Actuating the European energy system transition: Indicators for translating energy systems modelling results into policy-making

Mariliis Lehtveera\*, Lisa Göranssona, Verena Heinischa, Filip Johnssona, Ida Karlssona, Emil Nyholma1, Mikael Odenbergera, Dmytro Romanchenkoa2, Johan Rootzénb2, Georgia Savvidoua, Maria Taljegarda, Alla Toktarovaa, Jonathan Ullmarka, Karl Viléna, Viktor Waltera

a *Energy Technology Division, Department of Space, Earth and Environment, Chalmers University of Technology, Gothenburg, Sweden*

b *Department of Economics, University of Gothenburg, Gothenburg, Sweden*

1 *Current address: Profu AB, Mölndal, Sweden.*

2*Current address: Energy Group, Department of Sustainable Society, IVL Swedish Environmental Research Institute, Gothenburg, Sweden.*

*\*Corresponding Author:* [mariliis.lehtveer@chalmers.se](mailto:mariliis.lehtveer@chalmers.se); *Current address:* *Strategy Division,* Göteborg Energi AB*, Gothenburg, Sweden*

# Appendix A1



**Figure A1.1** Map of regions considered in this work. Northern Europe is subdivided into 12 regions based on major bottlenecks in the transmission grid and key differences in renewable resources.

# Appendix A2

Table A2.1 gives the investment and variable costs for the electricity generation technologies considered in the model. The investment costs and fixed operation and maintenance costs are based on IEA World Energy Outlook 2016 [1], with the exception of the costs for onshore wind power, which are based on the costs presented by [2] with a yearly learning rate of 0.4%. In the model, annualised investment costs are applied assuming a 5% interest rate. Technology learning for thermal generation is included as gradual improvement in the efficiencies of these technologies, reflected as a reduced variable cost in Table A2.1. The variable costs listed in Table A2.2 exclude the cost of carbon dioxide, which vary between years. The cost of cycling thermal generation is not part of the variable cost. Instead, the start-up costs and part-load costs are included explicitly in the optimisation. The start-up costs, part-load costs, and minimum load level applied here are based on the report of [3], in which all the technologies that employ solid fuels use the cycling costs given for large sub-critical coal power plants. The start-up fuel is, however, changed to biogas rather than oil in all bio-based generation in the present work. The cost of carbon dioxide emissions related to starting thermal generation vary from year to year and is therefore not included in the start-up costs in table A2.1. The cycling properties of nuclear power are based on the paper by [4], in which a start-up time of 20 h and a minimum load level of 70% are given.

Biogas is assumed to be produced through the gasification of solid biomass, with 70% conversion efficiency. The cost of the gasifier equipment is included in the form of 20 €/MWh added to the fuel cost, rather than being incorporated into the investment cost of the biogas technologies. This, since biogas is storable, which means that the gasifier equipment may attain a much higher number of full-load hours compared to the power plant consuming the biogas. The total cost of the gasification equipment is taken from [5], and 8,000 full-load hours are assumed.

Table A2.1: Costs and technical data for the electricity generation technologies. The variable costs and start-up cost are for year 2030 and exclude costs of CO2 emissions.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Technology | Investment cost 2030  [M€/MW] | Investment cost 2050  [M€/MW] | Variable costs  [€/MWh] | Fixed O&M costs  [k€/MW,yr] | Life-time  [yr] | Minimum load level [share of rated power] | Start-time [h] | Start cost  [€/MW] |
| Coal ST | 1.56 | 1.56 | 17 | 27 | 40 | 0.35 | 12 | 192 |
| Coal CHP | 1.56 | 1.56 | 21 | 27 | 40 | 0.35 | 12 | 192 |
| Coal CCS | 3.00 | 3.00 | 21 | 91 | 40 | 0.35 | 12 | 192 |
| NG CCGT | 0.78 | 0.78 | 39 | 13 | 30 | 0.2 | 6 | 44 |
| NG GT | 0.39 | 0.39 | 64 | 8 | 30 | 0.5 | 0 | 32 |
| NG CHP | 1.01 | 1.01 | 48 | 17 | 30 | 0.32 | 12 | 102 |
| NG CCS | 1.80 | 1.80 | 53 | 35 | 30 | 0.35 | 12 | 192 |
| Biomass ST | 1.86 | 1.86 | 90 | 50 | 40 | 0.35 | 12 | 192 |
| Biomass CHP | 3.15 | 3.15 | 119 | 58 | 40 | 0.35 | 12 | 192 |
| Waste CHP | 6.63 | 6.63 | 7 | 443 | 40 | 0.35 | 12 | 192 |
| Biogas CCGT | 0.76 | 0.76 | 117 | 13 | 30 | 0.2 | 6 | 47 |
| Biogas GT | 0.38 | 0.38 | 195 | 8 | 30 | 0.5 | 0 | 55 |
| Bio-coal CCS (flex) | 3.46  (3.64) | 3.46  (3.64) | 40 | 107  (113) | 30 | 0.35  (0.15) | 12  (6) | 192  (110) |
| Hydropower | 2.06 | 2.06 | 1.0 | 47 | 500 | 0 | 0 | 0 |
| Nuclear | 5.15 | 5.15 | 16.5 | 154 | 60 | 0.7 | 24 | 670 |
| Solar PV | 0.99 | 0.60 | 1.1 | 10 | 25 | 0 | 0 | 0 |
| Onshore wind | 1.33 | 1.23 | 1.1 | 30 | 25 | 0 | 0 | 0 |
| Offshore wind | 3.29 | 2.21 | 1.1 | 100 | 25 | 0 | 0 | 0 |
| Transmission (OHAC) | 0.6 (per km) | 0.6 (per km) | 0.01 | - | 40 | 0 | 0 | 0 |
| Transmission (HVDC) | 0.756  + 0.63 (per km) | 0.756  + 0.63 (per km) | 0.01 | - | 40 | 0 | 0 | 0 |

The wind power generation profiles are calculated for wind turbines with a specific power of 200 W/m2 (i.e. a low value corresponding to state-of-the art wind turbines assumed to dominate by 2030), with the power curve and losses proposed by [6]. The wind speed input data are a combination of the MERRA and ECMWF ERA-Interim data for year 2012, whereby the profiles from the former are re-scaled with the average wind speeds from the latter [7, 8]. The high resolution of the wind profiles from the ERA-Interim data was processed into wind power generation profiles and put together into 12 wind classes for each region. The wind farm density is set to 3.2 MW/km2 and is assumed to be limited to 10% of the available land area, accounting for protected areas, lakes, water streams, roads, and cities [9].

Solar PV is modelled as mono-crystalline silicon cells installed with optimal tilt with one generation profile for each region and a park density of 61 MW/km2. Solar radiation data from MERRA is used to calculate the generation with the model presented by [10], including thermal efficiency losses. The full-load hours of solar PV in each region are shown in Table A2.2.

Table A.2.2: Full-load hours (FLH) and maximum capacity (Cap) limits for onshore wind classes 4–12, offshore wind, and solar PV.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Wind class and technology** | **ES3** | | **IE** | |
| FLH [h] | Cap [GW] | FLH [h] | Cap [GW] |
| **4** | 2,310 | 7.1 | - | - |
| **5** | 2,560 | 6.1 | - | - |
| **6** | 2,790 | 6.3 | - | - |
| **7** | 3,020 | 4.6 | - | - |
| **8** | 3,300 | 1.3 | - | - |
| **9** | - | - | - | - |
| **10** | - | - | 4,240 | 0.3 |
| **11** | - | - | 4,640 | 13.8 |
| **12** | - | - | 5,360 | 2.1 |
| **Offshore** | - | - | 5,360 | … |
| **Solar PV** | 1,770 | 24.7 | 1,000 | 9.6 |

The cost and technical data for VMSs are shown in Table A2.3[11]. The hydrogen storage is assumed to be of the large-scale, steel lined cavern type.

Table A2.3: Costs and technical data for the variation management technologies. The costs for electric boilers and electrolysers are given per MW and the costs of the batteries and hydrogen storage are given per MWh. For the thermal storages there are heat losses in addition to efficiency losses when charging.0.01/240 of the heat content of the storage together with heat corresponding to 0.07/360 of the storage capacity is lost every hour.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Investment cost  [M€/ MW(h)] | Efficiency [%] | Fixed O&M costs  [k€/MW(h),yr] | Life-time  [yr] |
| Battery, Li-ion | 0.15 | 95 | 25 | 15 |
| Battery, Flow | 0.10 | 70 | 13 | 30 |
| Electrolyser | 0.59 | 75 | 20 | 20 |
| H2 storage | 0.01 | 100 | - | 50 |
| Heat pump | 1.00 | 300 | 8 | 25 |
| Electric boiler | 0.05 | 100 | - | 20 |
| TES tank | 0.03 | 95 | - | 20 |
| TES pit | 0.004 | 80 | - | 20 |

# Appendix A3

## Additional Indicators and information

**A3.1 Land-use for variable renewable energy**

For the energy system transformation land-use for wind and solar power plants will have effects on the natural landscape. Wind power has a visual and audible impact that has led to resistance towards wind power projects and the expansion of wind power can thereby be limited by social acceptance [12]. Solar photovoltaic (PV) plants if placed on land such as in solar PV farms will compete with other land-use (although not the case for roof top solar PV installations). Other VRE such as offshore wind power (included in this study, but not in the results for this indicator), roof-top solar PV, wave power and tidal power opens other areas for harvesting of energy, but sees other conflicts of interest or additional costs as well as benefits. We present land-use (*LU*) for onshore wind and solar power as the share of total area that is used for these Variable Renewable Electricity (VRE) plants to give indication of these effects and calculate it as follows:

*Eq 1*

Where *C* is installed capacity, *CD* capacity density and *LA* the land area. The capacity (*C*) is a result from for example an investment model, limited by exogenous capacity constraints representing limitations of useful area. The capacity density (*CD*) and land area (*LA*) are exogenous limits assumed to be constant over time, where the capacity density is set partly according to expected technical limits, but wind farms and solar PV plants also include distances between the turbines/modules to reduce lost output due to wake effects and shading, respectively.

**A3.2. Fossil emissions phase out rates**

In order to reduce greenhouse gas emissions, the use of energy sources using fossil fuels without capturing the CO2 emissions must decrease. The rate of the phase out of such fossil sources, however, relates to the structural changes in economy such as jobs and regional distribution of activity [13]. By comparing the phase out rate at different time periods it can be seen if the phase out is accelerating or not. There is also an important aspect to differentiate the phase out rate in terms of capacity and produced energy. Even though fossil plants may remain in the system they may not be used to produce energy but remain as reserve power. In this study it is the technical lifetime which determines when a plant is phased out. In reality decision to phase out may be influenced by policy measures such as increased carbon pricing forcing plants to be phased out before they reached their technical or economical lifetime.

We measure the phase out pace of fossil plants in how much of the capacity and the related energy supply for each fossil technology has been phased out each time period (here decade) in percentage compared to the previous decade. Expressed as an equation, the average annual phase out rate (*pt*) can be calculated as follows:

|  |  |  |
| --- | --- | --- |
|  |  | Eq 2 |

where *E* is produced energy *between year ym and year yn of energy source t.*

**A3.3. Sectoral emissions**

***Transport sector.***

CO2 emission intensity of the passenger cars in 11 countries (UK, Ireland, Sweden, Norway, Finland, Germany, Poland, Lithuania, Latvia, Estonia, Denmark) was studied. As assumed in [14], an electricity demand is 0.17 kWh/km and an annual driving distance is 15,000 km per year. From this we calculated average electricity demand per year equalled 2550 kWh/year. By dividing the total annual electricity demand for passenger vehicles for the regions and years (39 1300 GWh/year) considered in [15] to average electricity demand per year we found car fleet of the Norther Europe (153 million passenger vehicles). Total CO2 emissions of fossil fuelled transport sector was calculated based on transport sector electrification rate, average carbon dioxide emissions of light vehicles per km and total car fleet.

Table A3.3.1. Assumptions for transport sector

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | Value | Unit | Reference |
| Electricity demand per km | 0.17 | kWh/km | [1] |
| Annual driving distance | 15000 | km/year | [1] |
| Average electricity demand per year | 2550 | kWh/year | Own calculation |
| Car fleet | 153450980 | passenger vehicles | Own calculation |
| Average CO2 intensity of new passenger cars registered in 2019 in the EU28 | 122.4 | g CO2/km | [2] |
| Electrification rate | | | [1] |
| 2030 | 50 | % |  |
| 2040 | 70 | % |  |
| 2050 | 100 | % |  |
| Total emissions from fossil fuel cars | | | Own calculation |
| 2020 | 282 | mtonne |  |
| 2030 | 141 | mtonne |  |
| 2040 | 85 | mtonne |  |
| 2050 | 0 | mtonne |  |

***Heat sector.***

CO2 emission intensity of the residential heating in UK, Ireland and Germany was studied. The total heat demand derived from the model results; average CO2 intensity of fossil fuelled heat sector is based on [16]. The electrification rate is based on modelled scenarios.

Table A3.3.2. Assumptions for heat sector

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | Value | Unit | Reference |
| Total heat demand | 363700 | GWhheat/year | [1] |
| Average CO2 intensity of residential heating in UK, Ireland and Germany | 200 | g CO2/kWhheat | [3] |
| Electrification share | | | [1] |
| 2030 | 9 | % |  |
| 2040 | 50 | % |  |
| 2050 | 91 | % |  |
| Total emissions from fossil fuel cars | | | Own calculation |
| 2020 | 73 | mtonne |  |
| 2030 | 66 | mtonne |  |
| 2040 | 40 | mtonne |  |
| 2050 | 6.5 | mtonne |  |

***Industry sector.***

CO2 emission intensity of the steel sector in Sweden, Germany, Poland, Finland and southern UK was studied. The total industry demand derived from model results; average CO2 intensity of the primary steelmaking is based on [17]. The electrification rate is based on modelled scenarios

Table A3.3.3. Assumptions for steel sector

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | Value | Unit | Reference |
| Total steel demand | 62 | Mtonnesteel/year | [1] |
| Average CO2 intensity of steel sector | 1600 | kg CO2/tonne steel | [4] |
| Electrification rate | | | [1] |
| 2030 | 0 | % |  |
| 2040 | 64 | % |  |
| 2050 | 100 | % |  |
| Total emissions from fossil fuel cars | | | Own calculation |
| 2020 | 100 | mtonne |  |
| 2030 | 100 | mtonne |  |
| 2040 | 36 | mtonne |  |
| 2050 | 6.5 | mtonne |  |

**A3.4. Running to capital cost ratio**

The transformation of the electric power sector poses significant economic challenges as large amounts of new capacity needs to be built. In systems with large amounts of VRE, the running cost gets low and the revenues to cover investments may rely on income from high-price hours with supply from storage or thermal units. Hence, the ratio between the capital and running cost of electricity generation is deemed important for the analysis and decision making regarding the distribution of monetary resources in the future. The Running-to-Capital Cost (RtCC) ratio is defined in this work as follows and presented on annual bases:

|  |  |  |
| --- | --- | --- |
|  |  | Eq 3 |

where, and are the running and capital costs, respectively, of a generation technology in region and year .

**A3.5. Changing load patterns**

Traditionally the balance between supply and demand has been handled by the supply side, i.e. variations in demand are matched by variations in electricity generation. Yet, there is significant potential in making use of demand side flexibility, which has become easier with digitalisation. In addition, employment of storage technologies, e.g. batteries, opens for additional flexibility in when electricity is used or returned to the electricity grid. Thus, the exact timing of our electricity consumption can, with the employment of demand response (DR) and energy storage technology options, be decoupled from our basic needs driving the demand. In order to understand the role of DR and energy storage on a system level the correlation between current demand profiles and the future demand profiles, i.e. the new demand profile from an investigated scenario, can be used. Thus, such correlation factor (corr) can be calculated as follows:

|  |  |  |
| --- | --- | --- |
|  |  | Eq 4 |

where *D* denotes the electricity demand, current and new, for region *r* at year *y* and the profile spans over the annual hours *h*. A correlation factor equal to one means that the investigated scenario has a demand that has the same profile as current demand and a correlation factor equal to minus one means that electricity is used with a profile totally opposite to the current usage. Even though a low correlation to current demand give little information on exactly how the future demand has changed it provide a bases for understanding how variations in the electricity system develop and that measures are needed in terms of, for instance, complementary generation, demand flexibility (DSM) or storage. Thus, this can in turn assist policy makers to understand how big the changes to the system are. The correlations in demand between scenarios can be complemented by indicators on how large part of the total demand that is affected by DR (delayed or brought forward) and the part of total load that is being used via an energy storage.

**A3.6. System structure – Degree of decentralisation**

The growing penetration of small-scale, distributed technologies for generation and storage of electricity and heat increasingly challenges the traditional, centralised structure of the energy system. New electricity demands from electrification arise at different levels in the energy system, from electric vehicles to large scale industrial processes. Thus, a more decentralised operation and balancing of the energy system is likely to occur in the future [18, 19]. Scenarios investigating the development of electricity systems seldom reflect on this aspect. Here we present a first step to quantify decentralisation in energy systems with respect to energy technologies and demands that can be found in small scale decentralised systems. We categorise technologies for electricity generation, consumption and storage and the cross-regional trade of electricity into decentralised and centralised and provide an indicator on the share of decentralisation which we compare to the share of centralisation for each of these aspects.

|  |  |  |
| --- | --- | --- |
|  |  | Eq 5 |
|  | |  | Eq 6 |
|  | |  | Eq 7 |
|  | |  | Eq 8 |

where is the ratio of decentralised/centralised generation () over the total generation *G*, is the ratio of decentralised/centralised electricity demand () over the total electricity demand *D*, is the ratio of decentralised/centralised energy storage volume () over the total energy storage volume *S* and is the ratio between centralised cross-regional trade () and the total electricity generation *G* in region *r* and year *y*..

Table A3.6.1. summarises categorisation of electricity generation, demand and storage in decentralised and centralised. Electricity generation from solar PV can be employed both, on a small-scale or as large solar parks, which is not differentiated in the modelling tool used. Electricity generation from CHP units on urban scale are here counted as decentralised. Electricity consumption from charging of electric vehicles as well as the storage volume in EV batteries that can be used for smart charging and V2G in the *Collaboration* scenario are defined as being on the decentralised level. Electricity for electrolysers to produce hydrogen for the steel industry and the connected hydrogen storages to provide flexibility to this process in the *Collaboration* scenario are categorised as centralised technologies. Li-Ion and flow batteries are very modular and can be installed both on the decentralised and the centralised levels. Trade between modelling regions is categorised as centralised variation management strategy.

Table A3.6.1.Categorisation of electricity generation, demand and storage into decentral and central, for the calculation of the degree of decentralisation.

|  |  |  |
| --- | --- | --- |
|  | **Decentral** | **Central** |
| **Electricity generation** | Solar PV, Coal CHP, Natural gas CHP, Waste CHP | Coal ST, Coal CCS, NG CCGT, NG GT, NG CCS, Biomass ST, Biomass CHP, Biogas CCGT, Biogas GT, Bio-coal CCS (flex), Hydropower, Nuclear,  Solar PV, Onshore wind, Offshore wind |
| **Electricity consumption** | EV driving demand, Heat pump, Electric boiler | Electrolyser |
| **Storage** | EV-batteries, Li-ion & flow batteries | H2 storage, Li-ion & flow batteries |

# Appendix A4

## Results

***A4.1 Land-use for variable renewable energy***

The land-use for VRE is similar in the two scenarios, reaching 4.8% in the Collaboration and 4.6% in the No Collaboration scenario for wind power by 2050 with up to 7.6% in a single region, which can be compared to 15% in Bremen community, the most wind power dense region in Germany, and 4.6% in the entire country as of Year 2018 assuming the same capacity density as in the model [20]. Wind power reaches the limit set on capacity expansion in the model for good and medium wind conditions for all regions except the Nordic countries, and it happens to a large degree already by 2030. A lower acceptance of onshore wind power than assumed in the model could lead to challenges on transitioning the electricity system. The corresponding land-use for solar PV plants is on average 0.29% and 0.24% in the Coll and the No Coll scenario, respectively, which is similar to 0.30% in Saarland, the most PV dense region in Germany as of 2018 (assuming the same capacity density as in the model). The land-use for solar PV is in the model mainly located in the southern areas and the highest values are seen for southern and northern Germany with around 1% land-use for solar PV in 2050 indicating a significant increase compared to today’s values. Detailed land-use for onshore wind and solar power are seen in Tables A4.1.and A4.2.

With targets on climate, an increased share of renewable electricity generation – in particular wind and solar power - is obviously a key element in meeting such targets. At the same time, siting of new wind power has met public and political resistance in many places, resulting in that projects either were abandoned or delayed for many years. Thus, to use indicators which put wind power density into a perspective on a large scale (e.g. as land use share in the above examples) or quantify minimum distances to the built environment could possibly serve as a clear way of communicating to the public and other decision makers and interest groups. At present, regional scenarios showing a certain share of wind and solar power at a certain year into the future may underestimate the challenge to obtain such renewable share. At the same time, if communicating land-use figures and put them into perspective by comparing to existing cases may increase social acceptability.

Land usage for wind power covers up to 8% of the land in some regions. A doubling the wind farm density would most likely not lead to much more wake effects if the tightening is done perpendicular to the most common wind direction. Also, the wind turbine design could be optimized for increasing the energy output to land-use ratio by harvesting more energy at high wind speeds.

Table A4.1.1.: Land-use for wind power in each scenario, region and time period, as well as maximum allowed land-use for wind power.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **2030** | | **2040** | | **2050** | |
|  | **Available area in the model** | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** |
| **BAL** | 7.6% | 7.6% | 7.6% | 7.6% | 7.6% | 7.6% | 7.6% |
| **DE\_N** | 7.7% | 7.2% | 7.2% | 6.7% | 6.7% | 6.4% | 6.4% |
| **DE\_S** | 6.9% | 5.7% | 5.7% | 5.8% | 5.8% | 5.7% | 5.7% |
| **FI** | 7.3% | 1.3% | 1.1% | 2.7% | 2.3% | 2.5% | 2.5% |
| **IE** | 8.2% | 5.0% | 4.7% | 7.1% | 7.1% | 7.1% | 7.1% |
| **NO** | 5.4% | 1.8% | 2.2% | 3.1% | 2.6% | 3.1% | 2.6% |
| **PO\_N** | 7.1% | 7.1% | 7.1% | 7.1% | 7.1% | 7.1% | 7.1% |
| **PO\_S** | 7.2% | 6.9% | 6.9% | 6.9% | 6.9% | 6.9% | 6.9% |
| **SE\_N** | 4.7% | 0.9% | 0.9% | 3.4% | 2.4% | 3.3% | 3.0% |
| **SE\_S** | 7.5% | 1.5% | 1.5% | 1.4% | 1.4% | 1.2% | 1.2% |
| **UK\_N** | 7.4% | 7.4% | 7.4% | 7.4% | 7.4% | 7.4% | 7.4% |
| **UK\_S** | 6.7% | 6.7% | 6.7% | 6.7% | 6.7% | 6.7% | 6.7% |

Table A4.2.: Land-use for solar PV in each region and time period.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **2030** | | **2040** | | **2050** | |
|  | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** |
| **BAL** | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| **DE\_N** | 0.2% | 0.2% | 0.7% | 0.3% | 1.3% | 0.5% |
| **DE\_S** | 0.2% | 0.2% | 0.5% | 0.5% | 0.8% | 1.2% |
| **FI** | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| **IE** | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| **NO** | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| **PO\_N** | 0.0% | 0.0% | 0.2% | 0.2% | 0.4% | 0.2% |
| **PO\_S** | 0.0% | 0.0% | 0.0% | 0.3% | 0.3% | 0.3% |
| **SE\_N** | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| **SE\_S** | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| **UK\_N** | 0.1% | 0.1% | 0.5% | 0.3% | 0.9% | 0.7% |
| **UK\_S** | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |

**A4.2. Biomass use**

The regional results for biomass use are presented in table A4.2.1.

Table A4.2.1.: Biomass use in EJ for each region and time period

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **2030** | | **2040** | | **2050** | |
|  | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** |
| **BAL** | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 |
| **DE\_N** | 0.01 | 0.00 | 0.04 | 0.05 | 0.05 | 0.11 |
| **DE\_S** | 0.01 | 0.00 | 0.13 | 0.07 | 0.53 | 0.47 |
| **FI** | 0.01 | 0.00 | 0.02 | 0.01 | 0.03 | 0.03 |
| **IE** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| **NO** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **PO\_N** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| **PO\_S** | 0.00 | 0.00 | 0.01 | 0.01 | 0.03 | 0.05 |
| **SE\_N** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **SE\_S** | 0.00 | 0.00 | 0.01 | 0.01 | 0.02 | 0.02 |
| **UK\_N** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **UK\_S** | 0.00 | 0.00 | 0.08 | 0.03 | 0.20 | 0.23 |

**A4.3. Basic material use**

The regional results for basic material use are presented in table A4.3.1. to A4.3.4.

Table A4.3.1.: Cement use (kt)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **2030** | | **2040** | | **2050** | |
|  | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** |
| **BAL** | 3465 | 3466 | 1385 | 61 | 406 | 26 |
| **DE\_N** | 1340 | 1331 | 1239 | 1204 | 651 | 618 |
| **DE\_S** | 2696 | 2693 | 849 | 832 | 447 | 418 |
| **FI** | 498 | 778 | 199 | 1088 | 13 | 321 |
| **IE** | 771 | 697 | 2049 | 801 | 472 | 88 |
| **NO** | 1698 | 2103 | 2748 | 545 | 422 | 39 |
| **PO\_N** | 2372 | 2285 | 1361 | 5 | 387 | 7 |
| **PO\_S** | 3426 | 3401 | 1456 | 157 | 447 | 65 |
| **SE\_N** | 407 | 409 | 1686 | 1082 | 19 | 447 |
| **SE\_S** | 503 | 478 | 206 | 247 | 13 | 20 |
| **UK\_N** | 2633 | 2640 | 97 | 107 | 275 | 1375 |
| **UK\_S** | 752 | 751 | 70 | 181 | 952 | 751 |

Table A4.3.2.: Steel use (kt)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **2030** | | **2040** | | **2050** | |
|  | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** |
| **BAL** | 6823 | 6825 | 2724 | 123 | 797 | 298 |
| **DE\_N** | 3780 | 59 | 5007 | 562 | 1988 | 59 |
| **DE\_S** | 5319 | 822 | 1692 | 1656 | 886 | 822 |
| **FI** | 1012 | 631 | 392 | 2143 | 361 | 631 |
| **IE** | 1517 | 172 | 4026 | 1576 | 927 | 172 |
| **NO** | 38901 | 80 | 17758 | 1076 | 10663 | 80 |
| **PO\_N** | 4692 | 1122 | 2681 | 2133 | 759 | 1122 |
| **PO\_S** | 6758 | 128 | 2870 | 319 | 877 | 128 |
| **SE\_N** | 802 | 459 | 3316 | 1105 | 38 | 459 |
| **SE\_S** | 1017 | 32 | 407 | 267 | 361 | 32 |
| **UK\_N** | 5185 | 2700 | 863 | 216 | 3292 | 2700 |
| **UK\_S** | 1486 | 1940 | 139 | 358 | 1869 | 1940 |

Table A4.3.3.: Aluminium use (kt)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **2030** | | **2040** | | **2050** | |
|  | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** |
| **BAL** | 618 | 628 | 117 | 79 | 9 | 37 |
| **DE\_N** | 433 | 438 | 517 | 413 | 250 | 51 |
| **DE\_S** | 761 | 734 | 768 | 641 | 263 | 41 |
| **FI** | 104 | 103 | 41 | 33 | 0 | 19 |
| **IE** | 114 | 102 | 115 | 106 | 0 | 3 |
| **NO** | 122 | 477 | 60 | 162 | 0 | 67 |
| **PO\_N** | 1050 | 91 | 318 | 20 | 9 | 0 |
| **PO\_S** | 1004 | 980 | 318 | 305 | 9 | 2087 |
| **SE\_N** | 169 | 188 | 207 | 146 | 0 | 72 |
| **SE\_S** | 201 | 296 | 92 | 126 | 0 | 77 |
| **UK\_N** | 457 | 505 | 163 | 148 | 22 | 39 |
| **UK\_S** | 292 | 289 | 61 | 74 | 22 | 14 |

Table A4.3.4.: Copper use (kt)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **2030** | | **2040** | | **2050** | |
|  | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** |
| **BAL** | 823 | 837 | 155 | 105 | 13 | 49 |
| **DE\_N** | 839 | 848 | 712 | 579 | 333 | 86 |
| **DE\_S** | 1015 | 978 | 1024 | 855 | 350 | 54 |
| **FI** | 139 | 137 | 55 | 44 | 0 | 25 |
| **IE** | 152 | 136 | 154 | 141 | 0 | 5 |
| **NO** | 566 | 637 | 276 | 216 | 0 | 89 |
| **PO\_N** | 1400 | 122 | 423 | 26 | 13 | 0 |
| **PO\_S** | 1339 | 1306 | 423 | 406 | 13 | 2099 |
| **SE\_N** | 0 | 264 | 278 | 195 | 0 | 96 |
| **SE\_S** | 0 | 467 | 123 | 168 | 0 | 102 |
| **UK\_N** | 609 | 673 | 217 | 197 | 29 | 52 |
| **UK\_S** | 390 | 385 | 82 | 99 | 29 | 19 |

***A4.4. Installation rates***

The regional results for biomass use are presented in table A4.4.1. to A4.4.3.

Table 4.4.1: Average annual growth rates (%) in the Collaboration scenario in the period 2030-2040.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **COLLABORATION 2030 to 2040** | | | | | | | | | | | | |
|  | **SE\_N** | **SE\_S** | **DE\_N** | **DE\_S** | **BAL** | **PO\_S** | **IE** | **NO** | **FI** | **PO\_N** | **UK\_S** | **UK\_N** |
| Wind onshore | 13.6 |  |  | 0.1 |  |  | 3.6 | 5.8 | 7.7 |  |  |  |
| Wind offshore |  |  | 12.3 |  |  |  |  |  |  |  | 3.8 | 5.4 |
| PV |  |  | 16.4 | 11.6 |  | 55.2 |  |  |  |  | 15.0 |  |
| Biogas |  |  | 51.8 | 83.3 |  |  | 37.6 |  | 25.0 |  | 56.5 |  |
| Battery, Li-ion |  |  |  |  |  |  |  |  |  |  |  |  |
| Battery, Flow |  |  |  |  |  |  | 5.8 |  |  |  |  |  |
| Electrolyser | 26.3 | 20.9 | 51.2 | 74.3 |  |  |  |  |  |  |  |  |
| H2 storage | 74.2 | 70.7 | 114.7 | 148.6 |  |  |  |  |  |  |  |  |
| Heat pump |  | 0.3 | 4.7 | 8.3 | 0.1 | 0.6 | 14.2 | 3.4 |  |  | 13.1 | 18.4 |
| Electric boiler |  |  | 4.1 | 4.5 | 5.5 |  | 16.5 | 3.4 |  |  | 12.6 | 17.2 |
| TES tank |  |  | 5.9 | 20.3 |  |  | 20.8 |  |  |  | 19.3 | 20.2 |
| TES pit |  |  | 8.2 | 18.4 |  |  | 18.2 |  |  |  | 20.7 | 21.8 |

Table A4.4.2: Average annual growth rates (%) in the Collaboration scenario in the period 2040-2050.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **COLLABORATION 2040 to 2050** | | | | | | | | | | | | |
|  | **SE\_N** | **SE\_S** | **DE\_N** | **DE\_S** | **BAL** | **PO\_S** | **IE** | **NO** | **FI** | **PO\_N** | **UK\_S** | **UK\_N** |
| Wind onshore |  |  |  |  |  |  |  |  |  |  |  |  |
| Wind offshore |  |  | 1.7 |  |  |  |  |  |  | 5.8 | 7.4 | 21.2 |
| PV |  | 7.7 | 5.9 | 4.3 |  | 8.8 |  |  |  | 26.1 | 6.1 |  |
| Biogas |  |  | 4.5 | 4.5 |  |  |  |  | 19.6 |  | 8.8 |  |
| Battery, Li-ion |  |  |  |  |  |  |  |  |  |  |  |  |
| Battery, Flow |  |  |  |  |  |  |  |  |  |  |  |  |
| Electrolyser |  | 0.1 | 5.2 | 0.2 |  |  |  |  |  |  |  |  |
| H2 storage |  |  | 1.6 |  |  |  |  |  |  |  |  |  |
| Heat pump | 2.4 | 1.9 | 3.2 | 5.0 | 2.1 | 1.9 | 6.6 | 2.8 | 0.8 | 2.5 | 9.3 | 6.6 |
| Electric boiler | 1.6 | 1.0 | 6.2 | 13.4 |  | 0.9 |  | 2.8 | 0.5 | 3.2 | 6.9 | 3.4 |
| TES tank |  |  | 0.6 | 4.1 |  |  | 3.8 |  |  |  | 5.9 | 5.0 |
| TES pit |  |  |  |  |  |  |  |  |  |  | 1.8 |  |

Table A4.4.3.: Average annual installation rate (GW(h)/yr) per region in Collaboration scenario in the period 2030-2040.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **COLLABORATION 2030 to 2040** | | | | | | | | | | | | |
|  | **SE\_N** | **SE\_S** | **DE\_N** | **DE\_S** | **BAL** | **PO\_S** | **IE** | **NO** | **FI** | **PO\_N** | **UK\_S** | **UK\_N** |
| Wind onshore | 1.9 |  |  |  |  |  | 0.6 | 1.7 | 1.5 |  |  |  |
| Wind offshore |  |  | 1.7 |  |  |  |  |  |  | 0.2 | 0.4 |  |
| PV |  |  | 6.4 | 5.4 |  | 2.2 |  |  |  | 0.2 | 3.5 |  |
| Biogas |  |  | 0.6 | 4.3 |  |  | 0.2 |  | 0.1 |  | 0.9 |  |
| Battery, Li-ion |  |  |  |  |  |  |  |  |  |  |  |  |
| Battery, Flow |  |  |  |  |  |  | 0.2 |  |  |  |  |  |
| Electrolyser | 0.1 | 0.1 | 0.6 | 2.6 |  |  |  |  |  |  |  |  |
| H2 storage | 2.6 | 2.1 | 20.8 | 90.2 |  |  |  |  |  |  |  |  |
| Heat pump |  |  | 0.4 | 1.0 |  |  |  |  |  |  | 0.3 |  |
| Electric boiler |  |  | 0.1 | 0.1 |  |  |  |  |  |  | 0.3 |  |
| TES tank |  |  | 1.6 | 6.3 |  |  | 0.1 |  |  |  | 4.5 | 0.4 |
| TES pit |  |  | 18.0 | 37.3 |  |  | 1.8 |  |  |  | 22.3 | 2.2 |

**A4.5 Fossil emissions phase out rates**

The combined produced electricity and installed capacity of fossil fuelled power without CCS for all regions obviously decreases in both scenarios and is presented in Figure A4.5.1. The phase out rates, both in terms of capacity and production, differ between scenarios. The phase out rates for different regions, the capacity and electricity production from different fossil fuel sources without CCS are presented in Appendix III. Important to note is that the plants are phased out when their technical end of life has been reached, not their economic lifetime. This means that the capacity is only retired the end of lifetime, not due to low utilization.

The phase out of coal in terms of production is faster for the No Collaboration scenario, even though no coal capacity remains in 2050 in either scenario. The phase out rate of natural gas usage is however slower in the No Collaboration scenario.

There are investments into new gas capacity in the No Collaboration case which decreases the phase out rate for gas capacity. Phase out rate for coal capacity is the same for the two scenarios since no new investments are made into new coal plants.

One important difference between the scenarios is that in the No Collaboration scenario there are large investments into new CCS plants, with no net emissions, using a mix of coal and biomass as fuel, but in the Collaboration scenario the investments into CCS are very low. This implies that some of the coal industry related jobs will be maintained in this scenario but at significant lower level.

Chart, histogram

Description automatically generated

**Figure A4.5.1.** Generation and installed capacity of fossil fuelled power plants in the different scenarios in different years. The model is not run for 2020, therefore the production is not presented for that year.

Table A4.5.1.: Coal power capacity and generation (GW/TWh)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **2030** | | **2040** | | **2050** | |
|  | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** |
| **BAL** | 0.04/0.50 | 0.04/0.042 | 0.04/0.03 | 0.04/0.01 | 0.00/0.00 | 0.00/0.00 |
| **DE\_N** | 10.17/18.81 | 10.17/16.01 | 6.52/7.35 | 6.52/3.54 | 3.35/0.00 | 3.35/0.00 |
| **DE\_S** | 7.96/16.92 | 7.96/15.41 | 6.15/6.60 | 6.15/2.87 | 0.91/0.00 | 0.91/0.00 |
| **FI** | 0.36/0.22 | 0.36/0.23 | 0.13/0.14 | 0.13/0.08 | 0.13/0.00 | 0.13/0.00 |
| **IE** | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 |
| **NO** | 0.04/0.02 | 0.04/0.02 | 0.04/0.04 | 0.04/0.01 | 0.00/0.00 | 0.00/0.00 |
| **PO\_N** | 0.19/0.10 | 0.19/0.09 | 0.01/0.01 | 0.01/0.00 | 0.00/0.00 | 0.00/0.00 |
| **PO\_S** | 5.85/7.77 | 5.85/6.47 | 3.05/2.90 | 3.05/1.51 | 1.22/0.00 | 1.22/0.00 |
| **SE\_N** | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 |
| **SE\_S** | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 |
| **UK\_N** | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 |
| **UK\_S** | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 |
| **Total** | 24.64/43.91 | 24.60/38.26 | 15.92/17.06 | 15.92/8.02 | 5.61/0.00 | 5.61/0.00 |

Table A4.5.2.: Gas power capacity and generation (GW/TWh)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **2030** | | **2040** | | **2050** | |
|  | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** |
| **BAL** | 2.25/1.27 | 2.25/0.98 | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 |
| **DE\_N** | 13.00/14.17 | 13.00/12.74 | 1.20/2.50 | 1.20/2.06 | 0.00/0.00 | 0.00/0.00 |
| **DE\_S** | 14.13/25.57 | 27.85/51.63 | 4.49/11.55 | 18.21/40.46 | 3.35/0.00 | 17.08/2.31 |
| **FI** | 0.23/0.17 | 1.09/0.84 | 0.00/0.00 | 0.86/1.01 | 0.00/0.00 | 0.86/0.04 |
| **IE** | 5.46/4.56 | 5.46/4.61 | 0.95/1.42 | 0.95/1.45 | 0.00/0.00 | 0.00/0.00 |
| **NO** | 1.62/0.64 | 1.62/0.61 | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 |
| **PO\_N** | 0.64/0.86 | 2.73/1.74 | 1.07/2.60 | 3.74/5.04 | 0.00/0.00 | 3.13/0.18 |
| **PO\_S** | 1.29/1.27 | 4.55/7.19 | 1.19/2.33 | 4.45/9.89 | 0.00/0.00 | 3.25/0.59 |
| **SE\_N** | 0.00/0.00 | 0.00 | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 | 0.00/0.00 |
| **SE\_S** | 0.32/0.16 | 0.32/0.11 | 0.02/0.05 | 0.02/0.03 | 0.00/0.00 | 0.00/0.00 |
| **UK\_N** | 14.15/22.68 | 24.60/28.40 | 5.65/13.33 | 14.55/19.43 | 3.97/0.00 | 12.87/0.43 |
| **UK\_S** | 0.01/0.01 | 0.01/0.01 | 0.03/0.07 | 0.00/0.00 | 0.03/0.00 | 0.00/0.00 |
| **Total** | 53.11/71.35 | 83.48/108.87 | 14.60/33.85 | 43.98/79.37 | 7.81/0.00 | 37.19/3.56 |

Table A4.5.3.: Phase out rates of gas and coal power capacity and generation

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **2020-2030** | | **2030-2040** | | **2040-2050** | |
|  | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** |
| **Coal production** | - | - | 6.1% | 7.9% | 10.0% | 10.0% |
| **Gas production** | - | - | 5.3% | 2.7% | 10.0% | 9.6% |
| **Coal capacity** | 6.9% | 6.9% | 3.5% | 3.5% | 6.5% | 6.5% |
| **Gas capacity** | 7.2% | 5.6% | 7.3% | 4.7% | 4.6% | 1.5% |

**A4.6. Sectoral emissions reduction rate**

The results for total and sectoral emission intensities are presented in table A4.6.1.

Table A4.6.1.: Total and sectoral emission intensities

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Total CO2 intensity** |  | **2020** | **2030** | **2040** | **2050** |
| Electricity system | gCO2/kWh(el) | Collaboration | 230 | 32 | 11 | 0 |
|  |  | No Collaboration | 230 | 35 | 16 | 1 |
|  |  |  |  |  |  |  |
| Transport | gCO2/km | Collaboration | 122 | 64 | 38 | 0 |
|  |  | No Collaboration | 122 | 66 | 41 | 0 |
|  | Electrification rate, % | |  | 50 | 70 | 100 |
| Heat | gCO2/kWh(heat) | Collaboration | 200 | 185 | 107 | 18 |
|  |  | No Collaboration | 200 | 185 | 107 | 18 |
|  | Electrification rate, % | |  | 9 | 50 | 91 |
| Industry | kgCO2/tonne steel | Collaboration | 1600 | 1600 | 625 | 0 |
|  |  | No Collaboration | 1600 | 1600 | 654 | 3 |
|  | Electrification rate, % | |  |  | 65 | 100 |
|  | **CO2 intensity of electricity sector and electrified sectors, gCO2/kWh(el)** | | | **2030** | **2040** | **2050** |
| Electricity system | | Collaboration |  | 32 | 11 | 0 |
|  |  | No Collaboration |  | 35 | 16 | 1 |
|  |  |  |  |  |  |  |
| Transport |  | Collaboration |  | 29 | 12 | 0 |
|  |  | No Collaboration |  | 54 | 25 | 1 |
|  |  |  |  |  |  |  |
| Heat |  | Collaboration |  | 64 | 29 | 0 |
|  |  | No Collaboration |  | 68 | 28 | 1 |
|  |  |  |  |  |  |  |
| Industry |  | Collaboration |  | - | 16 | 0 |
|  |  | No Collaboration |  | - | 24 | 1 |

***A4.7. Investment cost ratio***

The investment cost ratios on country level are presented in table A4.7.1.

Table A4.7.1.: The ICtGDP ratios in % for each country and time period

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **2030** | | **2040** | | **2050** | |
|  | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** |
| **Sweden** | 0.36% | 0.36% | 0.46% | 0.33% | 0.13% | 0.13% |
| **Germany** | 0.30% | 0.32% | 0.73% | 0.66% | 0.40% | 0.44% |
| **Baltics** | 2.89% | 3.00% | 0.04% | 0.13% | 0.02% | 0.16% |
| **Poland** | 0.78% | 0.85% | 0.21% | 0.30% | 0.29% | 0.15% |
| **Ireland** | 0.46% | 0.49% | 0.38% | 0.47% | 0.05% | 0.06% |
| **Norway** | 0.73% | 0.90% | 0.52% | 0.19% | 0.01% | 0.01% |
| **Finland** | 0.74% | 0.67% | 0.65% | 0.59% | 0.17% | 0.24% |
| **UK** | 0.19% | 0.22% | 0.26% | 0.22% | 0.25% | 0.22% |

***A4.8. Running to capital cost ratio***

The ratio between the running and capital costs for the electricity system in the region modelled increases with time for both investigated scenarios. The RtCC (running-to-capital cost) ratios in the Collaboration and No Collaboration scenarios increase from 13% and 15% in Year 2030 to 17% and 22% in Year 2050, respectively. However, on the regional level these increases in the RtCC ratio are not consistent across the geographical scope (see Table A3-18, Appendix A for the RtCC ratios in all the investigated regions). For example, the RtCC ratio of the Southern Germany region increases by Year 2050, as compared to 2030, by 24 p.p. in the Collaboration Scenario and by 17 p.p. in the No Collaboration scenario. Whereas, the RtCC ratio for the Southern UK region decreases from 9% to 3% in both scenarios during the same period. This is mainly due to increased investments in biomass-fired CHPs in Germany and wind and solar power in the UK.

Table A4.8.1.: The RtCC ratios in % for each region and time period

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **2030** | | **2040** | | **2050** | |
|  | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** |
| **BAL** | 4% | 4% | 5% | 5% | 3% | 3% |
| **DE\_N** | 16% | 14% | 8% | 13% | 6% | 17% |
| **DE\_S** | 21% | 26% | 19% | 29% | 45% | 43% |
| **FI** | 12% | 14% | 8% | 10% | 15% | 17% |
| **IE** | 16% | 15% | 8% | 8% | 4% | 9% |
| **NO** | 3% | 3% | 3% | 3% | 3% | 3% |
| **PO\_N** | 5% | 6% | 8% | 12% | 3% | 7% |
| **PO\_S** | 8% | 11% | 9% | 13% | 10% | 15% |
| **SE\_N** | 2% | 2% | 3% | 3% | 2% | 2% |
| **SE\_S** | 15% | 16% | 11% | 13% | 18% | 17% |
| **UK\_N** | 9% | 9% | 7% | 7% | 3% | 3% |
| **UK\_S** | 18% | 20% | 16% | 23% | 17% | 32% |

***A4.9. Changing load patterns***

Both investigated scenarios, Collaboration and No collaboration, show a significant change in load profile compared to current electricity use. Figure A4.9.1 gives the correlation between the current load profile and the load profile derived from the modelling for Years 2030, 2040 and 2050, i.e. when there is an increased share of VRE as well as integration of new loads in the form of EVs, hydrogen production via electrolysers and power to heat, i.e., there is a significant change in load profile already by Year 2030. Yet, it can be seen that without collaboration, a scenario with fewer new dynamic energy consumers, the future load profiles have generally higher correlation to present electricity use. It should be noted that there is electrification of transportation in both scenarios, which explains the rather low correlation also in the No collaboration scenario. Further, it can be expected that the energy system management, e.g. market setup and rules, need more adaption in futures with lower correlation between current and future loads, and thus, this type of indicator can point to need for policy action.

A close up of a map

Description automatically generated

Figure A4.9.1. Correlation between the current load profile and the load profile derived from the modeling of the future scenarios. A correlation factor close to one indicates a load similar to current electricity use.

**A4.10. System structure – Degree of decentralization**

Table A4.10.1. presents the share of electricity generation, consumption, storage and cross-regional trade divided into decentralised and centralised from the modelling results for Year 2050. Here we categorise as decentralised the energy technologies and demands that are small in size and distributed over a larger number of units, such as electric vehicles, and those that are operated in a small-scale systems, such as district heating systems. As centralised systems, we define large-scale generation and demands, such as hydrogen demand for industrial processes (see table A3.6.1.). Decentralised technologies often offer flexibility on distribution grid scale, while centralised technologies are used for balancing over larger geographical areas. The share of electricity generation that can be decentralised is slightly higher in the Collaboration scenario than in the No Collaboration scenario. While electricity demand is higher for EVs than for electrolysis, an equally large storage volume is available for hydrogen storages as compared to the batteries in the part of the electric vehicle fleet that is available for smart charging and V2G in the Collaboration scenario. The battery systems in the No Collaboration scenario can be installed both centralised and decentralised, which is not distinguished in the modelling tool. In the *Collaboration* scenario also thermal storages are utilised, which can be categorised as decentral on a city/municipality level. However, the focus in Table A4.10.1. is on technologies, which utilise or generate electricity. The cross-regional trade considered in the modelling as a centralised variation management strategy is almost equally large in both the model scenarios. Understanding the degree of decentralisation in energy supply, demand and flexibility potential is important in order to determine which actors and at what levels (e.g. municipal, national, European) energy policies and regulations should target. For example, to secure that the large storage volume available in decentralised EV batteries in the *Collaboration* scenario can be used in an efficient way, will most likely require policies aimed at private car owners and municipal actors that design EV charging infrastructure. A large share of centralised cross-regional electricity trade on the other hand requires infrastructure maintained and constructed on a national or European level.

Table 4.10.1. Share of decentralised and centralised electricity generation, consumption, storage and cross-regional trade, given for the sum of all modelled regions in the two scenarios for Year 2050.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Scenario:** | **Collaboration** | | **No Collaboration** | |
|  | **Decentralised** | **Centralised** | **Decentralised** | **Centralised** |
| **Electricity generation** [share of total generation] | 0 – 0.19 a | 0.81 – 1.0a | 0 – 0.16 a | 0.84 – 1.0 a |
| **Electricity consumption** [share of total consumption] c | 0.26  *(EV: 0.16, P2H: 0.1)* | 0.13  *(Electrolyser* b*)* | 0.26  *(EV: 0.16, P2H: 0.1)* | 0.13  *(Electrolyser* b*)* |
| **Storage** [share of total storage energy volume] | 0.5d  *(EV)* | 0.5d *(H2* b*)* | 0 - 1 d  *(Bat)* | 0 - 1 d  *(Bat)* |
| **Cross-regional trade** [share of total electricity generation] | 0 | 0.24 | 0 | 0.22 |

a The modelling tool does not separate between decentral and central solar PV, which explains the range given for the electricity generation.   
b Hydrogen demand is added to the modelling to represent the replacement of coke in the steel industry with hydrogen. As the only source for hydrogen production in the modelling is through electricity, electrolysers and H2 storage have been added to the table.   
c The model utilises in addition to the loads given in the table also an electricity load profile that includes both, decentral and central demands for each region. Thus, the shares do not add up to 1, only the part of the electricity consumption which is clearly decentralised and centralised in the two scenarios is given in the table.  
d The share of batteries in the *Collaboration* scenario is <0.01 and has therefore been omitted in the table. In the *No Collaboration* scenario batteries are the only source of electricity storage and can be employed both, decentral and central.

Table A4.10.2.:Additional results for the “Degree of decentralisation” indicator, for both scenarios and Years 2030 and 2040.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Collaboration** |  | **No Collaboration** |  |
|  | **Decentralised** | **Centralised** | **Decentralised** | **Centralised** |
| **2030** |  |  |  |  |
| Electricity generation [share of total generation] | 0.01 – 0.04 | 0.96 – 0.99 | 0.01 – 0.04 | 0.96 – 0.99 |
| Electricity consumption [share of total consumption] | 0.16  *(EV: 0.1, P2H: 0.06)* | 0  *(Electrolyser)* | 0.16  *(EV: 0.1, P2H: 0.06)* | 0  *(Electrolyser)* |
| Storage  [share of total storage energy volume] | 1  *(EV:0.99, Bat: 0.01)* | 0 *(H2* b*)* | 0 - 1  *(Bat)* | 0 - 1  *(Bat)* |
| Cross-regional trade [share of total electricity generation] | 0 | 0.22 | 0 | 0.22 |
| **2040** |  |  |  |  |
| Electricity generation [share of total generation] | 0.01 – 0.13 | 0.87 – 0.99 | 0 – 0.10 | 0.90 – 1.0 |
| Electricity consumption [share of total consumption] | 0.2  *(EV: 0.12, P2H: 0.08)* | 0.1  *(Electrolyser**)* | 0.2  *(EV: 0.12, P2H: 0.08)* | 0.1  *(Electrolyser**)* |
| Storage  [share of total storage energy volume] | 0.48  *(EV)* | 0.52 *(H2* b*)* | 0 - 1  *(Bat)* | 0 - 1  *(Bat)* |
| Cross-regional trade [share of total electricity generation] | 0 | 0.26 | 0 | 0.24 |

While the results above use the degree of decentralisation indicator on the total system modelled, Table A4.10.3 gives an example of analysing the system structure with respect to the different modelled regions. The table presents results for the degree of decentralisation in the electricity consumption. On the centralised side the introduction of hydrogen in the steel industry can clearly be seen in Sweden, the UK and Poland in 2040 and 2050. On the decentralised side a gradual increase in electrification of transport and usage of power-to-heat technologies over time can be seen in all regions.

Table A4.10.3.:Regional results for degree of decentralisation of the electricity consumption (both the Collaboration and No Collaboration scenarios yield the same numbers).

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | | **2030** | | | **2040** | | | **2050** | |
|  | **Decentralised** | | **Centralised** | **Decentralised** | | **Centralised** | **Decentralised** | | **Centralised** |
| **BAL** | 0.25 | | 0 | 0.29 | | 0 | 0.34 | | 0 |
| **DE\_N** | 0.18 | | 0 | 0.23 | | 0.09 | 0.27 | | 0.17 |
| **DE\_S** | 0.18 | | 0 | 0.2 | | 0.25 | 0.27 | | 0.23 |
| **FI** | 0.17 | | 0 | 0.19 | | 0 | 0.19 | | 0.14 |
| **IE** | 0.13 | | 0 | 0.18 | | 0 | 0.23 | | 0 |
| **NO** | 0.03 | | 0 | 0.04 | | 0 | 0.06 | | 0 |
| **PO\_N** | 0.22 | | 0 | 0.27 | | 0 | 0.34 | | 0 |
| **PO\_S** | 0.23 | | 0 | 0.28 | | 0 | 0.3 | | 0.12 |
| **SE\_N** | 0.05 | | 0 | 0.04 | | 0.39 | 0.06 | | 0.39 |
| **SE\_S** | 0.14 | | 0 | 0.16 | | 0.06 | 0.2 | | 0.06 |
| **UK\_N** | 0.14 | | 0 | 0.21 | | 0 | 0.28 | | 0.05 |
| **UK\_S** | 0.15 | | 0 | 0.23 | | 0 | 0.31 | | 0 |

***A4.11. Import dependency and export dependency***

The regional results for import and export dependency are presented in tables A4.11.1 and A4.11.2.

Table A4.11.1.: Import dependency for all regions, years and scenarios.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **2030** | | **2040** | | **2050** | |
|  | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** |
| **BAL** | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 |
| **DE\_N** | 0.19 | 0.21 | 0.08 | 0.12 | 0.11 | 0.13 |
| **DE\_S** | 0.33 | 0.31 | 0.47 | 0.37 | 0.40 | 0.26 |
| **FI** | 0.19 | 0.15 | 0.13 | 0.12 | 0.19 | 0.19 |
| **IE** | 0.08 | 0.05 | 0.10 | 0.05 | 0.13 | 0.07 |
| **NO** | 0.10 | 0.26 | 0.04 | 0.23 | 0.06 | 0.21 |
| **PO\_N** | 0.12 | 0.09 | 0.09 | 0.03 | 0.05 | 0.03 |
| **PO\_S** | 0.24 | 0.23 | 0.19 | 0.19 | 0.18 | 0.26 |
| **SE\_N** | 0.08 | 0.08 | 0.01 | 0.03 | 0.02 | 0.02 |
| **SE\_S** | 0.32 | 0.32 | 0.62 | 0.58 | 0.61 | 0.69 |
| **UK\_N** | 0.01 | 0.02 | 0.04 | 0.05 | 0.07 | 0.07 |
| **UK\_S** | 0.20 | 0.20 | 0.20 | 0.24 | 0.17 | 0.23 |

Table A4.11.2.: Export dependency for all regions. years and scenarios.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **2030** | | **2040** | | **2050** | |
|  | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** |
| **BAL** | 0.74 | 0.72 | 0.73 | 0.72 | 0.71 | 0.71 |
| **DE\_N** | 0.03 | 0.04 | 0.16 | 0.10 | 0.18 | 0.10 |
| **DE\_S** | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.02 |
| **FI** | 0.06 | 0.05 | 0.14 | 0.14 | 0.06 | 0.08 |
| **IE** | 0.34 | 0.28 | 0.46 | 0.44 | 0.40 | 0.40 |
| **NO** | 0.42 | 0.44 | 0.50 | 0.49 | 0.52 | 0.51 |
| **PO\_N** | 0.43 | 0.42 | 0.46 | 0.46 | 0.46 | 0.46 |
| **PO\_S** | 0.17 | 0.18 | 0.18 | 0.19 | 0.12 | 0.09 |
| **SE\_N** | 0.65 | 0.64 | 0.72 | 0.67 | 0.71 | 0.71 |
| **SE\_S** | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| **UK\_N** | 0.64 | 0.63 | 0.58 | 0.61 | 0.57 | 0.61 |
| **UK\_S** | 0.02 | 0.02 | 0.03 | 0.02 | 0.03 | 0.02 |

***A4.12 Operating reserves***

In addition to Figure 8 shown in the Results section of the paper for reserves, there is also value in having a single number to give a quick indication of differences between regions or scenarios. Either maximum duration or number of hours of low reserves could be fitting for such an indicator, the first indicating how large of a storage would be needed to cover the worst event, and the second indicating the general lack of reserves. In Table A4.12.1 below, such values can be found for all scenarios, regions and years.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Table A4.12.1:Total number of hours with insufficient reserves for all regions, years and scenarios. | | | | | |  |
|  | **2030** | | **2040** | | **2050** | |
|  | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** |
| **BAL** | 0 | 231 | 78 | 7125 | 30 | 6798 |
| **DE\_N** | 21 | 267 | 165 | 7257 | 18 | 7566 |
| **DE\_S** | 24 | 492 | 27 | 975 | 78 | 39 |
| **FI** | 0 | 1437 | 39 | 42 | 3 | 15 |
| **IE** | 0 | 207 | 0 | 825 | 96 | 6843 |
| **NO** | 48 | 93 | 51 | 2397 | 42 | 2340 |
| **PO\_N** | 117 | 372 | 78 | 675 | 90 | 6891 |
| **PO\_S** | 3 | 708 | 75 | 1584 | 66 | 7404 |
| **SE\_N** | 204 | 2412 | 174 | 2880 | 72 | 2553 |
| **SE\_S** | 81 | 3924 | 30 | 4044 | 15 | 3693 |
| **UK\_N** | 39 | 8241 | 111 | 8262 | 108 | 7293 |
| **UK\_S** | 57 | 438 | 159 | 894 | 129 | 3 |
|  |  |  |  |  |  |  |
| Table A4.12.2:Longest continuous event (in hours) with insufficient reserves for all regions, years and scenarios. | | | | | | |
|  | **2030** | | **2040** | | **2050** | |
|  | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** | **Collaboration** | **No Collaboration** |
| **BAL** | 0 | 15 | 45 | 876 | 21 | 903 |
| **DE\_N** | 21 | 18 | 42 | 969 | 15 | 885 |
| **DE\_S** | 21 | 18 | 24 | 27 | 75 | 15 |
| **FI** | 0 | 87 | 21 | 15 | 3 | 9 |
| **IE** | 0 | 15 | 0 | 27 | 27 | 489 |
| **NO** | 45 | 15 | 24 | 114 | 24 | 132 |
| **PO\_N** | 72 | 21 | 33 | 30 | 39 | 348 |
| **PO\_S** | 3 | 48 | 24 | 48 | 63 | 546 |
| **SE\_N** | 90 | 234 | 39 | 300 | 45 | 135 |
| **SE\_S** | 24 | 135 | 21 | 117 | 15 | 120 |
| **UK\_N** | 33 | 1665 | 30 | 1563 | 54 | 1170 |
| **UK\_S** | 27 | 21 | 48 | 27 | 45 | 3 |

As can be seen in Table A4.12.2: there is no universally true trend across all regions. However, most regions and years have less issues with reserves in the Collaboration scenario due to the higher access to flexibility and high storage capacities in EVs. Furthermore, while the two indicators (Maximum duration and number of events) often follow the same trend between years and scenarios, there are some cases where they do not. There is also a distinct difference between the two scenarios, both in 2030, 2040 and 2050. This indicates that the increased flexibility of sector collaboration also has an impact on frequency control – even if the collaboration itself is not for frequency control. This is exemplified in the Results section where the increased flexibility in the Collaboration scenario leads to the available storage being used less and thus more available as reserves.

# References

1. IEA, *World Energy Outlook 2016*. 2016.

2. Mone, C., et al., *2015 Cost of Wind Energy Review*. 2017, National Renewable Energy Laboratory: Golden, Colorado.

3. Jordan, G. and S. Venkataraman, *Analysis of Cycling Costs in Western Wind and Solar Integration Study*. 2012: United States.

4. Persson, J., et al., *Lastföljning i kärnkraftverk*, Elforsk, Editor. 2012.

5. Thunman, H., A. Larsson, and M. Hedenskog. *Commissioning of the GoBiGas 20 MW biomethane plant*. in *The international conference on thermochemical conversion science*. 2015. Chicago, IL USA: Gas technology institute.

6. Johansson, V., et al., *Value of wind power – Implications from specific power.* Energy, 2017. **126**: p. 352-360.

7. Lucchesi, R., *File specification for MERRA products*, in *GMAO office note no. 1 (version 2.3)*. 2012.

8. ECMWF. *ERA-Interim u- and v-components of horizontal wind, surface solar radiation downward, skin temperature*. 2010 [cited 2010 2010-10-10].

9. Nilsson, K. and T. Unger, *Bedömning av en europeisk vindkraftpotential med GIS-analys*. 2014, PROFU.

10. Norwood, Z., et al., *A geospatial comparison of distributed solar heat and power in europe and the US.* PLoS ONE, 2014. **9**(12): p. 1-31.

11. Energistyrelsen, *Technology data for energy plants*. 2012.

12. Wolsink, M., *Wind power and the NIMBY-myth: institutional capacity and the limited significance of public support.* Renewable Energy, 2000. **21**(1): p. 49-64.

13. Johnsson, F., J. Kjärstad, and J. Rootzén, *The threat to climate change mitigation posed by the abundance of fossil fuels.* Climate Policy, 2019. **19**(2): p. 258-274.

14. Göransson, L., et al., *The Benefit of Collaboration in the North European Electricity System Transition—System and Sector Perspectives.* Energies, 2019. **12**(24): p. 4648.

15. *Average CO2 emissions from new light-duty vehicles registered in Europe increased in 2019, requiring significant emission reductions to meet the 2020 targets*. 2020; Available from: <https://ec.europa.eu/clima/news/average-co2-emissions-new-light-duty-vehicles-registered-europe-2019_en#:~:text=The%20provisional%20data%20shows%20that,km%20that%20applied%20until%202019>.

16. Bertelsen, N. and B. Vad Mathiesen, *EU-28 Residential Heat Supply and Consumption: Historical Development and Status.* Energies, 2020. **13**(8): p. 1894.

17. EUROFER, *Steel Roadmap for a Low Carbon Europe 2050*. 2013.

18. Funcke, S. and D. Bauknecht, *Typology of centralised and decentralised visions for electricity infrastructure.* Utilities Policy, 2016. **40**: p. 67-74.

19. McKenna, R., *The double-edged sword of decentralized energy autonomy.* Energy Policy, 2018. **113**: p. 747-750.

20. Energien, A.f.E. [cited 2020 09.07]; Available from: <https://www.foederal-erneuerbar.de/uebersicht/bundeslaender/BW>|B|BB|HB|HH|HE|MV|NI|NRW|RLP|SL|SN|ST|SH|TH|D/kategorie/top%2010/auswahl/726-neu\_installierte\_lei/versatz/1/#goto\_726.