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Energy Economics - Energy Sector Modeling

The long-term interaction of a carbon infrastructure and the European energy system

Introducing carbon capture, transport and storage (CCTS) infrastructure into energy system modeling

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Abstract

Carbon capture and storage technologies, along with the expansion of renewable energies, are a potentially essential measure for achieving the climate targets set by the European Commission.

This paper investigates to what extent CCS technologies can be implemented in the next few years, how a potential CO2 infrastructure could look like and what costs are associated with this. The foundation of the analysis is provided by three scenarios which differ with respect to the general availability of carbon infrastructure and the investment costs as well as assumed future cost reduction of CCS power plants. These three approaches are accompanied by a rising CO2 price, which has a strong impact on the use of conventional power and heat generators, but also has an impact on the expansion of CCS technologies. The regions included in the model are Germany, Denmark, France, Norway and the UK.

The analysis has shown that no deployment of CCS in Europe is associated with the highest energy system costs due to the great investments in the renewable energy supply. The affordable scenario has proven to be the most cost-effective scenario, as early investments in CCS technologies generate fewer emissions and thereby reducing the costs of CO2 pricing. The analysis has clearly shown that the deployment of CCS technologies takes place mainly in the heat sector, as in this sector the need for decarbonization is more crucial and complicated to achieve since there are fewer renewable technologies available than in the power sector. While the energy supply in the scenario with no CCS was mainly provided by gas and gas CHP plants, it was further shown that the deployment of CCS is mainly related to coal CHP, as the variable cost of procuring coal is lower than the cost of procuring gas. It was further shown that the use of CCS is mostly related to coal CHP plants, as these power plants have a higher CO2 storage capacity compared to gas. In addition, differences in geological and political circumstances are a critical factor for the storage of CO2. Especially countries with great energy demand and generation capacities like Germany or France export a large amount of captured CO2 emissions to countries which rely more on renewable energy source but have large CO2 storage capacities like Norway.

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1 Introduction

The European Commission has set ambitious environmental goals as part of the EU Green Deal. These goals include reducing greenhouse gas (GHG) emissions by 55% by 2030 compared to 1990 levels and achieving net climate neutrality by 2050 (European Commission 2019). Achieving these goals requires concrete actions, such as switching from fossil fuels to renewable energy sources, minimizing energy and resource consumption and optimizing energy efficiency across all sectors.

Technologies for carbon capture and storage (CCS) and carbon capture, utilization, and storage (CCUS) could support achieving these ambitious goals by capturing CO2 emissions from power plants as well as industrial processes and storing them in inactive oil or gas reservoirs as well as in salt domes. This approach could potentially reduce the total GHG emissions and drive progress towards national and international sustainability goals.

The deployment of CCS technologies appears particularly attractive in industries such as steel production, cement manufacturing, the chemical industry and waste management, as these global industrial processes were responsible for over 26 % of worldwide GHG emissions in 2022 (IEA 2023) and are traditionally considered to be difficult to decarbonize. Furthermore, the role of CCS in the energy sector is subject of a controversial discussion. On the one hand it is argued that expanding the run-time of existing fossil-fueled power plants provides not only dispatchable electricity complementing the volatile infeed of renewables but is also a key factor in a least-cost transition to a climate-neutral electricity system (Heuberger et al. 2016), (Oxburgh et al. 2016). However, the deployment of CCS technologies in the power sector would not only impact energy generation but also the transmission, distribution and low-voltage network. While the massive expansion of renewable power supply requires a substantial expansion of the existing power grid due to a generally more decentralized power infeed, centralized power infeed from both nuclear and coal-fired power plants is scaled back in many countries, i. e. Germany (Bundesregierung 2021). Therefore, it is also argued that the large-scale retrofitting of existing conventional power plants for the use with CCS or the rollout of new power plants with CCS could potentially slow down the speed of the grid expansion and thereby also potentially alleviate the expansion of renewables due to grid congestions (Holz et al. 2021).

Using CCS technologies in European energy supply requires an examination of the legal foundations and the current development of this technology. In 2009, the European Parliament enacted Directive 2009/31/EC with the aim of establishing a legal framework for environmentally safe geological storage of CO2 to combat climate change (Art. 1 S.1) (European Commission 2009).

Despite this legal basis, the adoption of CCS technologies in Europe remains limited, as CCS has encountered significant hurdles in the past. Although more than 70 CCS and CCUS projects with a planned total capacity of nearly 80 MT/year are anticipated by 2030, currently, only seven plants with a total capacity of approximately 2 MT/year are in actual operation (as of January 2023) (IOGP 2023).

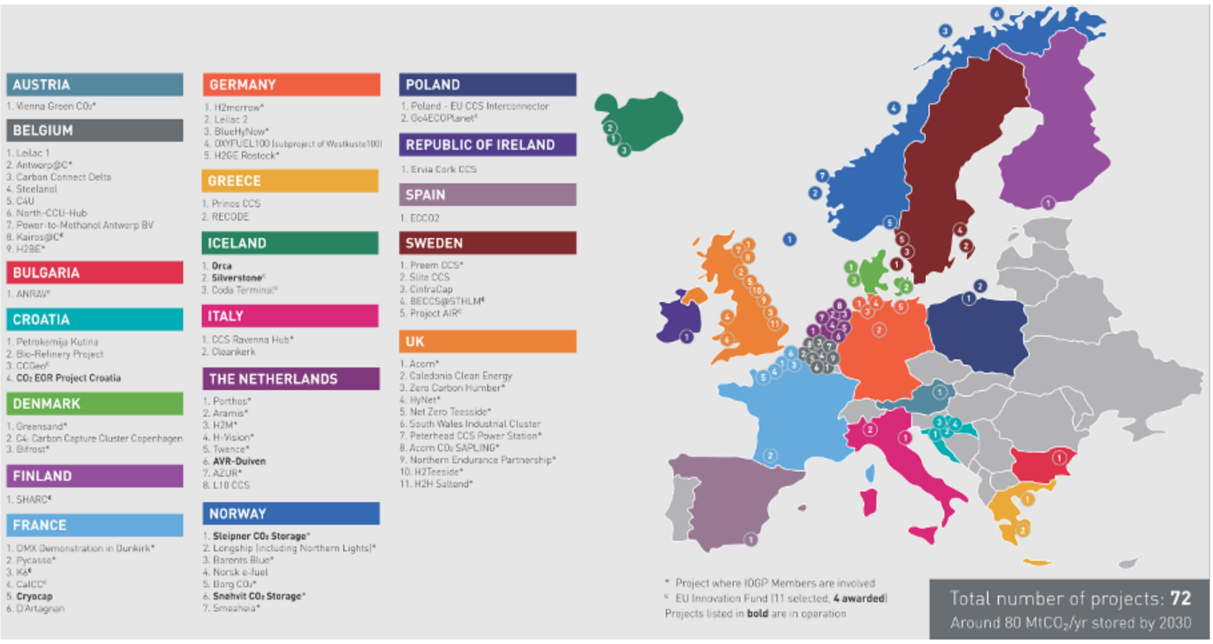

Figure 1: Overview over existing or planned CCS projects in Europe

Source: Environmental Agency, 2023

Faced with these significant challenges, the European Union has established various funding programs to support research, development, and demonstration of CCS and CCU technologies. These include the "Innovation Fund", the "Connecting Europe Facility" (CEF), and "Horizon Europe". For instance, the Innovation Fund mobilizes over €25 billion over a ten-year period, depending on carbon prices, for breakthrough technologies in carbon capture, utilization and storage, as well as in renewable energy, energy-intensive industries, and energy storage (European Comission 2023).

Despite such financial assistance being available even in the years following the described EU directive, several CCS projects in the EU have been abandoned during the planning phase. The high costs of CCS projects and doubts about their cost-effectiveness in a competitive energy market have deterred governments and businesses (Holz et al. 2021).

In some regions, CCS also faces public resistance due to safety concerns, health issues, and potential CO2 leakage, as CO2 storage technologies are not yet sufficiently researched. The capture technology itself is still in development and faces technical challenges that raise doubts about its long-term feasibility as a solution for reducing carbon emissions (European Comission 2023).

Despite the challenges and controversies, CCS is still - given Europe's consistently high levels of GHG emissions - considered a potential instrument for emission reductions especially in the industry but also in the energy sector. On that account this analysis aims to investigate the long-term impact of the integration of CCS technologies on a simplified European energy system. Additionally, we aim to outline the rough structure of the resulting carbon infrastructure within the five European model regions. Due to the scope of this thesis the main goal of our investigation is the identification of key trends and developments rather than precise prognoses. For this purpose, we expand the existing EW-MOD energy system model developed by the Department of Economic and Infrastructure Policy (WIP) (WIP 2023b) by a CO2 infrastructure model extension. This model extension represents the entire carbon capture, transport and storage (CCTS) process by introducing several different open- as well as combined-cycle power plants with carbon capture, a CO2 pipeline network considering pipelines with different diameters as well as different geological on- and offshore storage options into the energy system model framework. To accurately represent the trade-off between bearing the emission costs caused by the European Emission Trading Scheme (ETS) and investing in CCS technologies, we introduce a CO2 price for every unit of CO2 which is emitted into the atmosphere. The basis of our analysis is provided by three different scenarios which differ with respect to the general availability of CO2 infrastructure as well as the cost assumptions of power plants with carbon capture.

The general scope and main features of the EW-MOD energy system model are portrayed in Subchapter 3.1 whereas the new CO2 infrastructure model extension is presented in Subchapter 3.2.Afterwards the data as well as the scenario assumptions are described in Subchapter 3.3 and 3.4, respectively. A critical confrontation with the model limitations as well as the simplified data assumptions is conducted in Subchapter 3.5. The specific impact of CCS technologies on the electricity and heat generation, the expansion of generation capacities, emissions as well as the total energy system costs in the EW-MOD energy system are presented in Chapter 1 which is followed by the Conclusion in Chapter 5.

2 Literature review

Many research papers on this subject use and further develop so called integrated assessment models (IAM), that consider many aspects of a real world system, such as TIAM-ENC (van der Zwaan, Broecks, and Dalla Longa 2022; Dalla Longa, Detz, and van der Zwaan 2020), CCTS-MOD (Oei, Herold, and Mendelevitch 2014; Holz et al. 2021), EMPIRE (Holz et al. 2021), FOREcast-Industry (Holz et al. 2021), TEPES, the EPPA model (Paltsev et al. 2021), and the TIMES model generator (van der Zwaan, Broecks, and Dalla Longa 2022; Dalla Longa, Detz, and van der Zwaan 2020). These models mostly use top-down methodologies in pursuit of meeting decarbonization goals set by politics. They are characterized as scalable mixed-integer models designed for a detailed analysis of long-term system dynamics while simultaneously aiming to minimize the respective total system costs. Holz et al. 2021 extend these analyses with a bottom-up perspective by not only incorporating the existing power sector infrastructure and diverse industry sectors but also integrating infrastructure considerations for the distribution and storage of captured CO2 into the optimization framework, thereby including the entire CCS value chain. This extension serves as the basis for the approach developed in this study: a comprehensive exploration of different CCS technologies with varying costs, efficiencies related to production, transport and storage, and technology developments (see Chapter 3).

In all studies, technological progress is postulated to lead to decreasing investment and operational costs over time as the marginal costs of the technologies fall. One characteristic of this paper is that variations in the pace of technological development are deeply analyzed in terms of their cost-effectiveness and efficiency. This technological development is considered as essential to ensure long-term competitiveness against alternative CO2 mitigation strategies such as increasing renewable energy capacity and energy efficiency to reduce final energy consumption (Holz et al. 2021). Regarding the transport of captured CO2, only few approaches have been discussed in the literature. The most common technology is pipelines with different diameters (Oei, Herold, and Mendelevitch 2014; Holz et al. 2021), which is why it is also considered in this paper.

It is assumed that public acceptance holds a great importance for the construction of these models, as it can influence policy decisions concerning the amount of deployable storage capacity and potential delays in implementation. Especially in the European context, CCS technologies encounter considerable public skepticism as confirmed by Van der Zwaan et al. (2022). A striking example is the vehement opposition to the construction of onshore CO2 storage facilities documented in works by van der Zwaan, Broecks, and Dalla Longa 2022; Holz et al. 2021; Oei, Herold, and Mendelevitch 2014; von Hirschhausen et al. 2010. Consequently, offshore storage configurations are typically prioritized in modeling efforts, and in some cases, they represent the only options under consideration, thereby significantly affecting the results of the optimization models.

The geographical scope of the research investigations varies among the considered studies, although the majority primarily focuses on Europe. Depending on the specific research objectives, different scenarios are designed and analyzed. Some studies define a reference scenario without climate targets and contrast it with scenarios that include climate targets and CCS technologies (Paltsev et al. 2021). Others use a reference scenario without CCS technologies, comparing it to alternative scenarios featuring varying degrees of CCS affordability, as exemplified by (Holz et al. 2021; van der Zwaan, Broecks, and Dalla Longa 2022; Oei, Herold, and Mendelevitch 2014; Dalla Longa, Detz, and van der Zwaan 2020). Given the improbability of transporting CO2 via pipelines over large distances overseas and the need to investigate the unique impacts for European systems infrastructure and pricing dynamics, this paper focuses on nations of Germany, the United Kingdom, France, Norway, and Denmark.

The common findings of the existing literature converge on the point that deployment of CCS technologies may be a reasonable strategy to achieve the 2-degree-target set in the Paris Agreement and provide cost savings compared to non-implementation, albeit dependent on the underlying assumptions, as Holz et al. 2021 point out. Many studies agree that both the timing of deployment and the amount of installed CCS capacity strongly depend on the price of CO2 certificates, as underlined by Oei, Herold, and Mendelevitch 2014, and in public acceptance, as mentioned before. In the context of these considerations, this paper further explores the impact of rising CO2 prices on CCS infrastructure, although the area of CCS deployment in this study is exclusively limited to the energy industry, not to other industries, where CCS would also have a great, if not greater, influence.

3 Methodology

To investigate the long-term effects of a CO2 infrastructure on an entire energy system rather than a particular sector or market, we introduced CO2 capture technologies, pipeline transport and carbon storages as well as an CO2 price to the EW-MOD energy system model developed by the Department of Economic and Infrastructure Policy (WIP) (WIP 2023b). In the next Subchapter we first outline the basic model structure as well as model features of the EW-MOD energy system model. In Subchapter 3.2 we explain how the CO2 infrastructure model extension was integrated into the EW-MOD energy system model framework and how the CCTS value chain is represented in the model. Following this, the main data (Subchapter 3.3) and scenario assumptions (Subchapter 3.4) are presented.

3.1 EW-MOD energy system model

The EW-MOD energy system model is a multi-period model which contains five model regions and minimizes the total discounted system costs from the perspective of a "social planner" with perfect foresight . Between 2020 and 2050 the model simulates demand, supply, trade flows as well as infrastructure investments within the electricity, heat and mobility sector as well as exchange and conversion of energy between these sectors (sector coupling) in ten-year steps[1].

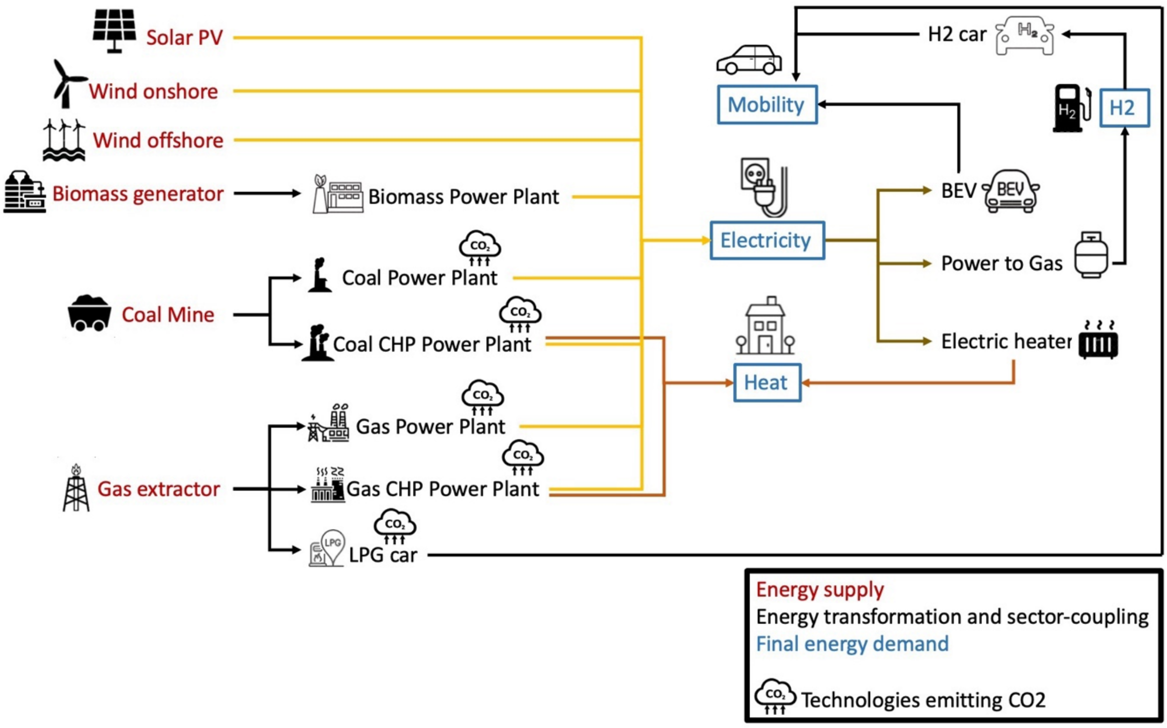

Figure 2: Basic structure of the EW-MOD energy system model

Source: Based on WIP 2023a, own illustration

To represent the volatile energy generation of renewable energy sources accurately, the model incorporates a reduced hourly timeseries of 120 hours with intra-seasonal weather patterns in each model-year, differentiates between dispatchable as well as non-dispatchable generation technologies

[1] These ten-year steps between 2020 and 2050 are called "model-years" hereafter.

and accounts for generation curtailment. In addition, several energy storage types provide necessary energy flexibility.

In the model greenhouse gas emissions (GHG emissions) in the form of CO2 equivalents are limited by two types of emission constraints: annual emission limits and a total emission budget. The annual emission limits set a specific limit for the sum of the emissions of all regions in each model-year whereas the total emissions budget constrains the sum of all emissions from all regions over the entire model horizon. To represents regional differences in the regulatory emission limits, we modified the annual emission limits constraint and introduced annual emission limits which depend on the regions (cf. Subchapter 3.3). In addition to these two regulatory climate change policies, we introduce direct CO2 taxation as a fiscal climate change policy (cf. Subchapter 3.3).

To accurately simulate the investments in infrastructure, whose technical lifetime exceeds the model horizon, salvage values are deducted from the cost-minimization objective function. In the original model version, an error in calculation of the salvage values led to unrealistically high investments in the last model-year. We removed this error by adopting the approach of Candas et al. 2022.

The resulting linear model is implemented in Julia's optimization environment Jump (Lubin et al. 2023) and solved using the open-source solver HiGHS (Huangfu and Hall 2019).

For information about further model features as well as the data of the EW-MOD energy system model please refer to (WIP 2023b).

3.2 CO2 infrastructure model extension

The CO2 infrastructure model extension represents the entire value chain of captured CO2 and docks onto the EW-MOD energy system model without changing the basic model structure or affecting existing model features. Overall, it calculates the development of a carbon infrastructure in which the captured CO2 is allocated cost-efficiently across the regions via a pipeline-network. The complete mathematical formulation of the model extension which includes the referenced equations in this Subchapter is provided in the Chapter 1 in the Appendix.

To model the substitutive competition between conventional power plants with and without carbon capture, for each conventional type of power plant an equivalent power plant type equipped with carbon capture was added. In addition, we introduced a biomass power plant without carbon capture and zero CO2 emissions as a counterpart to the biomass power plant with carbon capture (*BECCS*) and negative emissions which was already included in the original model version. The basic structure of the energy system model is displayed in Figure 3.

In the CO2 infrastructure model extension, all power plants except for biomass power plants with carbon capture emit no CO2 into the atmosphere. Instead, if they generate energy, captured emissions[2] are passed into the new value chain of the carbon infrastructure model extension (cf. Eq. (**1**)-(**2**)). Captured CO2 can either be stored domestically or be transported via the pipeline network to foreign storages (cf.

[2] In the model captured CO2 is represented by a new *fuel* called *Stored_CO2*.

Eq. (**2**)). Hereby, both transporting and storing CO2 require sufficient pipeline and storage capacities, respectively. All steps of the CCS chain as well as their main features are illustrated in Figure 4.

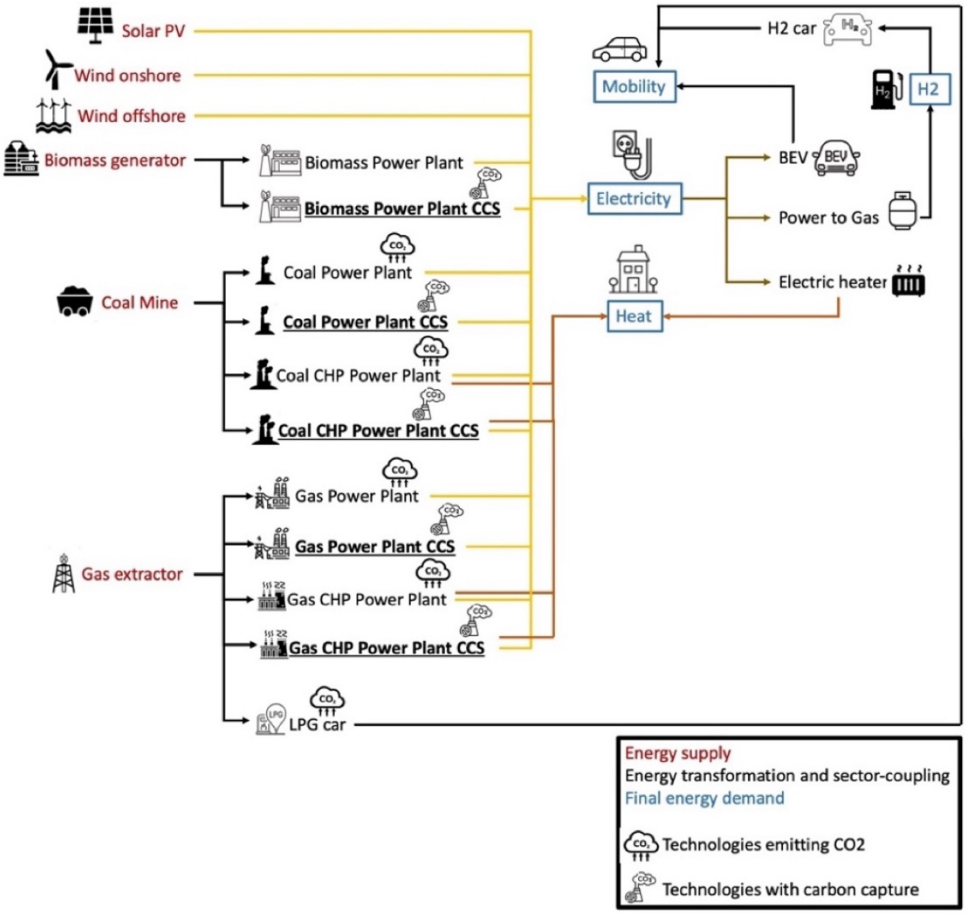

Figure 3: Basic structure of the EW-MOD energy system model with the CO2 infrastructure model extension

Source: Based on WIP 2023a, own illustration

CO2 in a super-critical state can be transported similarly as crude oil or natural gas. Therefore, transport via pipelines is commonly considered as the only economically viable onshore transport solution (Oei, Herold, and Mendelevitch 2014). The new model extension calculates the cost-minimal development of a pipeline-based carbon infrastructure. Hereby, it considers four different pipeline diameters each with a fixed capacity (cf. Table 10, Appendix). In other words, if the investment decision to build a specific type of pipeline between two regions is made, CO2 exports through this pipeline are limited by the fixed capacity of this respective pipeline type. To further increase the CO2 export capacity between these two regions additional pipelines must be build (cf. Eq. (**11**)-(**13**)). The discrete number of pipelines of a specific type between two regions is limited to a maximum of three to restrict the necessary computing time for solving this mixed-integer problem (MIP)[3]. In addition, distance depended operational costs are

[3] In the CO2 infrastructure model extension, the discrete number of pipelines with a specific diameter between two regions is represented using the integer variable $\mathrm{CO2\_Pipeline\_Quantity}_{\mathrm{Year,CO2\_Pipelines,Regions,Regions}} \in \{0,1,2,3\}$. For this reason, the model is no longer a linear but a mixed-integer problem (MIP) requiring significantly longer computing times.

considered (cf. Eq. (**17**)). Our model framework generally allows for pipeline transport from region A to region B across multiple other regions.

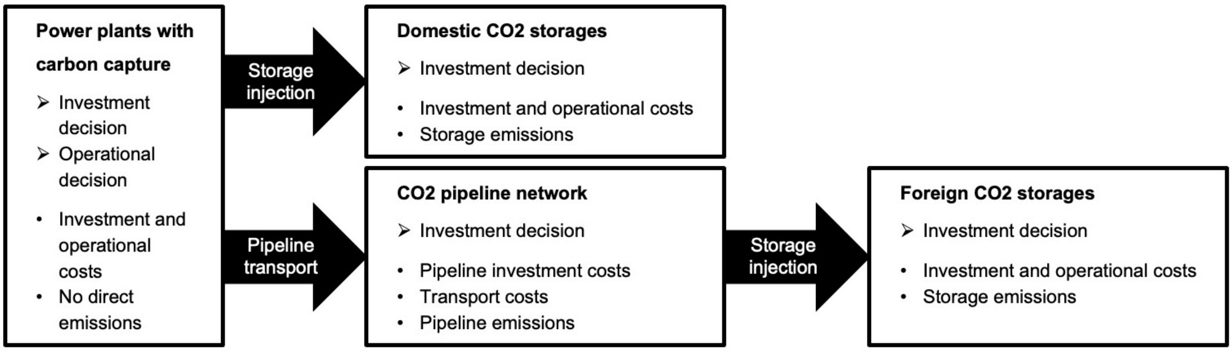

Figure 4: CCTS chain in the CO2 infrastructure model extension

Source: Own illustration

In the CO2 infrastructure model extension, we consider four different types of on-/ and offshore geological storage types. The capacity of a specific storage site can be extended through investments until the maximum capacity is reached (cf. Eq. (**6**) and (**7**)). This exogenous maximum capacity depends on the respective storage type and region (cf. Eq. (**8**)). For the operation of a storage variable costs depending on the type of storage occur (cf. Eq. (**19**)).

A potential externality of a carbon infrastructure is related to CO2 leakages from pipelines and storages. So far, there is a lack of research regarding the probability and extend of CO2 leakages (Holz et al. 2021). However, since even small proportions of leakages can – depending on the scale of the carbon infrastructure – add up over time and have a substantial effect on the social acceptance of CCS technologies, we decided to include leakages from CO2 pipelines and storages in the model extension (cf. Eq. (**9**) and (**12**)). Pipeline and storage emissions are considered in the annual emission limits as well as the total emission budget and result in emission costs caused by the CO2 price.

From the perspective of a power plant operator the decision to invest in new generation capacities with carbon capture or to keep existing conventional power plants running is highly depended on the existence and level of CO2 taxation. Therefore, we incorporated emission costs into the total energy system costs by introducing a CO2 price for every unit of CO2 which is emitted into the atmosphere (cf. Eq. (**20**)).

3.3 Data assumptions

For our basic model framework (cf. Subchapter 3.1) we inherited most data used from the EW-MOD energy system model (WIP 2023b). However, a couple of key data assumptions were modified. In the original parameterization of the EW-MOD energy system model the share of conventional open-cycle power plants[4] in the total electricity generation and generation capacities was underrepresented whereas the share of renewable energy sources was overrepresented in the model years 2020 and

[4] *GasPowerPlant, CoalPowerPlant*

2030. As part of our analysis focuses on the substitutive competition between power plants with and without CCS as well as the transition from power plants without to power plants with CCS, we notably increased the respective residual capacities of open-cycle gas- and coal-fired power plants as well as the coal mine and decreased both slightly for all renewable energy sources. Additionally, the maximum capacities of the coal mine and the gas extractor were notably increased over the entire model horizon. Besides capacities, a couple of cost parameters were slightly adopted as well. In the original data gas- and coal-fired combined-cycle power plants had the same investment costs as their open-cycle equivalents. To represent the different cost structures more accurately, we increased the investment costs of the combined-cycle power plants. Lastly the variable cost of biomass power plants with and without CCS were increased slightly. A comprehensive overview over the variable and investment costs of all energy generation technologies is provided in Table 5 and Table 6 in the Appendix.

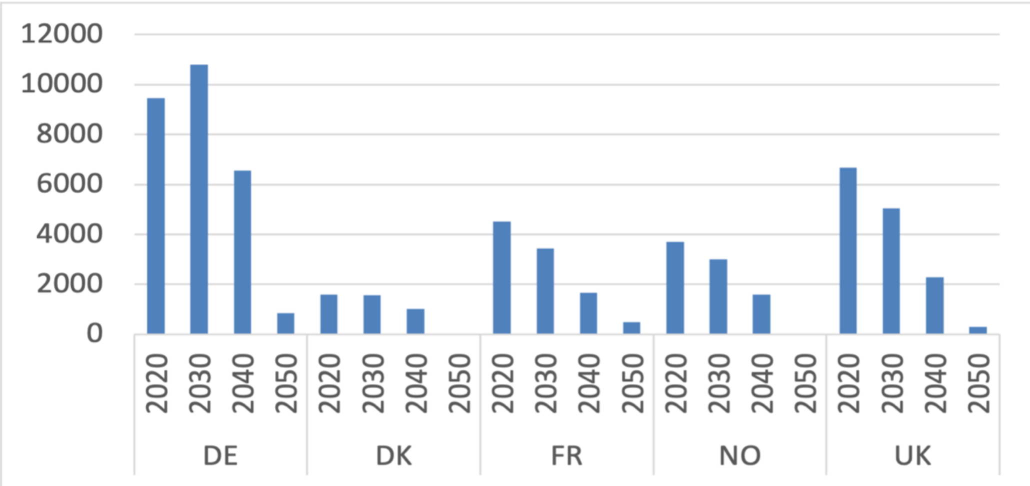

Figure 5: Annual CO2 Emission Limits by Country and Year

Source: Own estimates and illustration

As described in Subchapter 3.1 we introduced regional depended annual emission limits into the basic model framework. Part of the reason for this modification was that disabling the biomass power plant with CCS[5] enabling negative emissions in the *No_CCS* scenario led to the model being infeasible. The new regional depended annual emission limits are approximately in accordance with the scale of the actual CO2 limits of the respective countries. An overview is provided in Figure 5.

The newly introduced CO2 price functions as a Pigovian tax and is supposed to mimic the estimated future rise of the European ETS price. In our model the CO2 price doubles every model year adding increasingly more pressure to minimize emissions (cf. Figure 5).

[5] The biomass power plant with CCS was called *BECCS* in the original model setup.

For the parameterization of the CO2 infrastructure model extension, we relied on data provided by Oei, Herold, and Mendelevitch 2014 and Holz et al. 2021 which was adopted to match the scale of our model. However, in order to prevent the distortion of our findings, the dimensions of the individual values compared to each other we kept. An overview over the key data assumptions regarding the CO2 pipelines and storages is provided in Table 8, Table 9 and Table 10 in the Appendix. Moreover, we want to highlight two aspects regarding the investment costs of the pipelines and storages. First, to incorporate economies of scale, pipelines with larger diameters have a cost advantage in case of the upfront investment costs compared to smaller ones. Second, offshore saline aquifers are expected to have the largest capacities among the offshore storage possibilities. However, they are also associated with the highest uncertainty of accessibility and availability and are therefore assumed to have significantly higher storage costs compared to depleted hydrocarbon fields (Holz et al. 2021).

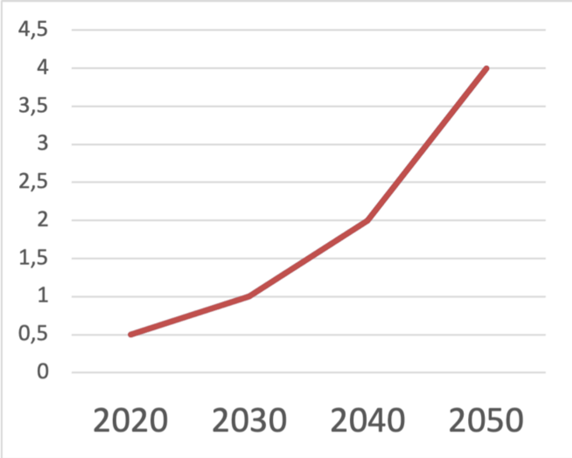

Figure 6: Annual CO2 price curve

Source: Own illustration

3.4 Scenario assumptions

The main goal of our stylized analysis is to examine the long-term impact of CCS technologies on the electricity and heat generation, the expansion of generation capacities, emissions as well as the total energy system costs of the existing EW-MOD energy system. Additionally, we aim to outline the rough structure of the resulting carbon infrastructure within the five model regions.

Our analysis and our scenario design are both inspired by the work of Holz et al. 2021. Overall, we compare three scenarios which differ only with respect to the general availability of CO2 infrastructure as well as the investment and the operational costs of power plants with CCS while all other assumptions remain the same. In other words, the assumptions of all other energy supply and transformation technologies (i. a. efficiencies, costs, emissions) as well as the final energy demand, the regional annual emission limits, the total emission budget, the CO2 price et cetera remain identical. A comprehensive overview over the scenario assumptions is provided in Table 1.

In the *No_CCS* scenario the entire CO2 infrastructure model extension is disabled which leaves only the EW-MOD energy system model which is described in Chapter 3.1.

In the *CCS_costly* and the *CCS_affordable* scenarios CO2 infrastructure is available. However, since CCS technologies are currently not deployed on a large scale any investments in CCS power plants are prohibited until 2030 in both scenarios. Furthermore, we distinguish between more and less favorable cost assumptions for the CCS power plants by applying a different carbon capture cost factor and varying the speed of the estimated cost reductions. The carbon capture cost factor describes how much more expensive a power plant with carbon capture is compared to an equivalent power plant without carbon capture. To represent the estimated cost degression, we applied cost reduction factors which result in earlier cost reductions in the *CCS_affordable* scenario compared to *CCS_costly*. An overview over the investment and operational costs of all scenarios is provided in Table 5 and Table 6 in the Appendix.

Table 1: Scenario assumptions

	No_CCS	CCS_costly		CCS_affordable	
Availability of CO2 infrastructure?	No	Yes		Yes	
Investment costs of power plants with carbon capture		**Carbon capture cost factor**			
		1.8		1.2	
		Cost reduction factors			
		2020	1	2020	1
		2030	1	2030	0.95
		2040	0.95	2040	0.85
		2050	0.85	2050	0.85
Variable costs of power plants with carbon capture		**Carbon capture cost factor**			
		1.5		1.2	
		Cost reduction factors			
		2020	1	2020	1
		2030	1	2030	0.90
		2040	0.90	2040	0.85
		2050	0.85	2050	0.80

Source: Own estimations

3.5 Research limitations

Due to the limited scope of this thesis, we want to emphasize the stylized and simplified character of our analysis. The small number of countries included as well as the generally low geographical resolution are oversimplifying the complexity of the energy system and result in e.g., low total pipeline investment costs. Although the data assumptions of our model mimic the real-world dimensions, they are generally too imprecise for the derivation of real prognoses and policy advises. For the latter we strongly recommend the work of Holz et al. 2021. In addition, we want to bring awareness to the following model limitations.

First, the demand for final energy is assumed to be inelastic and therefore highly simplifies the demand-side. For future research we recommend replacing the static demand with a demand function.

The CO2 infrastructure extension does not consider the option of retrofitting existing plants with carbon capture technology. However, Rohlfs and Madlener (2013) have showed that building new coal-fired power plants with CCS is preferable to converting existing ones. Additionally, several barriers associated with retrofitting carbon capture to existing plants such as reduced efficiency and limited lifetime have been identified by Rubin, Davison, and Herzog (2015).

In our model the application of CCS is limited to the energy sector which excludes the application of CCS in the industry sector[6] and prevents the exploitation of scale effects. Furthermore, the CO2 model extension does not account for any carbon capture and utilization (CCU) technologies such as Enhanced Oil Recovery (EOR) which might improve the economic viability of CCTS technologies by generating revenue from selling captured CO2.

[6] Industry sectors such as steel, cement, paper production and chemical industry are traditionally considered to be difficult to decarbonize which makes the large-scale application of CCS technologies attractive.

4 Results

In our analysis we examine the long-term impacts of the availability of CCS technologies to the electricity and heat sector of the EW-MOD energy system model. Hereby we lay the focus on total energy generation, the investments in capacity expansions, the total CO2 emissions as well as the overall energy system costs. Additionally, we aim to outline the rough structure of the resulting carbon infrastructure within the five European model regions. The foundation of our analysis is provided by the three scenarios: *No_CCS*, *CCS_costly* and *CCS_affordable* (see Table 1).

Due to the scope of this thesis the main goal of our investigation is the identification of key trends and developments rather than precise prognoses.

4.1 Energy generation and generation capacities

In both CCS scenarios carbon capture technologies are available in both the power and heat sector. In the following we will first discuss the scenario results with respect to the power sector and then to the heat sector.

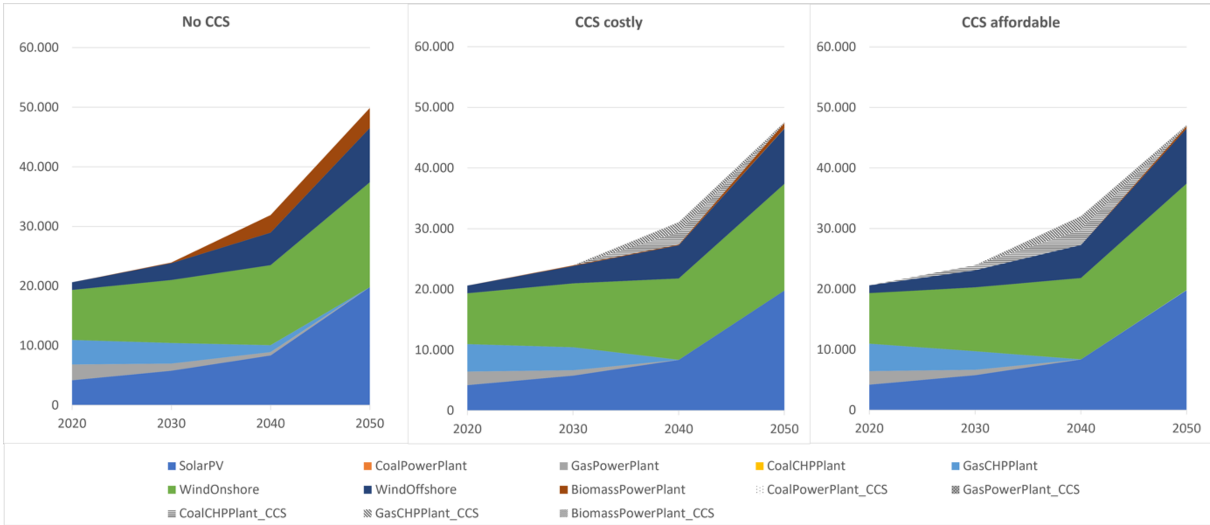

Figure 7: Electricity generation in all three scenarios

Source: Own illustration

For all scenarios the demand and the generation of electricity is depicted in Figure 7 whereas the total power generation capacities can be observed in Figure 8. The demand for electricity generally grows increasingly greater over time resulting in the constant need for additional investments in generation capacities.

Across all three scenarios *SolarPV* and *WindOnShore* emerge as the predominant contributors to electricity generation. Notably, the conventional generation exclusively features the utilization of either the *GasPowerPlant* or the *GasCHPPlant*. In comparison to coal CHP plants, gas CHP plants generate half the amount of GHG emissions while having comparably high investment and operational costs. This leads to higher costs due to the CO2 price which makes gas CHP plants more economically attractive, especially in the early stages of the examined time period (2020 and 2030). In the "costly" and "affordable" CCS scenarios, the deployment of CCS technology commences in *GasCHPPlant* and *CoalCHPPlant* in the year 2040 or 2030, respectively, dominated by Coal CHP plants. Now that CCS power plants and storages become more affordable, it becomes more economically viable to invest in coal CHP plants since their variable costs of resource procurement are cheaper than gas and it is economically acceptable to produce more CO2 since there are enough CCS capacities (Figure 8). Nevertheless, gas CHP plants are competitive, since using existing infrastructure of gas CHP plants is more feasible than investing in additional capacities in coal CHP plants with CCS. Simultaneously, the electricity generation stemming from gas and gas CHP plants experiences a gradual decline, until complete phase-out by 2040. This transition is particularly pronounced in the *CCS_affordable* scenario.

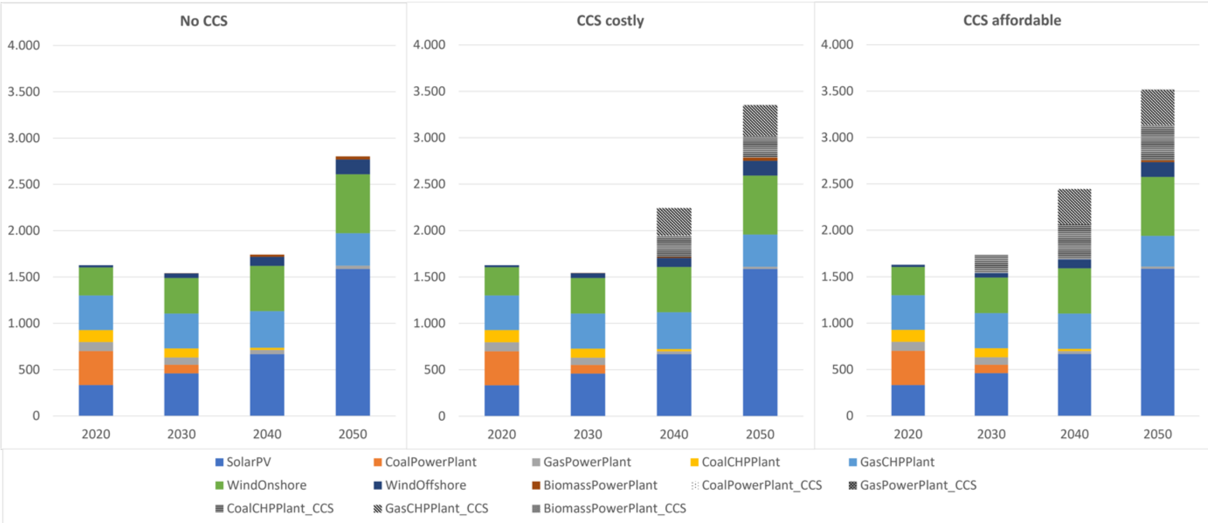

Figure 8: Total electricity generation capacities by technology

Source: Own illustration

It is essential to emphasize that in the scenario without CCS deployment, renewable energy sources account for a significant share of 86% of electricity generation capacity in 2050 (cf. Figure 15, Appendix). With the introduction of CCS technologies, this share drops to 72% in the “costly” scenario and 68% in the *CCS_affordable* scenario.

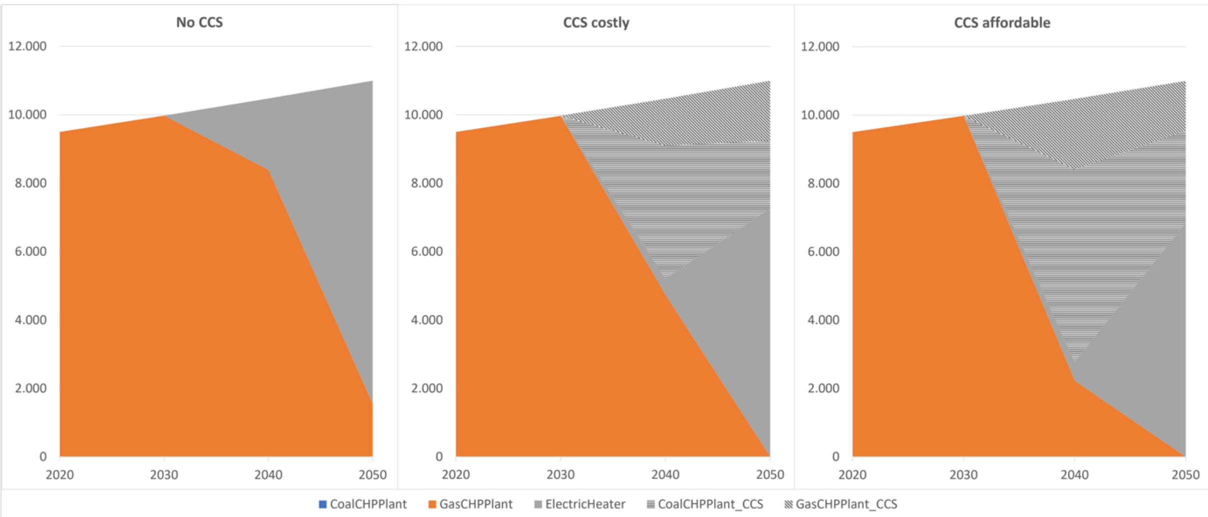

Figure 9: Total heat generation by technology

Source: Own illustration

Shifting focus to the heating sector, it comprises three technologies, including *ElectricHeater*, *GasCHPPlant*, and *CoalCHPPlant*. Nevertheless, the bigger share of heat generation is attributed to *ElectricHeater* and *GasCHPPlant*. As previously elucidated, the economic viability of gas, owing to its lower emissions profile at comparable costs relative to coal, underscores its prominence. Electric heating as a renewable source of heat generation offers a competitive advantage, as it does not generate additional costs associated with CO2 emissions.

CCS technologies find more extensive application in the heat sector compared to the power sector. This discrepancy arises from the fact that conventional generators in the energy sector can readily be replaced by renewable sources and thus save costs by exempting CO2 emissions. Figure 8 depicts a continuous increase in *SolarPV* and *WindOnshore*, with a notable expansion of *SolarPV* starting from 2040. In contrast, in the heating sector, a significant portion of heat generation from 2030 onwards is provided by gas and coal CHP plants coupled with CCS (*CoalCHPPlant_CCS* and *GasCHPPlant_CCS*), accompanied by a simultaneous decline in gas CHP plants without CCS (*GasCHPPlant*). The rising CO2 price has a significant impact on the competitiveness of these power plants and is therefore taken over by energy producers using CCS, which ultimately leads to the discontinuation of gas CHP plants in 2050.

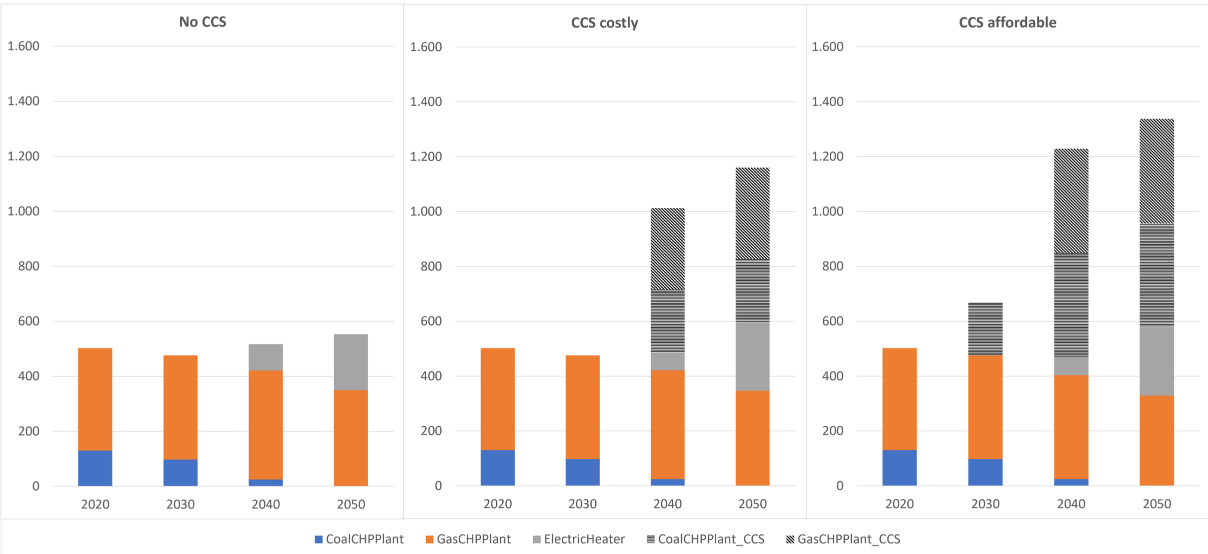

Figure 10: Total heat generation capacities by technology

Source: Own illustration

4.2 Total emissions

Investigating CO2 emissions is an essential aspect of this stylized analysis. This is because meeting political emission targets is not only a central component in achieving the 2°C target in climate policy but also because GHG emissions are directly correlated with the CO2 price. The rising price of CO2 per unit of emitted GHG has a significant impact on the macroeconomic costs of the whole energy system. Specifically, in the examined scenarios, the CO2 price increases every 10 years.

Figure 11 illustrates the relationship between CO2 emissions and the respective technologies responsible for them in the three analyzed scenarios. It is noticeable that both the operation of gas CHP plants and the utilization of LPG vehicles and gas power plants exert a great influence on CO2 emissions. The predominant presence of gas CHP plants can be attributed mainly to their contribution to heat supply. However, it can also be noted that the absolute volume of CO2 emissions produced from gas CHP decreases across all scenarios, as the *ElectricHeater* technology becomes more important over time. This is because the model progressively expands its electricity generation capacity. Consequently, the relatively lower efficiency of the *ElectricHeater* becomes less crucial at a certain point, as a sufficient supply of power becomes available without producing additional CO2 costs. Similarly, the emissions from LPG vehicles and gas power plants decrease over time as their utility is replaced by other technologies. LPG vehicles are replaced by Battery Electric Vehicles (*BEV*) and hydrogen cars (*H2Car*), while gas power plants are substituted with renewable electricity generation technologies.

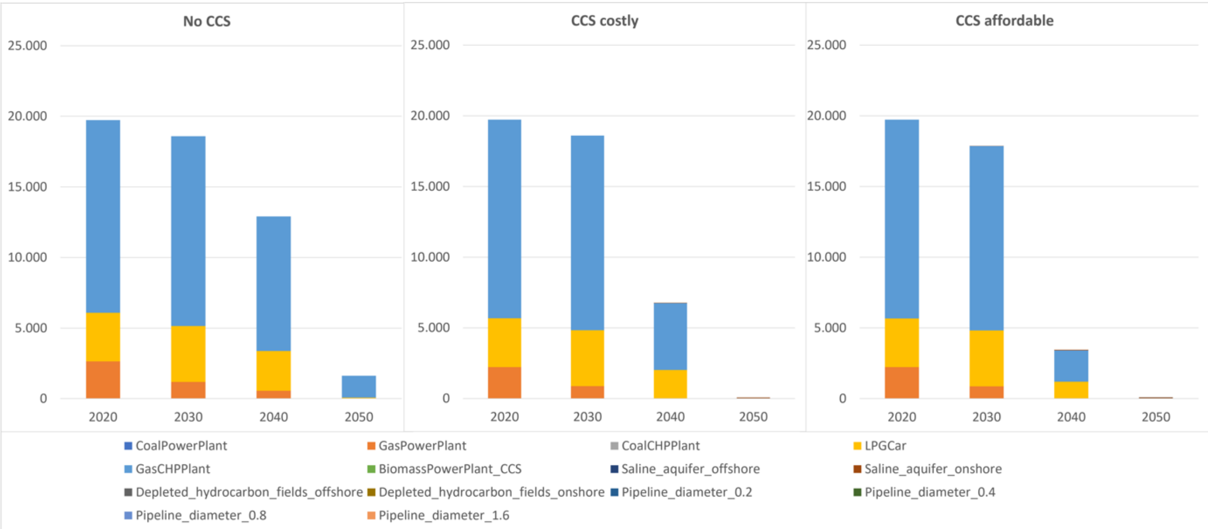

Figure 11: Total CO2 emissions by technology

Source: Own illustration

It can also be seen that there are significant disparities in absolute emissions between the scenarios in the year 2040. This is due to the stepwise integration of CCS infrastructure in the CCS scenarios starting from that year onwards. As the *CCS_affordable* model is relatively cost-effective, there are increased investments in this scenario, resulting in a reduction of absolute CO2 emissions (cf. previous Subchapter). As there are no CCS technologies in the *No_CCS* scenario, the reduction of CO2 needs to be achieved through increased use of renewable energies, which is not that fast and cost efficient. Emissions not only stick to certain technologies, but also to countries. The following figure provides an overview concerning this.

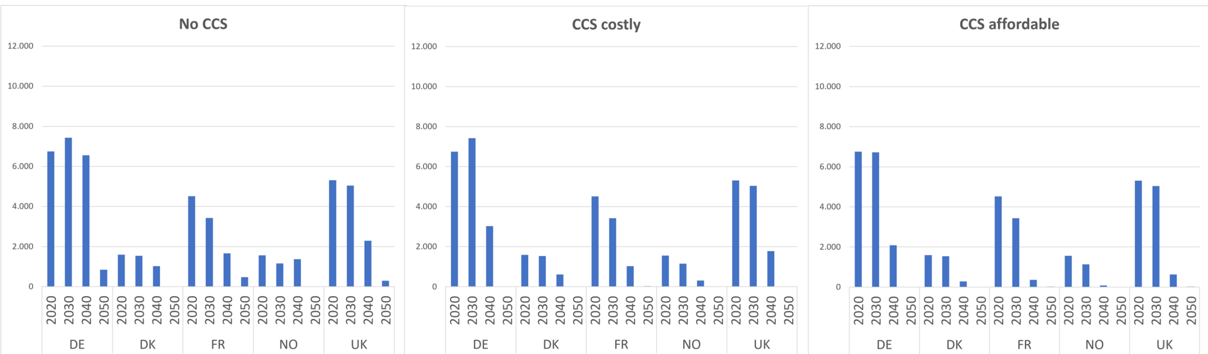

Figure 12: Annual CO2 emissions by country

Source: Own illustration

The CO2 emission levels in individual countries steadily decrease over time. However, differences between these countries become apparent. Especially Germany, but also France and the United Kingdom stand out with high GHG emissions. This is due to the special conditions in these countries. The high demand for electricity and heat in these regions leads to the construction of an increased capacity for energy generation. As explained in the previous subchapter, investments in CCS technology generally do not start until 2040 which explains the predominance of CO2-emitting power plants in the years 2020 and 2030. All countries experience a decline in emissions over time except Norway in 2040. This anomaly may be attributed to the rapid increase in European demand for heat and electricity in that year, which exceeds the supply capacities of non-emitting energy production units, although their share is growing. The additional energy does not necessarily have to be directly attributed to Norway but may also be imported from neighboring countries that obtain energy associated with emissions from Norway. Yet, this is an exceptional case.

4.3 Carbon infrastructure and CO2 trade

In addition to investments in conventional power plant technologies for power and heat generation, the CCS scenarios also include investments in technologies to reduce GHG emissions. These CCS technologies are used in the existing types of power plants that emit GHG during their operation. Following this, adapted generation technologies are *CoalPowerPlant_CCS*, *GasPowerPlant_CCS*, as well as the respective CHP plants and the *BiomassPowerPlant_CCS*. The annual investments in these technologies are shown in the following figure as well as in Figure 16 in the Appendix.

Investments in CCS technologies start in 2030 (*CCS_affordable* scenario) and in 2040 (*CCS_costly* scenario). The later start of investments in the *CCS_costly* scenario can be attributed to the higher absolute investment costs of CCS technology, which also decreases less over the years compared to the *CCS_affordable* scenario. Investments in generation technologies with CCS technologies, as well as the necessary storage technologies, are reasonable when the costs of capture, transport, and storage are lower than the emissions costs associated with conventional power plant technologies. From the year 2030 or, respectively, 2040 onward, the emissions costs associated with conventional generation technologies become significantly high due to increased emissions levels and rising CO2 prices, making investments in CCS technologies economically advantageous. This trend intensifies over time for all countries, both in the *CCS_costly* and *CCS_affordable* scenario.

In the following, the CO2 infrastructure is considered in detail, focusing on the construction of CO2 storage facilities in the *CCS_costly* and *CCS_affordable* scenarios. As discussed in Section 4.1, investments in CCS power plants in the *CCS_costly* scenario start in 2040, while in the *CCS_affordable* scenario they already start in 2030, although on a limited scale. A similar pattern appears for CO2 storage capacities, as the captured CO2 emissions must also find a location to be stored. The distribution of CO2 storage capacity across Europe over the entire time period is illustrated in Figure 13.

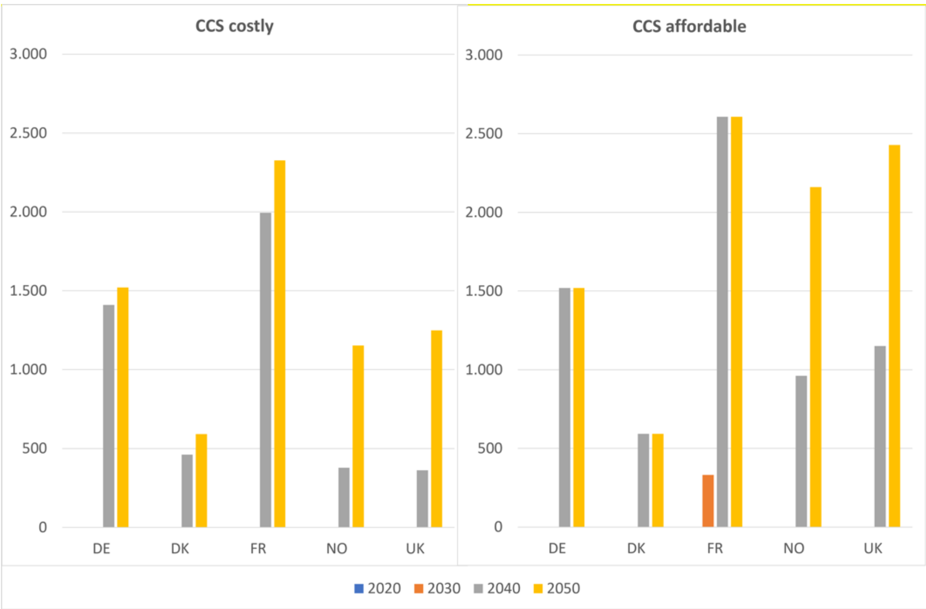

Figure 13: Total CO2 storage levels by country

Source: Own illustration

In the leading industrial nations France and Germany, where the energy consumption is relatively high, a large amount of CO2 is produced. As these countries are also the main locations for the installation of CCS power plants, it would make sense to set up CO2 storages right there, as transportation of CO2 incurs losses and, therefore, costs related to the CO2 price.

However, it is interesting to observe that in the *CCS_affordable* scenario, both Norway and the UK disproportionately invest more in CO2 storage capacities than, for instance, Germany. This can be attributed to the fact that the maximum CO2 storage capacity of countries does not necessarily correlate with their maximum production capacity. Various factors play a role here, such as geological characteristics or political circumstances (refer to Sections 1 and 2 for further information). Norway has the largest storage capacity, but it is not fully utilized in either scenario because the region is relatively remote compared to other countries, which results in long transportation routes and consequently CO2 losses and, therefore, costs. In both scenarios, Germany and Denmark fully utilize their CO2 storage capacities, while France's capacities are only fully utilized in the *CCS_affordable* scenario, but they also reach a high relative value in the *CCS_costly* scenario. This is, one the one hand, due to the central geographical location of Germany, Denmark and France, which enables shorter transportation routes to other regions. On the other hand, it has also to do with relatively limited storage capacities, especially in Germany and Denmark. The maximum storage capacities as well as the geographical distribution can also be compared in Table 8 in the Appendix.

The pipeline infrastructure also varies between the CCS scenarios. Table 2 illustrates that in the CCS_affordable scenario, more pipelines are installed. It can also be noticed that the infrastructure expansions occur over time as the captured CO2 levels increase, especially in industrialized countries, and subsequently need to be stored in other countries. Additionally, we can observe that in both scenarios only pipelines with the largest diameter and hence largest capacity are build.

Table 2: Pipeline network expansions

	CCS costly				CCS affordable			
Year	**Diameter**	**From**	**To**	**Number**	**Diameter**	**From**	**To**	**Number**
2030	1.6	FR	UK	1	1.6	FR	UK	1
2040	1.6	DK	DE	1	1.6	DK	DE	2
2040					1.6	FR	DE	1
2040	1.6	FR	UK	3	1.6	FR	UK	3
2040					1.6	NO	DK	2
2040					1.6	UK	FR	1
2050	1.6	DK	DE	2	1.6	DK	DE	2
2050	1.6	NO	DK	3	1.6	NO	DK	3
2050	1.6	UK	FR	1	1.6	UK	FR	1

Since the industrialized nations, especially Germany, produce significant amounts of CO2 but may not always have the capacity to store them within their own regions, they must export additional CO2 to other regions for storage. The developments concerning CO2 exports over the whole time period can be summarized in the Figure 14. It is evident that central states with limited storage capacities export the most CO2, while Norway, for instance, predominantly imports.

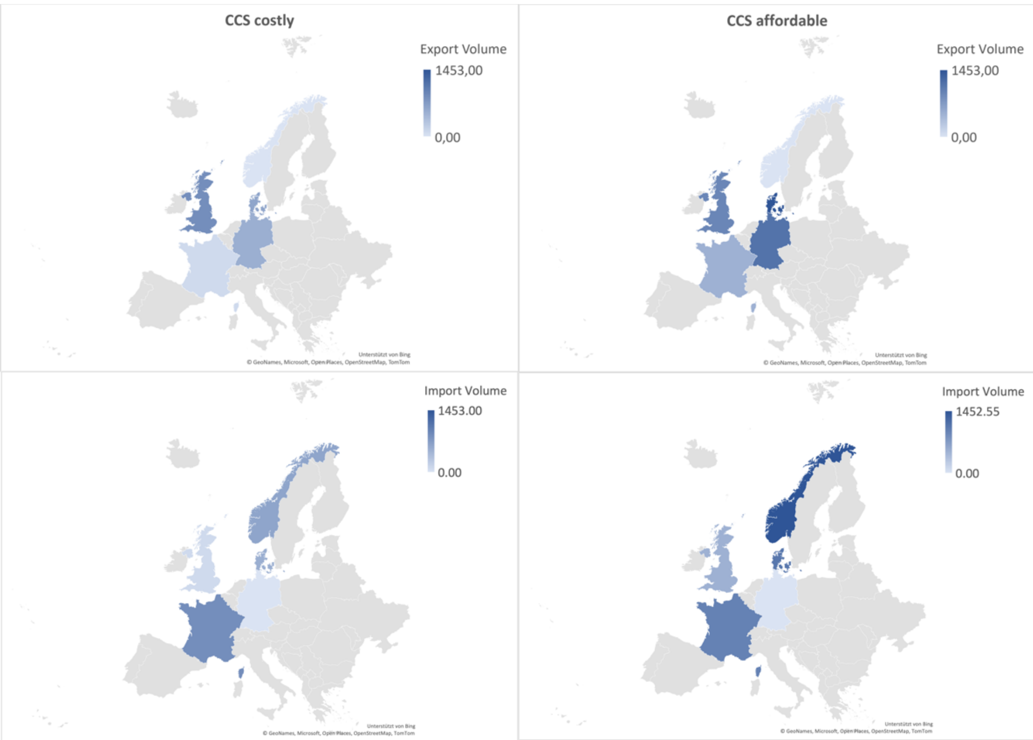

Figure 14: Total CO2 exports (above) and imports (below) over entire model horizon

Source: Own illustration

4.4 Energy system costs

In this section, a comparison of the total macroeconomic system costs is given. This cost analysis is the foundation for an economic evaluation for the purpose of the large-scale application of CCTS technologies. The following table summarizes the various cost components of our scenarios.

	No CCS	CCS costly	CCS affordable
Total energy system costs[7]	836.968	814.585	796.933
Costs of power plants without CCS[8]	236.999	219.817	209.279
Costs of power plants with CCS[8]	0	56.965	66.271
Energy storage investment costs	745	762	762
Transportation costs	5.756	4.323	3.548
CO2 pipeline investment costs	0	105	182
CO2 pipeline operational costs	0	384	904
Total CO2 pipeline costs	0	489	1.086
CO2 storage investments	0	691	1.049
CO2 storage operational costs	0	12.098	27.254
Total CO2 storage costs	0	12.790	28.303
Total CO2 infrastructure costs	0	70.243	95.660
Total CO2 emission costs	311.609	263.810	234.196

It can be observed that the overall system costs are highest in the *No_CCS* scenario. The main reason for the high overall system costs in the *No_CCS* scenario can be attributed to the installed capacity of emission-free power plants for electricity and heat generation, ergo to the installed capacity of renewable energies. Despite the high investments in this area, the model offers the highest costs for CO2 emissions, which can be justified by the fact that emission levels decrease later than in the CCS scenarios, where corresponding capture technologies and CO2 storages are built and utilized.

A direct comparison of the two CCS scenarios reveals that the investment costs in the *CCS_affordable* scenario exceed those in the *CCS_costly* scenario, while the opposite is true for the operating costs. This disparity results from the construction of a greater number of CCS power plants in the *CCS affordable* scenario, which can be operated at a lower cost due to a more favorable cost development compared to the *CCS_costly* scenario. Overall, the *CCS_affordable* scenario represents the most cost-effective scenario, as it involves higher investments in the CO2 infrastructure but simultaneously experiences lower costs for CO2 emissions. This fact becomes even more important as CO2 prices increase or the total emissions of individual countries are regulated more strictly, because there is less investment in CO2 transport and storage capacities in the costly scenario.

[7] The total salvage costs were added manually after the optimization.

[8] This includes investment and operational costs

5 Conclusion

Using the model, it was shown which technologies from the power and heat sectors would comprise the European energy system if either no CCS technologies were introduced, there was an affordable CCS technology, or there was a costly CCS variant. The result of this analysis has shown that the total energy system costs are highest in the *No_CCS* scenario and lowest in the *CCS_affordable* scenario. The reason for this is the increasing CO2 price over the years, as well as the cost of expanding renewable energy instead of investing in CCS. Although the affordable CCS scenario performs best in terms of costs, the cost advantages are relatively small. Since CCS technologies are not yet fully explored and large-scale deployment has not yet been tested, the question arises whether such a small cost advantage justifies the decision to invest in CCS technologies and thus inhibit the expansion of renewable energies.

It is important to note that the model has certain limitations. First, no real world data were used, which means that the statements of the model are not completely transferable to reality. One example of the modeling approach not accurately representing reality is that electric heaters are not expected to be able to meet all heat demand, especially in the industrial sector. Furthermore, only the energy sector was considered in this model. The extension of the model to other industry sectors and its results are not reflected here. It should also be mentioned that only one price path was chosen for the CO2 price. The analysis of different price paths with different degrees of increases would strengthen the model.

Besides the limitations, it can be summarized that under the given assumptions of the model, investments in large scale CCS infrastructure would be reasonable in the European energy system. This would not only lead to an earlier reduction of climate damaging CO2 emissions but also minimize overall system costs. Achieving the target values for CO2 emissions set by the EU without CCS technology would require a substantial financial outlay.

Nevertheless, further funding for research and deployment of CCS technologies is necessary in the future, as the decarbonization of the industry and energy sector and reduction of GHG emissions are inevitable to counteract climate change.

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Appendix

1 Mathematical formulation of the CO2 model extension

1.1 Sets, parameter, variables

Table 3: List of new sets of the CO2 infrastructure model extension

Set name	Description	Range
PowerPlantsWithCCS	Power plants which can capture CO2 Subset of the *technologies* set	CoalPowerPlant_CCS, GasPowerPlant_CCS, CoalCHPPlant_CCS, GasCHPPlant_CCS, BiomassPowerPlant_CCS
CO2_Storages	Underground storages which can store CO2	Saline_aquifer_offshore, Saline_aquifer_onshore, Depleted_hydrocarbon_fields_offshore, Depleted_hydrocarbon_fields_onshore
CO2_Pipelines	CO2 Pipeline technologies	Pipeline_diameter_0.2, Pipeline_diameter_0.4, Pipeline_diameter_0.8, Pipeline_diameter_1.6

Table 4: List of new parameters of the CO2 infrastructure model extension

Parameter name	Description
$CO2\_MaximumTradeCapacity_{Regions,Regions}$	Maximum annual export capacity between *Regions* and *Regions*
$CO2\_PipelineCapacity_{CO2\_Pipelines}$	Pipeline capacity of *CO2_Pipelines*
$CO2\_PipelineInvestmentCost_{CO2\_Pipelines}$	Investment costs for one distance unit of *CO2_Pipelines*
$CO2\_Price_{Year}$	Price of one unit emitted CO2 in *Year*
$CO2\_StoragesInvestmentCost_{CO2\_Storages}$	Investment costs for one unit of storage capacity of *CO2_Storages*
$CO2\_StorageMaximumCapacity_{Region,CO2\_Storages}$	Maximum CO2 storage capacity of *CO2_Storages* in *Regions*
$CO2\_StoragesVariableCost_{CO2\_Storages}$	Variable costs of storing one unit of *Stored_CO2* in *CO2_Storages*

Table 3: List of new variables of the CO2 infrastructure model extension

Variable name	Domain	Description
CO2_Emission_Costs	$\mathbb{R}_0^+$	Total CO2 emission costs resulting from the *CO2_Price*
CO2_Export$_{Year,Hour,CO2\_Pipelines,Regions,Regions}$	$\mathbb{R}_0^+$	CO2 export volume via *CO2_Pipelines* between *Regions* and *Regions* in *Hour* in *Year*
CO2_Import$_{Year,Hour,CO2\_Pipelines,Regions,Regions}$	$\mathbb{R}_0^+$	CO2 import volume via *CO2_Pipelines* between *Regions* and *Regions* in *Hour* in *Year*
CO2_PipelineCost_Investment	$\mathbb{R}_0^+$	Total CO2 pipeline investment costs of all *CO2_Pipelines* and all *Regions* over the model horizon
CO2_PipelineCost_Operational	$\mathbb{R}_0^+$	Total CO2 pipeline operational costs of all *CO2_Pipelines* and all *Regions* over the model horizon
CO2_PipelineEmissions$_{Year,Regions,CO2\_Pipelines}$	$\mathbb{R}_0^+$	CO2 pipeline emissions of *CO2_Pipelines* in *Regions* in *Year*
CO2_Pipeline_Quantity$_{Year,CO2\_Pipelines,Regions,Regions}$	$\{0,1,2,3\}$	Quantity of new *CO2_Pipelines* between *Regions* and *Regions* in *Year*
CO2_PipelineTotalCapacity$_{Year,CO2\_Pipelines,Regions,Regions}$	$\mathbb{R}_0^+$	Total CO2 pipeline capacity of *CO2_Pipelines* between *Regions* and *Regions* in *Year*
CO2_StorageCharge$_{Year,Regions,Hour,CO2\_Storages}$	$\mathbb{R}_0^+$	CO2 storage injection into *CO2_Storages* in *Regions* in *Hour* in *Year*
CO2_StorageCost_Investment	$\mathbb{R}_0^+$	Total CO2 storage investment costs of all *CO2_Storages* and all *Regions* over the model horizon
CO2_StorageCost_Operational	$\mathbb{R}_0^+$	Total CO2 storage operational costs of all *CO2_Storages* and all *Regions* over the model horizon
CO2_StorageEmissions$_{Year,Regions,CO2\_Storages}$	$\mathbb{R}_0^+$	CO2 storage emissions of *CO2_Storages* in *Regions* in *Year*
CO2_StorageLevel$_{Year,Regions,Hour,CO2\_Storages}$	$\mathbb{R}_0^+$	CO2 storage level in *CO2_Storages* in *Regions* in *Hour* in *Year*
CO2_StorageNewCapacity$_{Year,Regions,CO2\_Storages}$	$\mathbb{R}_0^+$	CO2 storage capacity expansion of *CO2_Storages* in *Regions* in *Year*
CO2_StorageTotalCapacity$_{Year,Regions,CO2\_Storages}$	$\mathbb{R}_0^+$	Total CO2 storage capacity of *CO2_Storages* in *Regions* in *Year*

1.2 Constraints

CO2 capturing constraint

$$\forall\, y \in Years, r \in Regions, h \in\; Hour, t \in Technologies$$

$$Production_{y,r,h,t,Stored_{C}O2} = \sum_{f \setminus Stored\_CO2} OutputRatio_{t,f} * Production_{y,r,h,t,f} \tag{1}$$

CO2 mass balance constraint

$$\forall\, y \in Years, r \in Regions, h \in\; Hour$$

$$\begin{aligned}
&\sum_{t} Production_{y,r,h,t,Stored_CO2} + \sum_{t \in C_O2_Pipelines, rr \in Regions} CO2_Import_{y,h,t,r,rr} \\
&\quad = \sum_{t \in C_O2_Pipelines, rr \in Regions} CO2_Export_{y,h,t,r,rr} \\
&\quad + \sum_{s \in C_O2_Storages} CO2_StorageCharge_{y,r,h,s}
\end{aligned} \tag{2}$$

CO2 storage mass balance constraint (1/3)

$$\forall\, y \in Years, r \in Regions, h \in Hour\ if\ h > 0, s \in CO2\_Storages$$

$$\begin{aligned}
&CO2_StorageLevel_{y,r,h,s} \\
&= CO2_StorageLevel_{y,r,h-1,s} * StorageLosses_{s,Stored_CO2} \\
&+ CO2_StorageCharge_{y,r,h,s}
\end{aligned} \tag{3}$$

CO2 storage mass balance constraint (2/3)

$$\forall\, y \in Years\ if\ y\ >\ min(Year), r \in Regions, h \in Hour\ if\ h = 1, s \in CO2\_Storages$$

$$\begin{aligned}
&CO2_StorageLevel_{y,r,h,s} \\
&= CO2_StorageLevel_{y-10,r,120,s} * StorageLosses_{s,Stored_CO2} \\
&+ CO2_StorageCharge_{y,r,h,s}
\end{aligned} \tag{4}$$

CO2 storage mass balance constraint (3/3)

$$\forall\, y \in Years\ if\ y\ =\ min(Year), r \in Regions, h \in Hour\ if\ h = 1, s \in CO2\_Storages$$

$$CO2\_StorageLevel_{y,r,h,s} = CO2\_StorageCharge_{y,r,h,s} \tag{5}$$

CO2 storage capacity constraint

$$\forall\, y \in Years, r \in Regions, h \in Hour, s \in CO2\_Storages$$

$$CO2\_StorageLevel_{y,r,h,s} \leq CO2\_StorageTotalCapacity_{y,r,s} \tag{6}$$

CO2 total storage capacity constraint

$$\forall\, y \in \text{Years}, r \in \text{Regions}, h \in Hour, s \in CO2\_Storages$$
$$CO2\_StorageTotalCapacity_{y,r,s} = \sum_{yy \,\in\, Year\; if\; yy \leq y} CO2\_StorageNewCapacity_{yy,r,s} \tag{7}$$

CO2 maximum total storage capacity constraint

$$\forall\, y \in Years, r \in Regions, h \in Hour, s \in CO2\_Storages$$
$$CO2\_StorageTotalCapacity_{y,r,s} \leq CO2\_StorageMaximumCapacity_{r,s} \tag{8}$$

CO2 storage emissions constraint

$$\forall\, y \in Years, r \in Regions, s \in CO2\_Storages$$
$$CO2\_StorageEmissions_{y,r,s} = \sum_{h} CO2\_StorageLevel_{y,r,h,s} * \left(1 - StorageLosses_{s,Stored\_CO2}\right) \tag{9}$$

CO2 import/export balance constraint

$$\forall\, y \in Years,\ h \in Hour,\ t \in CO2\_Pipelines,\ r \in Regions, rr \in Regions$$
$$CO2\_Import_{y,h,t,rr,r}$$
$$= CO2\_Export_{y,h,t,r,rr} * \left(1 - TradeLossFactor_{Stored\_CO2} * TradeDistance_{r,rr}\right) \tag{10}$$

CO2 export capacity constraint

$$\forall\, y \in Years,\ \ t \in CO2\_Pipelines,\ r \in Regions, rr \in Regions$$
$$\sum_{h} CO2\_Import_{y,h,t,rr,r} \leq CO2\_PipelineTotalCapacity_{y,t,r,rr} \tag{11}$$

CO2 total pipeline capacity constraint

$$\forall\, y \in \text{Years},\ \ t \in \text{CO2\_Pipelines},\ r \in Regions, rr \in Regions$$
$$CO2\_PipelineTotalCapacity_{y,t,r,rr}$$
$$= \sum_{yy \,\in\, Year\; if\; yy \leq y} CO2\_Pipeline\_Quantity_{yy,t,r,rr} * CO2\_PipelineCapacity_{t} \tag{12}$$

Maximum CO2 pipeline capacity constraint

$$\forall\, y \in Years,\ \ t \in CO2\_Pipelines,\ r \in Regions, rr \in Regions$$
$$\sum_{t \in CO2\_Pipelines} CO2\_PipelineTotalCapacity_{y,t,r,rr} \leq CO2\_MaximumTradeCapacity_{r,rr} \tag{13}$$

CO2 Trade emissions constraint

$$\forall\, y \in Years,\ t \in CO2\_Pipelines,\ r \in Regions$$

$$\begin{aligned} &\mathrm{CO2\_PipelineEmissions}_{y,r,t} \\ &= \sum_{t \in \mathrm{CO2\_Pipelines}} \mathrm{CO2\_Export}_{y,h,t,r,rr} \\ &* \left(1 - \mathrm{TradeLossFactor}_{\mathrm{Stored\_CO2}} * \mathrm{TradeDistance}_{r,rr}\right) \end{aligned} \tag{14}$$

CO2 infrastructure salvage value constraint ($SalvageValue_{y,r,t}$ are added to the objective function)

$$\forall\, y \in Years,\ t \in CO2\_Pipelines,\ r \in Regions\ if\ y\ +\ TechnologyLifetime_t \geq max(Year)$$

$$\begin{aligned} &SalvageValue_{y,r,t} \\ &= \sum_{rr \in Regions} CO2\_Pipeline\_Quantity_{y,t,rr,r} * CO2\_PipelineInvestmentCost_t \\ &* TradeDistance_{r,rr} * \frac{1}{(1 + DiscountRate)^{(y - min(Year))}} \\ &* \left(1 - \frac{max(Year) - y + 1}{TechnologyLifetime_t}\right) \end{aligned} \tag{15}$$

CO2 pipeline investment costs constraint ($CO2\_PipelineCost\_Investment$ are added to the objective function)

$$\begin{aligned} &CO2\_PipelineCost\_Investment \\ &= \sum_{y\, \in Year,\, t\, \in CO2\_Pipelines,\, r\, \in Regions,\, rr\, \in Regions} CO2\_Pipeline\_Quantity_{y,t,r,rr} \\ &*\ TradeDistance_{r,rr}\ * CO2\_PipelineInvestmentCost_t \\ &* \frac{1}{(1 + DiscountRate)^{(y - min(Year)\}}} \end{aligned} \tag{16}$$

CO2 pipeline operational costs constraint ($CO2\_PipelineCost\_Operational$ are added to the objective function)

$$\begin{aligned} &CO2\_PipelineCost\_Operational \\ &= \sum_{y\, \in Year,\, h \in Hour, t\, \in CO2\_Pipelines} CO2\_Export_{y,h,t,rr,r} * TradeCostFactor_{tStored\_CO2} \\ &* TradeDistance_{r,rr} * YearlyDifferenceMultiplier_y \\ &* \frac{1}{(1 + DiscountRate)^{(y - min(Year))}} \end{aligned} \tag{17}$$

CO2 storage investment costs constraint ($CO2\_StorageCost\_Investment$ are added to the objective function)

$$CO2\_StorageCost\_Investment = \sum_{y \in Year,\, r \in Regions, s \in CO2\_Storages} CO2\_StorageNewCapacity_{y,r,s} * CO2\_StorageInvestmentCost_s * \frac{1}{(1 + DiscountRate)^{(y-min(Year))}} \tag{18}$$

CO2 storage operational costs constraint ($CO2\_StorageCost\_Operational$ are added to the objective function)

$$CO2\_StorageCost\_Operational = \sum_{y \in Year, h \in Hour, r \in Regions, s \in CO2\_Storages} CO2\_StorageLevel_{y,r,h,s} * YearlyDifferenceMultiplier_y * CO2\_StorageVariableCost_s * \frac{1}{(1 + DiscountRate)^{(y-min(Year))}} \tag{19}$$

CO2 emission costs constraint ($CO2\_Emission\_Costs$ are added to the objective function)

$$\begin{aligned} CO2\_Emission\_Costs = & \sum_{y \in Year,\, r \in Regions, t \in Technologies} \Big(Annual\_Technology\_Emissions_{y,r,t} * YearlyDifferenceMultiplier_y * \frac{CO2\_Price_y}{(1 + DiscountRate)^{(y-min(Year))}}\Big) \\ & + \sum_{y \in Year,\, r \in Regions, t \in CO2\_Pipelines} \Big(CO2\_PipelineEmissions_{y,r,t} * YearlyDifferenceMultiplier_y * \frac{CO2\_Price_y}{(1 + DiscountRate)^{(y-min(Year))}}\Big) \\ & + \sum_{y \in Year,\, r \in Regions, t \in CO2\_Storages} \Big(CO2\_StorageEmissions_{y,r,t} * YearlyDifferenceMultiplier_y * \frac{CO2\_Price_y}{(1 + DiscountRate)^{(y-min(Year))}}\Big) \end{aligned} \tag{20}$$

2 Key data assumptions

Table 5: Investment costs of electricity and heat generation technologies

Technology	2020	2030	2040	2050
BiomassPowerPlant	1	1	1	1
BiomassPowerPlant_CCS_affordable	-	1.14	1.02	1.02
BiomassPowerPlant_CCS_costly	-	1.8	1.71	1.53
CoalCHPPlant	1.05	1	0.95	0.95
CoalCHPPlant_CCS_affordable	-	1.197	1.071	1.071
CoalCHPPlant_CCS_costly	-	1.89	1.7955	1.6065
CoalPowerPlant	1	0.95	0.85	0.85
CoalPowerPlant_CCS_affordable	-	1.14	1.02	1.02
CoalPowerPlant_CCS_costly	-	1.8	1.71	1.53
GasCHPPlant	1.05	1	0.95	0.95
GasCHPPlant_CCS_affordable	-	1.197	1.071	1.071
GasCHPPlant_CCS_costly	-	1.89	1.7955	1.6065
GasPowerPlant	1	0.95	0.85	0.85
GasPowerPlant_CCS_affordable	-	1.14	1.02	1.02
GasPowerPlant_CCS_costly	-	1.8	1.71	1.53
SolarPV	2	1.9	1.75	1.55
WindOffshore	1.2	1.15	1.05	0.9
WindOnshore	0.9	0.875	0.85	0.825

Source: WIP 2023b and own estimations

Table 6: Operational costs of electricity and heat generation technologies

Technology	2020	2030	2040	2050
BiomassPowerPlant	0.25	0.25	0.25	0.25
BiomassPowerPlant_CCS_affordable	-	0.27	0.255	0.24
BiomassPowerPlant_CCS_costly	-	0.375	0.3375	0.31875
CoalCHPPlant	0.8	0.8	0.7	0.7
CoalCHPPlant_CCS_affordable	-	0.864	0.816	0.768
CoalCHPPlant_CCS_costly	-	1.2	1.08	1.02
CoalPowerPlant	0.8	0.8	0.7	0.7
CoalPowerPlant_CCS_affordable	-	0.864	0.816	0.768
CoalPowerPlant_CCS_costly	-	1.2	1.08	1.02
GasCHPPlant	0.8	0.8	0.7	0.7
GasCHPPlant_CCS_affordable	-	0.864	0.816	0.768
GasCHPPlant_CCS_costly	-	1.2	1.08	1.02
GasPowerPlant	0.8	0.8	0.7	0.7
GasPowerPlant_CCS_affordable	-	0.864	0.816	0.768

GasPowerPlant_CCS_costly	-	1.2	1.08	1.02
SolarPV	0.01	0.01	0.01	0.01
WindOffshore	0.01	0.01	0.01	0.01
WindOnshore	0.01	0.01	0.01	0.01

Source: WIP 2023b and own estimations

Table 7: Annual regional depended emission limits

Region	2020	2030	2040	2050
DE	9440.18	10785.00	6548.71	842.57
DK	1592.33	1556.00	1023.00	0.00
FR	4517.90	3429.13	1668.85	477.59
NO	3692.97	3000.00	1580.67	0.00
UK	6667.87	5042.10	2293.28	300.16

Source: Own estimations

Table 8: Maximum CO2 storage capacity by storage type

Region	Saline aquifer onshore	Saline aquifer offshore	Depleted hydrocarbon fields offshore	Depleted hydrocarbon fields onshore
DE	608	912	0	0
DK	0	192	0	400
FR	2304	304	0	0
NO	0	1248	1904	256
UK	0	2304	1248	0

Source: Based on values of Oei, Herold, and Mendelevitch 2014, rescaled to match model dimensions

Table 9: Investment and variable costs by CO2 storage type

Storage type	Investment cost	Variable cost
Saline aquifer onshore	0.50	0.0225
Saline aquifer offshore	0.28	0.015
Depleted hydrocarbon fields offshore	0.26	0.0225
Depleted hydrocarbon fields onshore	0.20	0.015
Saline aquifer onshore	0.50	0.0225

Source: Based on values of Holz et al. 2021, rescaled to match model dimensions

Table 10: Pipeline capacities

Pipeline diameter	Total Capacity

0.2	6.00
0.4	13.5
0.8	53.25
1.6	253.5

Source: Based on values of Holz et al. 2021, rescaled to match model dimensions

3 Additional figures

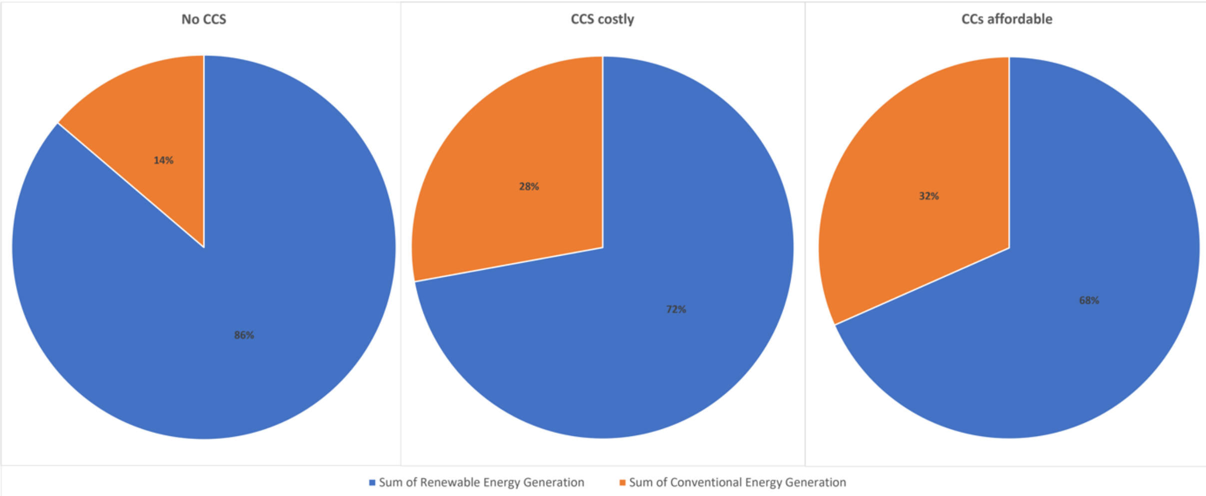

Figure 15: Share of renewable energy sources in total electricity generation capacities

Source: Own illustration

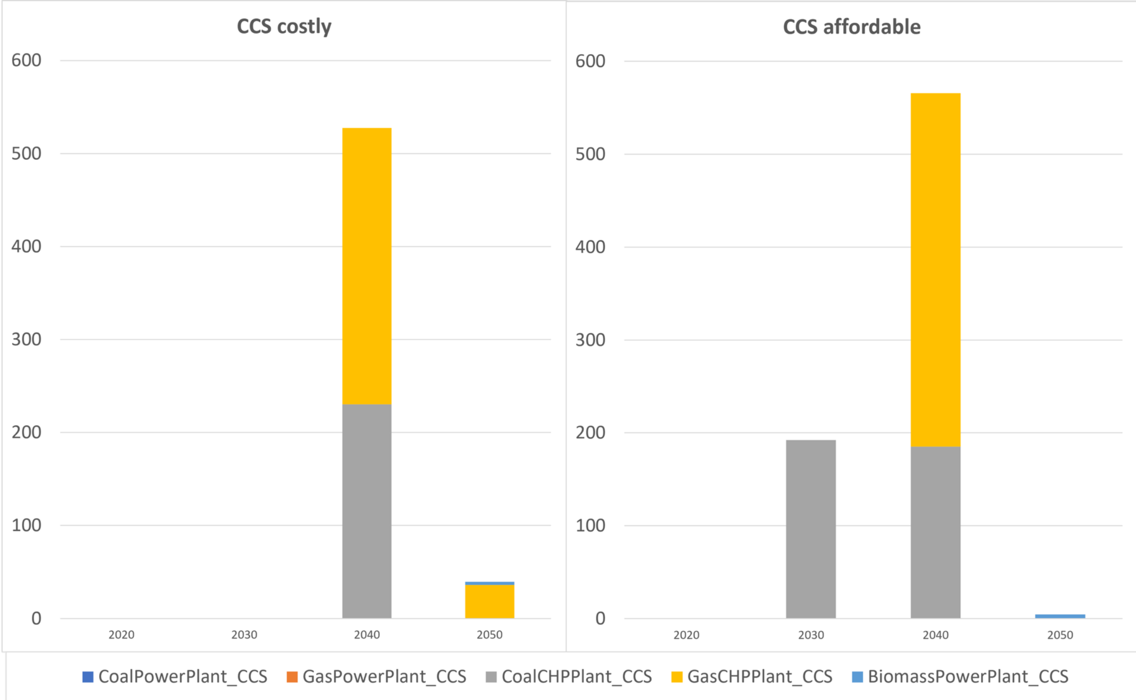

Figure 16: Total capacities of power plants with CCS

Source: Own illustration

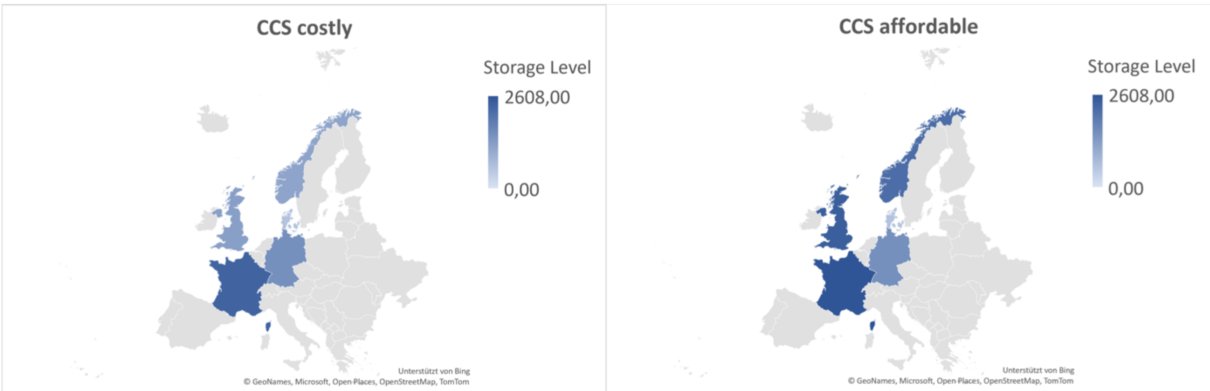

Figure 17: Total CO2 storage levels in 2050 by country

Source: Own illustration