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Report

Scenario quantification for the power sector in Europe and Norway until 2050

Linking of an integrated assessment model and a power system model

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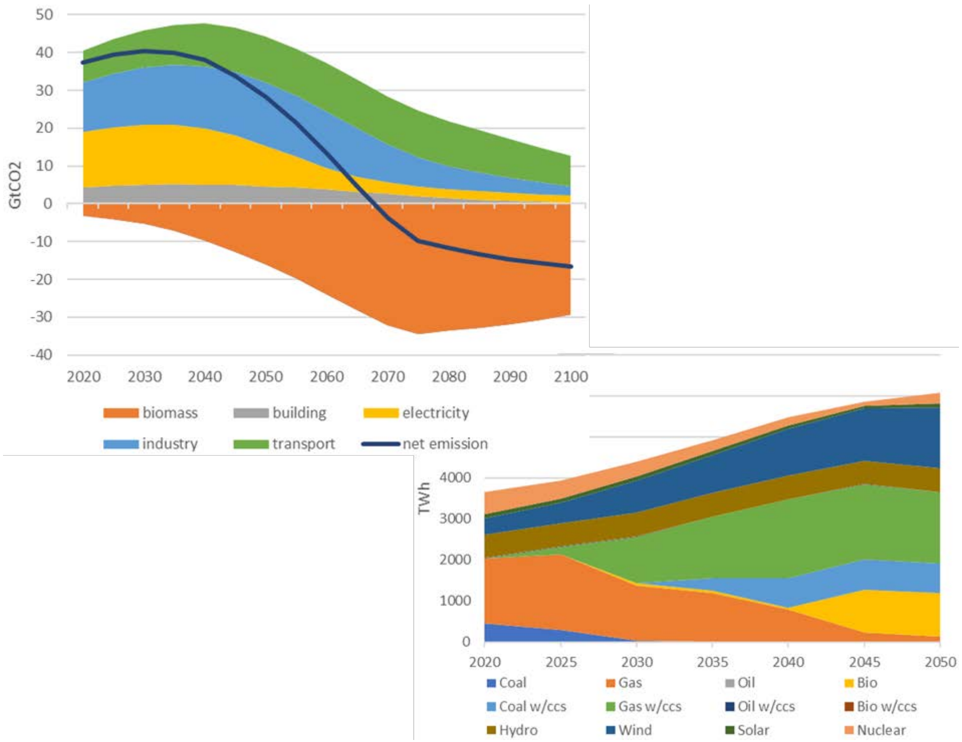

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ABSTRACT

In order to quantify a set of scenarios for the European and Norwegian energy system, a set of two linked models is applied. These comprise a global assessment model and an expansion model for the European power system. This setup of linked model allows to apply global framework developments in more specific sector models on a regional basis.

For the assessment of defined energy scenarios, global shared socioeconomic pathways are simulated in the global assessment models. Analysis results are then to provide a framework for cases, which are assessed in a power system expansion model, to achieve more detailed insight to the development European and Norwegian power system in the light of a necessary transition to a low emission society.

Results show that global development pathways have a significant impact on the European energy sector. Furthermore, a faster technology development allows for a postponing of emission reduction but relies on the availability of negative emission technologies in the second half of our century.

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APPENDICES

[List appendices here]

Abbreviations

IA(M) – Integrated assessment (model)

CCS – Carbon Capture and Storage

RCP – Representative Concentration Pathway

SSP – Shared Socio-economic Pathway

GCAM – Global Change Assessment Model

EMPIRE – European Model for Power system Investment with (high shares of) Renewable Energy

1 Introduction

The FME CenSES' research objective is to conduct research that supports public and private decision makers in strategic decisions and policies that will promote environment-friendly energy technologies and lead to a sustainable energy system. The objective of research area 5 in CenSES, "Scenario development", is to provide knowledge to policy- and decision makers based on scenario studies. In this framework, s in research area 5 defines and assesses a number of CenSES energy scenarios, including the qualitative and quantitative description in the form of pathways with model-based scenario analyses. The assessment is based on an improved modelling framework for scenario analysis, which is developed in co-operation with research area 2 "Energy systems and markets". Research area 2 targets the development of models and analysis methods.

The initial part of this process was the definition of scenarios, established for the horizon 2050 in a qualitative way. The following aim is to provide pathways for a selection of these scenarios. These pathways shall comprise a qualitative and quantitative description of the development of the Norwegian and European energy system to 2050. The general activity for research area 5 is sketched in Figure 1, where this report focusses on the circles "Quantification" and "Storylines", while a previous report (Jaehnert, 2016) focussed on the first two steps "Key research questions" and "Scenario definition". The development of "Pathways" based on model analyses will be the objective of future research activity.

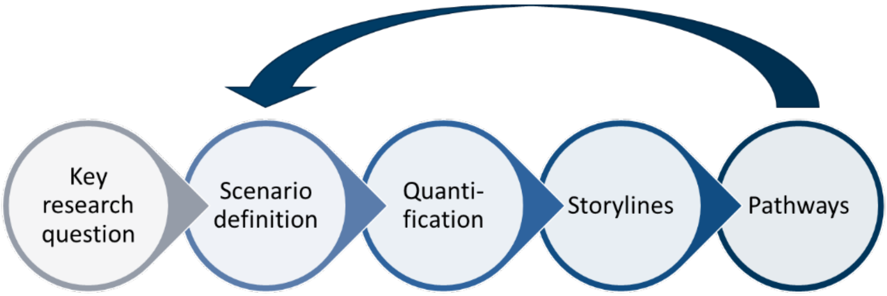

Figure 1: Development activity sketch in CenSES research area 5

This report describes analysis methods, that are applied to quantify selected energy scenarios and to draw storylines for the development of the European and Norwegian energy system. Storylines in the case of this report cover the discussion of the analysis results and a description of the future developments that can be observed in the analyses. The analysis results are presented and discussed for the global framework of the scenarios, as well as in the European and Norwegian power sector context.

As illustrated in Figure 1, the scenario development and assessment is an iterative process. Even though the process is not finalised, there are a number of lessons learnt from the development process, which to a substantial extend is based on cross-disciplinary discussion. These exchange on specific topics provided the possibility to familiarise with research methods of other disciplines. Finally, the process has led to a critical evaluation of the input to the quantification and the analyses and results of the quantification. This will be discussed later in the report.

1.1 Scenario definition

The developed CenSES energy scenarios address Norwegian energy and climate policies and consider EU and global policies where relevant. The main target group for the scenario results are policy and decision makers in Norway (in particular CenSES user partners) and Europe. These scenarios are based upon the cross-disciplinary knowledge developed in CenSES and include both quantitative and qualitative aspects. The main purpose of the scenarios is to define the scope, boundary conditions, parameter data and framework for the energy system analyses to be carried out in the next step. A bottom-up approach is applied to develop the scenarios. The scenarios are a combination of different futures and strategies, which combined described a potential development of the energy system within a global framework.

Future: A future is a possible development / prospective state of the system. It is the combination of various uncertainties, which mostly comprises EU / global developments that Norwegian society has rather limited or no influence on. The five futures are:

- Grass roots – A mitigation driven by local communities
- Fossil society – Relies on advanced technological solutions
- Green governance – Institutional driven mitigation efforts
- National ways – National concerns and well-being in the focus
- Green globe – Common mitigation efforts within and across countries

Strategies: The strategies are the combinations of various options, which the target group for the analyses can influence. In the context of the CenSES energy scenarios, this mostly comprises decisions with a Norwegian focus. The specification of the strategies was done in two main steps, as for the futures. The four strategies are:

- Renewable energy hub – Export of RES and flexibility sources
- Norwegian identity – Domestic energy use to preserve economy
- Power Gas & Oil – Value based on export of all energy resources
- New climate economy – Carbon neutral economy based on domestic RES

Combining futures and strategies provides a large number of scenarios, where two of these are chosen for the further quantification process.

1.2 Model analyses

In the further process the global framework is broken down to a regional description of higher temporal, geographic and sectoral resolution to quantify selected CenSES scenarios. The model setup applied in the quantification process comprises the global integrated assessment model GCAM (Edmonds, et al., 1997) and the European power sector development model EMPIRE (Skar, 2016), which are linked.

GCAM: The Global Change Assessment Model (GCAM) represents the behaviour of, and interactions between five important systems: the energy system, the water system, the agriculture and land use system, the economy system, and the climate system. It is used in a wide range of applications, from the exploration of fundamental questions about the complex dynamics between human and Earth systems, to those analyses associated with response strategies to address important environmental questions. GCAM is used to model the effect of different global developments, i.e. the impact of major global trends on electricity demand, fuel prices and emissions in Europe.

EMPIRE: The European Model for Power system Investment with (high shares of) Renewable Energy (EMPIRE) has been used to optimize operational and investment decisions in the European power system with a finer spatial and temporal resolution. The model is a capacity expansion model for Europe that optimize both investments in power generation and transmission capacity, as well as the operation of the power system. The model has the horizon of 2050, annual investment decisions and hourly operation, modelled by representative periods.

Once the scenarios are solved in GCAM, parts of the analysis results and input data are fed to EMPIRE. It is then possible to assess the development, i.e. operation and capacity expansion of the European power system with a higher temporal and geographical resolution. The main linking parameters are the power consumption, technology costs and the greenhouse-gas emissions. One of the main challenges in the quantification process has been to establish a consistent model linkage. Several iterations of adjusting the approach were required in the linking process. In addition to the original price coupling, the coupling of an emission cap and the linking of the CCS sector from GCAM to EMPIRE had to be established.

1.3 Results

With the help of the linked model set, the energy scenarios are quantified within a framework of different global developments. In general, the scenario assessment points to a large challenge in order to achieve the emission targets. Either a cut in economic development needs to be accepted, which will probably also have a negative impact on the technological development. Or it needs to be accepted that emissions will not decrease sufficiently, and it has to be relied on substantial negative emissions to the end of the century. However, the second alternative requires from the society to stay calm, accept a substantial overshoot of greenhouse gas emission and trust that there will be advanced technologies available for negative emissions at the end of the century. Following main conclusions are draw from the scenario assessment:

- Global socioeconomic pathways and climate targets significantly affect the European energy sector.
- A faster technology development allows for a postponing of emission reduction, as it is relied on the availability of negative emission technologies at the end of the century.
- Variability of iRES and higher geographic resolution affects the resulting electricity generation mix.
- The sum of greenhouse gases originating from the power sector is constant, however the utilisation of gas power plants with CCS lead to that a much larger share is captured until 2050.
- Due to the utilisation of gas power plants with CCS, there is an increasing demand for gas in the European power sector.
- While there is a two-doubling of generation capacity, there is a four-doubling of cross-border transmission capacity in the European power system.

1.4 Report structure

The remainder of the report is structured in the following way. First an overview of the quantification process is given, comprising the scenario analyses with GCAM and EMPIRE. This process description includes the discussion of the coupling methodology and the linking process applied for the models in section 2. Thereafter input parameters comprising data and assumptions based on the defined scenarios are described in section 3 Results of the scenario analyses with the two linked models are described and discussed in section 4. Finally, in section 5, a conclusion is provided. This includes a general discussion of results, a number of "lessons learnt" from the scenario process as well as modelling process and recommendations for future work. These recommendations point to questions that could not be answered within the scenario assessment or came up during the process described in this report.

2 Method

Following the definition of the CenSES scenarios in a qualitative bottom-up approach, selected scenarios are quantified using Shared-Socioeconomic Pathways (SSP) (O'Neill, et al., 2017), which are defined by IPCC and will be used in their reports on climate changes[1]. These SSPs are used as one of the inputs to a set of global assessment, socio-economic and power system models. The aim is to break down the global framework set by the SSPs to a regional description of higher temporal, geographic and sectoral resolution, which shall be used to quantify selected CenSES scenarios.

The model analyses applied in the quantification process comprise the model set GCAM (Edmonds, et al., 1997) and EMPIRE (Skar, 2016), which are soft-linked as well as a number of sensitivity analyses with ETSAP-TIAM[2] regarding the economic development in the SSPs. Input to both model sets are the same SSPs with climate targets. However, the underlying modelling philosophy is different in the models allowing for a later comparison of the analyses results and input validation.

2.1 Model setup

An overview of the model setup is shown in Figure 2. In this approach the two models GCAM and EMPIRE are linked, where different futures (SSPs) are used as input to the models. In addition, a climate policy (radiative forcing target) is defined as input. GCAM is a global assessment model, while EMPIRE is a regional power system development model. Once the SSP is solved in GCAM, providing a global development and major trends up to 2100, the analysis results and same SSP input data is fed into EMPIRE, in order to assess the development, i.e. operation and capacity expansion of the European power system with a higher temporal and geographic resolution.

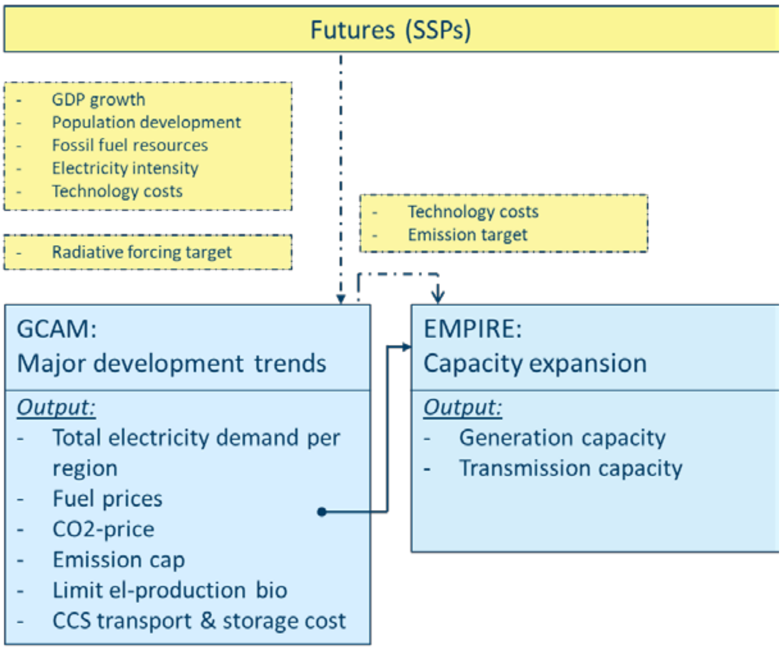

Figure 2: Linking method of GCAM and EMPIRE

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[1] https://www.ipcc.ch/assessment-report/ar6/

[2] https://iea-etsap.org/index.php/applications/global

The main coupling parameters are the power consumption, generation cost and the greenhouse-gas emissions. One of the main challenges in the quantification process has been to establish a consistent coupling. Several iterations were required in the coupling process, hence leading to a delay of the overall process. The reason for using the described method is that it has been established in the LinkS project (Bakken, et al., 2014), in which the EMPIRE model has been developed. Hence, the intention was to build upon existing competence. In the following a short description of the individual models and the coupling process is provided.

2.1.1 GCAM

The Global Change Assessment Model (GCAM) is a global model that represents the behaviour of, and interactions between five important systems: the energy system, water, agriculture and land use, the economy, and the climate. It is used in a wide range of applications from the exploration of fundamental questions about the complex dynamics between human and Earth systems, to those associated with response strategies to address important environmental questions. In the quantification process for the CenSES scenarios, GCAM has been used to model the effect of different global developments, described by the SSPs, on the power system, i.e. the impact of major global development trends on electricity demand, fuel prices and emissions in Europe. GCAM is an integrated assessment model which models the entire world divided into regions and several sectors from year 2010 to 2100. However, for such a broad model, there are limited details included, thus only providing a rather general framework for further analyses.

GCAM:
Major development trends

Integrated
assessment
model

Scope:
- Global
- 2010 - 2100 (5 year intervals)
- Energy, agriculture, land-use, climate

Resolution:
Spatial: Regional
Temporal: Annual

Figure 3: Overview of GCAM

Input parameters to GCAM are defined in line with the qualitative description of the SSPs and additional assumptions. In addition to the SSPs, radiative forcing targets have been used as climate policies. Inputs on a global level to GCAM among others are:

- Economic development (GDP)
- Population development
- Fossil resources
- Technology development (costs)
- Demand for products and services
- Climatic modelling based on the model HECTOR.

As depicted in Figure 3, within GCAM the world is divided in 32 regions. Table 1 lists the four European regions that are used for the further assessment, with the countries which are included in each of the regions.

Table 1: Geographical mapping Europe, Energy system

Region	Countries
European Free Trade Association	Iceland, Norway, Switzerland
EU-12	Estonia, Latvia, Lithuania, Poland, Czechia, Slovakia, Hungary, Slovenia, Romania, Bulgaria
EU-15	Finland, Sweden, Denmark, Netherlands, Belgium, United Kingdom, Ireland, Germany, Austria, Luxembourg, Italy, France, Spain, Portugal, Greece
Europe_non_EU	Albania, Bosnia and Herzegovina, Croatia, Serbia, Montenegro, Macedonia, Turkey

Resulting outputs from GCAM, which are further used in EMPIRE are:

- Electricity demand per region in Europe
- CO_2 price in Europe
- CO_2 emissions for the electricity sector in Europe
- CO_2 capture, transport and storage
- Prices for gas, coal, oil, biomass
- Amount of electricity generation from biofuels

While results from GCAM are available for the whole horizon up to 2100, only results up to 2050 are forwarded to EMPIRE. However, as will be discussed later, it is necessary to account for the full horizon up to 2100 as important impacts can happen after 2050.

2.1.2 EMPIRE

The European *Model* for *Power system* Investment with (high shares of) Renewable Energy has been used to optimize operation of and investments in the European power system with a finer spatial and temporal resolution. The model is a capacity expansion model for Europe that optimize both investments in power generation and transmission capacity, as well as the operation of the power system. The model has a time horizon to 2050, yearly investment decisions and hourly operation, modelled by representative periods. To account for the large shares of renewable energy sources that are expected in the future European power system, the model includes stochasticity in operational parameters such as availability of wind and solar power and hydrological inflow.

Results for year 2010-2050 from running the GCAM for different scenarios have been used as input to the EMPIRE. The results have been disaggregated to a country wise resolution.

EMPIRE:
Capacity expansion

Stochastic
optimization

Scope:
- Europe
- 2010 - 2050 (5 year intervals)
- Power sector (investment + operation)

Resolution:
Spatial: Countries
Temporal: Annual investments
Hourly operation

Figure 4: Overview of EMPIRE

Input to EMPIRE are as follows:

- Electricity demand per country in Europe
- Investment cost for generation technologies and transmission infrastructure
- Technology description for the different power generation technologies
- Weather data for wind solar and hydropower generation
- Prices for gas, coal, oil, biomass and for CO_2 transport & storage
- CO_2-price in Europe
- CO_2 emission constraints
- Amount of electricity generation from biofuels

2.2 Linking challenges and additional constraints

One of the main objectives with the model setup is to provide a global scenario framework from the global assessment model GCAM to the power sector model EMPIRE. Thereby, the global assessment is done until 2100, while the analysis of the power sector is until 2050. This requires a method for linking parts of the global assessment results to the sector model.

The initial linking of the two models was based on the demand for electricity, the generation mix and CO_2-prices. However, after this initial linking it became clear that some additional information had to be included in the linking, i.e. forwarded from GCAM to EMPIRE and to be used as additional constraints in EMPIRE. The additional soft-link between the models comprise a limitation of power generation from biofuels, the implementation of emission constraints and a more explicit modelling of carbon capture and storage. The following subsections discuss these additional coupling.

2.2.1 Limitation of power production from biofuels

Fuel prices used in EMPIRE are firm and time dependent, but do not change with the usage of the fuel. Hence, the EMPIRE model can use much more of a fuel resource than in the GCAM solution without impacting the price of this resource. This is a weakness in the applied linking method. With the initial coupling the EMPIRE model used large amounts of biofuel for electricity production as availability of the resource was unlimited. This overexploitation has been solved by limiting the annual power production from biofuels in Europe to the annual maximum observed production in the GCAM solution for Europe.

2.2.2 Emission constraint

With the initial model coupling it became clear that resulting CO_2 prices from GCAM not necessarily are sufficient to ensure that the climate targets are reached in the EMPIRE solution. In addition, the solution of EMPIRE is rather sensitive to the CO_2 price. To ensure that the climate target is achieved, accumulated CO_2 emissions in the EMPIRE solution was restricted to the accumulated emissions in the GCAM solution from the power sector in Europe.

However, this implementation of an emission budget caused two other challenges. Then the first challenge is the coupling horizon. As can be seen in diagrams further down (e.g. Figure 23), significant negative emissions can be expected to the end of the century, which means that postponing the coupling horizon from 2050 to later can reduce the actual available emission budget. Hence, it was decided to do the coupling with an emission budget up to the 2050 horizon and a budget based on the 2100 horizon, which will be discussed in a sensitivity further down. The second challenge occurred from using an emission budget in the long-term optimisation model EMPIRE. Whereat the model includes short-term uncertainty, the long-term is modelled deterministic. Thus, only using the budget leads to a constant shadow price for the emission constraint throughout the optimisation period. However, to be more in line with reality and to apply the GCAM results, the CO_2-price was used in addition to make CO_2-emissions increasingly expensive with time.

2.2.3 Carbon capture and storage

Finally, during the assessment of the power sector it is observed, that carbon capture and storage (CCS) plays an important role and that it was used quite extensively with the initial coupling method. On reason was, that the only costs for the capturing process were included comprising increased capital costs for power plants due to carbon capture as well as their reduced efficiency. However, to describe possible limitations of carbon capture in better way, limited storage resources and an increasing cost for storing CO_2 in the future are accounted for. Thus, information about the cost of transport and storage on the CO_2 in the sequestration process has been implemented in EMPIRE.

3 Input assumptions to the linked models

The linked global assessment and power sector models described above are used to assess a number of the energy scenarios defined previously (Jaehnert, 2016). The selected scenarios are shortly described in section 3.3. For the assessment of the scenarios, this chapter describes the most important input parameters, which are in line with the so-called shared socio-economic pathways, provided by IPCC[3].

3.1 Shared Socio-economic Pathways

The Shared Socio-economic Pathways (SSP) are used to describe different ways the world can develop with a horizon to 2100. The SSPs describe futures with different degree of socio-economic challenges for mitigation of and for adaption to climate change. Important input factors to the SSPs are economic growth, population growth, education, international cooperation, social acceptance for change and technological development. Thereby, the SSPs themselves do not include climate targets but can be combined with climate policies to evaluate the effect of policies given different pathways for the socio-economic development of the world.

As a result of the scenario definition process of CenSES, the scenarios "Green globe" and "Green governance" are prioritised, based on SSP1 and SSP4, considered to give the most interesting analyses. However, during the quantification process and assessment based on the model analyses, it became clear that SSP4 lead to significant inconsistencies, which gave challenges in the model coupling procedure. It was decided to shift the focus from SSP4 to SSP3, which has more societal challenges for mitigation of and adaption to climate change. Hence, the focus for the selected scenarios are the SSPs "Green globe" and "National ways", see **Error! Reference source not found.**.

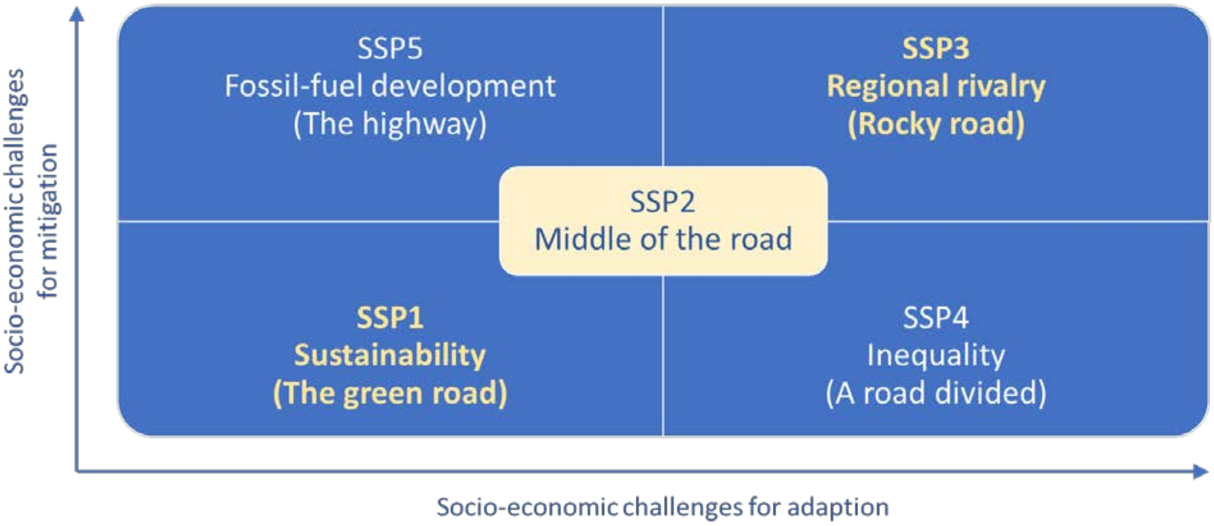

Figure 5: 2nd generation Shared Socio-economic Pathways (SSPs). The study focusses on SSP1 and SSP3.

Figure 5 indicates the subset of SSPs used for the further global analyses in the quantification process. A more detailed overview of input parameters to the models resulting from the SSPs is provided afterwards. The applied SSPs are described in the following way:

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[3] http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/SSP_Scenario_Database.html

SSP1: (Sustainability—Taking the green road) describes a world in a transition to a significant greener and more environmentally friendly future. The transition is driven from the bottom-up by the population and there is high degree of cooperation and awareness at all levels (communities, municipalities, nations, region, globally). Political measures are taken globally and nationally, but responsibility is also shown by the population through behavioural changes. The SSP is characterised by high economic growth, technology development and education. SSP1 is mapped to the "**Green globe**" future in the CenSES energy scenarios.

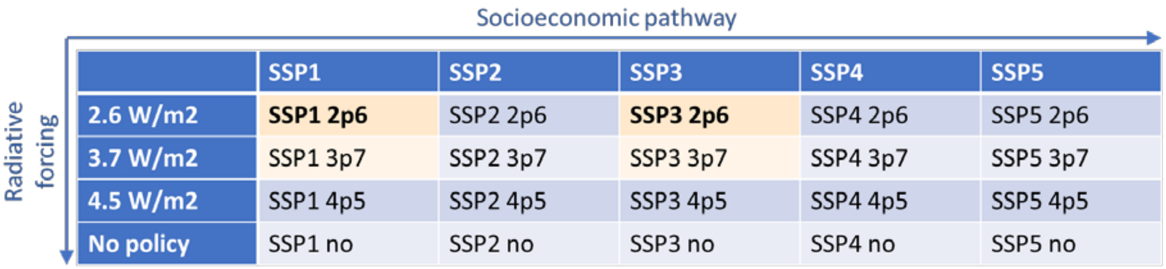
SSP3: (Regional rivalry—A rocky road) describes a world with increasing focus on domestic and regional challenges and increasing competition between regions including trading barriers. There is a low international cooperation for addressing environmental concerns. Most countries focus on achieving energy and food sufficiency and security goals within their own region. High resource intensity and fossil fuel dependency, low education, population growth and slow technology development lead to high challenges to mitigation of climate changes. In addition, there are high challenges to adaption to climate changes as a result of low economic growth, lack of effective coordinating institutions and in general limited progress on human development. SSP3 is mapped to the "**National ways**" future in the CenSES energy scenarios.

3.2 Climate forcing targets

In addition to different development paths of socio-economic factors, it is necessary to define climate policies that are expected to be in place. Thus, climate forcing targets have been used in combination with the SSPs to represent different climate policies. The forcing targets provide limits for the maximum radiative forcing per square meter, which is a consequence of the concentration of greenhouse gasses in the atmosphere and a good indicator of climate change. We have chosen to focus on two climate targets. In the first iteration of the linking process the 2.6 W/m^2 (2p6) and 4.5 W/m^2 (4p5) targets were used, but afterwards the 2p6 and 3p7 targets are chosen. The forcing target of 2p6 is approximately the same as the target for maximum 2-degree increase of the global average temperature, while 3p7 coincides with under 3 degrees. These radiative forcing targets are set for the end of the century (2100). However, specifically in the case of the 2p6 target, it is necessary to allow for passing the target (overshoot) before ending up within the target at the end of the horizon. This is necessary in order to find a feasible solution that achieves the radiative forcing target. Furthermore, assessing the analyses results for the whole horizon (2100) and not just up to 2050 becomes important to understand the implications of reaching the target when allowing overshooting in the solution.

Table 2 illustrates the resulting combinations of developments, that are analysed in the global assessment model GCAM. The combination in bold and that are marked orange, are the ones focussed on in the further assessment of the energy scenarios.

Table 2: Combination of socio-economic developments and climate targets



	SSP1	SSP2	SSP3	SSP4	SSP5
2.6 W/m2	**SSP1 2p6**	SSP2 2p6	**SSP3 2p6**	SSP4 2p6	SSP5 2p6
3.7 W/m2	SSP1 3p7	SSP2 3p7	SSP3 3p7	SSP4 3p7	SSP5 3p7
4.5 W/m2	SSP1 4p5	SSP2 4p5	SSP3 4p5	SSP4 4p5	SSP5 4p5
No policy	SSP1 no	SSP2 no	SSP3 no	SSP4 no	SSP5 no

3.3 Selected shared socio-economic pathways used for the energy scenario quantification

As described above, in the quantification process the focus is on SSP1 "Sustainability" and SSP3 "Regional rivalry". The two SSPs have been combined with the 2p6 and 3p7 radiative forcing targets giving four different futures overall. The radiative forcing targets are implemented as requirements in the model and have to be met within year 2100. Table 3 gives an overview of key factors defined for the different SSPs. These factors also provide some important input to the models in the quantification process. As the focus area for the analysis is Europe, specifically the high-income societies are of interest in the quantification process.

Table 3: General assumptions for the SSPs (Calvin, et al., 2017)

		SSP1	**SSP3**
Socioeconomics	Population in 2100	6.9 billion	12.7 billion
	GDP per capita in 2100	$46,306	$12,092
Fossil Resources (Technological development / Acceptance)	Coal	Med/Low	High/High
	Conventional Gas & Oil	Med/Med	Med/Med
	Unconventional Oil	Low/Med	Med/Med
Electricity (Technology cost)	Nuclear	High	High
	Renewables	Low	High
	CCS	High	Med
Fuel Preference	Renewables	High	Med
	Traditional Biomass	Low	High
Energy Demand (Service demands)	Buildings	Low	Low
	Transportation	Low	Low
	Industry	Low	Low
Agriculture & Land Use	Food Demand	High	Low
	Meat Demand	Low	High
	Productivity	High	Low
	Growth Trade	Global	Global
	Land Use Policy	Afforestation	No land policy
Pollutant Emissions	Emissions Factors	Low	High

These SSPs are used as the basis for the quantification of the CenSES scenarios and the definition of pathways. The analysis results for these SSPs will be used as the framework to specify the different futures for the scenarios.

3.4 Important input assumptions to GCAM

There are especially two important underlying assumptions which differ significantly in the selected SSPs that are taken as input in GCAM. These are the development of the population and the economy, as stated in the two upper rows of Table 3. The following figures illustrate the development of the population and the GDP globally and in Europe.

In case of population development trends are rather different for the SSPs as well as globally and in Europe, see Figure 6. In SSP1 a slight increase in population is expected in the next years, while there is a decrease to the end of the century. However, in SSP3 there is expected nearly a doubling of population globally, while there is a significant decrease of population in Europe. The differences in development in population are caused by the high differences between the regions throughout the world, mainly in education. The population development has an impact on the demand for energy, food and other services.

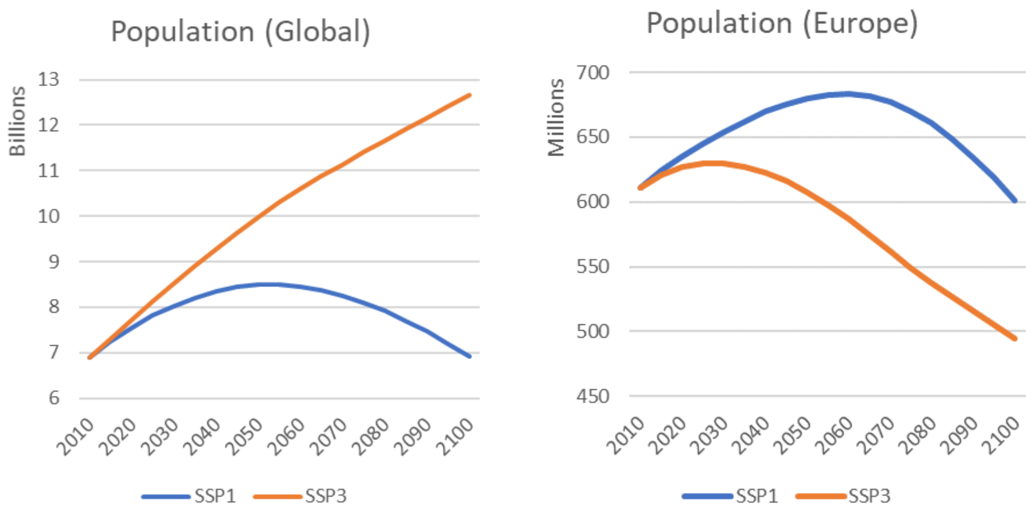


Figure 6: Drivers of the development - Population

Similar to the population there also is a difference in the development of GDP between the SSPs. There is a significantly higher economic growth expected in SSP1 both globally (six-doubling) and in Europe (four-doubling), despite a nearly constant development of the population. This is due to a high education level and rapid technological development. In contrast, in SSP3 there only is a minor increase in the European economy and close to a stagnation towards the end of the century in Europe. On a global level within SSP3, there is a three-doubling in GDP, nearly as much as the doubling of the population, indicating a much lower per capita increase than in SSP1, potentially due to less advances in education.

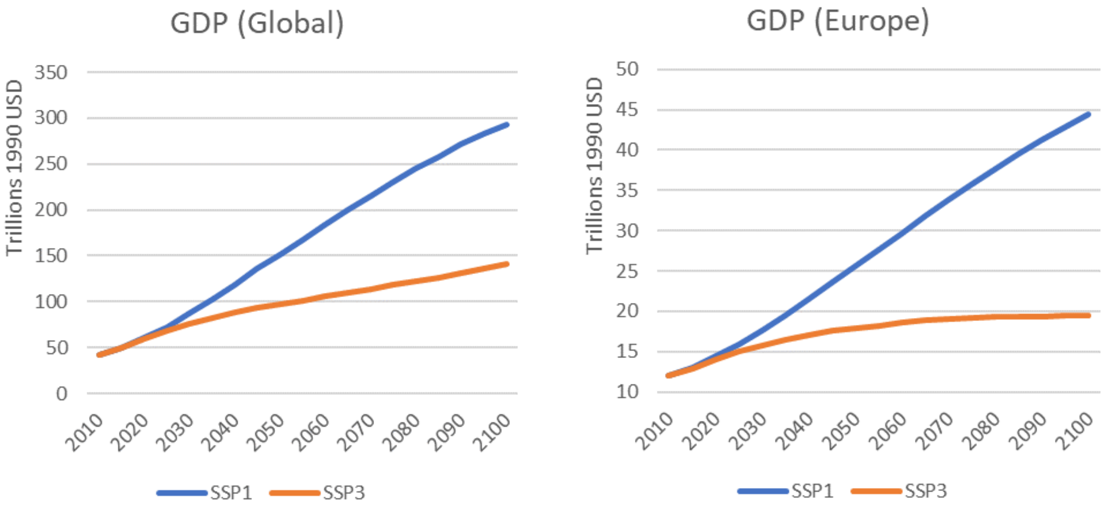


Figure 7: Drivers of the development - Economy

Both, the development of population and economy are important drivers for the energy demand and for other services. Figure 8 illustrates the resulting primary energy consumption in Europe. As shown in Figure 14 afterwards, there are only small variations depending on the implemented climate policy. This means that the energy consumption is to a large extend defined by the drivers shown above. Furthermore, it can be observed, that there is a decoupling of energy consumption, population development and most importantly the economic development. For Europe a decrease in energy consumption after 2050 by about 30% can be observed in SSP3.

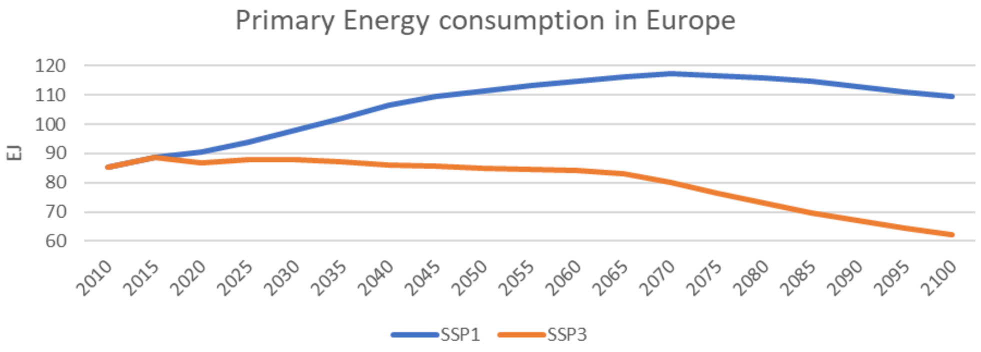


Figure 8: Demand for energy in Europe for both SSPs

Technology cost

In addition to the social and economic input assumptions, the development of technologies is an important input to the assessment model GCAM. Figure 9 illustrates the development of the fixed costs for the different power generation technologies. There is a substantial cost reduction for power generation technologies with CCS and power generation based on renewable energy sources. In contrary, the technology costs for fossil-based power generation without CCS as well as for nuclear power generation is rather constant. Especially gas and coal power generation have rather low fixed costs. However, for these technologies fuel costs and costs for the emissions or capturing and storing of CO_2 will come in addition.

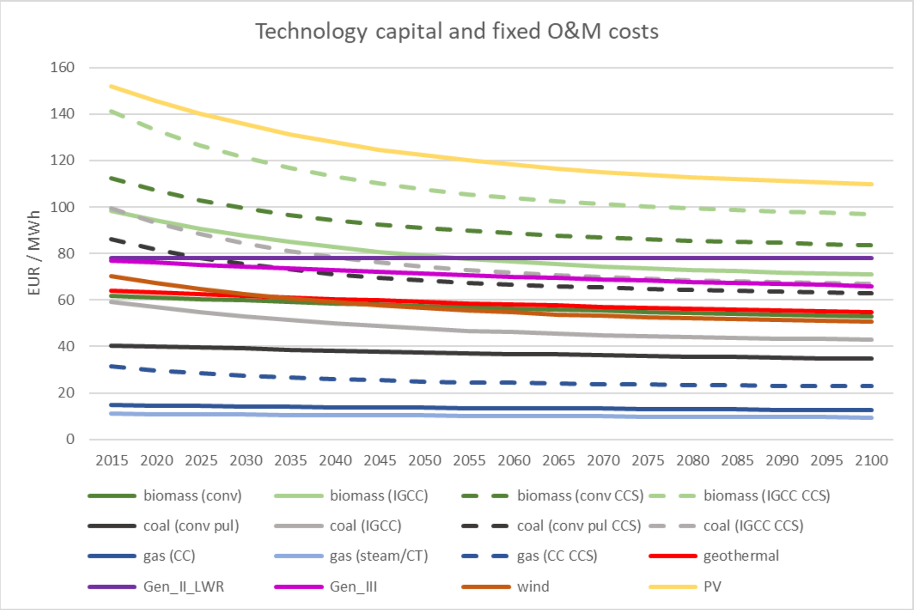


Figure 9: Capital and fixed operation & maintenance costs for selected power generation technologies

The capital costs of wind, solar and nuclear power have been updated in the SSPs during the iterations for GCAM and in the model coupling process, which is discuss in section 4.1.2. Figure 10 shows the resulting differences in wind and solar investment costs between SSP1 and SSP3 for Europe. The costs are per installed capacity, based on the assumed capacity factors for the European regions in GCAM. Costs are reduced in SSP1 compared to the initial definition of the SSPs, to be more in line with current expectations. The capital costs for wind and solar power production are slightly increased for SSP3.

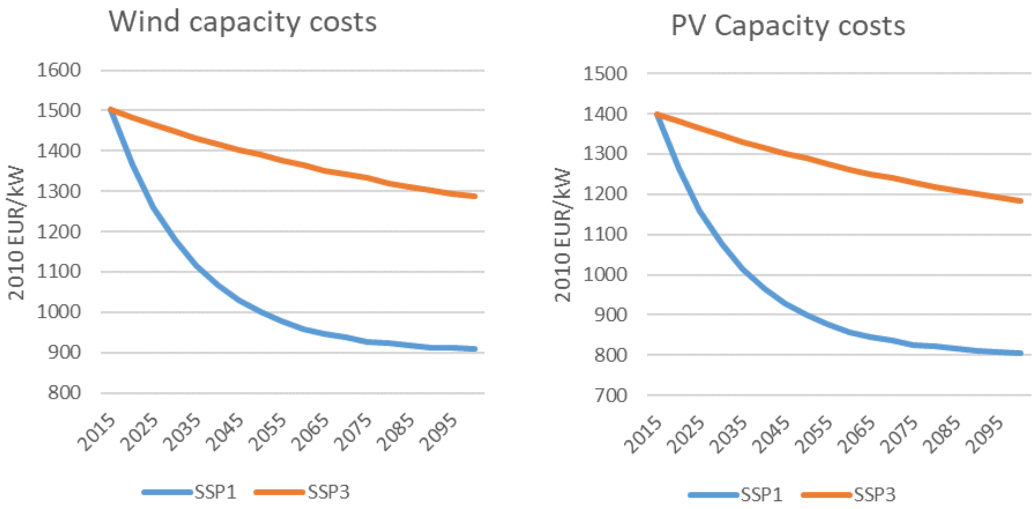


Figure 10: Cost development for wind power (left) and PV (right) in the SSPs

Costs for nuclear power have been increased for all the SSPs compared to the initial definition, accounting for the controversy regarding nuclear power. In addition, costs related to sequestration of CO_2, transport and storage costs of CCS, have been updated to reflect the differences between SSP1 and SSP3. The resulting availability of CO_2 storage and the according costs are shown in Figure 11.

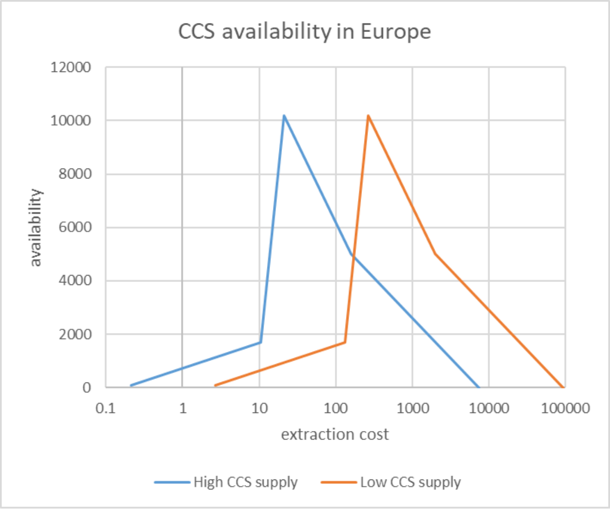


Figure 11: Availability and costs of onshore storage capacity for CO_2 in the SSPs

4 Model results and quantification of the energy scenarios

The results presented in this report are divided into three parts. At first results from GCAM are presented. Thereafter, the parameters and assumptions, that are coupled from GCAM to EMPIRE are illustrated and discussed. Finally, the simulation results for the chosen energy scenarios with EMPIRE are presented and discussed.

4.1 Analyses results from the integrated assessment model GCAM

Given the input assumption for the SSPs as described in the previous chapter, GCAM is run for several cases and the results are reported and discussed in this section. The results will then provide input to the simulations with EMPIRE, discussed in the following section 4.3.

The result presentation for GCAM in this chapter is divided into to three parts. In the first part some general results and insights to the GCAM simulations are provided, using all of the five SSPs and the three different climate policies. This provides the possibility to assess the effect of the pathways and the climate policies on the outcome of the assessment with GCAM.

The second part of the chapter discusses the iterations done for the simulations with GCAM and the according update of input assumptions, as well as the effect on the simulation results. In addition, a short argumentation is done of why the input assumptions are updated.

The third and final part of the chapter focuses on more detailed results for the two chosen pathways (SSP1 and SSP3) combined with the climate policies, resulting into a combination of four different analyses. This part presents the majority of GCAM results, which are used as the input for the following more detailed analyses done with the EMPIRE model.

4.1.1 General overview SSPs in GCAM

In the first step of the global assessment all the SSPs are simulated in GCAM in order to achieve an overview on the impact of the socioeconomic differences on the global development of the energy system. The pathways are run combined with the three different climate targets, the representative concentration pathways (RCP) 2p6 / 3p7 / 4p5, and a case with no climate policy.

Figure 12 shows the resulting radiative forcing for the various combinations, while Figure 13 shows the corresponding development of the mean global temperature increase. Nearly all of the scenarios achieve their radiative forcing target (despite of SSP3 3p7, which is not converging). Thereby it has to be recognised, that all of the 2p6 scenarios have the ability for an overshoot, which is necessary to achieve the targets. The size and the duration of the overshoot depends on the underlying pathway, which will have a substantial impact on the final temperature increase as illustrated afterwards. Furthermore, the lack of a climate policy leads to a substantial increase of the radiative forcing, especially under SSP5, a fossil-based society

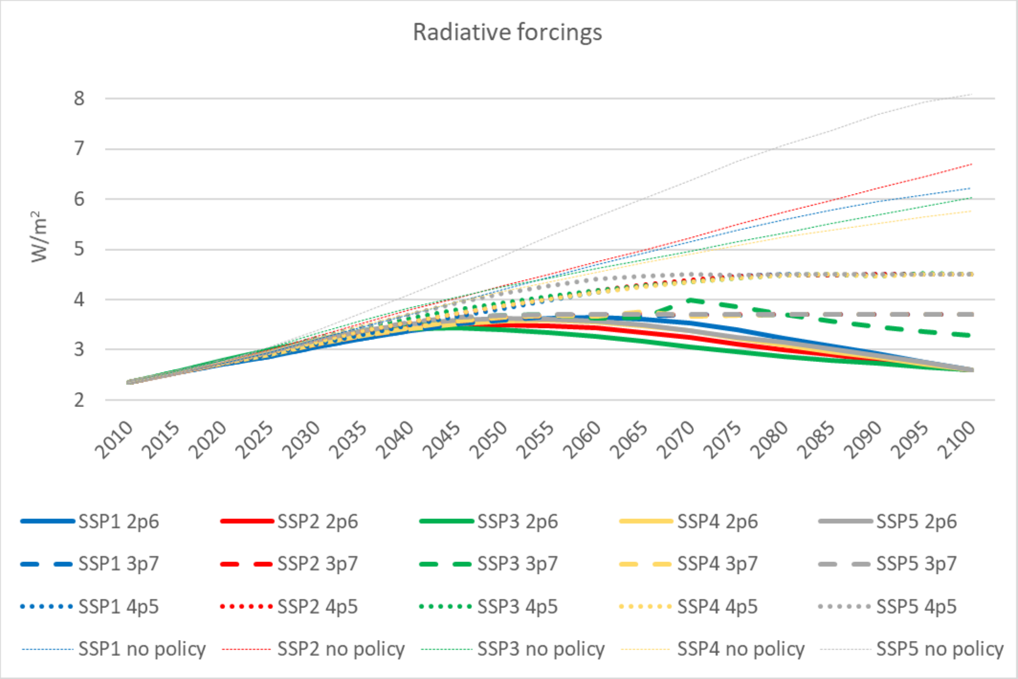


Figure 12: Radiative forcing for the combinations of SSPs and climate policies

For the temperature increase a huge variation can be observed depending on the climate target. If there is no climate policy, dramatic increases can be observed. The 4p5 policies lead to an increase of about 3 degrees, while the 3p7 policies lead to an increase of about 2.5 degrees. However, there is some significant variation in the final temperature increase for the 2p6 policies and an overshoot in the temperature during the mid of the century. Cases with a higher and longer overshoot of the radiative forcing lead to a higher temperature increase in 2100, such as SSP1 and SSP5. No climate policy results into a dramatic increase of the average temperature, with up to 5 degree Celsius in the case of SSP5, the fully industrialised future.

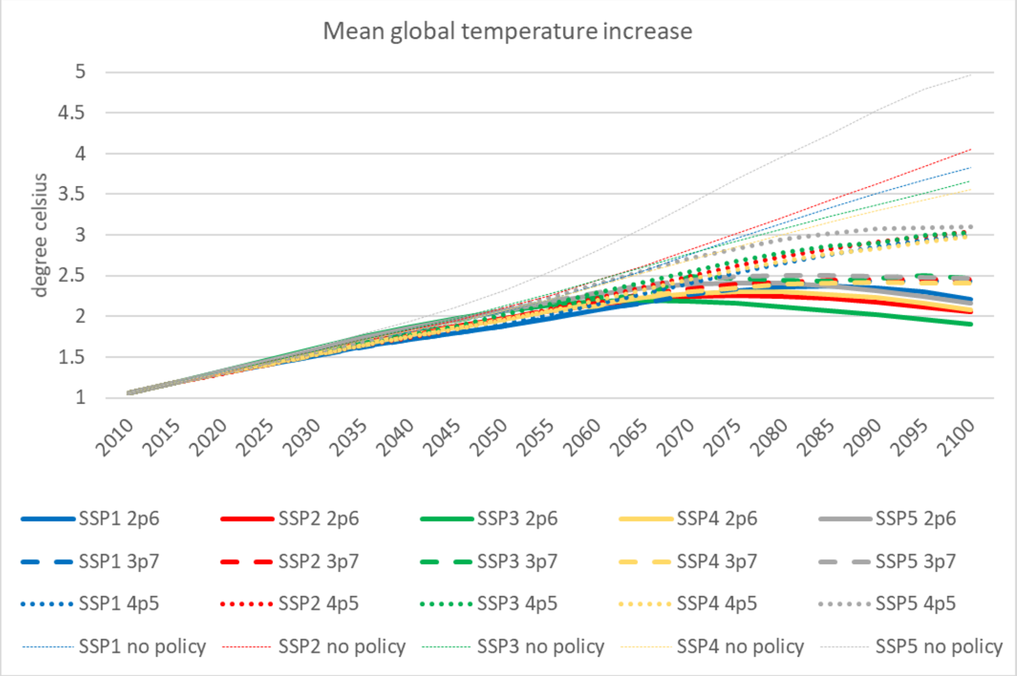


Figure 13: Global temperature increase up to 2100 for the combinations of SSPs and climate policies

Beside the impact of the SSPs and RCPs on the climate, the development of the global and European energy system is of interest for the further assessment. Figure 14 depicts the resulting global primary energy consumption for all the cases. In general, there is an increase in energy consumption for all of the cases, with a doubling up to 2100 in the lowest trajectories, while there is up to a four-doubling of energy consumption in the highest ones. Thereby, the increase in the energy consumption depends to the largest share on the socioeconomic pathway and not the given climate target. The pathways with a lower challenge for the adaption to climate changes (SSP5, SSP1 and SSP2) lead to a much higher increase of energy consumption, due to a higher increase in population and the economy. In contrary SSP3 and SSP4 lead to a somewhat smaller increase of energy consumption, which however still nearly doubles until 2100 on a global level.

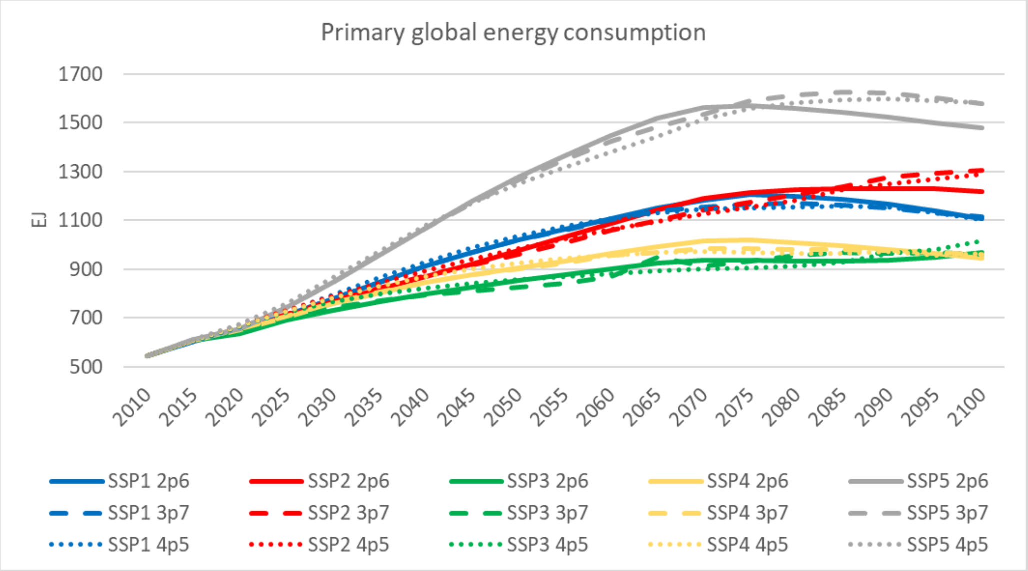


Figure 14: Primary energy consumption to 2100 for the combinations of SSPs and RCPs

Zooming in to Europe and the electricity sector, the following Figure 15 shows the resulting electricity generation in Europe for the different cases. In line with the previous figure of the global energy consumption, there is an increase in consumption to 2100. Again, there is a clustering of the development paths based on the socioeconomic pathway. However, this clustering is not as clear as for the global energy consumption, meaning that the climate target has a higher effect. The pathway SSP5 also leads to the highest increase in demand for electricity in Europe. Then, however it can be seen, that the cases with the strictest climate policy (2p6), lead to a higher increase in electricity demand. Finally, the demand is lowest for the SSP3 pathways in 2100 independent of the climate policy. However, the difference in the trajectories is not as significant at the 2050 horizon, which will be the coupling point to the analyses with the EMPIRE model.

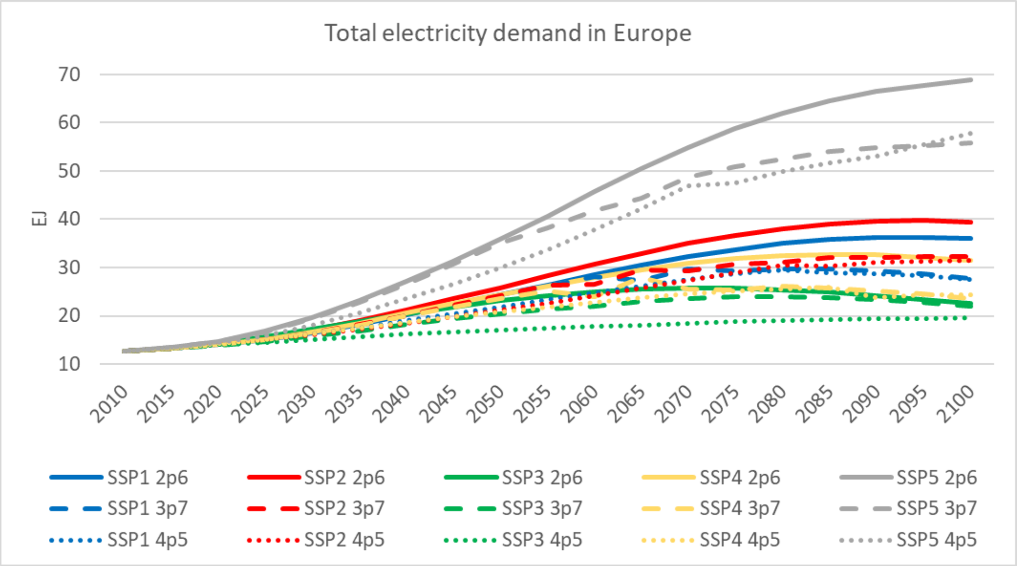


Figure 15: European electricity demand to 2100 for the combinations of SSPs and RCPs

4.1.2 GCAM simulations – iterations of the dataset

After the first general assessment of all the SSPs and RCPs with GCAM it was chosen to focus on the pathways SSP1 and SSP3 as described in section 3.3 above. Several iterations for GCAM, running and adapting the chosen scenarios were required. A number of main changes in input data resulted into a first and second iteration of GCAM simulation runs. These main changes included the following updates of the dataset:

1. In line with the selected energy scenarios "Green globe" and "National ways", it was chosen to focus on the socioeconomic pathways SSP1 "Sustainability" and SSP3 "Regional rivalry" as the main global frameworks for Europe in the further quantification and analyses process.
2. Parts of the input data were updated in order to represent the latest developments of technology costs and policies. This update included the adjustment of wind and solar power generation costs with different development lines for the two chosen SSPs, see Figure 10.
3. The available storage for CO2 (the cost and availability of CO2 storage) is adjusted to two different technology development paths as depicted in Figure 11.
4. The cost of nuclear power production is increased significantly, as unreasonably high shares of nuclear power were observed in the first iteration. The resulting phase-out of nuclear is in line with the current policies in Europe.
5. An overshoot of radiative forcing is also allowed for SSP3 for the 3p7 target to be able to converge, which was not the case in the first iteration.

Comparison of the iterations

In the following some main results for the first iteration versus the second iteration of GCAM with updated input data are presented. In addition, a short discussion of the outcome and a reasoning for the updates are given. The following assessment focusses on results for Europe, as the GCAM simulations will provide a framework for the quantification of scenarios for Europe.

Figure 16 and Figure 17 depict the primary energy consumption for both iterations in Europe. In both pathways SSP1 and SSP3 a reduction of nuclear from the first to the second iteration can be observed, which however is only minor in SSP3. Despite of the near doubling of investment costs for nuclear power generation, nuclear still provides a significant share of the production in the second iteration. While there is an increase of wind and solar in SSP1, it decreases in SSP3, which mainly is due to the updated investment cost trajectories for wind and solar in the both SSPs. Finally, a reduction of primary energy consumption of about 5% can be observed in SSP1 for the second iteration, while it is nearly equal in both iterations for SSP3.

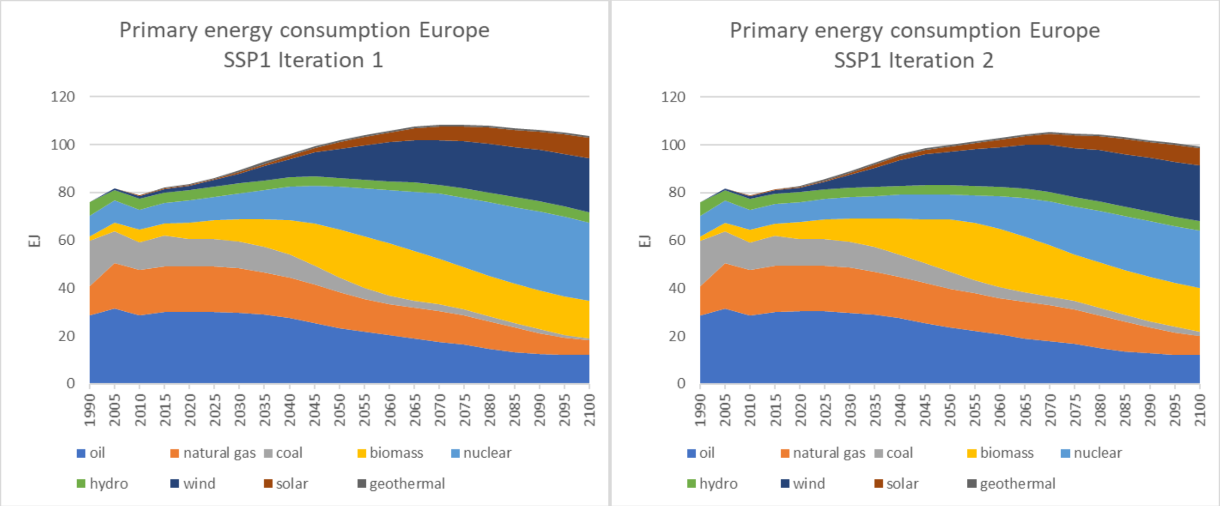


Figure 16: European primary energy consumption in SSP1 2p6 for both iterations

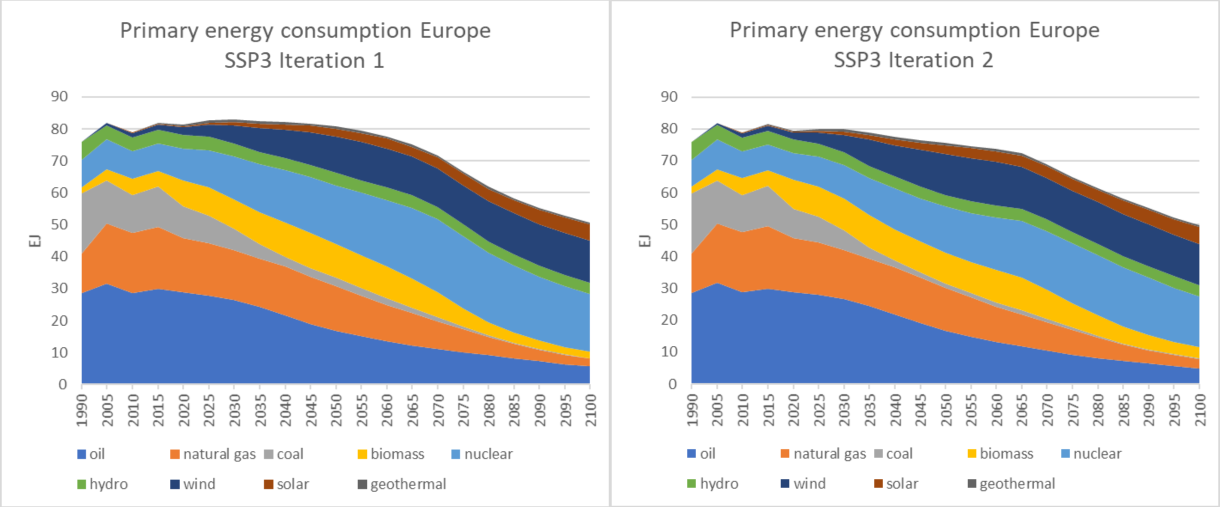


Figure 17: European primary energy consumption in SSP3 2p6 for both iterations

While the primary energy consumption gives a rough overview of the whole energy system, the development of the electricity demand and the generation mix is of interest for the following assessment. A slight reduction of electricity generation in the second iteration can be seen for both SSPs. In addition, a reduction of nuclear power generation occurs for both SSPs, where it is most significant in SSP1. Furthermore, there is an increase of power generation with CCS based on gas and biomass for both SSPs, whereat the phase-out of fossil-based power generation without CCS is not affected. Finally, there is an increase of about 5% of wind power generation in SSP1 in the second iteration compared to the first. This comparison shows that the adjustment in the underlying technology costs does not have a significant effect on the generation mix, while there are substantial differences between the SSPs. Furthermore, the electricity generation mix is also a result from EMPIRE. In the further analyses a comparison of the generation mixes from EMPIRE and GCAM will be used for judgement of convergence.

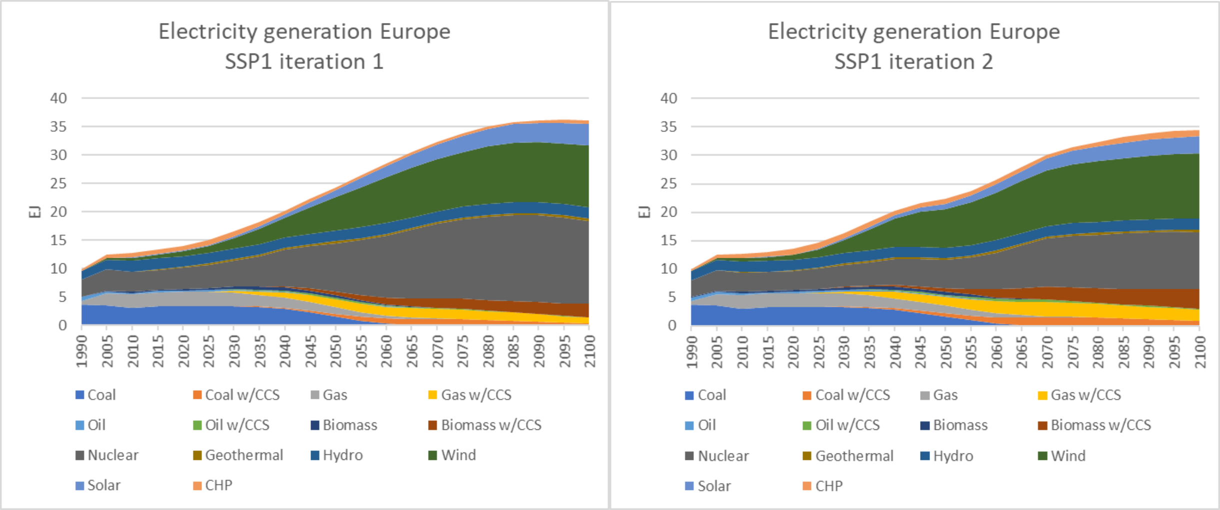


Figure 18: European electricity generation in SSP1 2p6 for both iterations

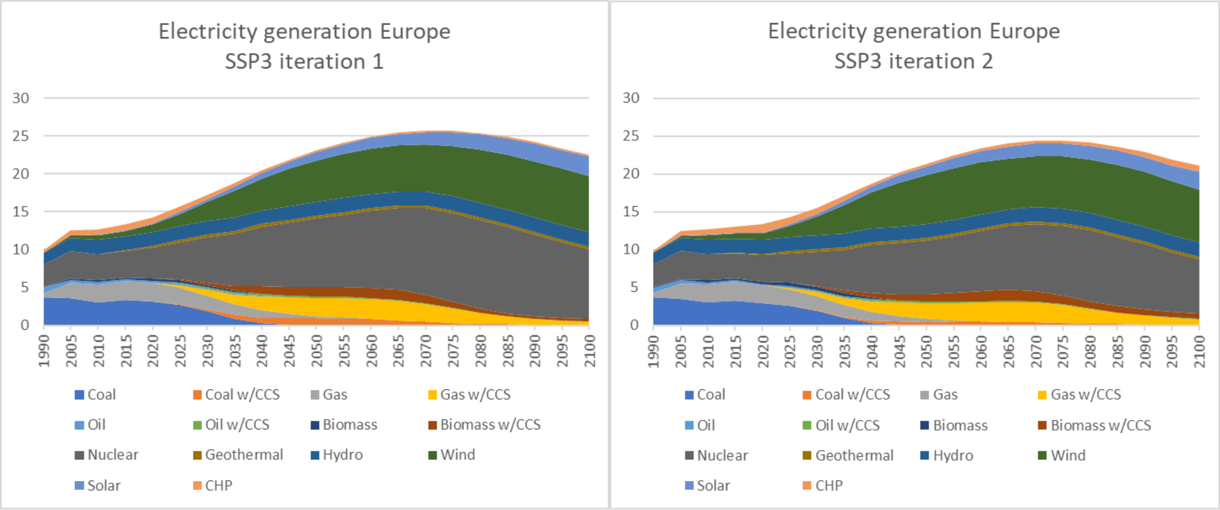


Figure 19: European electricity generation in SSP3 2p6 for both iterations

Finally, Figure 20 and Figure 21 illustrate the sequestration of CO_2 in both iterations of the GCAM runs. One can observe a bit higher capture of CO_2 in the second iteration, given the increased CO_2 storage possibilities. The increase can especially be seen in the power sector, which results in the increased power generation with CCS as shown above. For SSP3, which is adjusted for lower availability and higher cost of CO_2 storage (see Figure 11) a postponing of the CO_2 sequestration can be observed in the second iteration, which again has the highest impact on the electricity sector, also leading to a somewhat delayed implementation of power generation with CCS.

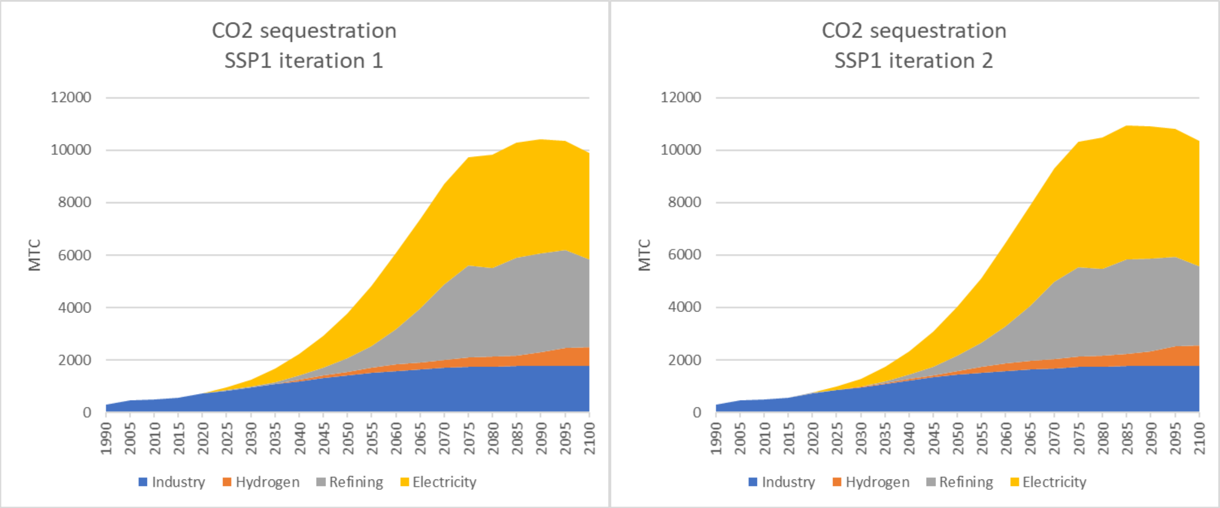


Figure 20: Global carbon sequestration in SSP1 2p6 for both iterations

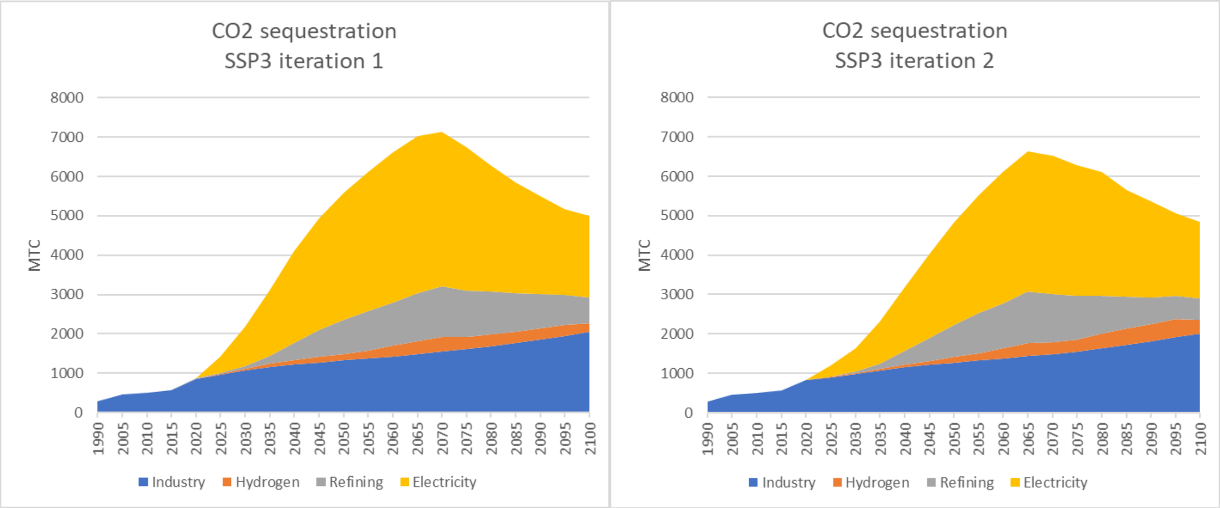


Figure 21: Global carbon sequestration in SSP3 2p6 for both iterations

Conclusion from the GCAM simulations and the updated iterations

The initial simulations of the SSPs provided a general overview of the development for the various pathways combined with the climate targets. However, assessing selected pathways more in detail showed some unreasonable respectively unwanted results and hence required a partial update of the inputs. This was especially the case for some of the power generation technologies as well as for CCS.

The updated scenario runs for SSP1 and SSP3 will in the following be used as the global framework for the more detailed analyses for Europe and Norway for the development of the power system. While the GCAM runs provide a large set of results for different regions in the world, the aim of the model coupling as described above is to provide a global framework through the SSPs for further regional analyses, with the focus on Europe.

In the two following subsections more detailed results of the second iteration of the GCAM simulation for the pathways SSP1 and SSP3 are presented and discussed. The focus in the first subsection is on results for climate policies and the development of the greenhouse gas emissions, which frame the potential development in Europe. Thereafter results for the development of the power sector are presented, which also provide the input for the further, more detailed analyses with EMPIRE.

4.1.3 Climate policies and development

The SSPs are run with two different climate policies, which are defined by the radiative forcing 2.6 W/m^2 and 3.7 W/m^2. The development in radiative forcing for the combinations are shown in Figure 22. It is important to observe that the tighter scenario (2p6), representing a 2 degree increase of the mean temperature, is only achievable when an overshoot of the radiative forcing during the mid-century period is allowed, see Figure 22 to the left. The same accounts for the SSP3 3p7 scenario. In the following the focus will be on the 2p6 scenarios.

It can be observed, that despite from the radiative forcing in SSP3 2p6, no significant changes in the trajectories can be seen before 2050, leading to a constantly increasing global mean temperature to above 2 degrees in 2050. Furthermore, it can be observed, that the size of the overshoot also has a large impact on the temperature increase at the end of the century. In Figure 22 depicting the mean temperature increase on the right-hand side it can be observed, that even though, the target for radiative forcing is the same, the development up to 2100 based on SSP1 or SSP3 has a significant impact on the final temperature increase that is caused.

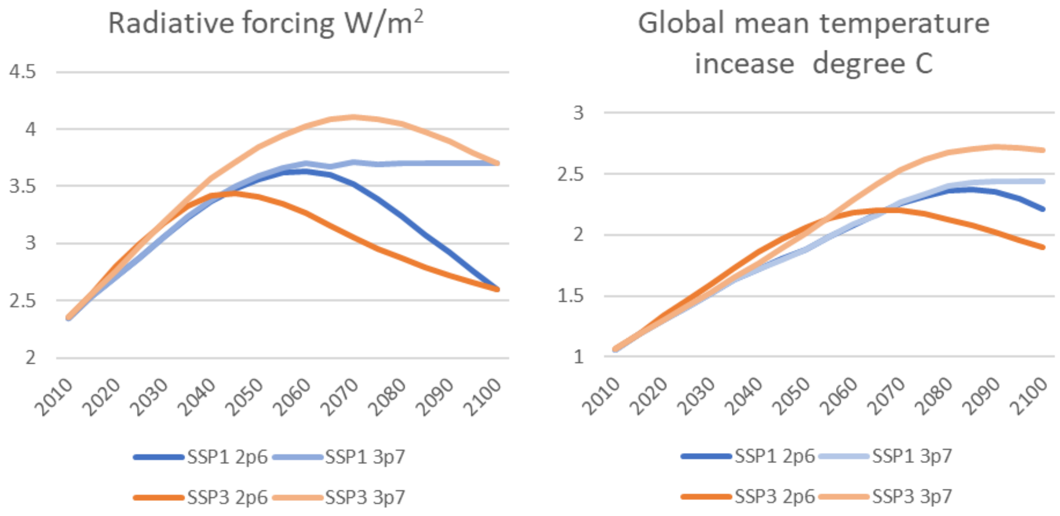


Figure 22: Radiative forcing (left) and global mean temperature increase (right) for the different SSPs

The radiative forcing and resulting temperature increase are to a large extend caused by the concentration of greenhouse gasses in the atmosphere, which can be evaluated in CO_2 equivalents. Hence, emission reduction of greenhouse gasses plays a central role in fulfilling the climate policies.

4.1.3.1 CO_2 emissions

Figure 23 and Figure 24 illustrate results for the development of global CO_2 emissions and emission in Europe up to 2100. When assessing these emissions, it is important to observe the global and European emissions in the framework of the SSPs, which can explain some rather unexpected developments.

Figure 23 depicts the global emissions per sector for SSP1 and SSP3. Thereby the biomass sector covers the removal of CO_2, resulting into negative emissions. To reach the 2-degree target (2p6 scenario) large amounts of negative emissions are expected and necessary from 2050-2100, especially in the SSP1 2p6 scenario. This is an important factor to consider when using data from 2010-2050 in the linking. Negative emissions are achieved through BioCCS, by withdrawing CO_2 from the atmosphere and storing the CO_2 underground. In the results, the BioCCS capture process lies within the biomass system. This implies that negative emissions will not be accounted for in other sectors. Thus, negative emissions from electricity generation using biofuels will not be accounted for in the electricity sector part, but rather in the biomass system.

In SSP1, the "Sustainability" pathway, an actual increase of emission can be observed until 2030, while zero net emissions are achieved around 2070 and a large amount of negative emissions are required to achieve the climate targets in 2100. Thereby emission levels in 2050 are only marginally lower than in 2015. This development looks rather different in SSP3, the pathway called "Regional rivalry". Here the peak in emission can be observed in 2015 and a significant reduction of net emissions to about 1/3 of the 2015 level up to 2050 can be observed. Furthermore, there is a much lower application of negative emission technology. This however requires a nearly full decarbonisation of all sectors up to 2100.

Comparing SSP1 and SSP3 on the global level at the horizon of 2050, it can be observed that the cumulative emissions in SSP3 are only around 2/3. Furthermore, especially in the electricity sector, there is a big difference. While there are still substantial emissions from electricity generation in SSP1, there are only minor emissions in SSP3. The reason for these different developments lies in the availability of technologies and different trajectories for demand.

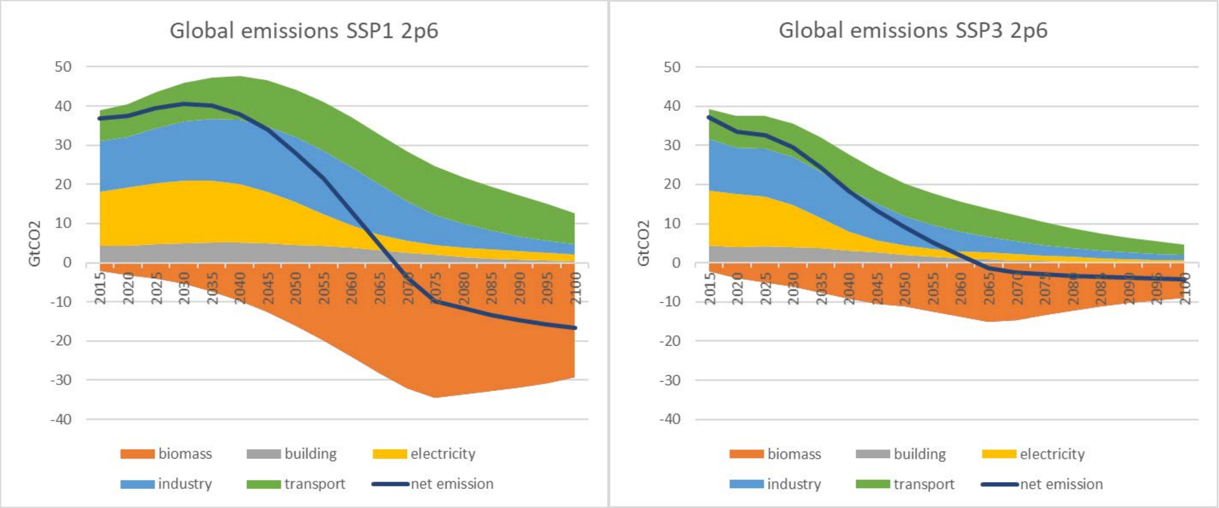


Figure 23: Global CO_2 emissions per sector SSP1 (left) and SSP3 (right) for the 2p6 policy

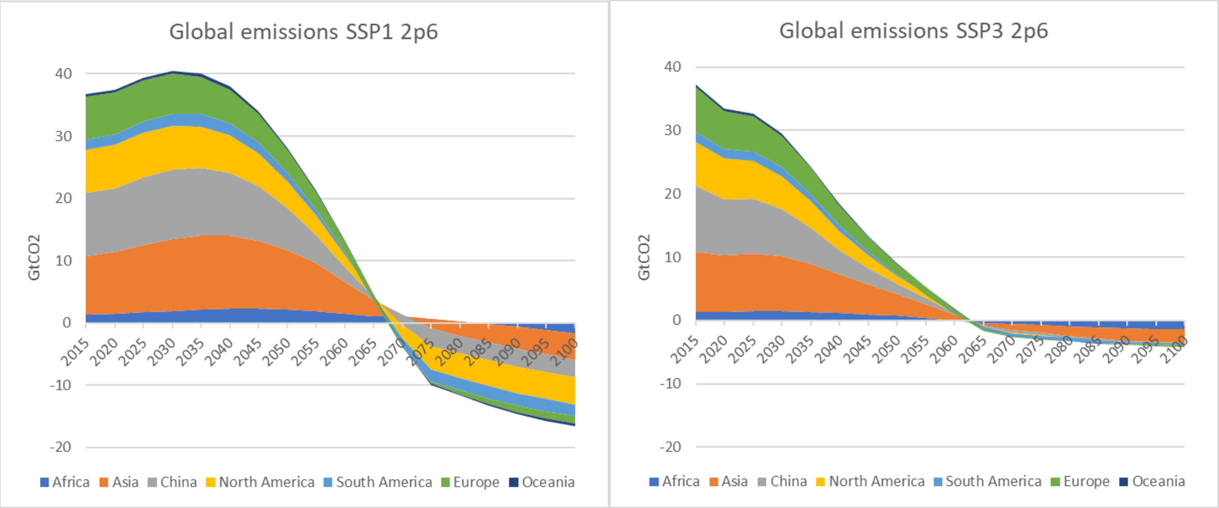


Figure 24: Global CO_2 emissions with a regional division for SSP1 (left) and SSP3 (right)

Zooming in on Europe, the differences between SSP1 and SSP3 become even larger. Net emissions in 2050 are about half in SSP3 compared to SSP1. Specifically, in SSP1, there are only minor reductions in direct emissions in Europe, while a significant part of the net reduction is due to larger negative emissions from an increasing biomass sector. That also accounts for the electricity sector. However, in SSP3 significant emission reductions can be observed, including a cut of emission in the electricity sector by about 80%. Finally, achieving net zero emissions in SSP1 in Europe occurs much later than on the global level.

Two reason can explain this difference in emission reduction for Europe. First, in SSP1 with its high economic and technology development, there is an expectation, that significant amounts of negative emissions can be achieved at the end of the century. This means, that there is not the necessity to reduce emissions immediately. A second, but not as significant reason is that, given the international cooperation in SSP1, measures to reduce greenhouse gas emissions are not necessarily taken in Europe, but other places as it can be more economical to do so on a global perspective.

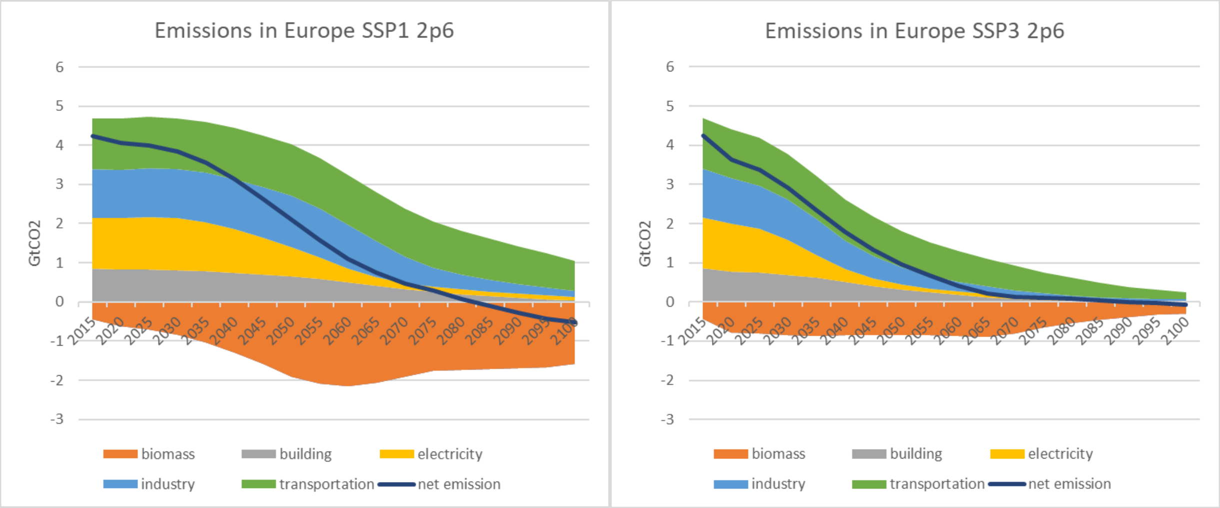


Figure 25: CO$_2$ emissions in Europe SSP1 (left) and SSP3 (right) for the 2p6 policy

As a sensitivity in Figure 26 shows the development of sector emissions in Europe in the case of a 3p7 climate target for SSP3. It can be observed, that the development in this case is more similar to the SSP1 2p6 to 2050, where only minor emissions reductions occur in the sectors. However, different to SSP1 2p6 also much fewer negative emissions can be observed. The actual reduction of emissions for the 3p7 target in SSP3 is delayed by about 20 years compared to the 2p6 target.

The results presented from GCAM are evaluated as not directly useable as a constraint for the further quantification in a more detailed model. Due to the rather different development of emissions and also based on the different application of CCS as it will be shown afterwards, it is necessary to assess the actual sequestration and storage of CO$_2$ in a bit more detail.

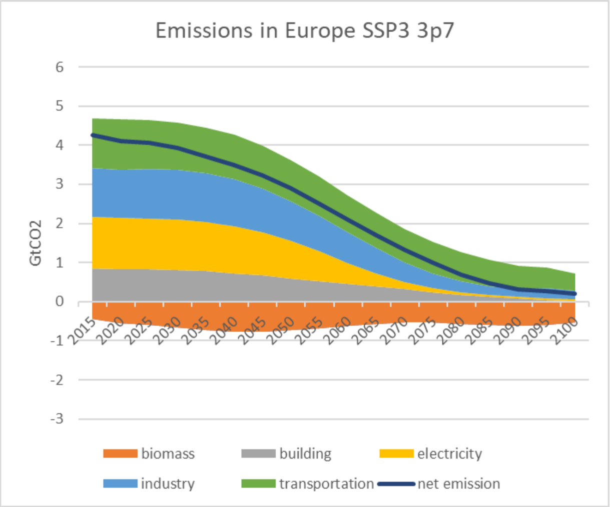


Figure 26: CO$_2$ emissions in Europe SSP3 for the 3p7 policy

4.1.3.2 CO_2 sequestration

Figure 27 shows the CO_2 sequestration for SSP1 compared to SSP3 in Europe. The figures are somewhat similar to the global development in Figure 20 and Figure 21. However, the refining has a lower share, while the electricity sector makes up a much larger share for sequestration in Europe. In general, it can be observed that the utilisation of sequestration technologies is much higher in SSP1 compared to SSP3. However, the CO_2 capture is applied much faster in SSP3 and reaches a top to the end of the century. A reason for the decrease during the last decades of the century can be the missing CO_2 storage possibilities.

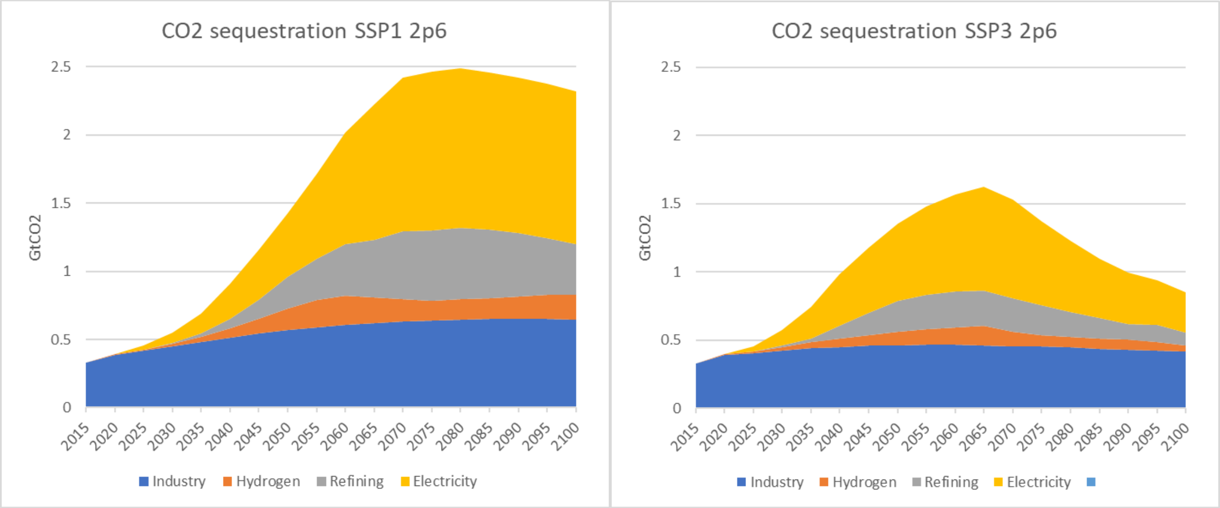


Figure 27: CO_2 sequestration in Europe

4.1.4 Power sector

The following figures target the power sector in Europe. For the quantification of the energy scenarios, a closer look is taken on the outcome of the scenarios in GCAM for the power sector in Europe, especially the generation mix. The development of the generation mix provides an indication of the development of different technologies and the speed of substitution of these technologies. As discussed above an important observation is that there is only a minor emission reduction for SSP1 in the European power sector until 2050, while the reduction is rather significant for SSP3.

In general, the global electricity generation mix by technology develops somewhat similarly in the both SSPs see Figure 28 and Figure 29. In the first place it can be observed, that there is a significant increase in global electricity generation for both SSPs, with nearly a five-doubling from 2010 until 2050. In the first decades of the century it can be seen, that coal and gas power production are being phased out and replaced by coal and gas with CCS. This also happens for the 3p7 targets (not shown here), but the development is a bit slower. Furthermore, from about 2030 onwards large amounts of nuclear, wind and solar power occur in the generation mix, making up about 50% to 70% at the end of the century. While there is this significant amount of RES in the electricity generation mix, the results show that power generation based on fossil fuels with CCS still makes up a certain share of the electricity generation mix at the end of the century.

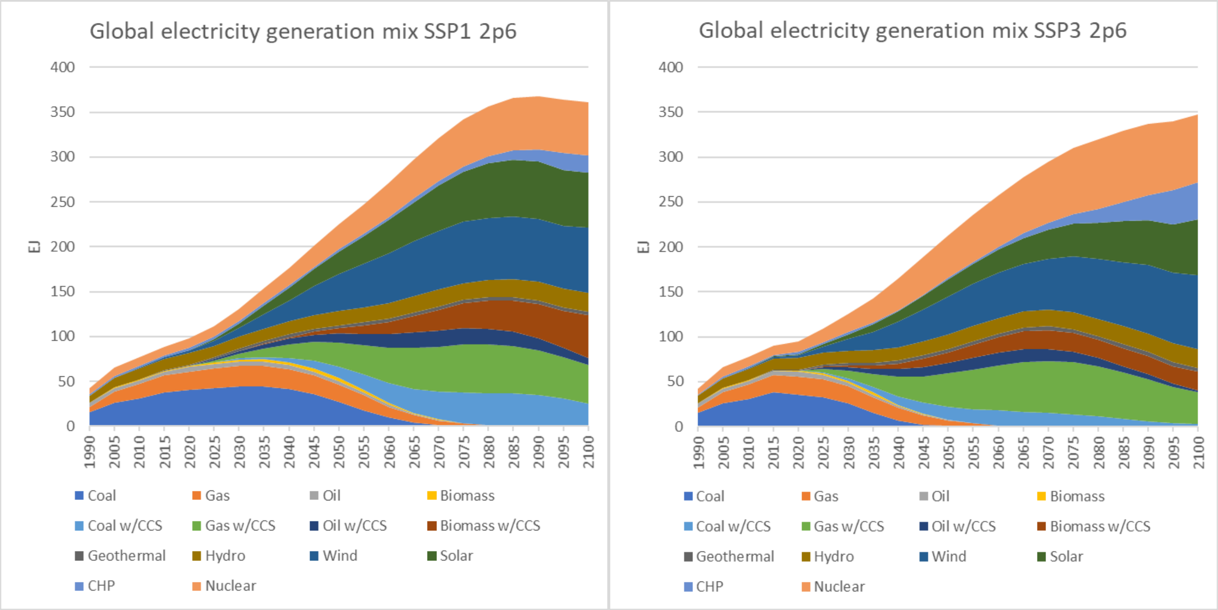


Figure 28: Global generation mix SSP1 (left) and SSP3 (right) for the 2p6 policy

For Europe the development of the generation mixes in SSP1 and SSP3 is somewhat different. At first it can be seen that there is a huge difference in the total power generation by 2100 in Europe, which is due to the difference in the SSPs for the development of the population and the economy. As on the global level the share of nuclear power generation increases, but not as much. Differently to the global figures, in Europe mostly wind power production is expanded and only a minor share of solar power production occurs. These developments are the same for both pathways. Finally, it can be observed that the phase-out of fossil-based power production without CCS occurs much faster in SSP3, nearly being completely phased out in 2050, while this processes only starts around 2040 in SSP1.

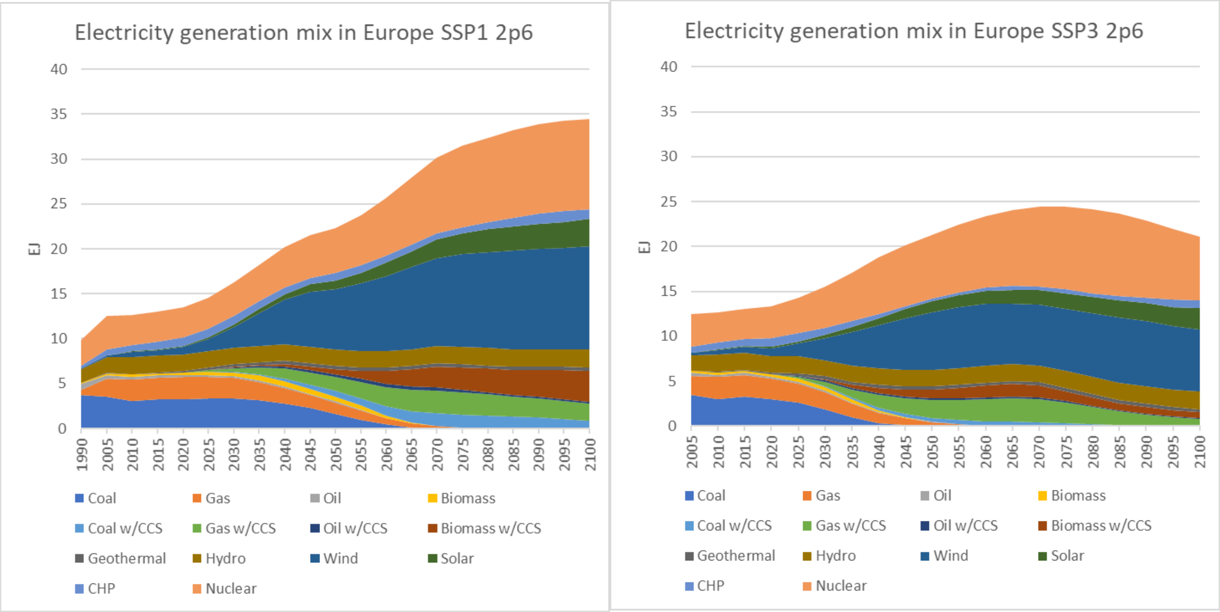


Figure 29: Generation mix in Europe SSP1 (left) and SSP3 (right) for the 2p6 policy

Assessing the 3p7 target for SSP3 shows a somewhat similar development to SSP1 2p6 in the case of fossil-based power production, while the expansion of RES based power production and the development of the electricity demand is more in line with SSP3 2p6, see Figure 30.

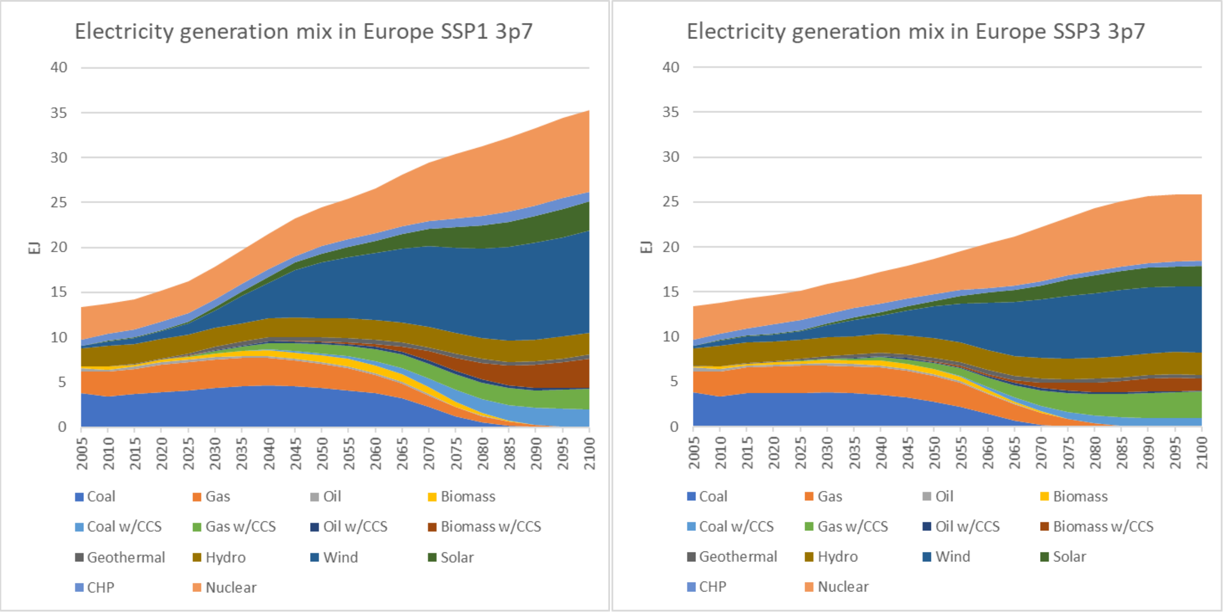


Figure 30: Generation mix in Europe SSP1 (left) and SSP3 (right) for the 3p7 policy

While the above figures illustrate the development until the end of the century, for the following more detailed analyses of the European power system, the horizon 2050 is of importance. Hence, Figure 31 shows the development of the power sector from 2010 to 2050. For both SSPs wind power and nuclear dominates the mix for all the scenarios in 2050. Another similarity between SSP1 and SSP3 is that power generation increases by about 80% up to 2050, whereat the generation mix is quite a bit different. In SSP1, there still are significant shares of fossil power generation without CCS in Europe, while in SSP3, these are substituted by nuclear power generation and power plants with CCS. The mixture of renewable is quite similar in both SSPs. This lead, as seen above, to significantly higher emission from the power sector in the "Sustainability" pathway SSP1 compared to the "National rivalry" pathway SSP3 to 2050.

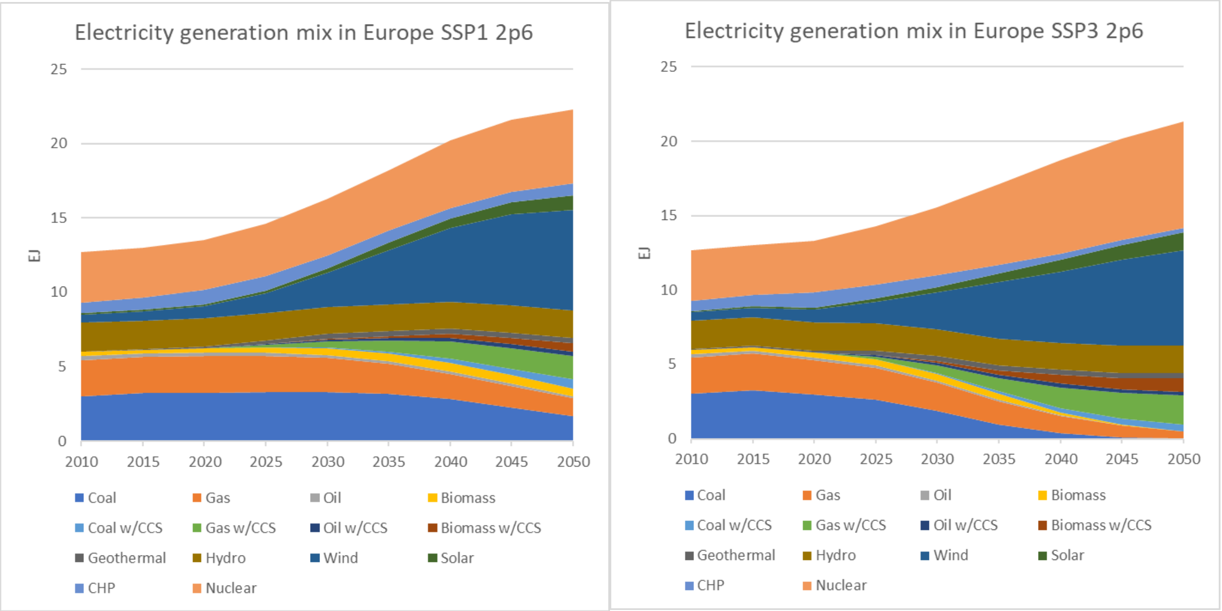


Figure 31: Generation mix in Europe up to 2050 SSP1 (left) and SSP3 (right) for the 2p6 policy

4.1.5 Summary of the GCAM results

In the first step all of the different pathways are run combined with a set of climate targets. Results show, that the climate target has the highest effect on the resulting average global temperature increase. However, in the strictest target (forcing of 2.6W/m2), which includes a possible overshoot of radiative forcing, the duration and level of the overshoot, has a substantial effect on the final temperature increase. This overshoot is partly defined by the SSP.

On the other side, the development of the primary energy consumption is mostly defined by the SSP and only to a minor part of the climate target. There the increase in primary energy is much higher in SSP1 "Sustainability" than in SSP3 "Regional Rivalry", which might be unexpected in the first place. However, this is due to the much higher economic development in SSP1, in a world with a high cooperation. In this definition of the sustainable pathway, a reduction of the energy consumption due to a circular economy or change in the consume behaviour of the population is not taken into account. Finally looking on the power sector in Europe, based on the total electricity demand, effects of the socioeconomic pathway and the climate target can be observed. Here it can be concluded, that a larger economic growth as well as a stricter climate target result into a larger electricity demand in Europe. Furthermore, it can be observed, that the European electricity demand in SSP3 decreases again to the end of the century, which is due to the assumption of a significant decrease in population.

In the second step the two pathways SSP1 and SSP3 are simulated with updated input as described above and results are assessed in more detail. The focus thereby is on the European level and the power sector. Especially on the European level differences for the pathways in the trajectories for emissions and the development of the power sector can be observed. Thereby, the development of the greenhouse gas emissions in the pathway SSP3 is most restricted, which is not the "sustainable" pathway. This includes a much faster reduction of emissions. This is especially the case for the electricity sector and even more so for Europe. Hence, SSP3 includes a faster transformation of the power system to generation assets with lower or zero carbon footprint. While there only is a partial reduction of emissions to about 2/3 of the 2010 level in SSP1 by 2050, emissions from the power sector in 2050 are nearly reduced to zero in SSP3. This development for the European power sector is contradictory to the descriptions of the pathways as "Sustainability" (SSP1) and "Regional Rivalry" (SSP3). However, it can be explained by the fact, that in both cases the same climate target is set for 2100 and there is a much higher global cooperation and development of negative emission technologies assumed in SSP1 than in SSP3. Hence, it is more effective to cut greenhouse gas emission in other places than Europe in SSP1 and to use negative emission technologies to the end of the century. At the same time, this means that Europe relies on future technologies and on the reduction of emission in other parts of the world, while not being a forerunner.

The selected global socioeconomic pathways with regional results for Europe provide a good framework for the following analyses of scenarios of the European system until 2050. While, GCAM results have a rather rough geographic and temporal resolution, the aim of the subsequent analyses with EMPIRE are to provide results on regional country level and to take into account the inherent variability of intermittent renewable energy sources in the long-term development of the power system.

4.2 Linking GCAM – EMPIRE

Given the global framework results from GCAM, the following step is to put this global framework into the EMPIRE model for a quantification of energy scenarios on a more detailed level. For that, the results that are used for coupling as input in EMPIRE simulations are described in this section. The following figures show results from GCAM, that are used as inputs to EMPIRE for the assessment of the scenarios "Green globe" (based on SSP1) and "National ways" (based on SSP3) for both climate targets 2p6 and 3p7. However, in the presentation of the analysis with EMPIRE below, it is concentrated on the 2p6 policy, while potential differences to the 3p7 policy will sometimes be discussed.

4.2.1 Linking procedure

The general method of linking GCAM and EMPIRE is described in section 2.2. The main aim is to break down global a multi-sector results from GCAM to the European power sector. For the coupling two main parameters are used. The first one is the resulting total electricity generation / demand for the region from GCAM, which is then distributed on the European countries. The second parameter is the greenhouse gas emission from GCAM and the according climate policies.

4.2.2 European Electricity Demand

The electricity demand increases with a stricter climate policy for both global pathways SSP1 and SSP3. This is a result of large-scale electrification of all demand sectors to reduce CO_2 emissions. The highest increase of electricity demand is observed in the SSP1 2p6 scenario, with a total increase of about 80% up to 2050. In general, the electricity demand is higher in the SSP1 scenarios than in the SSP3 scenarios, which is a result of higher economic growth and in population in Europe. However, while the electricity demand in the SSP3 2p6 is comparable to SSP1, it is much lower in the SSP3 with a 3p7 target. This difference in electricity demand will also have a significant effect on the simulation results with EMPIRE.

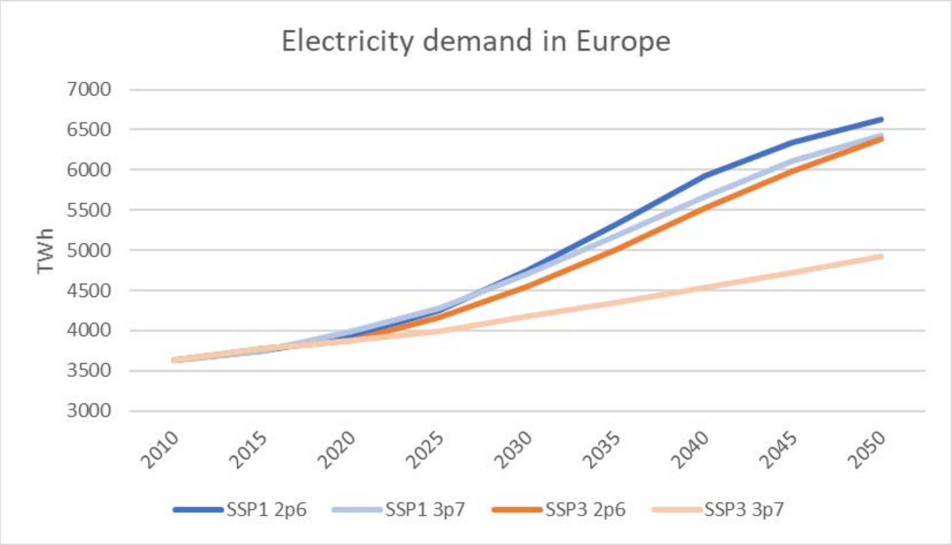


Figure 32: Total electricity demand in the different SSPs

The total electricity demand in Europe per period is coupled to the EMPIRE model, to achieve a finer geographic and temporal resolution as well as to assess the optimal generation mix to fulfil this demand. IN this coupling procedure the demand is scaled to only include the countries shown in Figure 33 compared to Table 1. This means for example that the electricity demand of Turkey is removed. The electricity demand is then distributed over the countries in EMPIRE based on historic values and future projections, as shown in Figure 33.

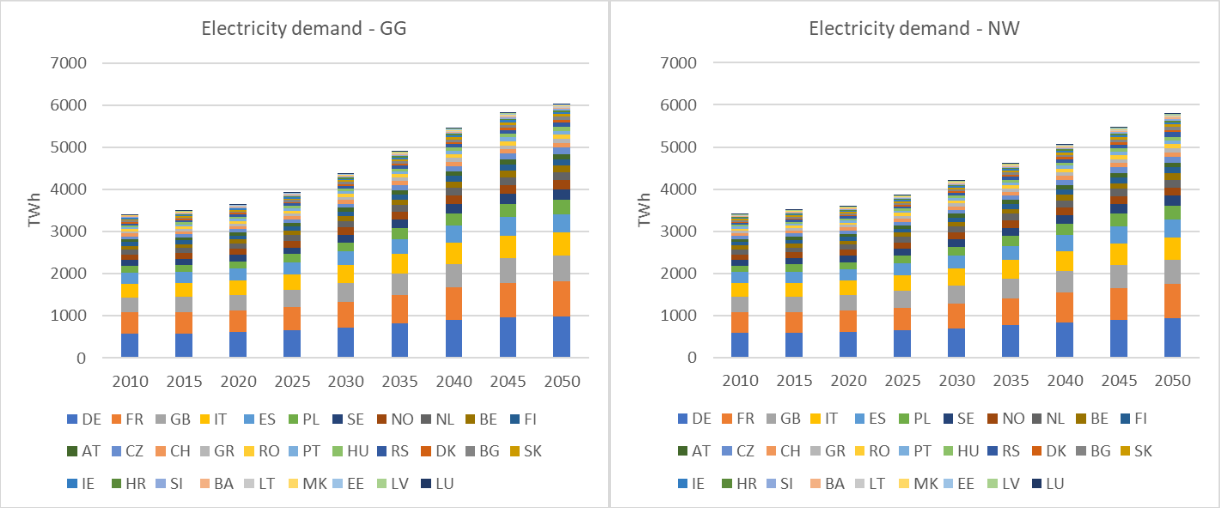


Figure 33: Resulting electricity demand per country in Europe defined in EMPIRE "Green globe" scenario (left) and "National ways" scenario (right)

4.2.3 CO_2 emissions, CO_2 price and CCS

Beside the electricity demand, CO_2 emissions are important results that are linked to the power system model EMPIRE. Initially, the CO_2-emissions have been used to set a cap of total emissions allowed in the EMPIRE model. Direct results from GCAM for the emissions of the power sector, as illustrated in Figure 25, do not account for negative emission from biomass-based power production, as this is done in a separate sector in GCAM. However, this has been taken into account when calculating the emission constraints in EMPIRE. Furthermore, the emission cap is scaled to fit the regions covered in EMPIRE. When coupling the emissions from GCAM to EMPIRE, the emission cap for EMPIRE is not set for each single time step, but an emission budget until 2050 is defined, based on the cumulative emissions from GCAM. During the simulation with EMPIRE, the definition of the budget was changed, from being based on the 2050 horizon to the 2100, as will also be discussed in the next section.

In addition to the initial emission constraint, CO_2 prices are forwarded to EMPIRE and applied in a number of simulations with EMPIRE. This also includes the simulations discussed in the following. To illustrate these inputs, Figure 34 shows the emission constraints and the CO_2 prices which are coupled to EMPIRE. It can be observed, that there are significant differences between the pathways, where SSP3 with the climate target 2p6 is the most restrictive one. In line with the differences in emission reduction is the development of the CO_2 price, which is highest for SSP3 2p6. It has to be mentioned, that the price curve in this case starts at about 63 EUR/t CO_2 already in 2020, what might be too high compared to current observed prices. Furthermore, it can be observed, that the CO_2 price is three times as high in SSP3 than in SSP1 and that there is an about 25% increase of the price every 5 year.

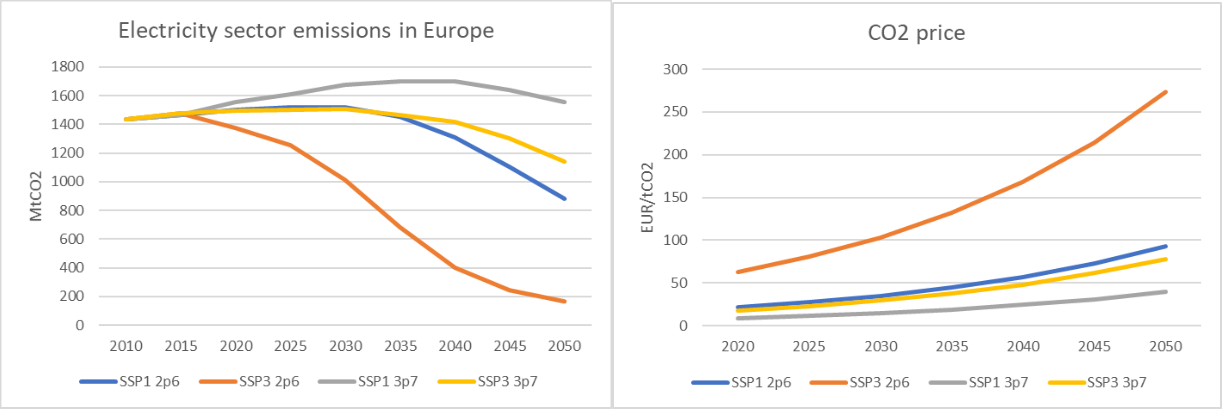


Figure 34: CO_2 emissions (left) and CO_2 price (right) in Europe

Finally, during the simulations with EMPIRE, it was observed, that the operation of CCS power plants is rather sensitive to the framework conditions. Hence, in addition to the previous two emission parameters above the resulting costs of transporting and storing CO_2 (sequestration) is forwarded to EMPIRE.

As the results from GCAM in the Figure 27 illustrate, CCS is applied somewhat earlier in Europe in SSP3 compared to SSP1, which at the same time results into a higher cost of CCS. Figure 35 shows simulations with EMPIRE to 2050. As also illustrated in Figure 27, the early application of CCS in SSP3 results into a decline of CCS utilisation in the second half of the century. While in SSP1, there is a significant utilisation of CCS in the electricity sector in the second half of the century.

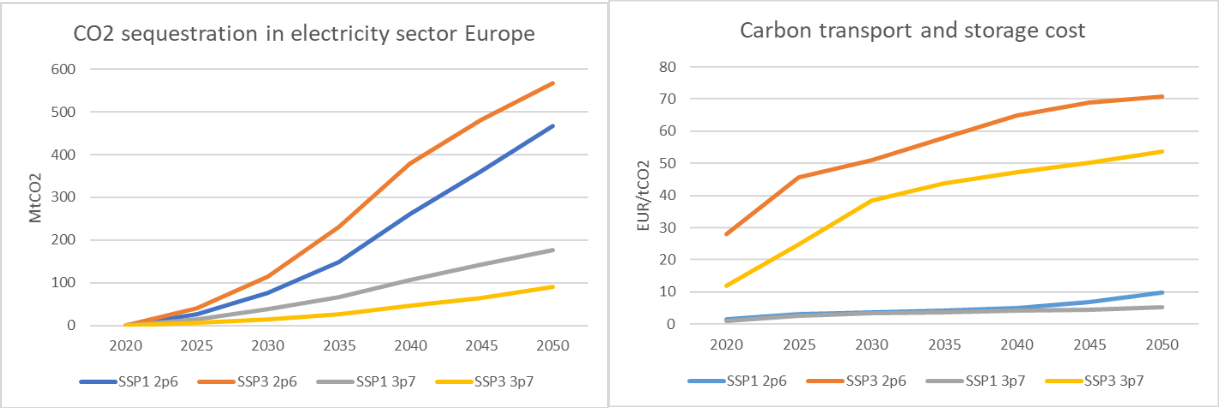


Figure 35: CO_2 sequestration in the electricity sector and CO_2 transport and storage cost

4.3 European power sector results of EMPIRE

Given the framework results for Europe from GCAM and parameters for the development of the power generation technology and other costs, a number of scenarios are simulated in EMPIRE. These scenarios are then used to assess the development of the European power system.

The following section at first provides an overview over the scenarios and afterwards presents and discusses results of four selected scenarios from the EMPIRE simulations. Some of the figures are used to compare results from EMPIRE and GCAM. If not stated otherwise, the results are from the EMPIRE simulations.

The linking methodology including the flow of input and output data is described in section 3.3 and illustrated in Figure 2. The energy scenarios assessed in EMPIRE are "Green globe" (GG) based on SSP1 and "National ways" (NW) based on SSP3. In addition to the underlying socioeconomic pathway, the actual implementation of the climate policies and the potential of transmission infrastructure expansion are evaluated.

Assessing these two different cases of transmission infrastructure expansion helps investigating, the benefit of a tighter cooperation in Europe as well as highlights potential effects on the geographic distribution of power generation and the exchange.

4.3.1 Linking iterations

Similar to the simulation runs for GCAM to achieve reasonable results, a significant number of iterations was necessary for running EMPIRE and adapting the model coupling. These iterations mainly consisted of a change in the coupling methodology and the change in parameters between GCAM and EMPIRE. An overview of the selected resulting cases for EMPIRE are shown below in Table 4. Thereof case 3 – 6 are chosen for the assessment for the energy scenarios including the potential expansion of the transmission system, while the other remaining cases are used for sensitivity analyses. These sensitivities include, the application of a CO_2 price as well as the size of the emission budget. As shown in Figure 32 the electricity demand in Europe to 2050 is rather similar for SSP1 and SSP3 2p6.

Table 4: EMPIRE simulation – case definition

Case	SSP	Climate policy	Technology costs	CO2 price	Emission constraint	Transmission investments	Scenario name
1	1	2p6	low	no	GCAM 2050	no	C7
2	3	2p6	high	no	GCAM 2050	no	C9
3	1	2p6	low	yes	GCAM 2050	no	GG no
4	3	2p6	high	yes	GCAM 2050	no	NW no
5	1	2p6	low	yes	GCAM 2050	low	GG trans
6	3	2p6	high	yes	GCAM 2050	low	NW trans
7	1	2p6	low	yes	2/3 GCAM 2100	low	C21
8	3	2p6	high	yes	2/3 GCAM 2100	low	C22

For the following discussion a number of cases from the above table are selected. The discussed scenarios all rely on the 2p6 policy and the coupling of the emission constraint of 2050 respectively 2100 from GCAM to EMPIRE. This emission budget until 2050 for the European power sector in the "Green globe" scenario is 10.44 Gt CO_2 and 6.44 Gt CO_2 for the "National ways" scenario. In addition to directly using the 2050 emission constraint, the coupling of the 2100 emission budget is tested. Using a 2/3 emission requirement of GCAM until 2100, leads to 4.59 Gt CO_2 for "Green globe" and 2.59 Gt CO_2 for "National ways". This emission budget for SSP3 might be unrealistically low, as it includes a significant share of negative emissions in the GCAM solution, which cannot be expected before the 2050 horizon. However, the simulation results with EMPIRE provide insights on what is necessary for a drastic reduction of emissions in the power sector.

Finally, the scenarios have a defined amount of power production from biomass in EMPIRE. The reason is, that there is no supply curve defined for biomass in EMPIRE and that the fuel cost is rather low in the first place. In some initial simulations with EMPIRE, this resulted in unrealistic high values of power production from biomass. It can be expected that the availability of biomass for power production is somewhat constrained, where an increased demand would result in a substantial increase in prices for biomass. This would require defining a supply curve, where not sufficient data is available. Hence, the power production from biomass is limited to the level resulting from the GCAM simulations.

4.3.2 Climate trajectories

Based on the above case definition, Figure 36 shows the possible development of emissions for three different variants of coupling the CO_2 emission constraints from GCAM to EMPIRE. Thereby, in the following detailed analysis of the selected scenarios, the focus will be on the cases plotted with solid lines in Figure 36.

The three different coupling methods illustrated in Figure 36 comprise:

1. Coupling purely based on the 2050 emission budget from GCAM (cases C7 and C9)
2. Coupling based on 2050 emission budget and CO_2 price from GCAM (cases GG and NW, which include without and with transmission expansion)
3. Coupling based on 2/3 2100 emission budget and CO_2 price from GCAM (cases C21 and C22, which include transmission expansion)

The development of CO_2 emissions for these coupling methods until 2050 show some clear differences. For the first coupling method the emissions from the power sector hit the emission cap in 2050, which then defines a somewhat linear trajectory of the emissions from 2015 to 2050. In the second coupling method the emission cap is not hit in 2050, but the CO_2 price defines the development, leading to a decrease of emission up to 2050. Given the third coupling method, with a rather strict emission budget and as well as a CO_2 price, the cap is hit again in 2050. Thereby especially for case C22 it can be seen, that nearly nothing is left of the emission budget after 2020, requiring a nearly instant carbon free power system.

The focus in the further analyses is on the cases GG and NW, which are lying in the middle of the emission trajectories. The other cases are used for a discussion of the sensitivity of the scenarios.

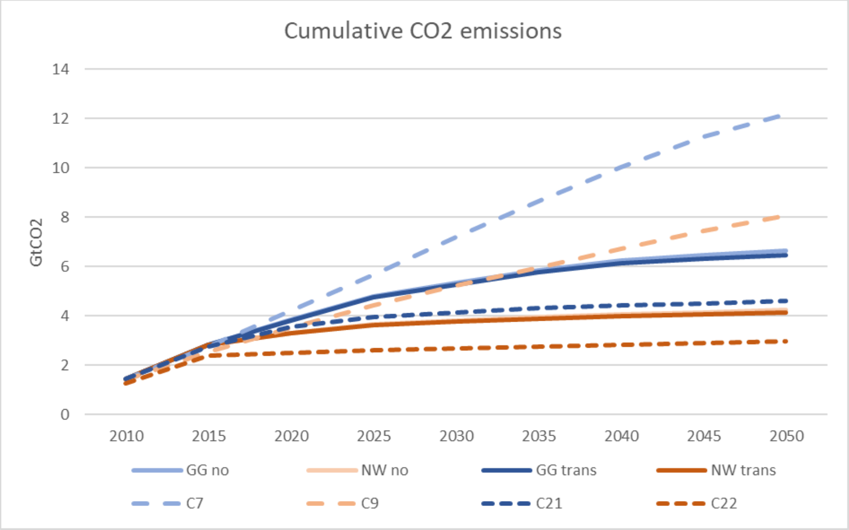


Figure 36: Emission trajectories for the European power sector with different coupling methods for CO_2 emissions

4.3.3 Generation Mix

A main input parameter from GCAM to EMPIRE is the increase in electricity demand for all of the scenarios, which requires a significant expansion of the power generation in the European system. In addition to this expansion, the necessary reduction of emissions requires a change of the type of generation assets in the power system. Hence, large changes of the generation mix can be observed to 2050 in all the scenarios. The European generation mix is shown in Figure 37 and Figure 38. Beside the changes in the generation mix within the scenarios, also characteristic differences between the "Green Globe" and "National ways scenario" can be observed.

In general, the power system expansion includes large increase in power generation from wind power resources, while solar power generation hardly increases at all in Europe. Gas becomes increasingly important, while coal-based power production becomes less important. While there is still some coal remaining in the "Green globe" (GG) scenario, it is completely phased out in the "National ways" (NW) scenario. For both scenarios carbon capture and storage (CCS) becomes a very important technology for power generation towards 2050 and already starting from 2015. Finally, while there are similarities in the development of the generation mix for the scenarios without and with transmission expansion, there are also some specific effects of the transmission expansion on the generation mix. The possible transmission expansion leads to an increase in power generation from renewable energy and a decrease in generation from fossil sources including nuclear power generation.

Assessing the GG scenario without transmission expansion, a lasting phase out of coal-power production without CCS can be observed, while there is a substantial expansion of gas-power production between 2020 and 2030. There is a constant expansion of wind power until 2050, at the same time nuclear is decreased.

In the NW scenario coal power production without CCS is phased out nearly immediately and replaced with gas-power. Also, in contrast to the GG scenario, there are no investment in coal power production with CCS. Furthermore, there is an earlier and higher increase of wind power production than in the GG scenario. This is also applicable for solar power production, however on a much smaller level. Finally, nuclear plays an important role to 2050. The differences in the generation mix between GG and NW can be explained by the much stricter emission constraints and higher CO_2 price in NW and the lower cost for carbon storage in GG.

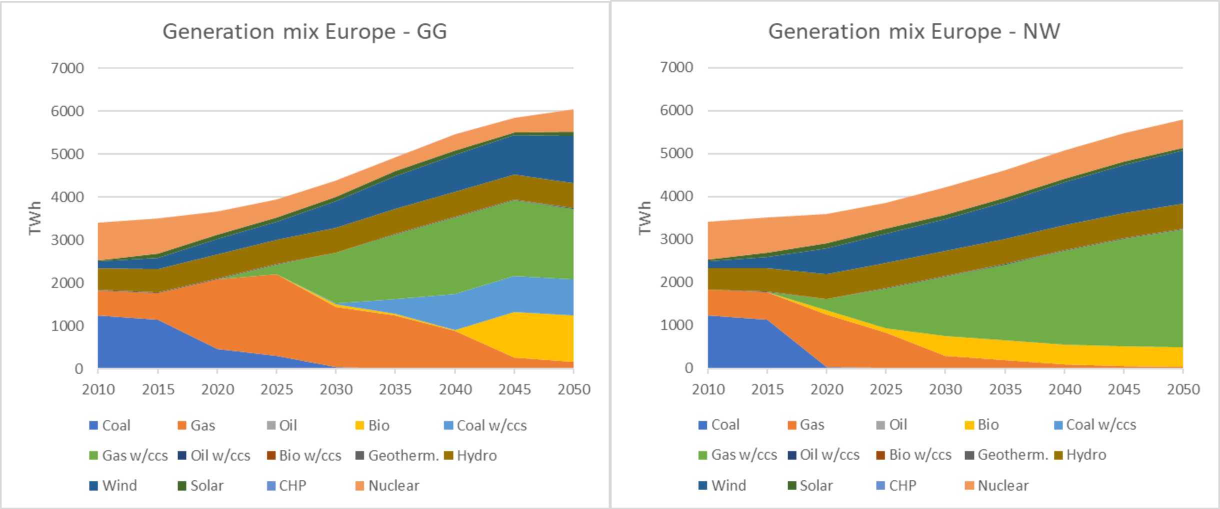


Figure 37: Generation mix in Europe without transmission expansion – Green globe (left) and National ways (right)

In order to assess the benefit of local or regional cooperation, the expansion of the transmission system is allowed in the following cases. This has some effect on the European generation mix, with a delayed and reduced development of power generation with CCS. The share of wind power production increases somewhat in both scenarios. In the GG scenario nuclear power generation is nearly phased out and substituted by power generation from intermittent renewable energy sources until 2050. In the NW scenario with transmission expansion a nearly immediate phase-out of coal power production can be observed, which partly is substituted with gas-power and wind-power in the first place. The transmission expansion enables the integration of more intermittent renewable power generation due to the increasing exchange over a larger geographic area. At the one side the transmission expansion allows a more efficient utilisation of these intermittent energy sources. On the other side an increased transmission capacity also ensures more firm generation capacity from intermittent renewable energy sources due the more geographic diverse availability of generation sources.

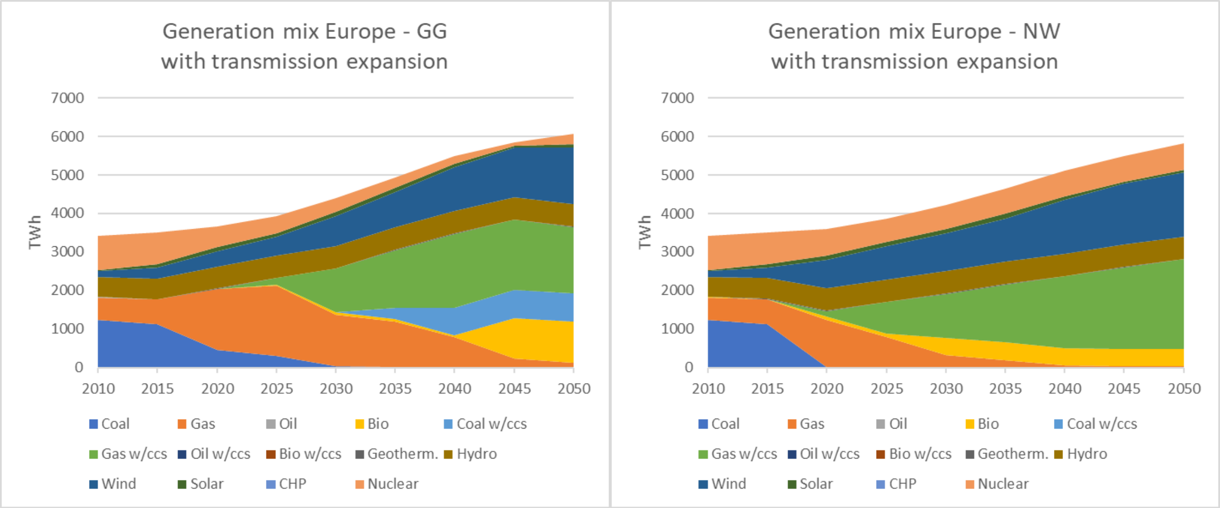


Figure 38: Generation mix in Europe with transmission expansion– Green globe (left) and National ways (right)

Figure 39 shows the scenarios GG and NW without transmission expansion in case of neglecting the CO_2 price. Here a much higher share of fossil-based power production without CCS can be seen, leading to much higher emissions, as illustrated in the previous subsection.

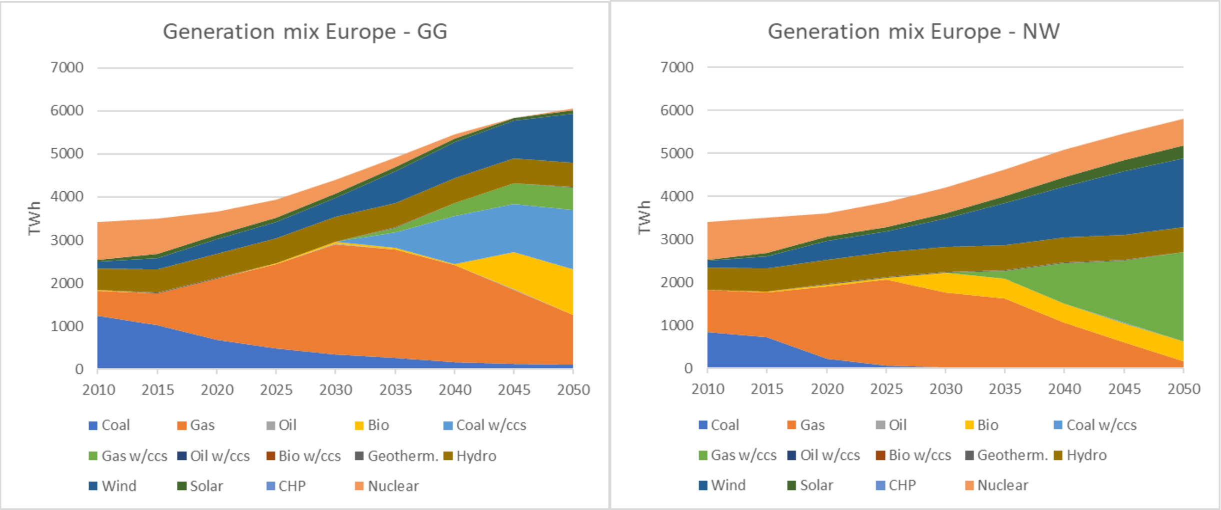


Figure 39: Generation mix in Europe without transmission expansion and no CO_2 price applied – Green globe (left) and National ways (right)

Figure 40 shows the GG scenario with a reduced emission constraint of 4.6 Gt CO_2 up to 2050, while the applied CO_2 price is the same as in the previous GG case. The resulting generation mix with the tighter emission constraint becomes more similar to the NW case, with an earlier and complete phase-out of coal-power and an earlier investment in gas-power with CCS. In addition, nuclear power production plays a bigger role, similar to NW. However, the share of power production from wind and solar is smaller than in NW, possibly due to the significantly lower cost of carbon storage in GG compared to NW. Likewise, in the case of NW significant changes can be observed due to the tighter emission constraint. Here nearly instant phase out of fossil power generation without CCS can be observed. This also includes the immediate expansion of gas power generation with CCS in 2020. While this is the optimal solution provided by EMPIRE, in reality the underlying generation technologies need to be available, which especially for CCS is not the case yet. However, the results indicate, that aiming for a significant emission reduction requires an as early as possible transition of the power system to generation technologies with a low carbon footprint.

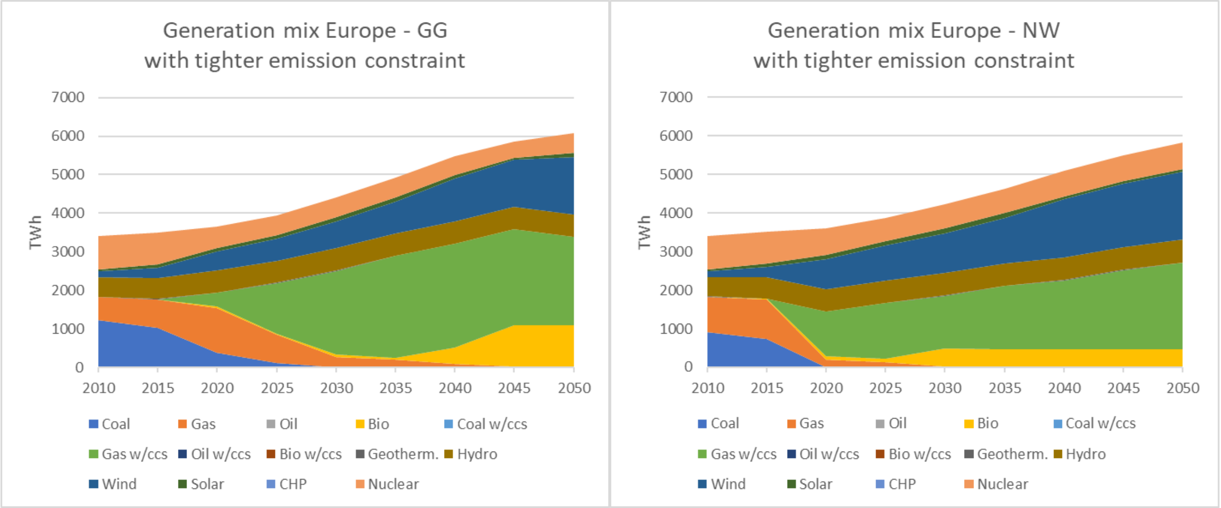


Figure 40: Generation mix in Europe with transmission expansion and a tighter emission constraint

Finally, comparing the resulting European electricity generation mix of EMPIRE to the one reported from GCAM, several differences can be observed. At first it can be stated, that there is a much smoother and less radical change in the generation mix in GCAM. Furthermore, the GCAM generation mix includes higher shares of power generation from renewable energy sources and nuclear power. Finally, there still are significant shares of fossil-based power generation without CCS left in the generation mixes of GCAM in 2050, specifically in SSP1.

There are several reasons for these differences. While, GCAM uses choice functions to decide, which technology to invest in, EMPIRE is a full optimisation model. Hence, changes in GCAM are somewhat smooth, while they can be quite radical in EMPIRE. The representation of time steps and geography is much higher in EMPIRE, which leads to a better modelling of variability and flexibility requirements in the power sector. This can result in lower shares of non-dispatchable RES or nuclear power and higher shares of dispatchable power production in EMPIRE compared to GCAM. Finally, EMPIRE is a specific model for the power sector, neglecting effects on other sectors. Large changes in results for the power sector can lead to significant changes in coupled sectors, which again might affect input parameters to the power sector and limit the initial changes. This feedback is not accounted for yet and can lead to a larger divergence of results.

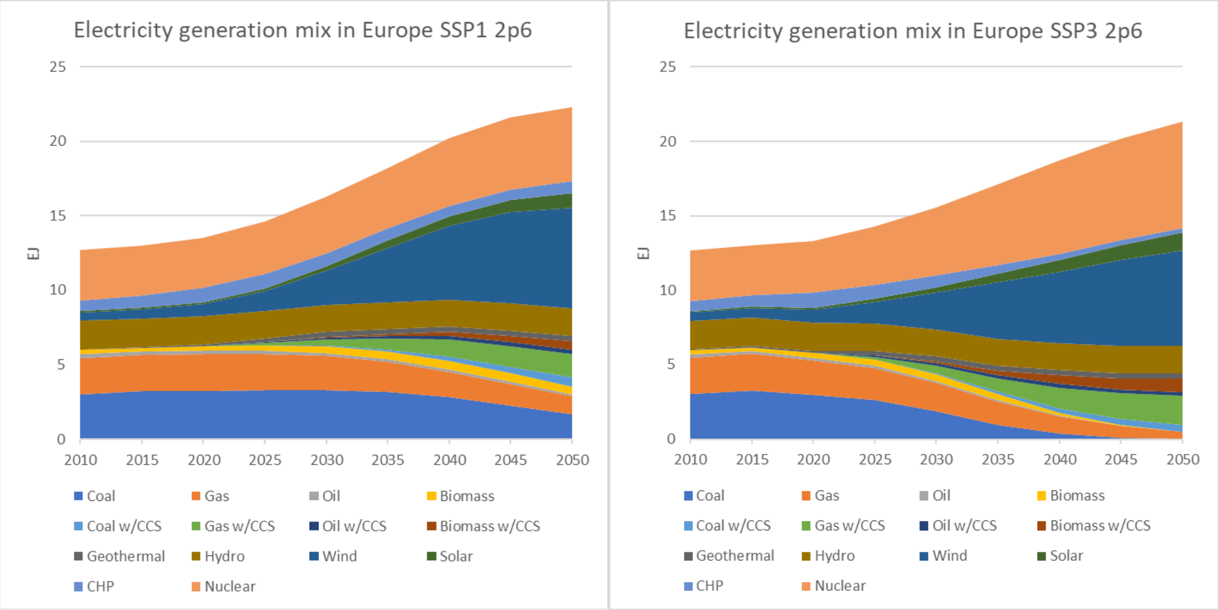


Figure 41: Generation mix in Europe from GCAM – SSP1/GG (left) and SSP3/NW (right)

Zooming in on a country level, Figure 42 shows the resulting generation mix from EMPIRE for selected country in northern and central Europe for 2050. The figure shows different characteristics for the countries. Coal and gas power, to the largest extend with CCS, is mostly located in Germany and Great Britain. Nuclear power generation is located in France, in addition to rather high shares of wind power production. The generation mix of Norway consists to a large degree of hydropower and wind power with a total generation of more than 200 TWh per year. Sweden has a similar generation mix, however still including some nuclear power generation in the NW scenario in 2050. A special case is Switzerland, where significant amounts of gas-power production with CCS can be observed, especially in the cases with transmission expansion. This might be explained by the central location of Switzerland in Europe, leading to the development of an exchange hub.

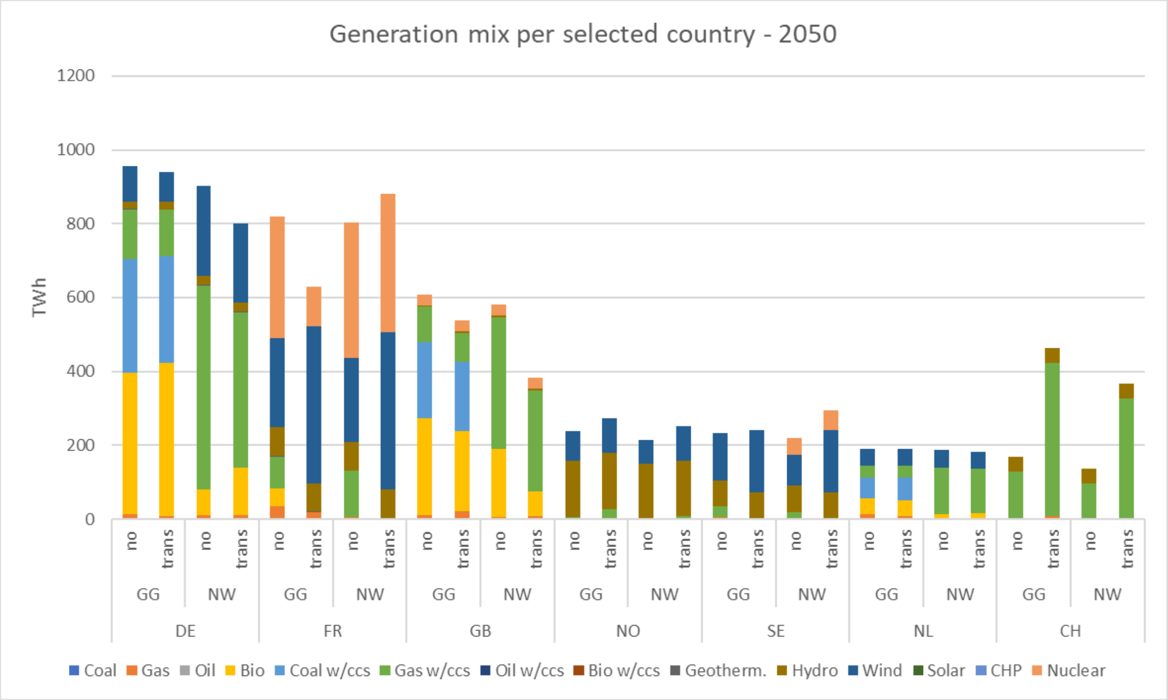


Figure 42: Generation mix for selected countries in Europe

Finally, shedding some light on the development of the intermittent renewable energy sources (iRES) in Europe, Figure 43 shows the electricity generation from these sources and the curtailed generation from intermittent renewable energy sources. A rather similar, linear expansion of iRES power generation can be observed, where the expansion in the NW scenarios is generally higher and earlier. The transmission expansion allows for the investment in more intermittent RES. The fast expansion of iRES in the NW leads to curtailment of up to 1% in 2020 for the case without transmission expansion. Finally, while the GG scenario has a lower generation of iRES in 2050 it actually has a higher curtailment pointing to a system with less flexibility to handle power generation from iRES.

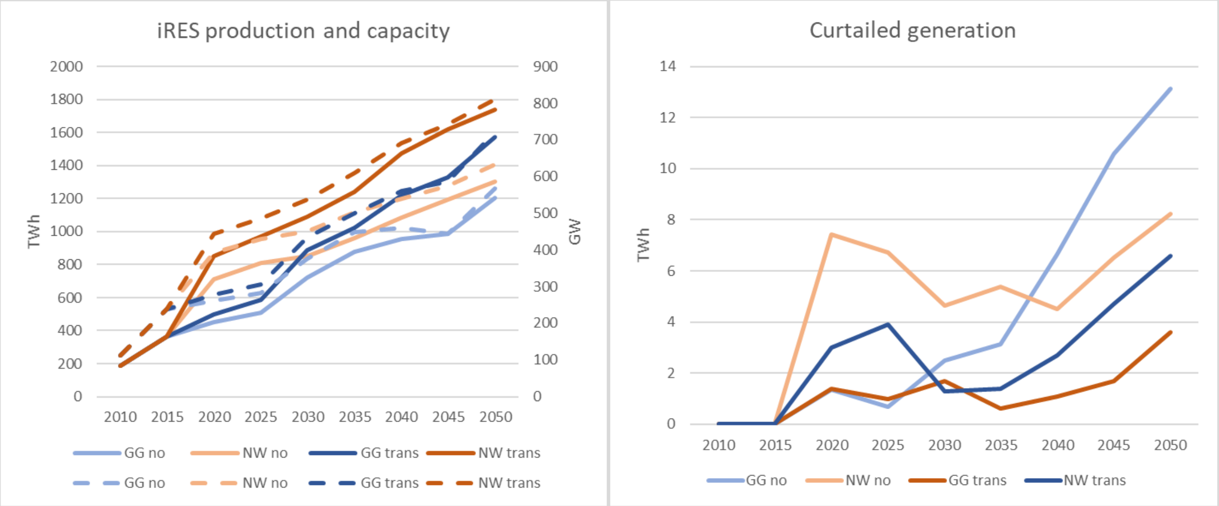


Figure 43: Power generation (bold) and generation capacity (dotted) from intermittent renewable energy sources (iRES) and resulting curtail of power generation

4.3.4 Generation Capacity

Beside the actual generation mix, results of EMPIRE allow to assess the underlying installed generation capacity for the development of the power system. In line with the generation mix, also large changes in the installed generation capacity can be observed. Similar to the generation mix, there is an investment in intermittent renewable generation capacity, as well as the phase out of fossil-based power production without CCS and its substitution with power production including CCS. Also, in line with the generation mix, there is a phase out of nuclear power generation capacity in the GG scenario.

However, in contrast to the generation mix, the intermittent renewable energy sources represent a larger share of the generation capacity, i.e. the amount of solar and wind capacity in the GG and NW scenarios are about 30%-50% respectively.

A specific characteristic, that can be observed for the installed generation capacity is the amount of gas-power generation without CCS, which is still present in 2050 in all of the scenarios. Thereby, the amount is higher in the scenarios without transmission expansion. As there nearly is no power generation from these assets in the generation mix, it causes a very low utilisation time. Hence, these assets are certainly used to cover demand peaks. These backup power plants are used in situations with scarcity, which are rare. Thus, these conventional power generation technologies do not cause significant emissions. For example, coal power generation can be seen in the installed generation capacity until 2035 but cannot be seen in the generation mix in most of the scenarios. Especially in the NW scenarios, coal is nearly phased out completely from 2020 onwards. Somewhat the same accounts for gas power without CCS at the 2050 horizon.

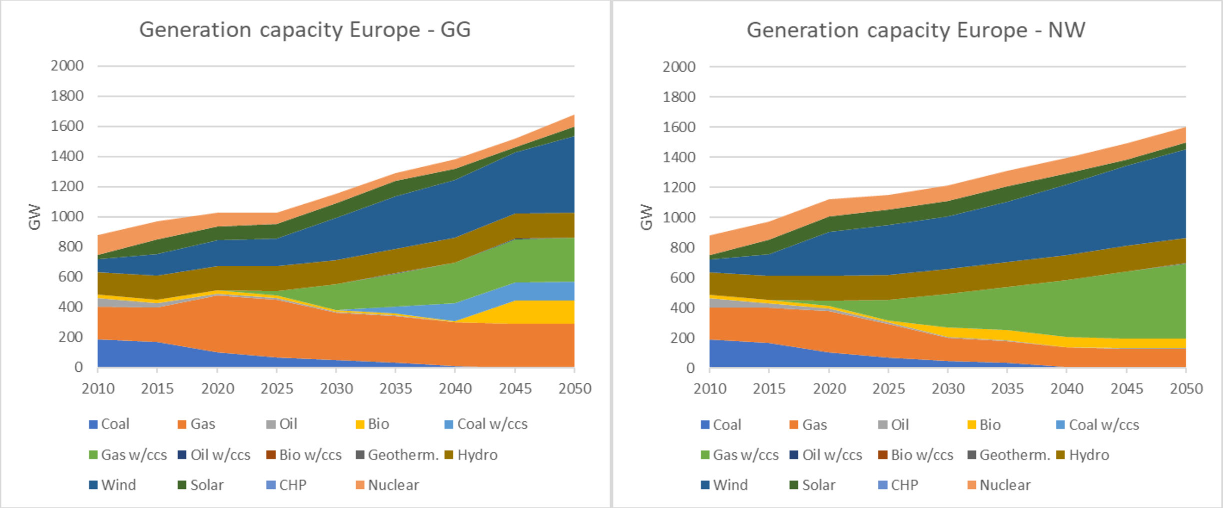


Figure 44: Generation capacity in Europe without transmission expansion – Green globe (left) and National ways (right)

When transmission expansion is made possible an increase of total generation capacity can be observed, which however consists of an increase in generation capacity of iRES and a decrease of dispatchable generation capacity. This change of power generation capacity is possibility due to the increased geographic smoothing effects, allowing for the averaging of intermittent power generation over a larger area. At the same time the capacity of gas-power without and with CCS is reduced, certainly as not that much backup capacity is necessary, when there is increased exchange capacity. In addition, there is a significant reduction of nuclear generation capacity, especially in the GG scenario with transmission expansion compared to without.

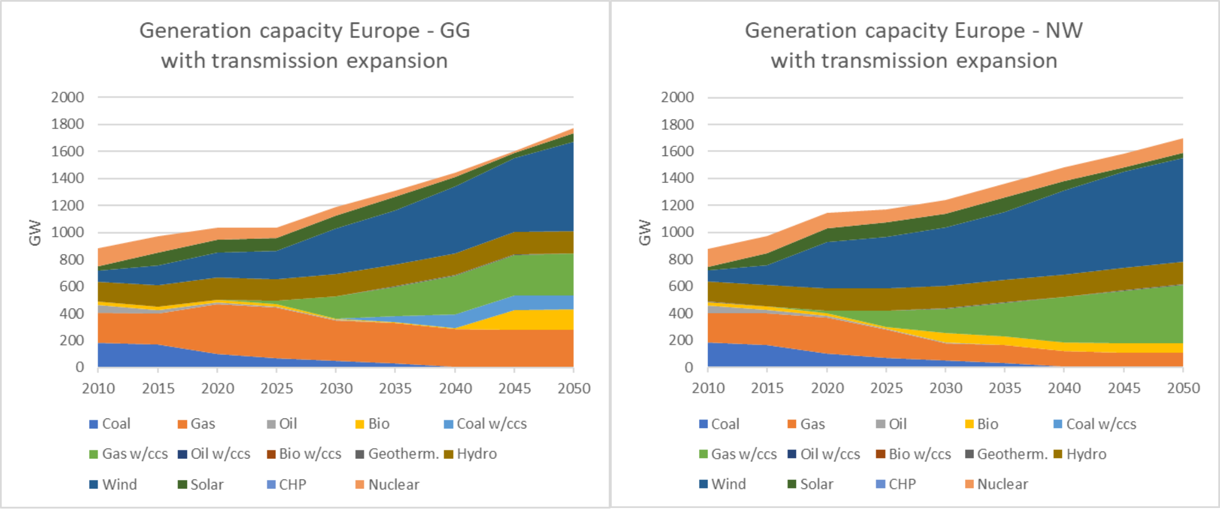


Figure 45: Generation capacity in Europe with transmission expansion - Green globe (left) and National ways (right)

4.3.5 Transmission Capacity

In addition to the change in installed generation capacity and the generation mix, the power system model EMPIRE is able to assess profitable and necessary changes in the transmission infrastructure. Figure 46 illustrates the development of the total cross-border interconnection capacity in Europe. It can be observed, that about 20% more transmission capacity is expended in NW compared GG. This also means about a four-doubling of cross-border transmission capacity from 2015 to 2050 in the power system. The difference between NW and GG can be explained by the higher challenges in emission reduction in NW. Hence, given the same costs for expansion, this opportunity is applied more in the NW scenario to allow the integration of intermittent renewable energy sources. This expansion will at the same time also require significant domestic transmission expansion, which are not explicitly modelled in EMPIRE.

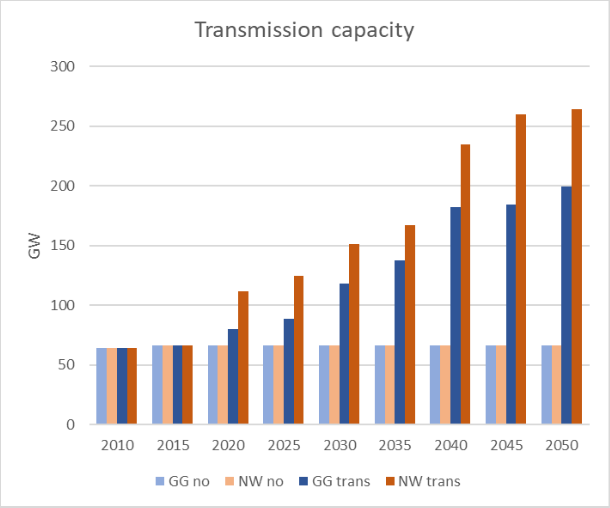


Figure 46: Cross-border transmission capacity in Europe

Figure 47 shows the development of the cross-border transmission capacity between the countries in Europe. It can be observed, that the highest increases are between France, Great Britain and Switzerland with installed cross-border transmission capacity of more than 25 GW. Furthermore, there also is some substantial expansion of cross-border transmission capacity throughout the Nordic countries Sweden, Norway as well as Denmark and to Germany. While Germany has the highest share of cross-border capacity in 2015, its expansion of cross-border transmission capacity is not that high as for France or Switzerland even though it also has a quite central location. Required domestic expansions of the transmission system are not taken into account in detail in this expansion analysis but are partly taken into account in the cost figures for the expansion of the cross-border interconnectors.

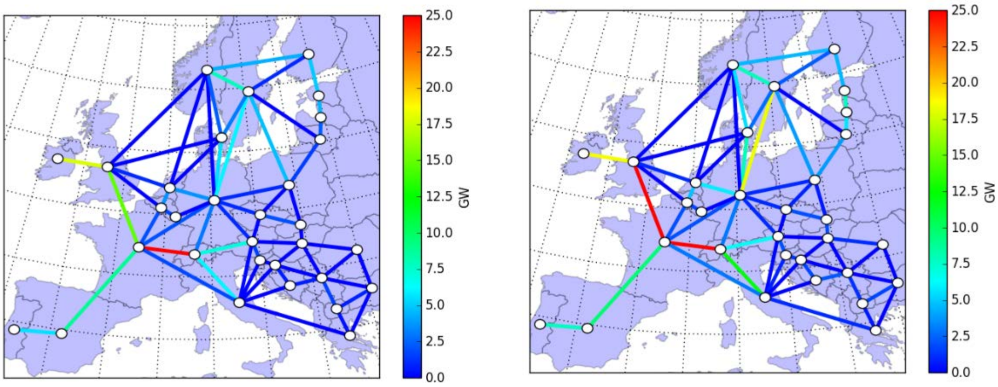


Figure 47: Expansion of exchange capacity in Europe - Green globe (left) and National ways (right)

Given the expansion of cross-border transmission capacity, Figure 48 depicts the sorted resulting net exchange for different countries in 2050. The general trends that can be observed are that Switzerland becomes a large energy exporter, certainly due to its central location. In addition, Norway and Ireland are developing into net electricity exporting countries in both scenarios, which is due to the availability of good wind resources. On the other side, Great Britain and Germany become significant net importers of power in both scenarios, where Great Britain at most imports about 30% of its domestic power demand. A rather special case is France, which is a net importer in the GG scenarios and a net exporter in the NW scenario. This change in import / export is certainly due to the available nuclear power generation, which is much lower in the GG scenario in France compared to the NW scenario. Putting the exchange pattern in relation to the generation mix, it can be observed, that the change in the exchange pattern is due to the much higher nuclear power production in the NW scenario.

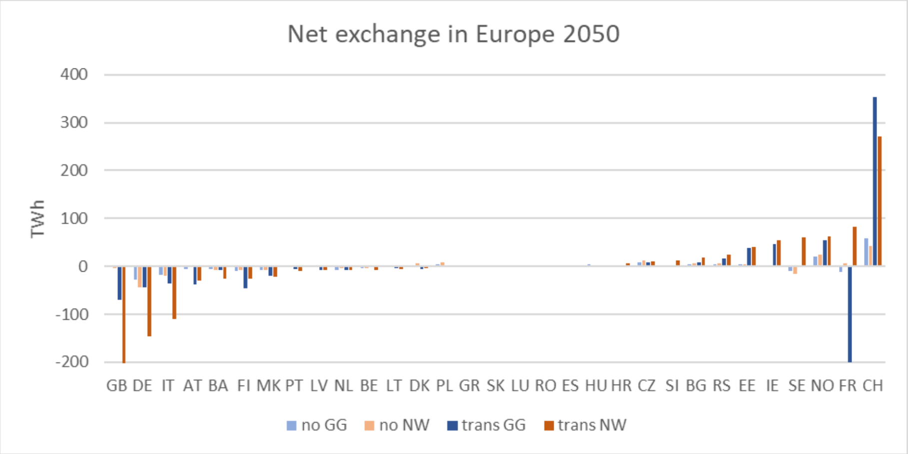


Figure 48: Net exchange on country level in Europe

4.3.6 CO_2 Emissions and Sequestration

The following figures illustrate the emissions, respectively capturing and storing of CO_2 in the European power sector. As described above EMPIRE is using both an emission cap, the CO_2 price from GCAM and the cost for storing CO_2. In addition, the cost of capturing CO_2 lies implicitly in the technology cost and efficiency of power generation assets with CCS.

Figure 49 shows the development of the CO_2 emissions and the captured CO_2 in the European power sector. In general, the development of emissions and capture is rather independent of transmission expansion. However, there are some substantial differences between the GG and the NW scenario. Of these, none of the scenarios reaches the emission cap, hence the CO_2 price and the costs for CCS are the guiding parameters in these scenarios. Emissions are higher in the GG scenarios than in the NW scenarios, due to the lower CO_2 prices in the Green Globe scenario. This contradictory result is already discussed in section 4.1.

In addition to the direct emissions from the power sector, the development in CO_2 sequestration in EMPIRE is illustrated. The amount of captured CO_2 in EMPIRE is plotted in Figure 49. There is a significant difference in cost for the captured CO_2 and storage between GG and NW, which clearly impacts the investment and utilisation of CCS in EMPIRE. Whereas there is not such a signficant difference in the application of CCS between SSP1 and SSP3 in GCAM, as discussed above. In EMPIRE, the total CO_2 capture is higher in the GG scenario up to 2050, while it starts at an earlier stage in the NW scenarios. In addition, the captured CO_2 is somewhat higher in the scenarios without transmission expansion, meaning that power generation with CCS is used instead of iRES based power generation.

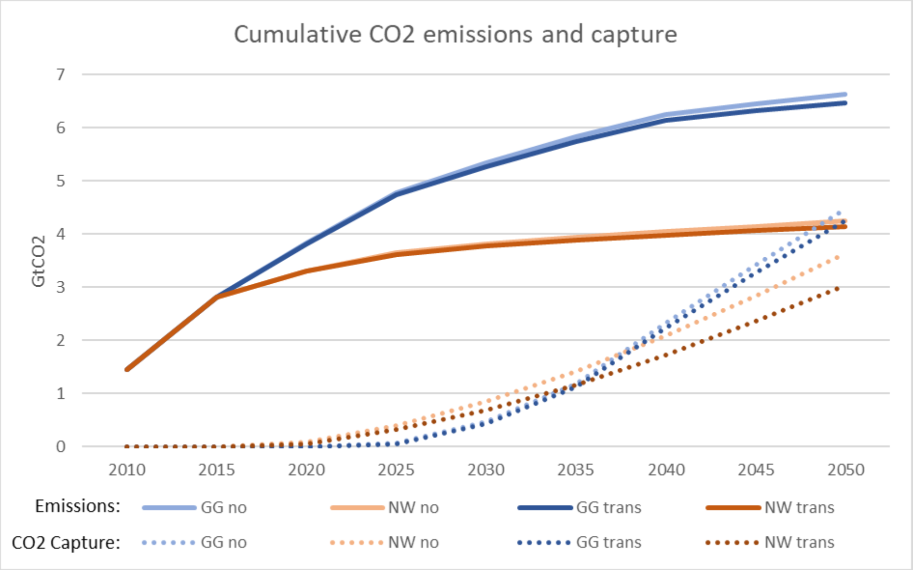


Figure 49: CO_2 emissions and capture in Europe

The emission intensity (emission per consumed power) is illustrated in Figure 50. It shows a drastic reduction of intensity in the decade from 2020-2030 for both scenarios, where again the transmission expansion does not have a significant effect. While in NW, the highest share of reduction in emission intensity is already achieved in 2020, this is the case for up to 2030 in GG. In line with the results of GCAM, the resulting transition pattern is rather ambitious/unrealistic as such a sudden transition in the power sector can certainly not be expected. The reason is probably the very high CO_2 price from GCAM and the strict CO_2 emission caps. Furthermore, in the NW scenario, the overall potential for CCS is rather low and quite costly, which also can be seen in the resulting generation mix above.

The amount of direct CO_2 emissions and CO_2 capture and storage per time step is illustrated in Figure 51. The largest share of CO_2 from the power sector is captured in 2050 in all of the scenarios. Looking on the sum of CO_2 emissions and capture, it shows that the total level of CO_2 originating from the power sector is not decreasing throughout the last decades up to 2050. This means that CO_2 emissions are not necessarily cut, but it is relied on CCS to avoid that CO_2 escapes to the atmosphere.

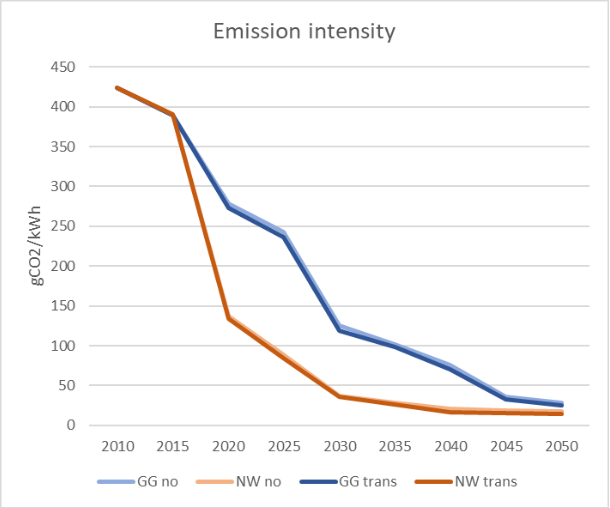


Figure 50: CO_2 emission intensity in Europe

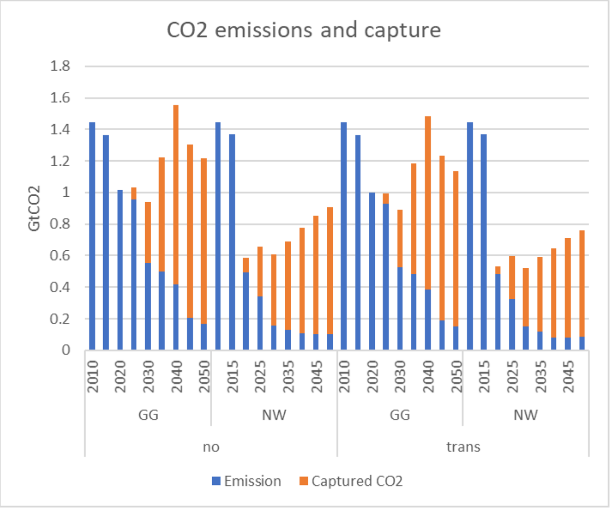


Figure 51: CO_2 sequestration and storage

The following figures assess the distribution of CO_2 emissions and capture over the different countries. Figure 52 shows the share of emissions by country, with the four largest emitters being Germany, Great Britain, Poland and Italy. While the total emissions in Europe decrease, as illustrated above, the share of emissions from the countries is somewhat stable up to 2050. In addition, the distribution of emissions in the GG and NW scenarios is rather similar. The same accounts for a comparison between the cases without and with transmission expansion. The only major change is in the share of emissions from France, which becomes nearly zero in the NW scenario with transmission expansion in 2050.

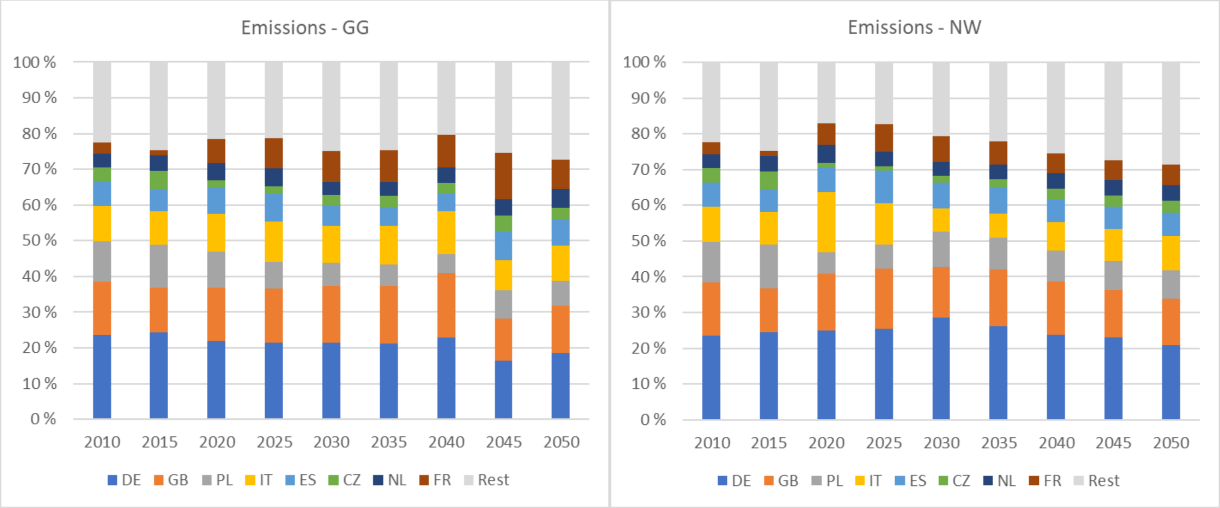


Figure 52: Share of CO_2 emissions for the highest emitting countries in Europe without transmission expansions

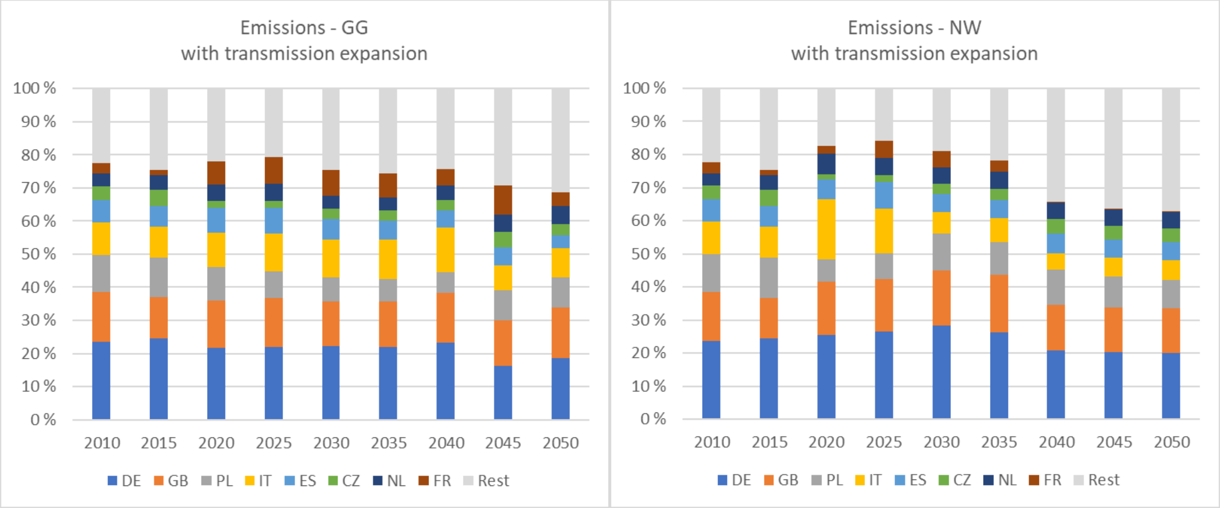


Figure 53: Share of CO_2 emissions for the highest emitting countries in Europe with transmission expansions

Beside the CO_2 emissions, Figure 54 and Figure 55 plot the share of CO_2 capture per country. Similar to the development of the CO2 emission, it can be stated, that the development of CO_2 capture is rather similar in all cases, while the European total of CO_2 capture increases signficantly up to 2050. In line with the biggest emitters of CO_2, the highest share of CO_2 capture is in Germany, Great Britain, Poland and Italy. However, the large exception is the CO_2 capture in Switzerland in the cases with transmission expansion, which is due to the large expansion of generation with CCS. This generation shift also leads to increasing CO_2 capture in

Switzerland and a reduction in the other countries. It has to be mentioned, that within the analysis only cost parameters for capturing and storing CO_2 are implemented, where there is no differentiation between countries. Hence in reality it might be questionable if exactly this development will happen. However, the results indicate a benefit in centralising the assets in a location, that can be used as a hub in the power system. In addition, within the scenario analysis no assumption are made on where the CO_2 is stored. Hence, CO_2 transport cost will most probably be added to these results, potentially leading to a relocation of the power generation assets with CCS.

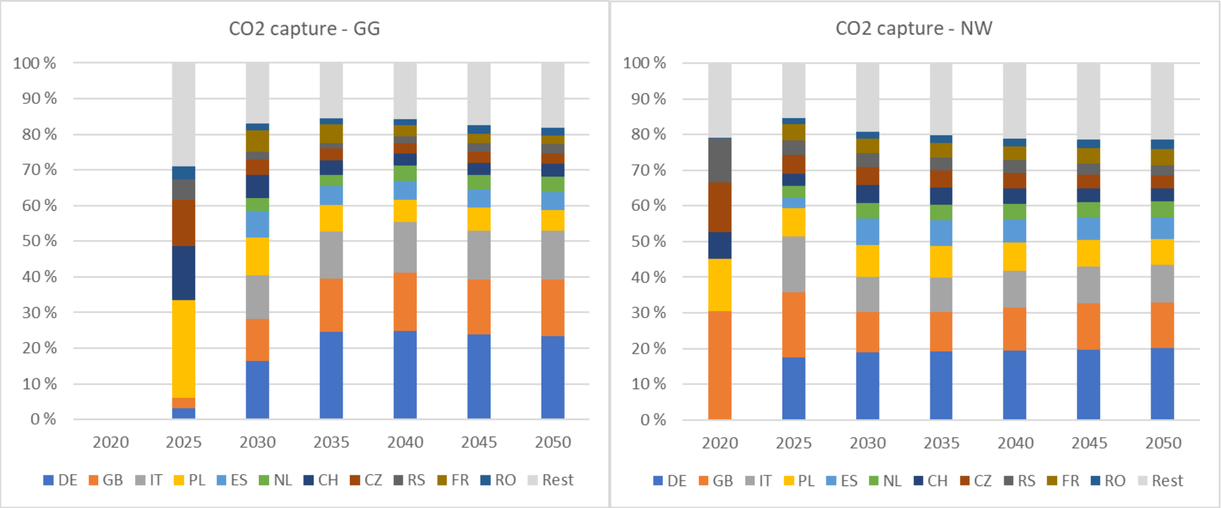


Figure 54: Share of CO_2 sequestration and storage for the highest emitting countries in Europe without transmission expansions

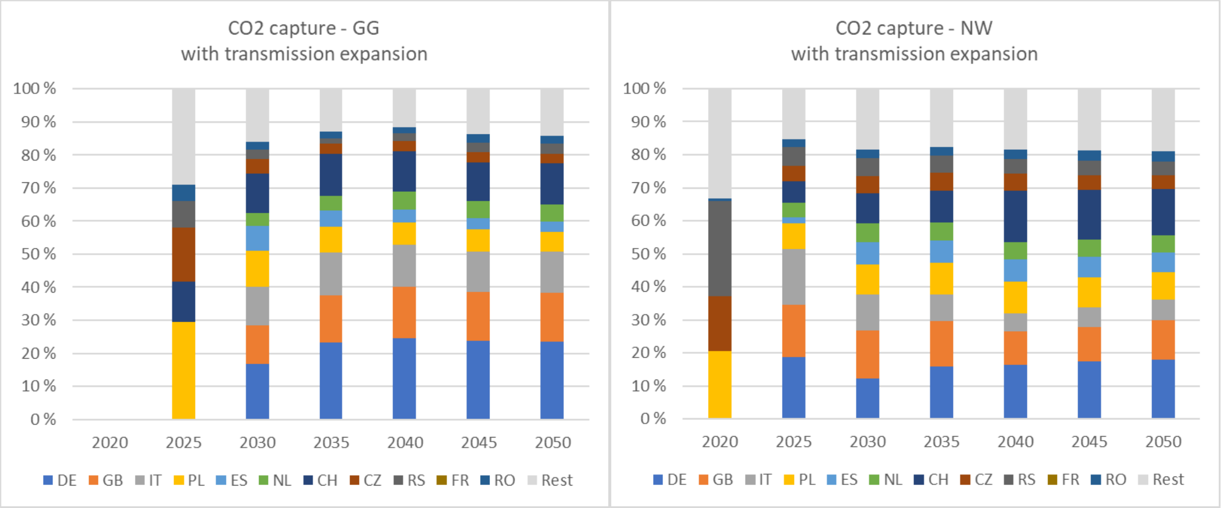


Figure 55: Share of CO_2 sequestration and storage for the highest emitting countries in Europe with transmission expansion

4.3.7 Natural gas uptake

Beside the actual generation of power another important factor is the development of demand for fuel in the power sector. As it can be observed in the generation mix and the installed generation capacity of the power system, there still is a significant amount of fossil-based power production in 2050. However, it includes a phase-out of nearly all coal-based power generation and a significant expansion of gas-power generation with CCS, while some gas power plants without CCS are kept in the system, used for covering demand peaks. The following Figure 56 illustrates the consumption of natural gas in the power system to 2050 in

Europe. All of the scenarios show a substantial increase in gas consumption from 2015 onwards. Thereby the gas consumption is four-doubled in the NW scenario around 2035 and decreases thereafter, however to a level still substantially higher than 2015. Within the NW scenario gas consumption increases constantly up to 2050 at about three times the level of 2015. This development of the gas consumption means, that one of the most effective measures in these analyses is the substitution of fossil fuels with less carbon intensive fuels plus CCS, while keeping the ability of dispatchable power plants. Furthermore, it implies that gas resources, that are available in Europe are also a valuable source for the transition of the power system.

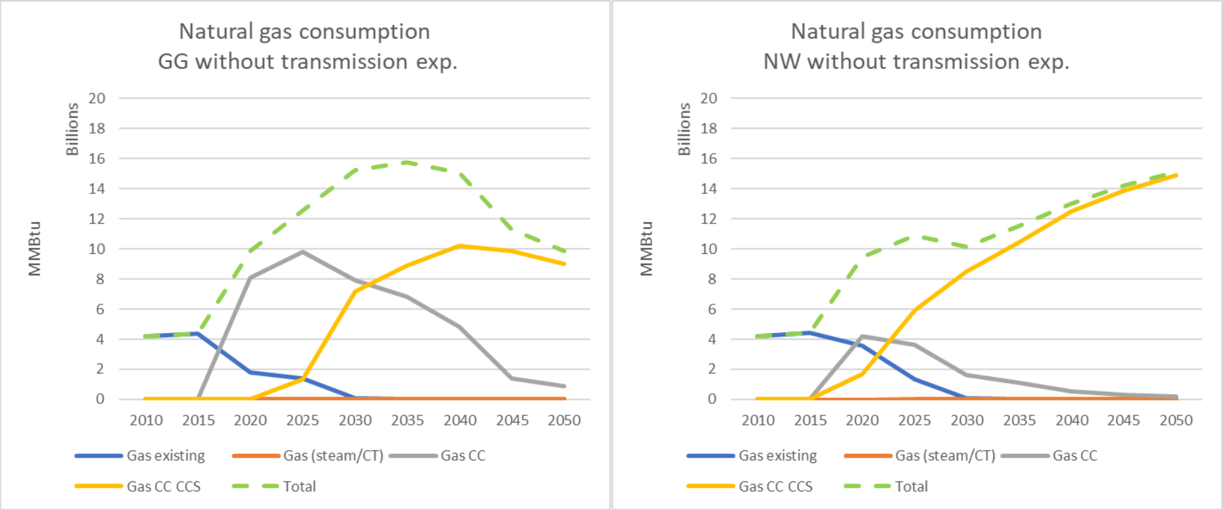


Figure 56: Gas consumption in the European power sector

4.3.8 System cost

After assessing characteristic developments of the European power system, given the scenario framework from GCAM, finally the economic outcome in form of cost development is assessed in this subsection. Figure 57 illustrates the development of the total system costs given the demand development in the scenarios. These system cost comprise:

- Capital costs
- Fixed operation & maintenance costs
- Fuel costs
- Variable operation & maintenance costs
- Costs for CO2 emissions
- Costs for the transport and storage of captured CO2

A similar development of the total system costs for all of the scenarios can be observed, where the scenarios without transmission expansion lead to somewhat higher costs. In addition, the NW scenario has a bit higher costs, even if the demand for electricity is lower. This is due to higher technology and fuel costs and a higher price for CO_2.

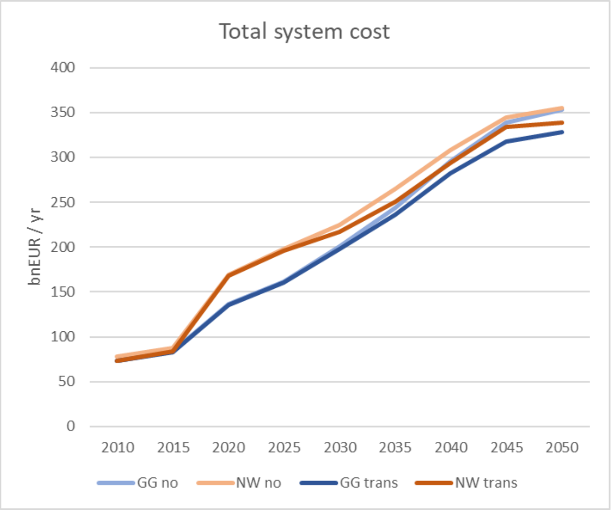


Figure 57: Total system costs for the European power system until 2050

The cost distribution is shown in Figure 58 and Figure 59. In these figures some clear trends can be observed. The share of the capital costs increases significantly, due to the expansion of the system, which requires the investment in additional assets. In addition, the investment in RES has large capital cost, while the actual operational costs are rather low, which contributes to this trend. At the same time the share of O&M costs and fuel costs decreases. In the first year, a substantial share of costs is also caused by the direct emissions. However, this share decreases and is partly substituted by the costs for capturing and storing CO_2. Thereby, the cost share of CO_2 emissions and for CCS is significantly higher in the NW scenario and in the GG scenario, due to the higher CO_2 price and the higher technology costs for CCS.

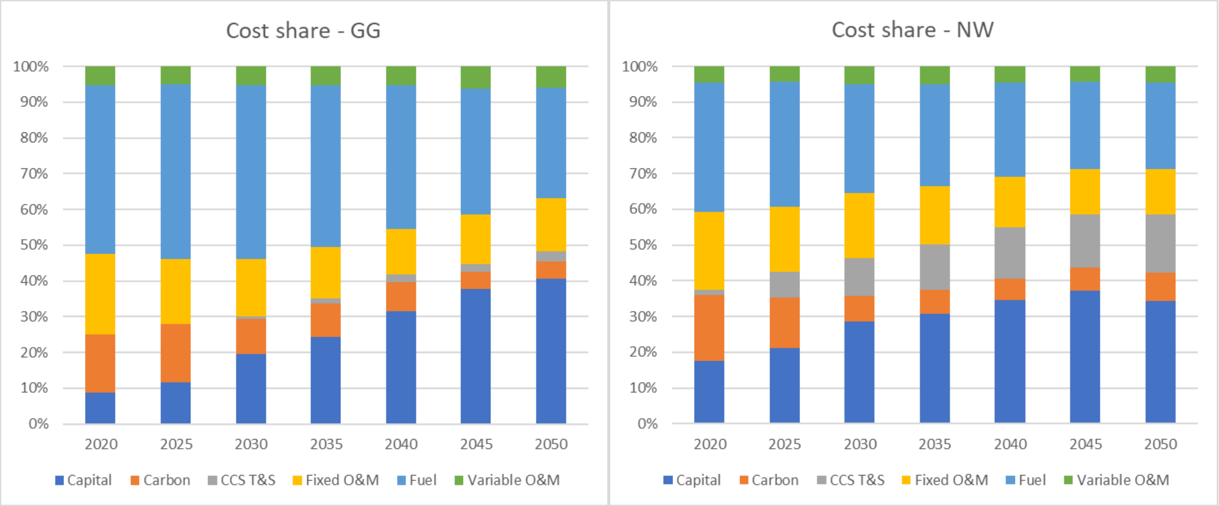


Figure 58: System cost distribution for the scenarios without transmission expansion

Figure 59 shows the cost distribution for the scenarios with transmission expansion. Compared to the previous figures there is an increase in the share of capital costs, certainly due to the additional investments in the transmission system. However, the remaining distribution is equal to the cases without transmission expansion.

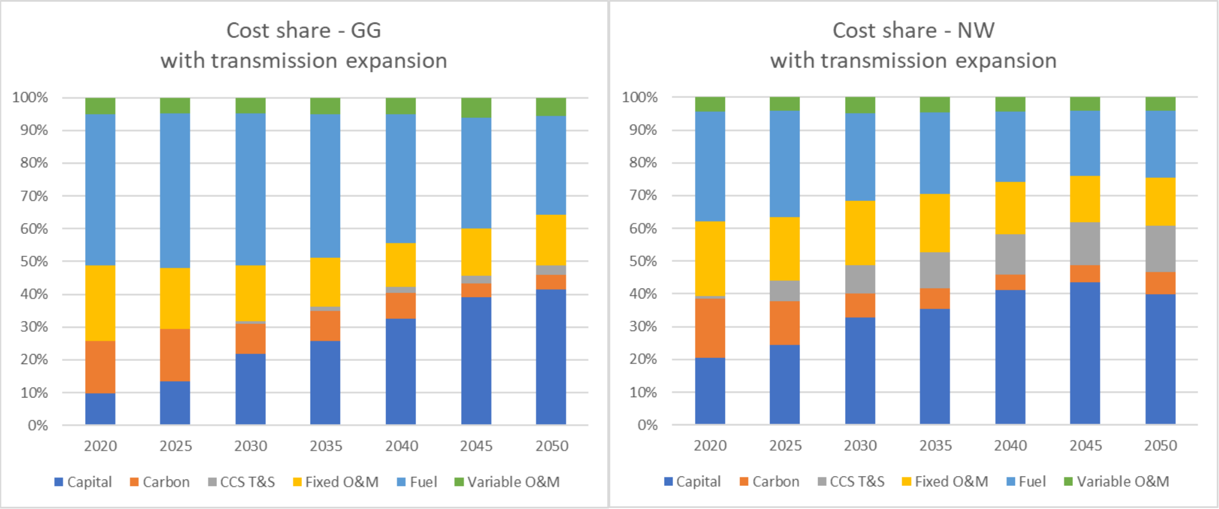


Figure 59: System cost distribution for cases with transmission expansion

4.3.9 Summary of the EMPIRE results

The assessment of the scenarios run with EMPIRE, given the global framework of the two selected pathways, shows some differences from the scenario results run with GCAM and provide more insight to the development of the European electricity sector. At first, the power sector is dominated more by dispatchable power production based on fossil-fuels including CCS. At the same time, the share of nuclear power and power generation from intermittent renewable energy sources is lower. This is due to EMPIRE respecting nuclear policies in Europe and accounting for the inherent variability of intermittent renewable energy sources. The stricter climate policy for Europe in the "National ways" scenario results in a faster phase-out of power production from fossil-fuel power plants without CCS and a complete phase-out of coal power plants until 2050. Furthermore, it also results in a higher share of iRES power production and nuclear power production than in the "Green globe" scenario. While the production from power plants without CCS is nearly zero, there share in installed generation capacity is still substantial and these plants are used as backup capacity. This backup capacity is only used in rare situation with very low power generation from iRES in order to supply the electricity demand.

In addition to the transformation and expansion of power generation, the effect of expansion of electricity transmission infrastructure is assessed. The scenarios are analysed with and without the possibility of expansion in infrastructure. In general, it can be concluded that the possibility of expanding transmission capacity is exploited substantially if possible. This means European cross-border transmission capacity is four-doubled. However, this capacity expansion has only a minor effect on the total electricity generation mix in Europe, but a significant effect on the localisation of the generation capacity. An expansion of cross-border transmission capacity allows for a higher share of iRES power generation and decreases the share of fossil power plants with CCS.

Assessing the CO_2 emissions and capture, a significant reduction of emissions can be seen in the first decades until around 2035. At the same time an increase of CO_2 capture can be observed. In total, that means, that power generation causes a somewhat stable level of greenhouse gases to the horizon 2050, whereat a larger amount is captured. The increase in power generation from iRES is used to supply the increase of electricity demand in Europe.

The continuous use of dispatchable power plants based on fossil fuels, specifically gas power plants with CCS, actually lead to an increase of gas consumption in the European power sector. Thereby a demand top for gas can be observed in the "Green globe" scenario, while the demand continuously increases for the "National ways" scenario. This means, that there still is a significant value in European gas resources for the transition of the power system.

Finally, assessing the cost for the transition of the system, it can be seen, that the share of capital costs increases in both scenarios, which is due to the investment in more capital-intensive power production technologies, such as iRES power generation and power generation with CCS. The share of handling CO_2, including costs for CO_2 emissions and CCS, decreases in the GG scenario, while it is somewhat constant in the NW scenario. However, the total system costs increase significantly. The increase is somewhat comparable in both scenarios as well as without and with transmission expansion, but the costs in the cases with transmission expansions are lower.

4.4 Additional remarks to the GCAM and EMPIRE analysis results

Investments in solar power production is rather low, both in GCAM and in EMPIRE. This can indicate that cost assumptions for these technologies are too high in the models. It can also indicate, that there are other drivers for investments than pure investment costs and profit margin for solar power production, which are not accounted for in the models.

Fuel prices in EMPIRE are constant and do not change with the demand in fuel. Thus, the EMPIRE model uses cheap resources without seeing the impact on the market. It causes a mismatch with the CGAM solution. For example, low use of CCS gives low CCS T&S costs from GCAM into EMPIRE and higher utilisation in EMPIRE. However, this cost would rapidly increase with higher demand in GCAM, which is not accounted for in EMPIRE. Hence, it needs to be evaluated how fuel supply functions can be accounted for in EMPIRE.

Biomass for use in electricity generation is restricted in EMPIRE based on the GCAM solution in order to account for limited resources due to land-use. However, the limitation might be too strict as increasing prices for biomass could lead to an increasing availability by using additional, more costly resources.

It is chosen to use both a total emission cap and a CO_2 -price in EMPIRE, where one or the other becomes the binding factor for CO_2 emission. In theory one should be enough, but when only applying a total cap the model will see the cost of emitting CO_2 as constant for all years, as EMPIRE sees the whole horizon up to 2050 when optimising the power system development. To make the cost of emitting CO_2 increases towards 2050 we chose to include the CO_2 price as well. In most of the scenarios the CO_2 -price is sufficient to keep the emissions within the target levels.

5 Conclusions

The objective of research area 5 is to define a set of pathways for the European and Norwegian energy system. A set of qualitative CenSES energy scenarios have been defined (Jaehnert, 2016), applying a bottom-up process, including the definition of global/European futures and Norwegian strategies. Thereby the global development is mapped to a number of Shared Socio-economic Pathways, which are published by IPCC and used in their latest reports. This report describes the process of the quantification and assessment of selected scenarios for Europe.

With the help of a linked model set, consisting of a global assessment model (GCAM) and a European power system development model (EMPIRE), selected CenSES energy scenarios are quantified. The underlying model linking was developed in the KPN project LinkS, which was part of research area 5 in CenSES. The analyses with the linked models are done to break down results from a global perspective to countries in Europe, with higher geographic, temporal and sector resolution. This method is applied to establish a framework for European energy scenarios given by different global developments. Within the model analyses, applying the linking, it was experienced that transferring emission levels and emission reductions paths from a global to a regional (European) perspective is rather challenging. In addition to the original price coupling, the coupling of an emission cap and the linking of the CCS sector from GCAM to EMPIRE had to be established.

In general, the scenario assessment points to a large challenge in order to achieve the emission targets. Either a cut in economic development needs to be accepted, which will probably also have a negative impact on the technological development, or it needs to be accepted that emissions will not decrease sufficiently. In such a case, it has to be relied on substantial negative emissions to the end of the century. However, the second alternative (in line with the GG scenario) requires to be calm, accept a substantial overshoot of greenhouse gas emission and trust that there will be global technologies available for negative emissions at the end of the century. In addition, this alternative requires a cooperation and substantial development of the society in terms of education and awareness of climate challenges.

Based on the global framework achieved from assessing the underlying shared socioeconomic pathways and the applied coupling method, following main conclusions are draw from the scenario assessment:

1. The linking of a global assessment model (GCAM) and a model for the European power sector (EMPIRE) provides good insights on the requirements for and the development of the power sector in different global frameworks.
2. Different global socioeconomic pathways and climate targets do have a significant impact on the development of the energy sector in Europe including electricity.
3. The development of negative emission technologies and the level of global cooperation affect how much, how fast and where greenhouse gas emissions are reduced. A faster technology development causes a postponing of emission reduction, as it is relied on the availability of negative emission technologies, increasingly to the end of the century.
4. Accounting for variability of iRES and a higher geographic resolution affects the resulting electricity generation mix, including a higher share of dispatchable power plants and less power generation from iRES.
5. Due to the climate policy, fossil-based power generation without CCS is substituted with CCS and iRES power generation is used to supply the increase in electricity demand.
6. The sum of greenhouse gases originating from the power sector is not decreasing from 2020 to 2050, see Figure 51. However, the utilisation of gas power plants with CCS lead to that a much larger share of CO_2 is captured until 2050.
7. Due to the utilisation of gas power plants with CCS, there is an increasing demand for gas in the European power sector in both of the scenarios.
8. Transmission expansion does not change the overall electricity generation mix in Europe significantly. However, it affects the localisation of the power generation assets, leads to decreased

share of installed dispatchable generation capacity and allows for the integration of more intermittent renewable energy sources.

9. While there is a two-doubling of generation capacity, there is a four-doubling of cross-border transmission capacity in the European power system.

Two of the pathways, SSP1 "Sustainability" and SSP3 "Regional rivalry" are selected for the assessment. These pathways are rather different in their description regarding the development of society, economy and the cooperation between nations and among the various stakeholders within the countries. However, it was experienced, that quantitative result from these SSPs are counterintuitive to their qualitative description, especially for the European region.

SSP1 "Sustainability" gives nearly no emission reduction in the European power sector before 2050, due to relying on future technologies with significant negative CO2 emissions after 2050 and reductions in other regions.

SSP3 "Regional rivalry" with less cooperation and slower technology development results into stronger reduction of emissions in the European power sector, as reductions have to be done here and now. This means Europe cannot rely on future technologies.

During the evaluation of results in a series of workshops, the importance of responsibility of developed countries and the recognition of the national commitments in the Paris Agreement were identified. As SSP1 "Sustainability" gives rather unreasonable results, SSP3 seems to be more in line with current developments. Hence, it is suggested to call SSP3 not "regional rivalry", but "regional division of labour", where each of the regions worldwide needs to take its share to tackle climate changes. There within the division of tasks and amount of labour might not be distributed economically optimal over the world but could be seen to be distributed in a fair way accounting for the development state of the various regions.

EU Commission's "Clean planet for all"

In November 2018, the European Commission publish their vision for the development to a low carbon society until 2050 in the form of the document "A clean planet for all" (EU Commission, 2018). The assessment for the scenarios is done with a set of models, where PRIMES is used for the energy sector[4]. The baseline scenario results into an emission reduction of 65%, whereat the other seven scenarios give a reduction from 80% - 100% depending on the scenario.

In contrast to the scenarios assessed above the baseline scenario and most of the other seven established scenarios assume a significant decrease in primary energy consumption in Europe up to 2050, which is not the case in our scenarios. However, in line with our assessment a significant increase of electricity generation is expected up to 2050. This results in a much higher share of electricity in the final energy consumption than in our assessment. When going a bit more in detail a much higher share of renewables including intermittent renewable energy sources (65% - 70%) are expected by the European Commission, than we can see in our scenarios. On the other side, we could observe a higher share of power production from gas power plants, including CCS to capture the greenhouse gas emissions.

The difference in the power generation mix also has a significant impact on the gas consumption in Europe, which is reduced substantially in the EU Commissions scenarios, while it increases in our assessments. However, there is an increasing utilisation of hydrogen in the Commissions scenarios, up to the range of natural gas.

Finally, in accordance with our assessment, nuclear power still plays a role as electricity generation technology in 2050, whereat coal as an energy source is phased out in all of the scenarios.

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[4] https://ec.europa.eu/clima/policies/strategies/analysis/models_en

5.1 Lesson learnt

As discussed above, the results of the scenario development and assessment in CenSES RA5 are two-fold. Within the finalisation of the research area, one loop through the process sketched in Figure 1 has nearly been achieved. This is partly caused by the fact that the development process and the applied assessment process have been more demanding than expected. However, in addition to stepping forward in the scenario development and assessment process, there are a number of lessons learnt from the process, which should be taken into account in a future scenario work:

1. To establish scenarios / pathways for analyses in a bottom-up process, it is essential to define a detailed research question, that limits the space of factors that go into defining the scenarios. This definition of the objective also helps to identify the most important factors, that should be used to span the scenario space. An example is to focus on development paths for specific technologies.
2. Inter-disciplinary work to establish a qualitative and a quantitative description of scenarios is resource demanding. A successful cooperation thereby depends on a continuous longer-term regular exchange on research and specifically on the willingness to dive into research methods of other disciplines. Through a series of workshops, we achieved a better understanding of other research disciplines, which also contributed to the evaluation of the analyses done during the quantification.
3. The process (sketched in Figure 1) of developing and analysing pathways for the transition of the energy system is resource intensive and requires continuity over a longer time frame. Hence, it is important to take care of established methods and the scenario (qualitative and data) framework, where a long-term research centre is a favourable place.
4. Targeting the challenges of climate change mitigation requires solutions within the society covering several different sectors. In the scenario definition and during the analyses done in the quantification we experienced, that even though we put the energy system at the centre of our research it is necessary to take cross-sectoral effects into account. This is especially valid as the analyses have a rather long horizon and significant changes in the society and economy need to happen to limit climate changes. This also means that it is important in the future to further develop coupling methods for sector and regional specific models.

Beside these more general learnings in the development process for CenSES energy scenarios, some more specific learnings in the quantification process are listed in the following.

1. The definitions of the CenSES energy scenarios are based on the SSPs from IPCC, which shall give a global framework for the scenarios. However, analysing these Shared Socio-economic Pathways in the global assessment model GCAM assume global optimisation with no restrictions / differences on regional climate policies. These differences are certainly necessary to account for when comparing the outcome of the SSPs with current developments, in order to explain emission developments in specific regions and sectors.
2. Results gained from the integrated assessment model GCAM for SSP1 "Sustainability" for Europe are in the first spot counter-intuitive, i.e. no emission reductions can be observed up to 2050 (in this green world). This development is not in line with current policies in Europe and will certainly not engage stakeholders to take better actions against climate change. The reason for this outcome is that Europe relies too heavily on other regions and future technologies to cut emissions.
3. Pure model analyses, based on mathematical optimisation models, do not necessarily provide outcomes that can be seen in reality. In reality, the development is more driven by changing policies and constellations of forerunners and followers. Finally, in reality there is probably a more conservative decision-making process accounting for risks due to large uncertainties, that cannot be fully covered in mathematical optimisation models.

5.2 Reflections on the interdisciplinary work

One idea that occurred during the discussions was whether it would be a good idea for those social scientists with no experience with modelling to actually go through a quick tutorial to learn more about how models work. One the other hand, coming entirely from the outside may be useful to ask questions that otherwise would not have been asked (the outside perspective). Otherwise it is important to note that working with modelling together with researchers from other areas who are not familiar to modelling work will demand quite a lot of time for learning how to bridge the cross-disciplinary gaps. It was evident that it was not only until the last meeting discussions involving everyone gained good traction, partially owing to the fact that it takes time to build up an understanding in outsiders in the suitable language to use as well as a rudimentary understanding of modelling.

The modellers that have been working with their scenarios and assumptions clearly are very ‘into’ their own work and may not know which steps of their analyses in unclear to others. One situation arose where one modeler said that ‘I had to change the inputs of year 2020 to make the model work’. For the others present, this was somewhat surprising as there was a question of the input at year 2020 had been only guesswork or a qualified assumption or just a technical finesse.

A rather uncomfortable outcome of the models was that Europe turned out to be very fortunate in both the scenarios presented: Europe did not have to make as many reductions, and Europe was not as affected by the negative consequences of climate change (reference to temperature/GDP article). This was discussed, and the concern from the modelers was that this occurred as a result mainly because of the assumptions made. Therefore, they wondered whether these results were interesting or relevant enough, compared to the task that they were given. To this it was answered from one of the other modelers that “no model is perfect, and we should only use these models if we believe they can provide us with some useful insights”. Also, a general question was posed is there might be other models that would be better to try to integrate, than the ones (a global GCAM and local EMPIRE model) chosen for this report. “Why was this model chosen compared to EMPS or TIMES?”.

5.3 Future research and questions

A significant number of research challenges emerged from the scenario definition and assessment process that has been performed. However, the applied method of model coupling and defining scenario is valuable and provides further insights.

The following challenges are suggested to be assessed in future work with energy scenarios:

- In all of the assessed scenarios, the CO2 price is one of the main drivers to limit greenhouse gas emissions, where it is assumed that there is a CO2 price. However, in pathways with low cooperation the challenge is how to establish a price or how to cut CO2 emissions without this price signal?
- An improved understanding of assumptions in the global assessment tools and a redefinition of areas in GCAM will allow a better mapping to the geographic areas to European models. What is the effect of the global framework for individual countries, when modelling them explicitly?
- Discuss and evaluate the development of the primary energy consumption in the sustainable pathway, which might be contradictory to the general definition of the pathway. In addition, evaluate the possibility to define regional climate policies / targets to make Europe a "climate forerunner" and avoid relying on other regions in the world.
- Assess the potential of including supply curves for fuels and other commodities in the power sector model, to achieve a better representation of change fuel in the electricity generation mix
- Represent domestic transmission expansion requirements in the power sector models

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