 5.

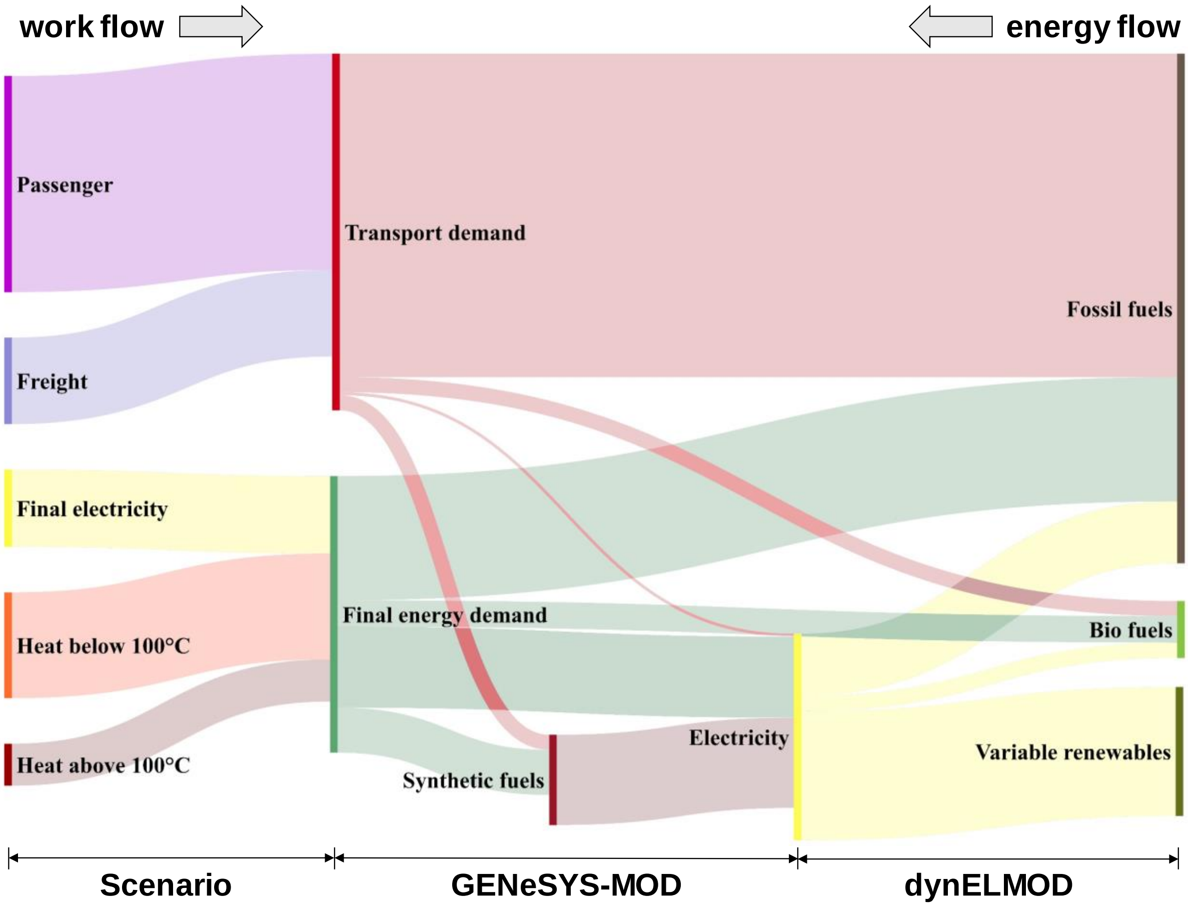


Figure 8: Energy flow diagram depicting the soft-linking process

Available potentials for biomass and rooftop photovoltaic need to adjust to results of the energy system model, too. Biomass may be used for electricity generation, heat, or mobility; rooftops may be used for solar photovoltaics and solar thermal systems. Consequently, potential already used in the heat or mobility sector must be subtracted from the potential available for the electricity sector. The same concept applies for emissions. Transport and heat sector emissions are subtracted from the scenario specific overall emission limits to derive the emissions budget still available for the electricity system model.

4.3.2 Spatial and temporal resolutions

So far, the documentation of the linking process focussed on the different sectoral resolution of models, while neglecting difference in spatial and temporal resolution. Generally, there is a trade-off between the two models. With computational efforts exponentially increasing, cross-sectoral models will need to rely on a coarser resolution. Thus, the energy system model applied relies on 17 macro region and 16 time intervals per year. If modelling is limited to one sector, much higher spatial and temporal resolutions become possible. Accordingly, the electricity system model differentiates between 99 clusters as used in the e-Highway2050 project and 90 time intervals in the first investment step and up to 8,760 steps in the second (see Section 4.2 for detailed explanation) [21]. This high degree of detail is crucial to correctly capture the fluctuating nature of solar and wind, that are expected to play a key role for future energy systems.

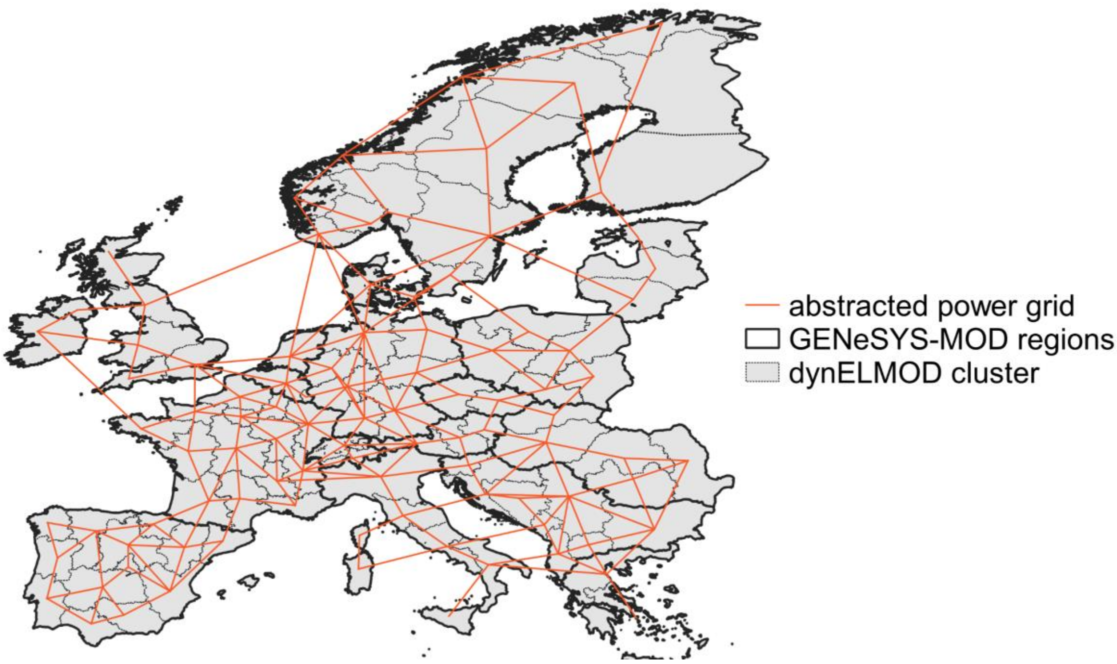


Figure 9: Spatial resolution of applied models

The difference in spatial resolution, as displayed in Figure 9, is addressed by distribution keys that breakdown values from a macro region to a country and then from a country to a cluster level. These keys differ depending on the value being broken down and are computed by appropriate indicators (e.g. power demand from electric vehicles is distributed among clusters based on the current vehicle fleet). A detailed summary can be found in Table 1 in Section 5. Addressing differences in temporal resolution is much more straightforward, since both models rely on similar methods to reduce hourly data for a full year into smaller yet largely consistent time sets[5]. Sources for hourly data are documented in Section 5 as well. While the number of time steps per year differs between models, both use investment time steps of 5 or 10 years starting in 2020. Both models also include 2015 but without any investment for backtesting purposes.

4.4 Summary of the methodology and limits

The whole methodology is summarized in Figure 10.

[5] See the publications documenting the respective models for details [17, 15]

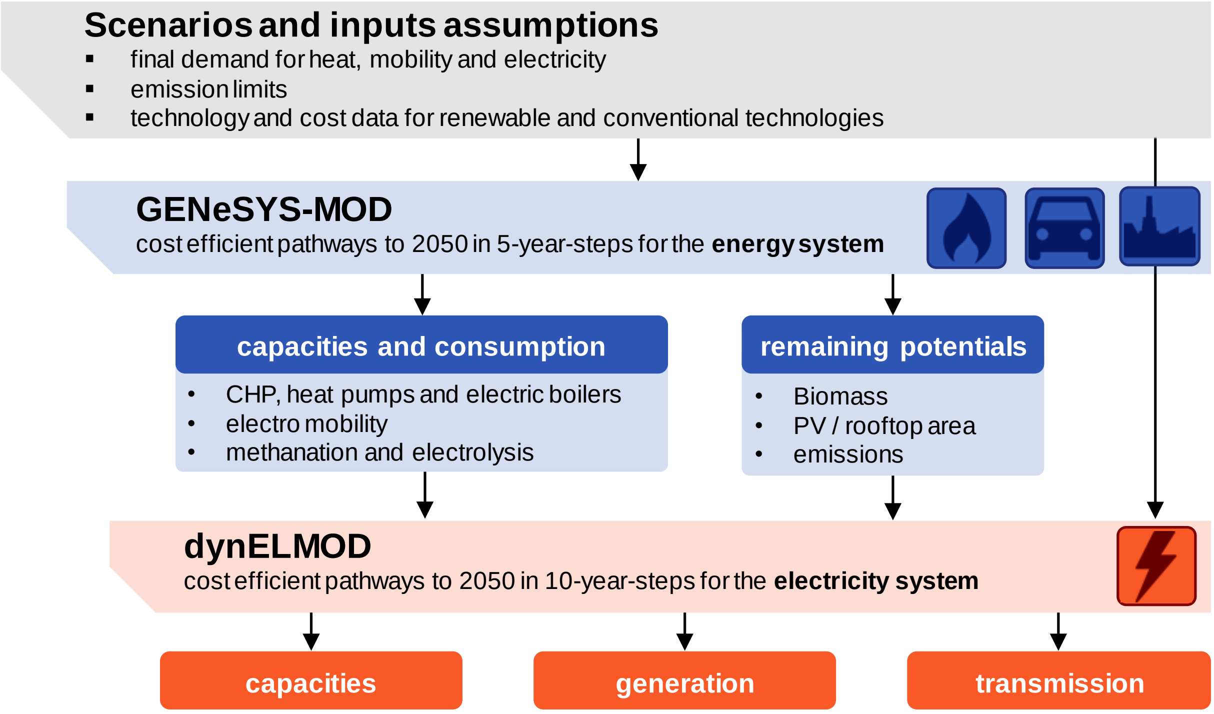


Figure 10: Comprehension of whole methodology

In conclusion, instead of an integrated optimization of the whole energy system, results are obtained by soft-linking two independent models in a top-down manner. This creates some drawbacks: the process can't capture the full flexibility of cross-sectoral technologies like electric heating systems, heat storage or electric vehicles. Therefore, synergies from sector integration are likely to be underestimated. In addition, transferring information from the energy system to the electricity system level is complex and requires substantial practical efforts, because none of the models were initially designed for this purpose. As a result, possibilities for additional cross-sectoral interaction modelling, such as the inclusion of the gas grid or a greater range of technologies, are limited. However, as discussed earlier, optimizing the whole energy system with the required level of detail, especially spatial and temporal, is computationally impossible. A possible solution could be a novel model framework, that covers the whole energy system, but varies the level of temporal and spatial detail depending on the respective energy carrier. Additional limitations of the methodology arise from the linearity of models: deciding whether to build large-scale grid-infrastructures for certain fuels (e.g. hydrogen or carbon grid) would require discrete variables.

Most other simplifying assumptions within the methodology are driven by a lack of suitable data. For example, data to make a reasonable differentiation of final demand by sector (industry, household, or service) or different types of use (e.g. cooling) for each hour and every of the 99 cluster is not available. Also, complex flows on the electricity grid could be modelled, if sufficient PTDF data existed. The data used within the calculation process is discussed in more depth in the following section.

5 Input data

In this section additional data necessary to carry out the process described above is summed up. Cost and technology data are not covered in detail again since they are already discussed in Deliverable D1.2 of the OSMOSE project. A comprehensive list can be found in Annex 9.1.

5.1 Distribution keys

As explained in Section 4 and mapped in Figure 9, spatial granulation across the used models varies. Results from the energy system model are either computed on a country or macro region (e.g. Scandinavia) level, but the power system model operates on a much lower cluster level. Furthermore, some aspects within the power system model are also represented on a country level. Most importantly, electricity demand for producing synthetic fuels via electrolysis can be satisfied on a country instead of cluster level, to reflect that these fuels can be stored and transported much easier than electricity. Also, the available energy potential from biomass and waste is not provided on a cluster, but on a country level. The following table shows on what basis results of the energy system level were disaggregated to cluster and countries.

Table 1: Overview of data used for disaggregation

		Cluster level	Country level
Demand	original electricity demand	local demand [21]	
	low temperature heat	low temperature heat demand [22]	
	high temperature heat	GDP [23]	
	transport sector	GDP [23]	
	Power-to-X		GDP [23]
Capacity	DSM from electric heat pumps	low temperature heat demand [22]	
	DSM from electric vehicles	GDP [23])	
	Power-to-X applications		GDP [23]
Potential	Biomass		Overall potential [24]
	Waste		Overall potential [25]
	Rooftop Space	urban and suburban area [26]	

5.2 Potential of renewables and others

Analysing the power system on a cluster level also requires assumptions on renewable energy potentials, most importantly wind and solar, at the cluster level. For this purpose, we adopted an approach introduced by Nahmacher et al. (2014) that computes the technical potential of renewables from the land use in specific region [27]. For example, they propose that 30% of agricultural areas and 5% of forest areas can be used for wind turbines, and that 4 GW of capacity can be installed per usable square kilometre. By applying assumptions from Nahmacher et al. (2014) for onshore wind, rooftop photovoltaic, open-space photovoltaic, and concentrated solar power to land use data from Corine Land cover, one can compute renewable potentials on a cluster level [26]. In Figure 11 the derived potentials are aggregated by country and compared to prove the plausibility of results. Potentials for wind offshore are not computed via this method. Instead, the median values from the three sources displayed are assumed for each country and allocated to clusters according to shares in e-Highway2050 [21].

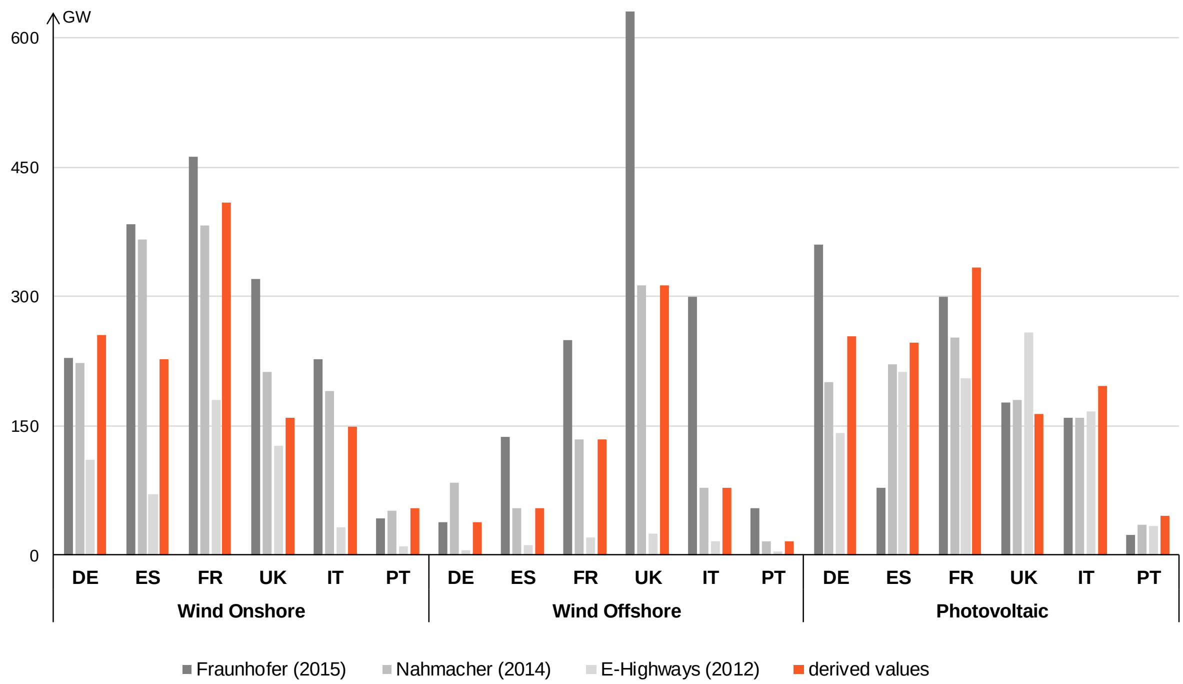


Figure 11: Overview of aggregated potentials[6]

Additional potential for pumped hydro storage is derived from the number of unused but suitable sites identified assuming an average size of 0.2 GW per plant [28]. The energy potential of non-renewable waste and biomass are based on 2015 values from Eurostat and other sources [24, 25]. Potentials for geothermal and tidal were based on previous assessments in academic literature [29].

[6] Value for offshore in the United Kingdom is off the chart and at 1274 GW in (Fraunhofer, 2015) [31].

5.3 Time series

All time series data was either taken from the Open Power System Data (OPSD) Data Platform[7] or directly provided by RTE (for demand, it is based on 2012 data). Time series for original electricity demand, photovoltaic, and onshore wind are cluster-specific. So far, other times series are identical for all clusters belonging to the same country.

In general, it is debateable whether one year of weather data is enough for modelling. From our experience, this greatly depends on the respective research question: if the focus is on the overall power plant portfolio as well as the resulting generation mix and emissions, considering one median year is sufficient and results do not vary greatly if other years are considered (this is particularly true since the full weather year is further reduced within the modelling process as described in Section 4.2.) However, if research instead is focused on system adequacy and the need for peak-load capacities, results are very sensitive to the considered weather year and a variety of years should be considered. Therefore, we think limiting our scope to one year is reasonable given the scope of the deliverable, but subsequent tasks within our work packages should probably refine this. Our results could be reiterated based on this work.

5.4 Demand side management

Heat pumps and electric vehicles are implemented into the power system model as demand side management technologies and parametrized according to previous technology assessments [30]. As a result, demand from heat pumps can be shifted by 4 hours and from electric vehicles by 1.6 hours. Of the total electric capacity of heat pumps, 25% are available to shift demand. For electric vehicles this value amounts to 5.6%. Since these assumptions are critical for the assessment of flexibility, they will be further fine-tuned in future work within the project (also see Section 7).

5.5 Installed capacities

Installed capacities of power plants in 2015 were mostly obtained from OPSD, while installed capacities of heating technologies were derived from Heat Roadmap Europe. In addition to the final phase-out dates for hard-coal and lignite, that depend on the respective scenario, already fixed national phase-out plans are taken into account irrespective of the scenario. The same applies for nuclear power plants. Planned and unplanned outages of power plants are taken into account as a fixed share of installed capacity that is not available for generation.

As explained in Section 3.2, upper and lower bounds on renewable capacities for 2030 on a country level based on the Sustainable Transition scenario of the TYNDP are included in the scenarios as well [7]: For *Neglected Climate Action* installed capacities can range between 65% and 75% of capacities installed in Sustainable Transition. *Current Goals Achieved* allows for a range between 75% and 85% and in *Accelerated Transformation* only a lower bound corresponding to 90% is included.

---

[7] See LINK

5.6 Grid

In the *Current Goals Achieved* and *Neglected Climate Action* scenarios, endogenous grid investment is only enabled after 2030[8] and, for clusters within the same country, limited to 700 MW/year. Between clusters within different countries, grid expansion is limited to 80 MW/year from 2030 to 2040 and 100 MW/year from 2040 to 2050. The *Accelerated Transformation* scenario additionally allows for investments between 2020 and 2030 of 350 MW/year within a country and 40 MW/year outside, because otherwise the model is unable to fully satisfy demand. For the same reason, maximum expansion between countries from 2040 to 2050 is increased to 120 MW/year. These assumptions are summarised in Table 2. They aim to reflect pragmatic limits on grid expansion in general and are initial conservative estimates. When assuming significantly higher values in earlier iterations, renewable expansion was limited to the areas with most favourable conditions and then extensively transported across Europe. This caused results that in terms of grid and renewable expansion were deemed implausible among project stakeholders. Deeper analysis will be carried out in the future OSMOSE work to assess how these limits are impacted by political, social, technical, or economic constraints.

Table 2: Overview of assumptions on grid expansion

in MW/year		**Neglected climate action**	**Current goals achieved**	**Accelerated transformation**
internal	until 2030	0		350
	2030 to 2050	700		
external	until 2030	0		
	2030 to 2040	80		
	2040 to 2050	100		120

All scenarios assume that net imports are limited to 20% of total demand in 2030 and can be increased to 40% until 2050.

5.7 Miscellaneous

Beside the total potentials and the currently installed capacities, hydro power plants are subdivided into run-of-river, reservoirs and pumped-storage. While run-of-river is non-dispatchable, generation from reservoirs can be controlled, but inflows are externally set. Lastly, pumped storage plants can both consume and generate power. The seasonal inflow patterns as well as the total amount of reservoir inflow have been calibrated using historical data on a country level [31].

[8] Until then the NTC capacities assumed in the e-Highway2050 project are being used.

Advanced adiabatic compressed air energy storage (AA-CAES) and carbon capture and storage (CCS) technologies have not reached the maturity to be widely used yet and it remains uncertain whether they ever will. Therefore, they are excluded from the analysis with the exception of biomass CCS, because it is necessary to achieve the emissions targets in some scenarios. Since both applied models include the full coverage of demand as a binding constraint, implicitly an infinite value-of-lost load is assumed.

6 Preliminary results

Given the number of scenarios, clusters, and time steps considered, the final results are quite extensive. Therefore, this section will only shed light on some key issues and not discuss every aspect in detail. Moreover, these results are preliminary: they will be the basis for future tasks in the project that should consider more aspects and refine the methodology.

To provide a better understanding of the results obtained from the applied methodology, Figure 12 displays result from 2030 and the accelerated transformation scenario as an energy flow diagram. Every flow leaving the *intermediate electricity* node is a result of the power system model, while all other information stems from the energy system model.[9] The ratio between flows entering and leaving a node reflects the losses. For example, the electricity used to provide low temperature heat is much smaller than the actual heat provided, because heat pumps have a coefficient of performance greater than zero.

[9] An exception to this is electricity demanded to create synthetic fuels, which is represented by a small flow both entering and leaving the *intermediate electricity* node.

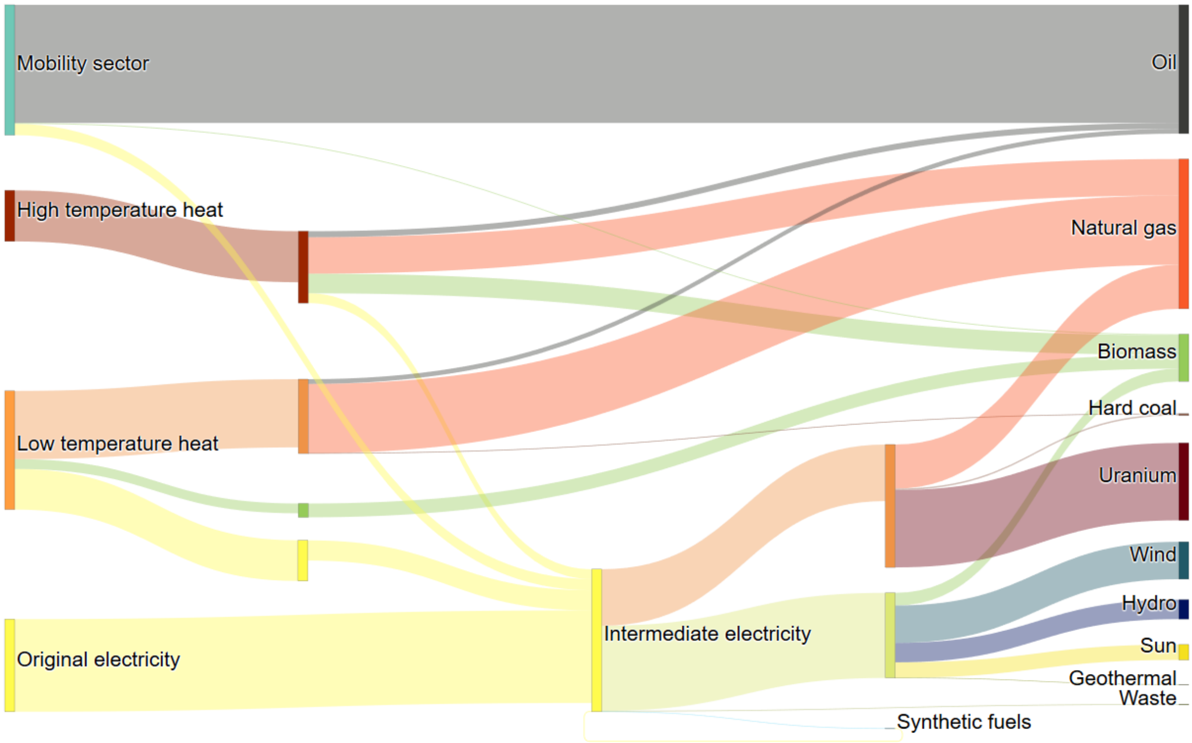


Figure 12: Energy flow diagram for 2030, Accelerated Transformation, Europe

6.1 Emissions per sector

Figure 13 shows how emissions of the energy sector assumed in Section 3 are allocated across the heat, mobility, and power sector. In all scenarios, until 2030, the greatest reductions of emissions can be observed in the power sector. In the heat and mobility sector decarbonisation only starts to gain momentum after 2030. The total emission limit of the power sector being used within the subsequent power system model amounts to 42 million tCO_2 in the *Current Goals Achieved scenario*. The respective values for *Accelerated Transformation* and *Neglected Climate Action* are 4.5 and 364 million tCO_2.

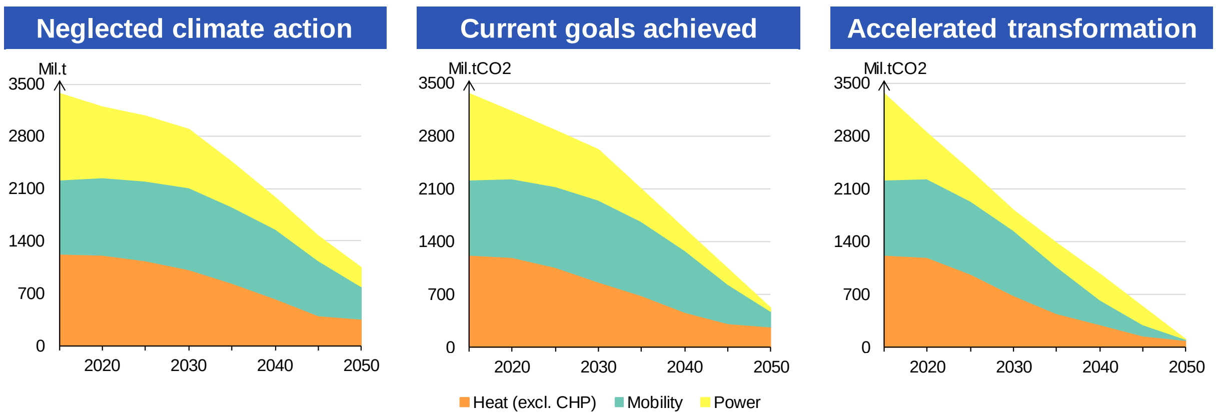


Figure 13: Allocations of emissions across energy sectors

6.2 Electricity demand

The total demand for electricity is being steered into different directions by the two main scenario drivers, emission limits, as displayed above, and final energy demand. Smaller emission limits on their own are found to increase the total demand for electricity, because more electricity is being used in the heat and mobility sector. Reduction in final energy demand on the other hand decreases the overall demand for electricity. This effect can also be observed in the total electricity demand across scenarios displayed in Figure 14. Generally, demand rises steeply as emission limits become smaller towards 2050.

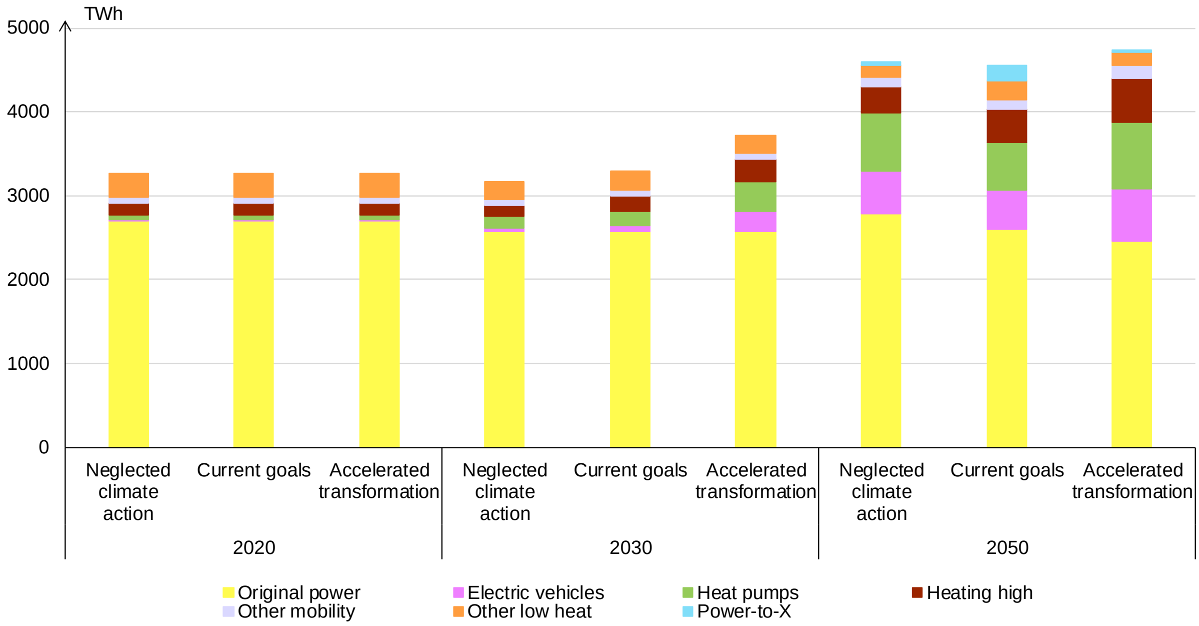


Figure 14: Total electricity demand across scenarios

However, in 2050 total demand in the *Current Goals Achieved* is below demand in *Neglected Climate Action*, although emissions are smaller in *Current Goals Achieved*. This is because the demand for low temperature heat in *Neglected Climate Action* is significantly higher and, as a result, more electricity is being needed to achieve the same degree of electrification in the heat sector. The same reason applies to other sectors of demand as well.

Electrification of the other sectors does not only impact total electricity demand, but also its hourly load profiles within the power system. To illustrate this, Figure 15 shows the aggregated load profile for Germany in 2020 and 2050.

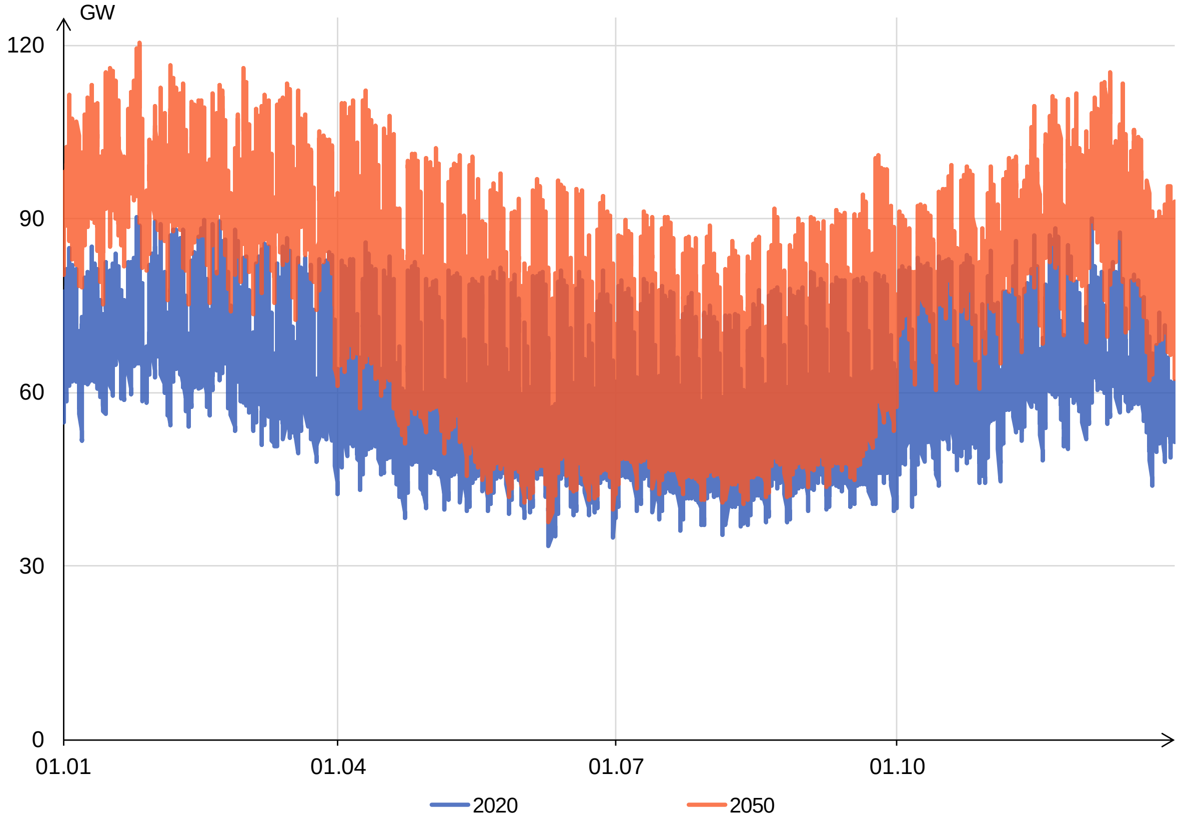


Figure 15: Aggregated load profiles for Germany in the *Current Goals Achieved* scenario

The volatility of load if found to greatly increase. This holds true when comparing the profiles across seasons, but also within every single same season. While the lower limit of load remains almost constant, in 2050 summer peak loads easily exceed 90 GW. In winter load even goes up to 120 GW, which is mainly driven by demand from electric heating appliances.

Figure 16 and Figure 17 compare total demand in the OSMOSE scenarios to other scenarios discussed in Section 3.1. Since PRIMES scenarios do not include Albania, Bosnia and Herzegovina, Switzerland, Montenegro, Serbia, and Norway, the OSMOSE values, indicated in orange, were added to the respective bars to ensure comparability.

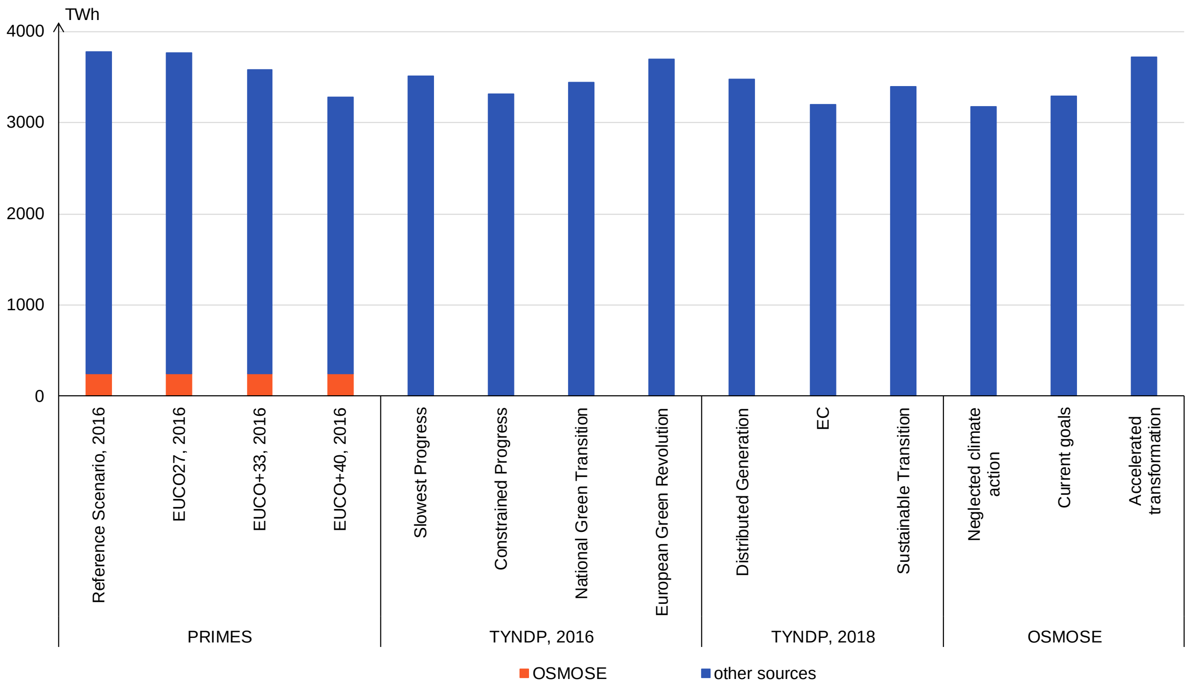


Figure 16: Electricity demand in OSMOSE and other scenarios, 2030

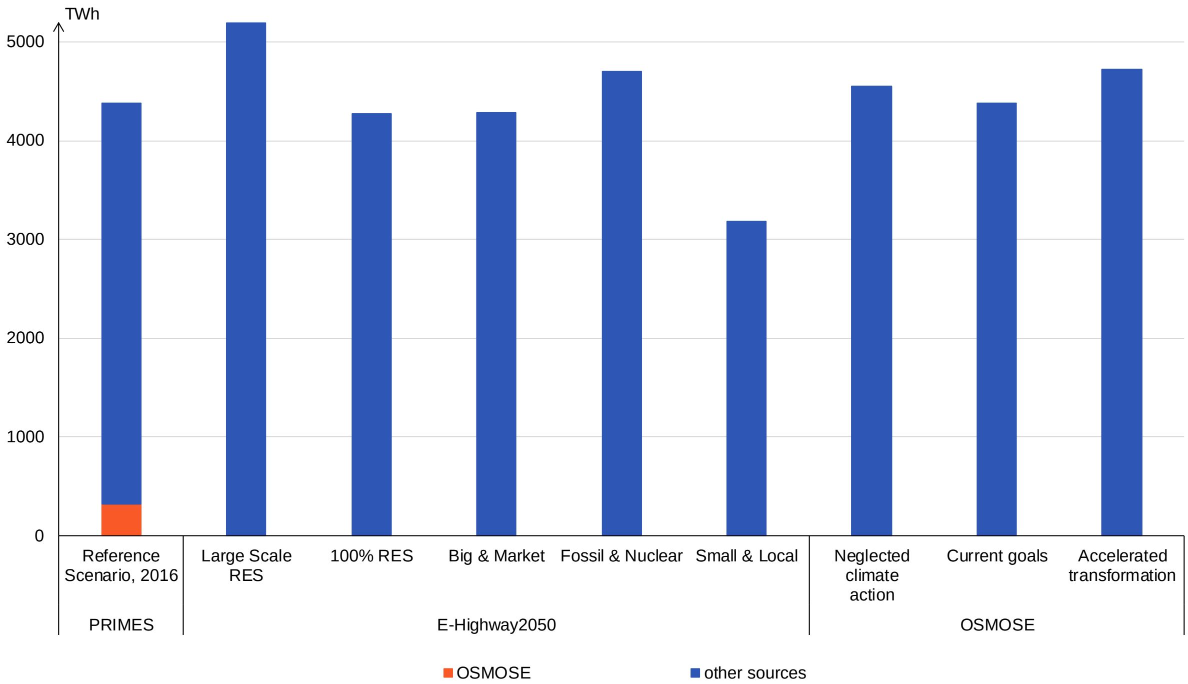


Figure 17: Electricity demand in OSMOSE and other scenarios, 2050

6.3 Installed capacities

Covering these demands requires substantial investment in renewable energies, as displayed in Figure 18. Aiming to minimize total system costs, expansion is focused on technologies found to be most cost efficient: onshore wind and open space photovoltaic. Although biomass holds the advantage of not being weather-dependent, its use in the electricity sector remains at current levels. This is due to the fact that, given its limited potentials, biomass is mainly used in the transport sector, because it is one of the few options to potentially decarbonize air and maritime transport.

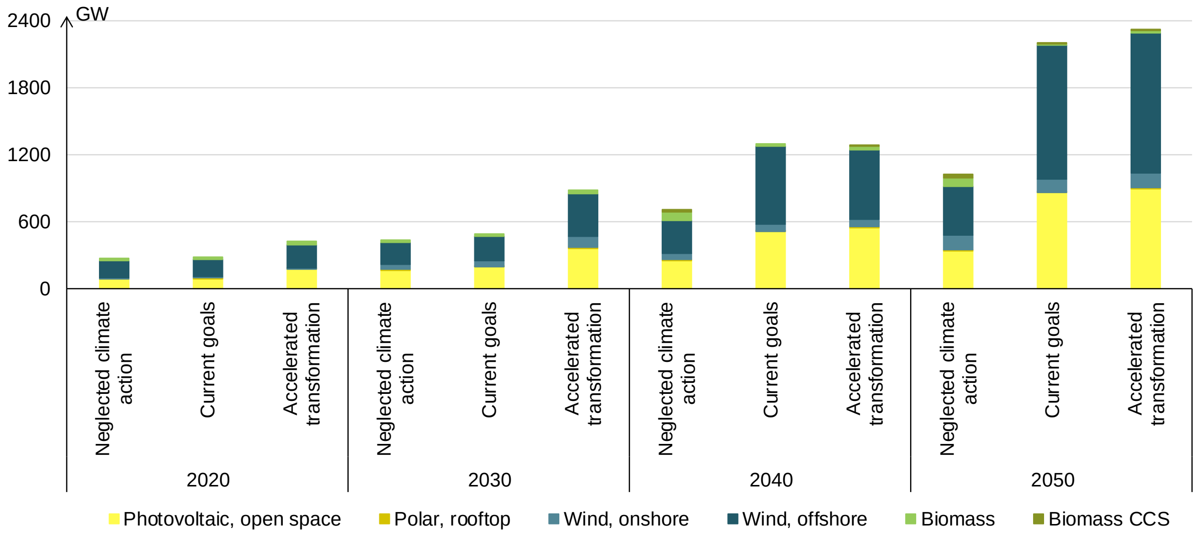


Figure 18: Installed capacities of renewables across scenarios

Changes in demand and supply also affect the need for flexibility within the power system. Figure 19 shows the installed capacities of novel technologies providing this flexibility that in today's power system still is mostly covered by thermal power plants. Short-term flexibility to compensate for hourly fluctuations of demand can be provided by demand side management from the heat and mobility sector covering the greatest share of additional need for flexibility in 2030. As decarbonisation progresses, increasing weekly and seasonal fluctuations need to be balanced, which is why installed capacities of batteries and power-to-gas rise. Especially the latter becomes highly relevant at low carbon limits, because it is the only option available to provide seasonal storage and cover peak-loads as displayed in Figure 14.

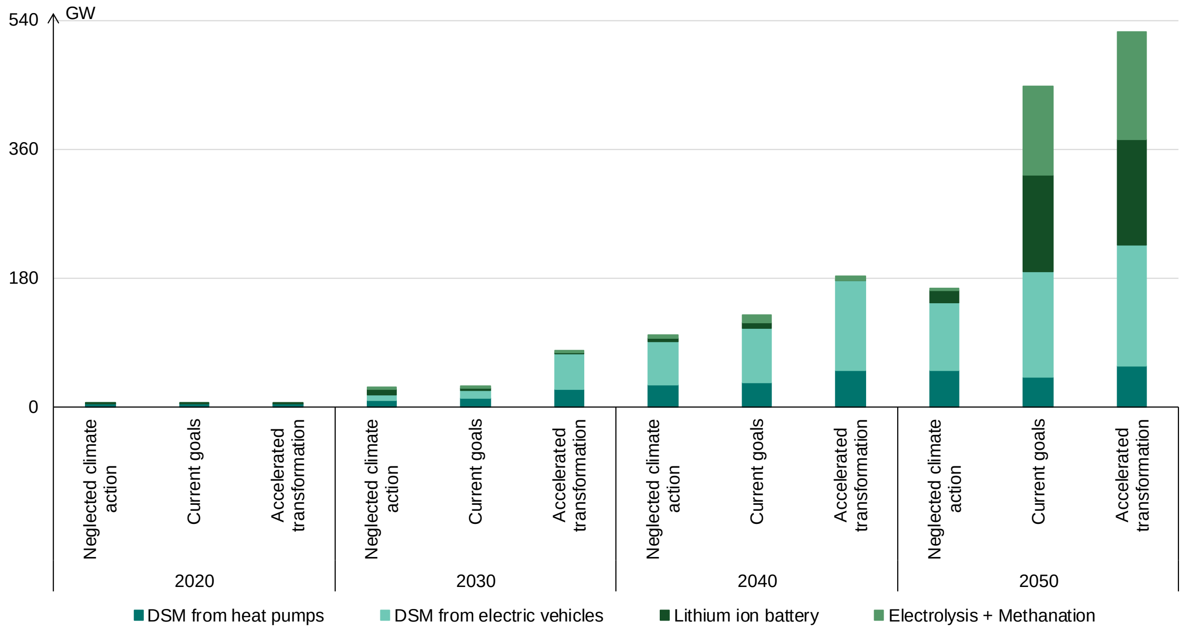


Figure 19: Installed capacities of storage and DSM across scenarios

In Figure 20 installed capacities of thermal power plant are displayed. Until 2030 these capacities decrease and, depending on the scenario, coal is increasingly substituted by gas. After 2030 also total installed capacity differs across scenarios. This is mainly driven by the increase of peak-load demand from the mobility and most importantly the heating sector as displayed in Figure 15. This peak-load demand is covered by gas power plants either fuelled with fossil gas or synthetic gas created from electricity via electrolysis and methanation.

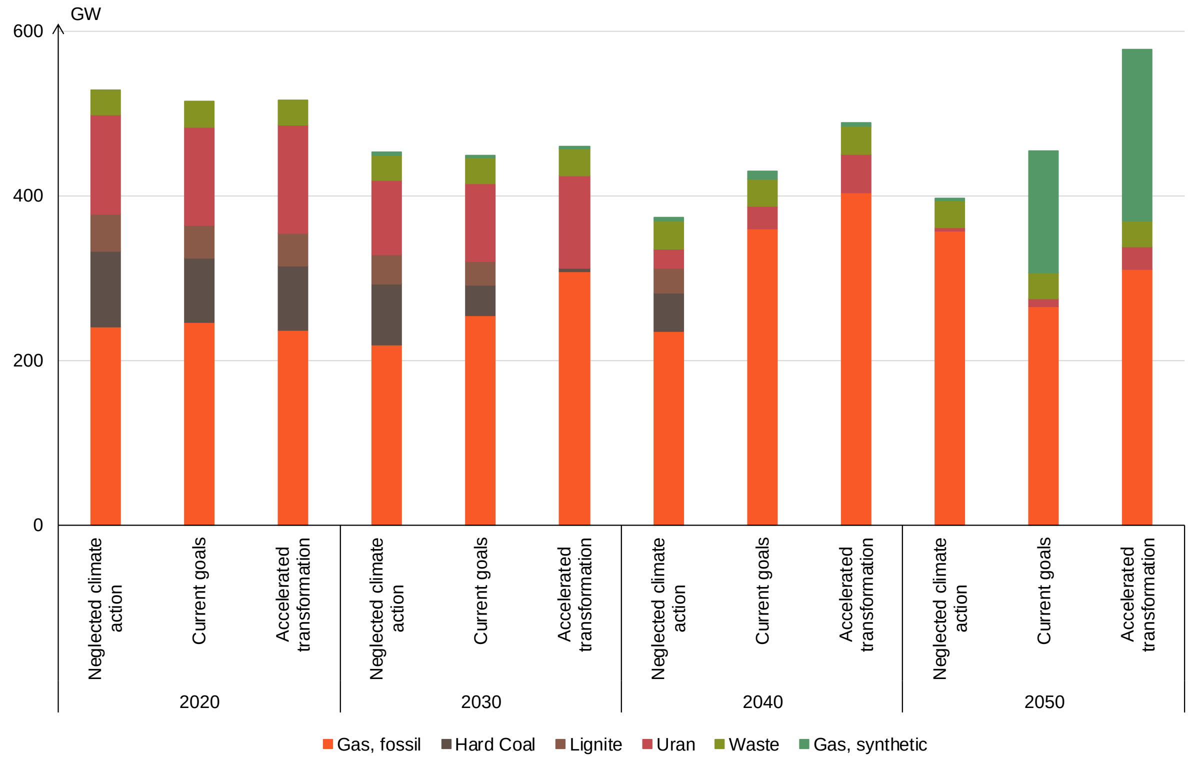


Figure 20: Installed capacities of thermal power plants

Figure 21 and Figure 22 compare total demand in the OSMOSE scenarios to other scenarios discussed in Section 3.1.

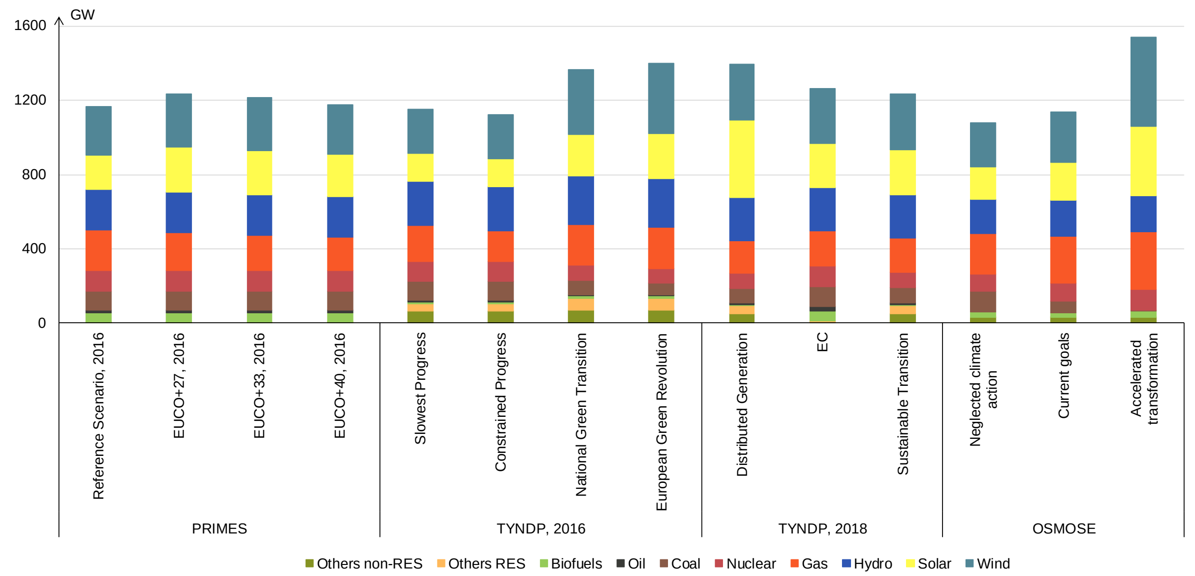


Figure 21: Installed capacities in OSMOSE and other scenarios, 2030

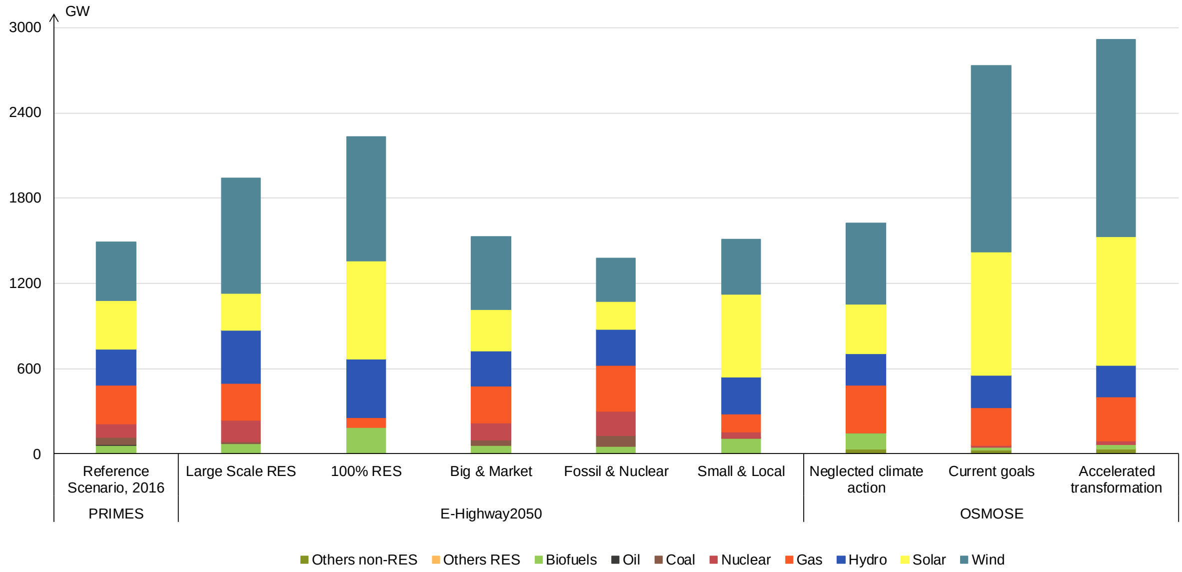


Figure 22: Installed capacities in OSMOSE and other scenarios, 2050

6.4 Grid expansion

In Figure 23 total grid capacities within clusters and between clusters are plotted across scenarios. As assumed, *Accelerated Transformation* is the only scenario with grid expansion until 2030. In general, in all scenarios a major expansion of the power grid takes place. In relative terms, external grid expansion always exceeds internal expansion. It can be observed that grid expansion is mostly driven by increased demand in regions with low renewable potentials and tighter emission limits. Furthermore, many lines are expanded to their upper limit in almost all scenarios, while others are rarely invested in.

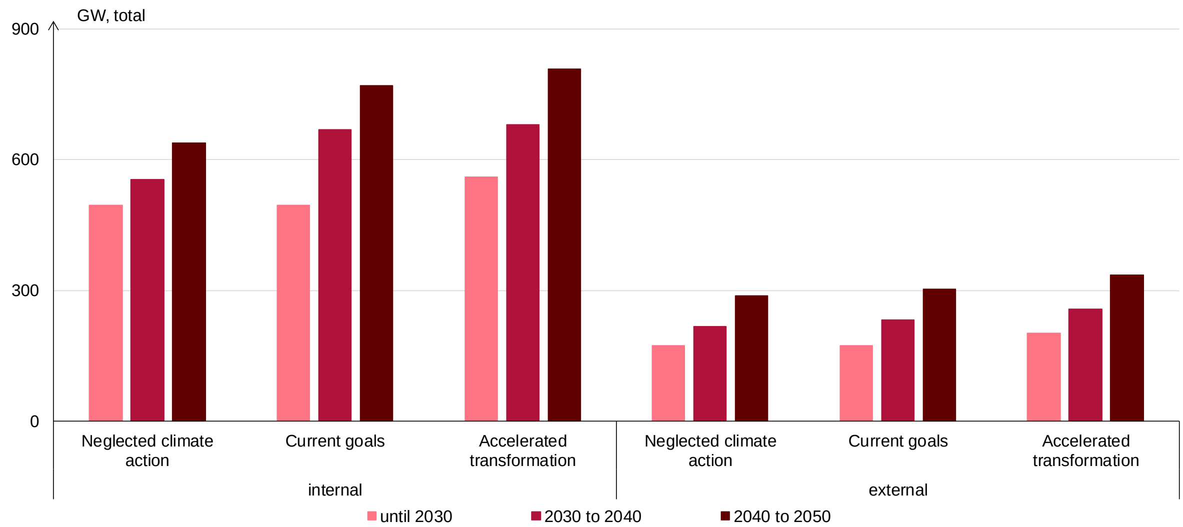


Figure 23: Total grid capacities across scenarios

7 Further research

Presented scenario results quantify the needs for and potentials sources of flexibility in future power systems that are increasingly shaped by tight emission limits and, as a result, increasing demand from the heat and mobility sector. These scenarios could be further enhanced by introducing greater variations of demand across scenarios, especially in the mobility sector, and examining the influence of social acceptance of technologies in greater detail. Furthermore, the methodology of soft-linking existing models currently applied fails to cover some of the potential synergies between sectors of the energy system. This could be resolved by developing a more integrated methodology that better reflects an integrated energy system.

Overall, the derived scenarios focus on the need and potential sources for flexibility, but how these needs are satisfied will be further investigated in the following subtasks. Although the scenarios also provide numbers on installed capacities of storage and DSM across scenarios, they cannot provide an in-depth answer on how the demand for flexibility is covered for several reasons. As explained in Section 5.3, the computation of scenarios was limited to one year of weather data and therefore the derived power plant portfolios probably need to be adjusted to achieve a desired level of system adequacy. Furthermore, the applied methodology is fully-deterministic and therefore unable to capture the need for short-term flexibility stemming from forecast errors (see Figure 1). Lastly, the representation of the power grid based on net-transfer capacities between clusters is still stylized and probably requires refinement. These questions will be addressed in the subsequent subtasks and especially in deliverable D1.3 of the OSMOSE project.

8 References

[1] E. Commission, „EU Reference Scenario 2016," 2016.

[2] E. Comission, „Energy modelling, https://ec.europa.eu/energy/en/data-analysis/energy-modelling," 2018.

[3] E. Lab, „Technical report on Member State results of the EUCO policy scenarios," 2016.

[4] EU-SysFlex, „EU-SysFlex Scenarios and Network Sensitivities," 2018.

[5] E3MLab, „Primes model 2013-2014, detailed model description," 2018.

[6] ENTSO-E, „TYNDP 2016 scenario report," 2015.

[7] ENTSO-E, „TYNDP 2018 scenario data," 2017.

[8] e-Highway2050, „Data sets of scenarios for 2050," 2014.

[9] T. v. Ireland, „Implementing Paris: Delivering the EU's "at least 40% GHG reduction" by 2030," *Webinar Series on NDCs,* 2017.

[10] eurostat, „Greenhouse gas emissions by source sector," 2018.

[11] Heat Roadmap Europe, „Baseline scenario of the heating and cooling demand in buildings and industry in the 14 MSs until 2050," 2016.

[12] E3M Lab, „PRIMES EU Reference Scenario, Summary report," 2016.

[13] International Energy Agency, „World Energy Outlook 2017," 2017.

[14] K. Löffler, K. Hainsch, T. Burandt, P.-Y. Oei, C. Kemfert und C. von Hirschhauen, „Designing a Model for the Global Energy System—GENeSYS-MOD: An Application of the Open-Source Energy Modeling System (OSeMOSYS)," *Energies,* Bd. 10, Nr. 1468, 2017.

[15] K. Hainsch, T. Burandt, C. Kemfert, K. Löffler, P.-Y. Oei und C. von Hirschhausen, „Emission Pathways Towards a Low-Carbon Energy System for Europe: A Model-Based Analysis of Decarbonization Scenarios," *DIW Discussion Paper,* Bd. 1745, 2018.

[16] C. Gerbaulet und C. Lorenz, „dynELMOD: A Dynamic Investment and Dispatch Model for the Future European Electricity Market," *DIW Data Documentation,* 2017.

[17] J. Deane, A. Chiodi, M. Gargiulo und B. P. Ó. Gallachóir, „Soft-linking of a power systems model to an energy systems model,“ *Energy,* Bd. 42, pp. 303-312, 2012.

[18] bdew, „Abwicklung von Standardlastprofilen Gas,“ 2018.

[19] M. Ketov, „Marktsimulation unter Berücksichtigung der Strom-Wärme-Sektorenkopplung,“ *Aachener Beiträge zur Energieversorgung,* Nr. 189, 2018.

[20] K. Jacqué, „Potentialanalyse und Modellierung von Lastverschiebung durch Demand-Side-Management und Elektromobilität im Kontext des Energiesystems der Zukunft,“ 2013.

[21] e-Highway2050, „Database per country,“ 2014.

[22] Heat Roadmap Europe, „Profile of heating and cooling demand in 2015,“ 2017.

[23] eurostat, „Regional gross domestic product by NUTS 2 regions,“ 2018.

[24] B. Elbersen, I. Startisky, G. S. M.-J. Hengeveld und H. Naeff, „Atlas of EU biomass potentials,“ 2012.

[25] eurostat, „Supply, transformation and consumption of wastes (non-renewable),“ 2018.

[26] CORINE Land Cover, „CLC 2018 data,“ 2018.

[27] P. Nahmacher, E. Schmid und B. Knopf, „Documentation of LIMES-EU - A long-term electricity system model for Europe,“ 2014.

[28] eStorage, „Overview of potential locations for new Pumped Storage Plants in EU 15, Switzerland and Norway,“ 2015.

[29] M. Delucchi, M. Jacobson, Z. Bauer, S. Goodman und W. Chapman, „Spreadsheets for 139-country 100% wind, water, and solar roadmaps,“ 2016.

[30] Z. A. Styczynski und D. U. Sauer, „Demand-Side-Management im Strommarkt,“ *Technologiesteckbrief zur Analyse „Flexibilitätskonzepte für die Stromversorgung 2050“.*

[31] ENTSO-E, „Entsoe.net – the transparency platform on Electricity in Europe,“ 2016.

[32] ENTSO-E, „TYNDP 2018 scenario data,“ 2017.

[33] Fraunhofer-Institut für Windenergiesysteme, „Interaktion EE-Strom Wärme Verkehr,“ 2015.

9 Annexes

9.1 Overview of technologies in the electricity system model

	2030			2050			
	Efficiency	Investment		Efficiency	Investment		Lifetime
	%	€/kW	€/kWh	%	€/kW	€/kWh	a
Nuclear	37%	4500		37%	4500		41
Lignite	46%	2000		50%	1800		50
Hard coal	47%	1633		50%	1500		50
Open cycle gas-turbine	64%	700		64%	700		32.5
Closed cycle gas-turbine	46%	275		46%	275		50
Oil	39%	581		41%	490		47.5
Pumped storage	78%	923		78%	923		40
Run-of-river	100%	4500		100%	4500		60
Waste	60%	2890		38%	2890		31
Biomass	60%	2890		38%	2890		25
Tidal	100%	3790		100%	2100		21
Geothermal	100%	12420		100%	10700		35
Photovoltaic, rooftop	100%	845		100%	588		25
Photovoltaic, open-space	100%	455		100%	317		25
Concentrated solar power	100%	2251		100%	1974		30
Wind onshore	100%	1360		100%	1268		25

Wind offshore, average	100%	3666		100%	3378		25
Wind offshore, shallow	100%	2710		100%	2497		25
Wind offshore, deep	100%	3188		100%	2937		25
Reservoir	75%	2200		75%	2200		60
Li-Ion Battery	88%	84	240	90%	75	164	15
Power-to-gas	46%	1588		51%	1420		20