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THE IMPACT OF CARBON CAPTURE AND STORAGE ON A DECARBONIZED GERMAN POWER MARKET

by

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07.10.2013

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Abstract

The European energy policy is substantially driven by the target to reduce the CO_2-emissions significantly and to mitigate climate change. Nevertheless European power generation is still widely based on fossil fuels. The carbon capture and storage technology (CCS) could be part of an approach to achieve ambitious CO_2 reduction targets without large scale transformations of the existing energy system. In this context the paper investigates in how far the CCS-technology could play a role in the European and most notably in the German electricity generation sector. To account for all the interdependencies with the European neighboring countries, the embedding of the German electricity system is modeled using a stochastic European electricity market model (E2M2s). After modeling the European side constraints, the German electricity system is considered in detail with the stochastic German Electricity market model (GEM2s). The focus is thereby on the location of CCS plant sites, the structure of the CO_2-pipeline network and the regional distribution of storage sites. Results for three different European energy market scenarios are presented up to the year 2050. Additionally, the use of CCS with use of onshore and offshore sites is investigated.

Index Terms— stochastic optimization, carbon capture and storage, power system economics

JEL-classification: Q3, Q4, C61

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1 INTRODUCTION

In the latest Energy Roadmap (EC 2011) the EU emphasizes the objective to transform the European energy sector into a low carbon economy. Hence, a reduction of greenhouse gas emissions by 80 to 95% compared to the levels of 1990 is the ambitious goal for 2050. This mitigation target determines efforts in all relevant energy sectors. Simultaneously an affordable, sustainable, competitive and safe energy supply should be guaranteed (EC 2011). It is a matter of fact that large scale emission cuts and the transformation of a whole economy into a decarbonized system is a mega-project that requires years if not several decades and billions of Euro. Despite the ambitious climate targets of the EU it is very likely that fossil fuels will have a certain share in the European energy sector for the next decades. The IEA projects in the main scenario of the latest World Energy Outlook (IEA 2012) a 75%-share of fossil fuels in 2035 concerning the world primary energy demand. The energy mix in the EU in 2011 is dominated by about 75% of fossil fuels. Whereas the transport sector is predominantly oil-driven, the electricity generating sector is to about 50% based on coal and gas plants (IEA 2012). The Carbon Capture and Storage-technology (CCS) could be instrumental to cut global or regional CO_2-emissions significantly without removing fossil fuel plants from the energy system overhastily and jeopardizing the security of electricity supply. CCS provides a technical solution to cut CO_2-emissions from punctual large-scale emissions sources like fossil power plants or large industrial producers. The CCS-technology requires a transport-system (e.g. a pipeline-net) to transport the separated carbon dioxide to geological storage formations like saline aquifers or exploited gas fields on- or offshore (Metz et al. 2005). CCS could therefore facilitate the transformation to a low carbon energy system without massive redeployments in the infrastructure of the electricity generating sector simultaneously providing the advantages of a controllable energy generation backing up the ongoing proliferation of renewable energies.

Germany, the biggest member state in the EU, realized a renewable share of more than 20% of the electricity production in 2011 (AGEB, 2012). Despite the unprecedented advance of the renewable energy sources in Germany, the fossil fuels lignite, hard coal, gas and oil stand up for more than 58% of the gross electricity production (AGEB, 2012). According to the new energy concept that has been announced by the German administration in the middle of 2011, the German nuclear phase out has to be completed till 2022. The loss of roundabout 20 GW installed capacity of the carbon free nuclear technology compared to 1990 makes the CO_2-reduction targets of minus 40% till 2020 and of minus 80% till 2050 (compared to 1990 levels) considerably more challenging. Until 2012 already about 10 GW of nuclear have been phased out and energy-related CO2 emissions have decreased by 22 % compared to 1990. However most of the emission reduction has been achieved until 2005 (-18 %) and between 2011 and 2012 there has been even an increase in emissions by 2.2 % (BMWi 2013). Thus the 2050 target is still ambitious. Notwithstanding the fast diffusion of renewable technologies it is quite likely that fossil fuel plants will continue to play a fundamental role in electricity generation in Germany for the next decades. Therefore, CCS might be an interesting solution for the German electricity market. In

accordance with the European Union, the German administration considers the CCS technology as a possible bridge into the forthcoming era of renewable energies (BMWI, 2010).

The implementation of the CCS technology in conventional power producing sectors has been topic of many modeling approaches. Gough et al. (2006), Fowler (2008) and McFarland and Herzog (2006) presented bottom-up models as well as top-down and integrated assessment model approaches. A variety of linear optimization model approaches can be found in Bakken and von Streng Velken (2008). An interesting approach of a scenario based policy analysis is presented e.g. in Capros et al. (2008). In the context of a mixed integer and nonlinear programming problem, Chen et al. (2010a) integrate the CCS technology as an investment alternative in the electricity sector. Szolgayova et al. (2008) and Chen et al. (2010b) discuss CCS in the frame of the real options method.

Differences in the regional observation occur beside different methodology approaches. Labriet et al. (2012) analyze the impact of technology and climate uncertainties on the future global energy system which may also include CCS power plants. A European perspective can be found in Lohwasser and Madlener (2012). They show the impact of techno-economic assumptions on the diffusion of the CCS technology in Europe using a bottom-up electricity sector model. Cremer (2007) formulates a modeling approach with special focus on the German power market. The presented bottom-up and multiperiodic linear optimization modeling approach contains a coupling with a geographical information system (GIS) based model for location decision support. That approach includes the opportunity to analyze the influence and importance of different geographical parameters e.g. the distance between the CO_2-source and the CO_2-storage site.

Further single country analyses especially for European and Asian countries exist which analyze the future potential of the CCS technology (i.a. Lund and Mathiesen 2012, Gerbelova et al. 2013). A crucial point in all these analyses are the cost assumptions for the CCS technology. This is further stressed by Voll et al. (2012) and Rubin (2012).

But social acceptance and policy support has also to be taken into consideration when it comes to the introduction of new technologies into the market. The social acceptance of CCS and the willingness to pay have been investigated by Kraeusel and Möst (2012). They found out that CCS technologies fall behind renewable technologies in public opinion. This makes policy support even more important if the CCS technology should obtain market maturity (cf. Nykvist 2013). A decision framework to answer the question whether at all CCS technology should be supported is presented by Torvanger and Meadowcroft (2011) while Lohwasser and Madlener (2013) analyze the effectiveness of different policy measures in order to promote the CCS technology.

Yet so far an approach is missing which combines a consideration of the interdependencies in the European electricity market with a detailed analysis of location and transportation issues inside Germany. Indeed, a carbon capture, transport and storage network model can be found in Mendelevitsch et al. (2010), but they set CO_2 prices exogenously and operational details are only roughly approximated.

The fast proliferation of intermittent renewable energies in Germany plus the nuclear phase out have a deep impact on the German electricity exchange with the neighboring countries. Moreover, the local availability of CO_2 storage sites must be considered as well as the challenging climate targets that have been announced by the German administration. These different market developments are considered in three scenarios. In addition to that, the political opposition of some German federal states and the local resistance against storing CO_2 close to inhabited areas is another issue that has to be taken into consideration. Due to this, two variations for each of the three scenarios are introduced: A variation with no restrictions for the transport and storage of CO_2 (all storage case) and an offshore-variation that implies the strict requirement to store CO_2 only in offshore sites in the North Sea (offshore storage case). A model based approach is used to analyze the influence of a CCS deployment together with the expanding fluctuating production of renewable energies on future electricity markets. Thereby an intertemporal optimization model is chosen to ensure a lifetime assessment of the storage sites and capacities as well as to guarantee sufficient storage space for the captured CO_2 from new CCS power plants.

The paper is organized as follows: The second section deals with the applied model framework and enhanced methodology to assure a detailed assessment of the CCS options. Section 3 explains the investigated system and the three main scenarios. Furthermore model results are shown and their implications are discussed. A brief conclusion on the obtained results is finally presented in section 4.

2 FORMULATION OF THE MODEL FRAMEWORK

2.1 Theoretical background

A two-stage approach is chosen to analyze the relevance of CCS for the future German power market (cf.

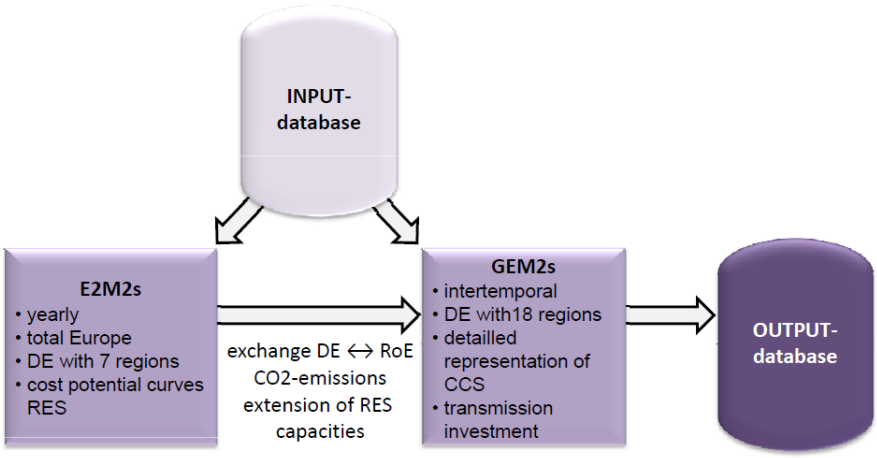

Figure 1). Therefore, basically a fundamental stochastic electricity market model called E2M2s (cf. Swider and Weber, 2007) is used with enhanced specifications. Additionally, a version of the model focusing specifically on Germany is employed (GEM2s). The main differences between the two models are the higher regional resolution and the more detailed representation of CCS related facilities in the GEM2s-model.

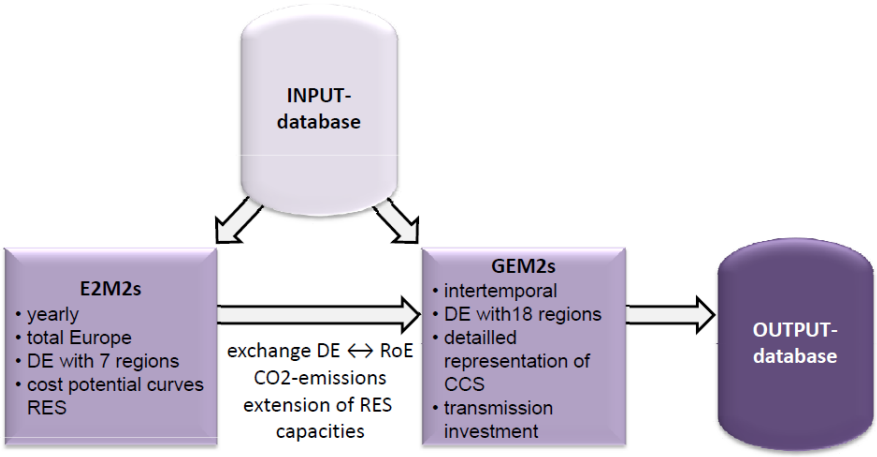

Figure 1: Model framework

Both models are based on the E2M2s. The E2M2s assumes functioning competitive markets and derives market results through optimization. That means that a cost minimal power plant configuration is chosen to cover electricity as well as heat demand. This approach is formulated as a linear, stochastic programming model and is implemented in the General Algebraic Modeling System (GAMS), (cf. Swider, Weber 2007 and Spiecker, Weber 2012). The specifics and extensions of the respective models are described in the course of this chapter.

Key variables within the optimization are electricity and heat production, generation capacities, transmission and pumping quantities. The model simultaneously determines the yearly vector of variables that minimizes total cost subject to load restrictions and detailed technical limitations of power system components.

Investments in new generation capacities are endogenously determined in the model beside power plant operation and transmission line loading. Thereby, yearly full load hours are a key driver of the investment decisions and selection of power plant technology. This decision is represented by annualized investment costs in the system objective function. This leads to investment decisions and pricing patterns in line with the peak-load pricing approach as developed by Boiteux (1960) and others.

Fluctuations of solar and wind infeed have an impact on future power markets. Thus, a modeling of 8760 hours is preferable in order to consider the whole range of possible infeeds. But this increases the computational burden in a way that the problem is impossible to handle. Therefore, typical time segments are modeled but additionally a stochastic approach is chosen to consider short-term fluctuations of renewable infeeds from wind and solar. Instead of a deterministic average with a single operation mode the future system must cope in each time segment with varying future system states. In this case, the system states are depending on the expected infeeds of wind and solar. The challenge at hand is the representation of stochastics in an extremely large system. By recombining the nodes at each stage (as shown in Figure 2), we avoid the exponential growth in the number of nodes and thus the curse of dimensionality. Cluster analysis is applied on historical wind and solar production data in order to

derive the probabilities of the nodes and the corresponding transition probabilities between the nodes. A more detailed description as well as further remarks on consistency can be found in Spiecker et al. (2013).

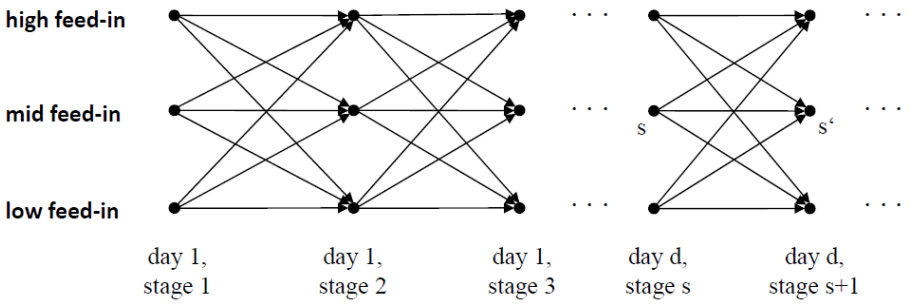

Figure 2: Concept of recombining decision tree

Typical time segments are used to reduce computational complexity further. On the one hand, these time segments should be short enough to capture fluctuations of load and renewable infeeds within a day. This is necessary to describe the power plant operation with start-up costs and operation at part load. On the other hand, a whole year is optimized simultaneously to model investments and the management of large-scale hydro reservoirs adequately. Therefore, eight typical days within one year are considered. They stand for a working day and a non working day in every third month. These typical days are again divided into seven time-steps. After a first time step of six hours a five hour time-step follows, succeeded by a one-hour noon peak time segment. The remaining twelve hours after the noon peak hour are divided into four segments of equal length. Thus there are altogether eight typical days with seven typical hours each.

Total costs TC_y within a simulated year *y* to be minimized include operating costs $OC_{r,u,t,y,n}$, start-up costs $SC_{r,u,t,y,n}$ and fixed costs $FC_{r,u,y}$ summed over regions *r*, unit types *u* time segments *t within a year* and stochastic nodes *n.* The summands are weighted by the duration d_t and frequency f_t of the corresponding time segment as well as the time segment related stage probability $\psi_{s(t),n}$.

$$TC_y = \sum_r \sum_u \sum_t \sum_n (d_t f_t \psi_{s(t),n} (OC_{r,u,t,y,n} + SC_{r,u,t,y,n}) + FC_{r,u,y}) \quad (1)$$

Since CO_2 costs are computed endogenously in the model, operating costs for power plants can be decomposed in fuel costs for operation at minimum load, fuel costs for incremental output and other variable costs $c_u^{oth,op}$:

$$OC_{r,u,t,y,n} = \frac{p_{r,u,t,y}^{FUEL}}{\eta_u^m}(P_{r,u,t,y,n} - l_u L_{r,u,t,y,n}^{onl}) + \frac{p_{r,u,t,y}^{FUEL}}{\eta_u^0} l_u L_{r,u,t,y,n}^{onl} + c_u^{oth,op} P_{r,u,t,y,n} \quad (2)$$

In this equation, $p_{r,u,t,y}^{FUEL}$ is the fuel price, η_u^m the marginal efficiency for an operating plant and η_u^0 the efficiency at the minimum load factor l_u. $P_{r,u,t,y,n}$ corresponds to the electric output and the variable $L_{r,u,t,y,n}^{onl}$ represents the capacity currently online. A linear approximation is used to consider part

load efficiencies. With $\eta_u^m > \eta_u^0$ it is less costly to increase the output of plants already operating instead of increasing the capacity online. Thus there is an incentive to reduce as far as possible the capacity online in the power system. Additional equations describe the operation restrictions and the operational costs of CHP plants (similar to Weber 2004). Depending on the flexibility, structure and size of the CHP system it facilitates or complicates the integration of renewable energies (cf. Andersen and Lund 2007)[1]. Besides operating costs, start-up costs are considered since they may influence scheduling decisions considerably.

When it comes to the consideration of long-term developments, for the optimization two aspects are crucial: The consideration of the generation scheduling and the treatment of fixed costs $FC_{r,u,y,n}$ including investment costs. Thereby the choice among different available investment alternatives with specific investment costs c_u^{inv} is modelled using the decision variable for newly built capacity $L_{r,u,y}^{new}$.

The German power market is embedded in the European power market. Hence, we focus on the European level and interactions between single countries at the first stage. As a result power transmission between Germany and other European countries (RoE) is determined from an optimal production allocation through optimized dispatch and investment-planning. In addition, CO_2 emissions and CO_2 prices are derived from European wide CO_2 bounds. These CO_2 constraints have a major impact on the future investment in conventional power plant capacities and renewable energies.

The results of the European model are used at the second stage as side constraints for the German market development. To avoid intertemporal inconsistencies, CO_2 emissions are transferred instead of CO_2 prices. At the second stage, intertemporal optimization is considered, including trading between several periods. In contrast to the first stage, a detailed description of CCS is implemented and line investments are determined endogenously in order to represent the trade-off between power transmission and CO_2 transport. Therefore a higher geographical resolution is chosen to analyze the regional distribution of investments in more detail.

The same general input data is used for both models in order to ensure consistent results. This is further ensured by the fixation of CO2 emissions and power exchange on the second stage. Nevertheless small differences occur due to the more detailed consideration of side constraints for the CCS technology in the GEM2s and the intertemporal approach.

2.2 Stage I

At the first stage power transmission between Germany and other European countries (RoE) as well as the regional distribution of CO_2 emissions are computed. Due to the fact that a European emission trading system exists, a common CO_2-price is derived using a dynamic recursive approach based on abatement costs. With a more challenging CO_2 bound B^{CO_2} the related CO_2 price increases. The amount

[1] Note that further flexibilities for RES integration resulting from integrated strategies covering also the heating, transportation and gas sectors are not considered here (cf. e.g. Lund et al. 2012).

of emitted CO_2 is dependent on production, power plant efficiencies η_u, CO_2 capture rate cr_u of different power plants u and CO_2 emission rates ε_u^{CO2}. Part load efficiencies are considered and emissions are weighted similarly to the operating costs (cf. equation 2).

$$B^{CO2} \geq \sum_r \sum_u \sum_t \sum_y \sum_n (d_t f_t \psi_{s(t),n} (1 - cr_u)(\frac{\varepsilon_u^{CO2}}{\eta_u^m}(P_{r,u,t,y,n} - l_u L_{r,u,t,y,n}^{onl}) + \frac{\varepsilon_u^{CO2}}{\eta_u^0} l_u L_{r,u,t,y,n}^{onl})) \quad (3)$$

RES are also analyzed at a European level because their expansion has strong influence on power generation and transmission. Endogenous investments in RES are especially important under a coordinated European energy policy with largely market–based RES expansion. This possibility is considered by implementing cost potential curves for RES. A detailed description can be found in (Spiecker and Weber, 2012).

2.3 Stage II

At the second stage we focus on the German power market with a detailed representation of the CCS technology and investments in transmission infrastructure. In order to consider the intertemporal aspects of CO_2 storage an intertemporal approach is chosen, which includes the whole lifetime of a CCS power plant in a single optimization. In contrast to the first stage, where a dynamic recursive optimization is used, a period of 40 years from 2010 to 2050 is integrally optimized at the second stage. With this approach it can be assured that CCS power plants built during the analysis period have sufficient storage capacity over their whole lifetime.

Therefore the objective function is extended to include CCS related costs, in particular fixed costs FC^{CCS} for CO_2 transmission capacity $C_{r\to r',y}$. Investment costs and other fixed costs as well as variable costs OC^{CCS} of CO_2 transport are modeled in detail. Moreover, costs for CO_2 storage $STC_{r,u,t,y,n}^{CCS}$ are determined depending on the stored volume $Stor_{r,t,y,n}^{CO2}$ and related costs for investment c_u^{inv} and operation of storage $c_u^{oth,fix}$. Investment costs are weighted with the annuity factor a depending on interest rate i and lifetime b_u^{life}.

$$FC_{r,r',u,y}^{CCS} = a(i, b_u^{life}) c_u^{inv} C_{r\to r',y} + c_u^{oth,fix} C_{r\to r',y} \quad (4)$$

$$OC_{r,r',u,t,y,n}^{CCS} = c_u^{oth,op} E_{r\to r',t,y,n}^{CCS} \quad (5)$$

$$STC_{r,u,t,y,n}^{CCS} = a(i, b_u^{life}) c_u^{inv} Stor_{r,t,y,n}^{CO2} + c_u^{oth,fix} Stor_{r,t,y,n}^{CO2} \quad (6)$$

In addition capacity restrictions for transmission $C_{r\to r',y}$ have to be considered.

$$E_{r\to r',t,y,n} \leq C_{r\to r',y} \quad (7)$$

These capacities are determined endogenously by capacities in the preceding period $C_{r\to r',y-1}$ and current investments $C_{r\to r',y}^{new}$:

$$C_{r\to r',y} = C_{r\to r',y-1} + C_{r\to r',y}^{new} \quad (8)$$

Concerning storage operation, the total amount of stored CO_2 $H^{CO\,2}_{r,t,y,n}$ has to be lower than total storage capacity $L^{CO\,2,Stor}_{r}$.

$$\sum_{t}\sum_{y}\sum_{n} \psi_{s(t),n} H^{CO\,2}_{r,t,y,n} \leq L^{CO\,2,Stor}_{r} \quad (9)$$

Again, injection decisions in the previous period are considered and are weighted according to the time resolution and the transition probability τ:

$$\sum_{t-1}\sum_{n-1} \tau_{t,t-1,n,n-1} \left(\psi_{s(t-1),n-1} H^{CO\,2}_{r,t-1,y,n-1} + d_t f_t Stor^{CO\,2}_{r,t,y,n} \right) \leq H^{CO\,2}_{r,t,y,n} \quad (10)$$

The amount of captured CO_2 $V^{CCS}_{r,t,y,n}$ is determined as the complement to the amount of emitted CO_2 $B^{CO\,2}$.

$$V^{CCS}_{r,t,y,n} = \sum_{u} cr_u \left(\frac{\varepsilon^{CO\,2}_{u}}{\eta^{m}_{u}} \left(P_{r,u,t,y,n} - l_u L^{onl}_{r,u,t,y,n} \right) + \frac{\varepsilon^{CO\,2}_{u}}{\eta^{0}_{u}} l_u L^{onl}_{r,u,t,y,n} \right) \quad (11)$$

To ensure the overall CO_2 balance, the captured CO_2 $V^{CCS}_{r,t,y,n}$ and the related CO_2 exchange $E^{CCS}_{r\rightarrow r',t,y,n}$ are set equal to the stored volume $Stor^{CO\,2}_{r,t,y,n}$ in each region *r*, time segment *t* and stochastic node *n*.

$$V^{CCS}_{r,t,y,n} + \sum_{r'} \left(E^{CCS}_{r'\rightarrow r,t,y,n} - E^{CCS}_{r\rightarrow r',t,y,n} \right) = Stor^{CO\,2}_{r,t,y,n} \quad (12)$$

Investments in the power grid are modeled analogously. Investment costs are following the description in formula (4) where the annuity of the new capacity is considered in the objective function. Operative costs of power transmission are considered in a different way. Losses of power transmission are used instead of having a cost unit rate. These losses are depending on the distance between two nodes.

3 SYSTEM AND SCENARIOS ANALYZED

3.1 Geographical scope and data

A different regional scope and resolution is chosen at the two stages. At the first stage, the entire European electricity system is modeled. Every country is considered as one single node in the model. Only Germany is split in seven regions to consider bottlenecks within the country. These bottlenecks especially occur with higher infeeds of renewable energies in the north. This energy has to be transmitted to the western and southern demand centers. Denmark is represented by two nodes in line with its zonal separation.

The second stage focuses on Germany. Therefore a higher resolution for Germany is chosen. Here, 18 regions are considered (cf. Figure 3).

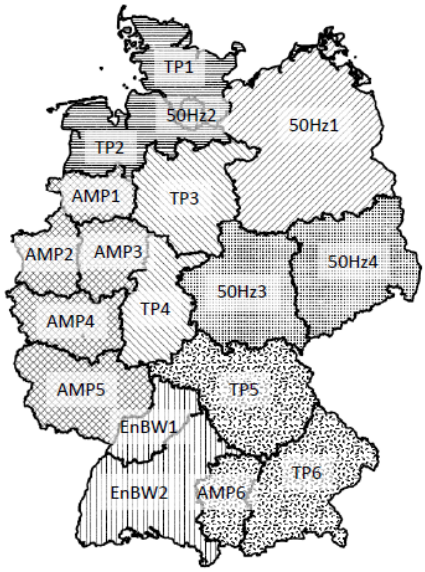

Figure 3: Regionalization of Germany

3.2 Modeled scenarios

We use different scenarios to model uncertainty that goes beyond fluctuations of stochastic renewable energy infeed and power plant outages. These are especially long-term uncertainties which impact the economic framework for new power plant capacities. The scenario *CLIMATE* describes a development which is in line with today's policy objectives. Electricity demand will slightly increase while CO_2 emissions are constrained. Until 2050 a reduction of 80% compared to 1990 should be reached. Current nuclear policy in different member states also determines whether new nuclear power plants can be built. The same holds for the scenario *CONVENTIONAL WISDOM*. Here, the focus lies more on security of supply. Electricity demand is higher and absolute CO_2 reductions are lower compared to the scenario CLIMATE. Nevertheless, reductions might be more ambitious due to higher demand growth. On the other side, the scenario CLIMATE+ has a stronger emphasis on sustainability. Energy demand is only slightly increasing until 2020 and nearly kept constant after 2020 while the CO_2 reduction target is 95%. Further on, nuclear power plants are no option for low carbon electricity production in most European countries. This makes it more difficult to reach the ambitious political targets. From today's point of view the scenario *CLIMATE* seems to be the most likely one as it considers economical issues as well as environmental objectives. The CLIMATE+ scenario has a stronger focus on environment and sustainability while the *CONVENTIONAL WISDOM* scenario focuses on economical targets. A main driver for the future development is the overcoming of the economic crisis. In this context, less ambitious environmental targets are pursued.

The development of fuel prices is the same in all three scenarios. Here, we have chosen a data set in line with World Energy Outlook scenarios (IEA, 2012). The same input data is also chosen for the expansion of renewable energies. Until 2020, new capacities are installed according to the country specific national renewable action plans (EC 2010) – with partly reduced investments in the *CONVENTIONAL WISDOM*

scenario. After the year 2020, investments in renewable energies are determined within the model under market conditions. Henceforward, renewable energies compete with other low carbon technologies like CCS or even efficient conventional power plants on a level playing field, i.e. no quota or support schemes are assumed to be in place. An important driver for these investment decisions is the CO_2 price obtained.

Table 1: Scenario overview

	Conventional Wisdom	Climate	Climate +
Demand	high	mid	low
CO2-reduction compared to 1990	50%	80%	95%
Acceptance of nuclear power	mid	mid	low

3.3 CCS technologies

The three main CO_2-capture technologies, the pre-combustion (pre_c), post-combustion (post_c) and oxy-fuel combustion (oxy_c) technology are implemented in the models. From the current point of view, there is no clear technological or economic advantage for any one of these three opportunities. Hence, all technologies are considered to have a realistic chance to be similarly competitive in the long term view (ZEP, 2011a), (IEA, 2010b). Table 2 and

fuel	capture tech-nology	invest-ment costs €/KW	max. effi-ciency %	annual fix costs €/KW	other variable costs €/MWh	capture rate %
Coal	oxy_c	2375	41	50	1,3	93
Coal	post-c	2328	42	53	2,5	93
Coal	pre-c	2660	42	63	1,5	93
Gas	oxy_c	1579	53	51	3,5	89
Gas	post-c	1140	50	43	2,8	89
Gas	pre-c	1235	52	45	3,2	89
Lignite	oxy_c	2850	37	43	1,2	93
Lignite	post-c	2470	35	65	3,4	93
Lignite	pre-c	2755	38	69	1,3	93

give a brief overview of the most important technology parameters used in this article, including also future improvements.

Table 2: Technology data for CCS with construction years 2020-2030

fuel	capture tech-nology	invest-ment costs	max. effi-ciency	annual fix costs	other variable costs	capture rate

		€/KW	%	€/KW	€/MWh	%
Coal	oxy_c	2500	39	56	1.5	90
Coal	post-c	2450	40	59	3.3	90
Coal	pre-c	2800	40	70	1.8	90
Gas	oxy_c	1662	51	60	5	86
Gas	post-c	1200	48	50	4	86
Gas	pre-c	1300	50	53	4.5	86
Lignite	oxy_c	3000	35	45	1.4	90
Lignite	post-c	2600	33	68	3.8	90
Lignite	pre-c	2900	36	73	1.5	90

Table 3: Technology data for CCS with construction years 2040-2050

fuel	capture tech-nology	invest-ment costs	max. effi-ciency	annual fix costs	other variable costs	capture rate
		€/KW	%	€/KW	€/MWh	%
Coal	oxy_c	2375	41	50	1,3	93
Coal	post-c	2328	42	53	2,5	93
Coal	pre-c	2660	42	63	1,5	93
Gas	oxy_c	1579	53	51	3,5	89
Gas	post-c	1140	50	43	2,8	89
Gas	pre-c	1235	52	45	3,2	89
Lignite	oxy_c	2850	37	43	1,2	93
Lignite	post-c	2470	35	65	3,4	93
Lignite	pre-c	2755	38	69	1,3	93

The key figures for investment costs, efficiency and the capture rate are based on the figures of various studies (e.g. ZEP 2011a, Damen et al. 2006, Abadie and Chamorro 2008, Otto and Reilly 2006, Cozijnsen 2005, Sasaki 2004, BMWI 2003 as well as Christensen and Holloway 2004) in combination with own assumptions (cf. TABLE 2). Beyond the year 2030, slight technological progress on various parameters is assumed (cf. TABLE 3). The investment costs per kW will be reduced by 5% and the capture rate will be increased by three percentage points till 2040. Improvements of the maximum efficiency occur in a range of 4% to 6% and depend on the technology. There is also a technology-dependent decrease of the annual fix cost between 5% and 15% and for other variable cost between 11% and 30%.

The costs for the CO_2 pipeline investments and the power grid are given in

	Investment costs	Operational costs
CO_2 pipeline	620 €/km/t/a	0.002 €/km/t
power grid	500 €/km/MW	calculated as losses of 1 %/100 km

. The assumptions for the pipeline-costs are based on own calculations according mainly to the latest ZEP-report (ZEP 2011b) and furthermore on Metz, (2005), Harrison (2010), McCoy and Rubin (2005) and May et al. (2005).

Table 4: Investment costs for CO_2 pipeline and power grid

	Investment costs	Operational costs
CO_2 pipeline	620 €/km/t/a	0.002 €/km/t
power grid	500 €/km/MW	calculated as losses of 1 %/100 km

As discussed before, two variants for every main scenario are considered. In the offshore-case dumping CO_2 in onshore-sites is prohibited due to local opposition or political resentments and only offshore storage sites are available. In the all storage case no political restrictions are considered.

For the onshore storage two options are available: deep saline aquifers and exploited gas fields. These options result in a cumulative storage capacity onshore of roundabout 8.3 Gigatons (Gt). Approximately 80 storage sites can be found in Germany (cf. Hipp 2011, WI et al. 2007). The mean storage volume per site is roundabout 100 million tons of CO_2. The locations of the sites have been mapped to the regional structure shown in Figure 3. The offshore capacity adds up to 2.9 Gt and is thus much more restricted and comes along with higher investment and variable costs. All in all the capacity assumptions stand for a rather conservative assessment and present a lower bound of various estimations (Hipp 2011, Christensen and Holloway 2004, May et al. 2005, WI et al. 2007). Table 5 shows the assumptions for the CO_2 storage costs for the on- and offshore variants. These costs imply the investment costs for the storage sites. The assumptions are based on own estimations and ZEP (2011c).

Table 5: CO_2-storage costs for the on-/offshore variants

scenario	storage type	costs (€/t)
onshore	exploited gas field	3
	saline aquifere	5
offshore	exploited gas field	6
	saline aquifere	14

The aforementioned scenarios are investigated to identify the impact of CCS on the German electricity system. First, production and CO_2 emissions at a European scale are presented. Next the implications on CCS power plant capacity and production are examined. Then the investments as well as the utilization of transmission infrastructure are analyzed. Finally, storage operation is described in detail.

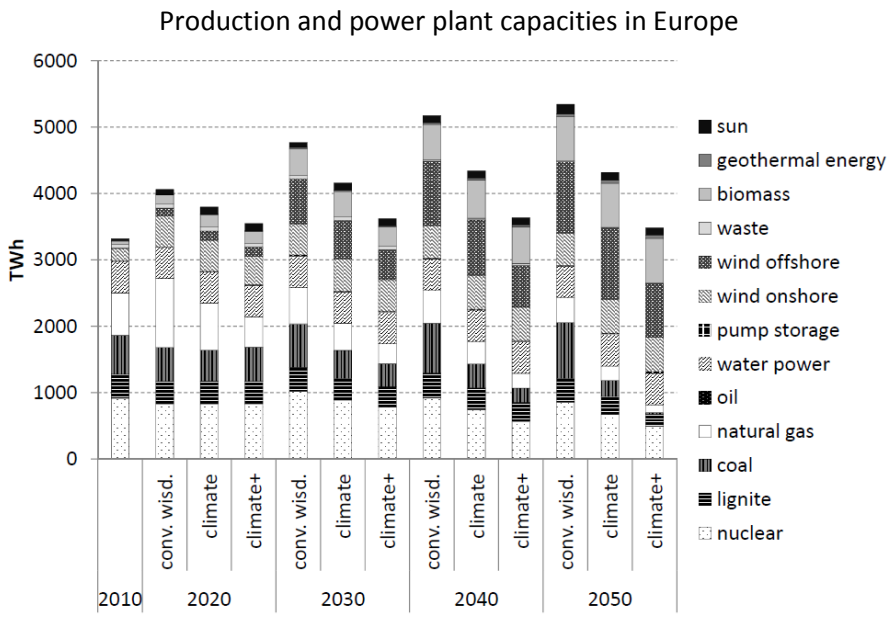

Figure 4 shows the development of European electricity production. Thereby, total production is determined by total demand corresponding to scenario assumptions. But differences occur in the structure of the power plant capacities. Policy targets are a main reason for these differences. But also differences according to power plant availability and cost structure influence the investment decisions.

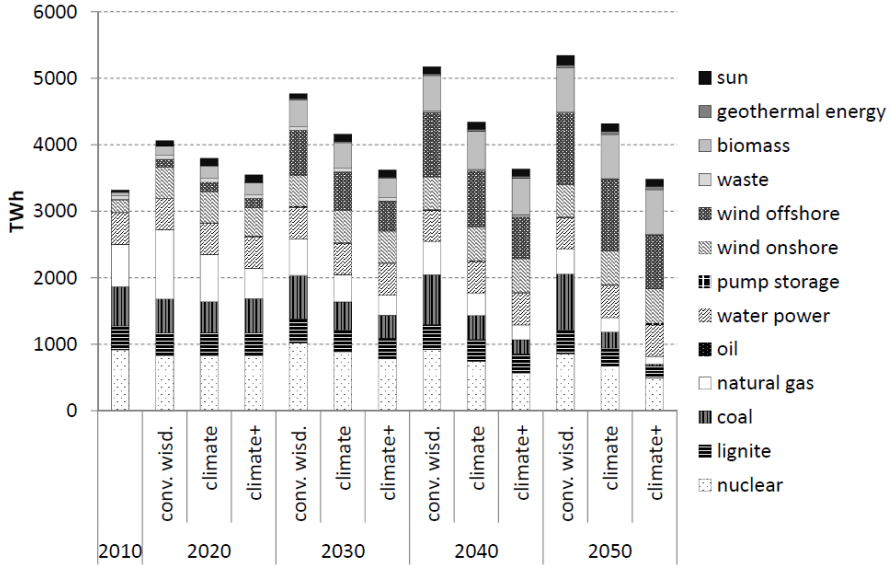

Figure 4: Electricity production development in Europe

The highest relative share of renewable energy production occurs in the scenario *CLIMATE+*. But also in the other scenarios, production of renewable energies increases to a large extent. The absolute production from renewables is quite similar in all scenarios. Thereby, especially with market driven investment in renewable energies, available resources are a key driver for investments in renewable energies. Solar technologies are consequently mainly installed in the southern parts of Europe, while wind farms are built at places where wind conditions are advantageous. Depending on fuel prices and further investment restrictions, the residual load is covered by conventional power plants.

Production developments go along with corresponding capacity developments (Figure 5). In general fluctuating renewable energies have rather low full-load hours compared to conventional power plants and therefore the share of those technologies on production and capacities differ. Until 2020 capacities of renewable energies are set exogenously in line with the objectives of the different countries according to their national renewable energy action plans (EC 2010). Only in the CONVENTIONAL WISDOM scenario, these objectives are not fully reached. After that new investments in renewable energies have to compete on a market basis. In the case of low CO2 prices they compete with conventional power plant technologies and in the case of high CO2 prices they compete with CCS power plants. In addition they are restricted by their availability to provide firm capacity. That means that for later years a combination of renewable energies and peak-load capacities compete with traditional base and mid-merit order capacities. But also full-load hours of conventional power plants are reduced with increasing fluctuating feed-in of renewable energies. Especially natural gas fired power plants are used as back-up capacities for fluctuating renewable energies and have less full load hours.

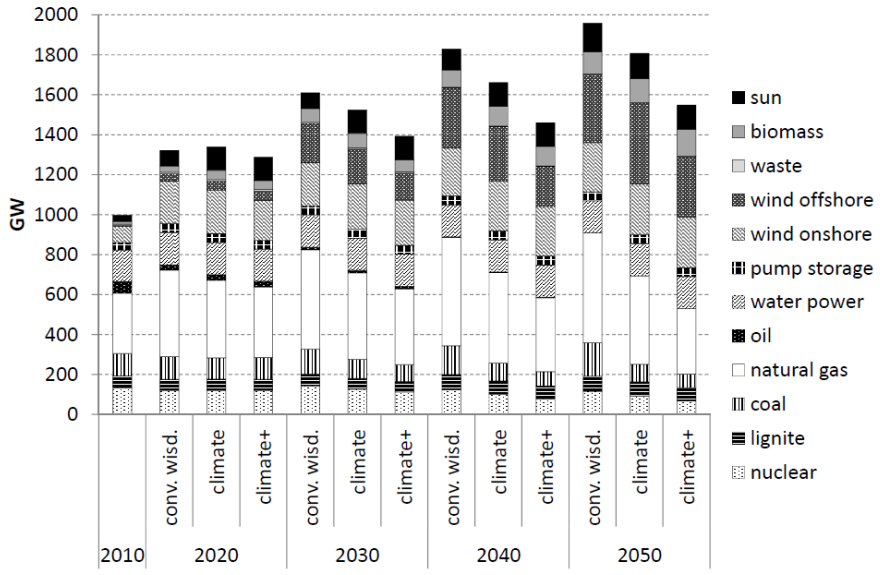

Figure 5: European capacity development for different scenarios

3.4 German power system development

Regional production patterns may differ from the total European patterns (Figure 6) and differences are cleared by electricity transmission. Due to a strong extension of renewable energies Germany for example increases its exports in the first years. These exports partly substitute domestic production in other countries until 2020. After that this effect is more than compensated by the nuclear phase-out in Germany (Figure 7) and further investments in renewable energies outside Germany. In the case of an efficient placement of renewable energies in a market based system, investments in RES often occur outside Germany where environmental conditions are more advantageous. From a system point of view, it is optimal to follow these rules and increase imports to Germany. As a result, the trade balance becomes negative. Already in 2030, net imports attain 5 % of total demand in the scenario *CLIMATE+*.

A further reason for this development are tight CO_2 bounds which put extreme pressure on fossil fuel dominated generation systems like the German one. Conversely, with less tight CO_2 reduction targets imports to Germany are lower and the share of fossil fuel fired power plants is higher. Thus, not only the total CO_2 emissions have to be considered but also the ratio of demand and CO_2 emissions. In summary, Germany becomes dependent on electricity imports which lead to a net import in a range of 22 TWh to 35 TWh in 2050 (Figure 8).

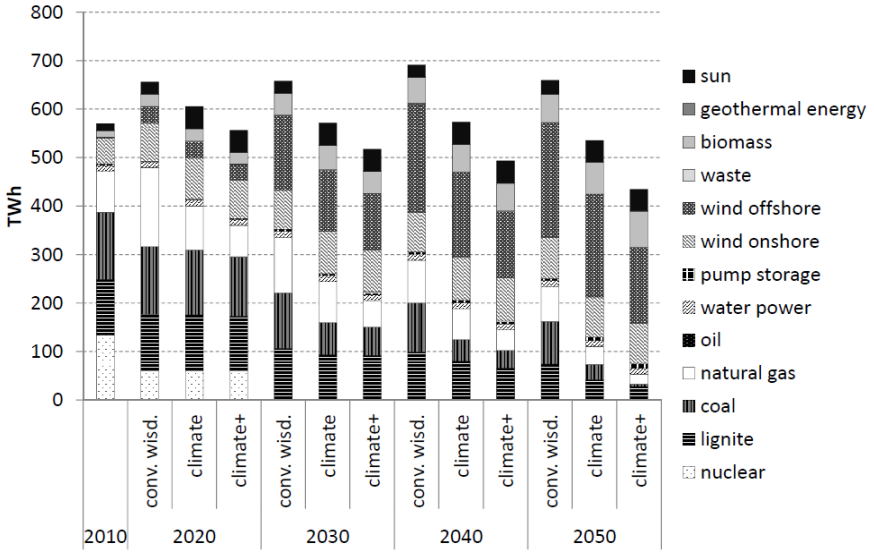

Figure 6: Electricity production development in Germany

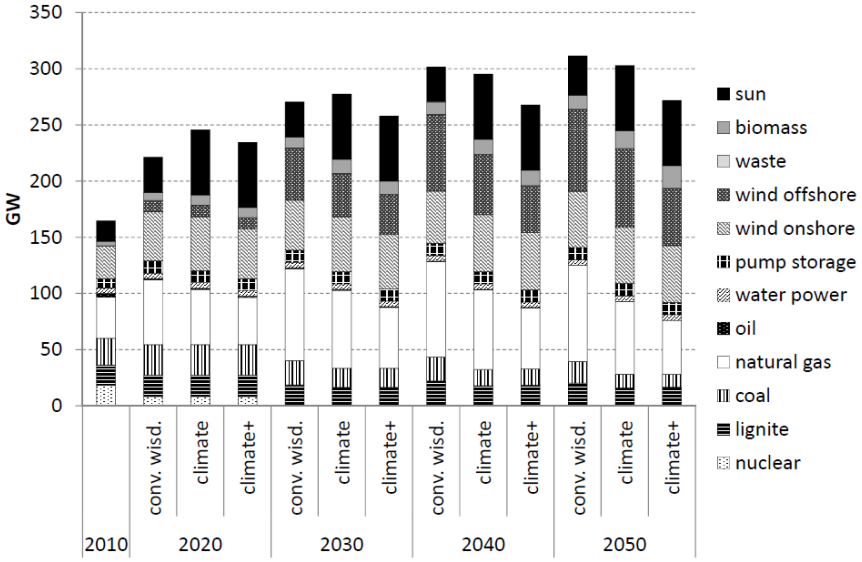

Figure 7: German capacity development for different scenarios

Besides data about installed capacities of renewable energies, CO_2 emissions as well as exports and imports are determined at the first stage. CO_2 emissions for single countries are computed from power plant operation. The transfer of CO_2 emissions bounds instead of CO_2 prices allows achieving overall greenhouse gas abatement targets. Moreover the emission budget can be allocated optimally over the

years. In contrast to the first stage with a recursive optimization approach, a shift of emissions between different periods is possible.. Total CO_2 reduction is driven by the exogenous European reduction objective. The distribution to different regions is done in the economically most efficient way. In the first decade, reductions are cost-efficiently done by modernization of old and inefficient power plants. Later, reductions are reached by investment in additional renewable energies and CCS power plants which become less expensive with further progress in research and development. Figure 8 shows the CO_2 emissions for Germany in different years. Reduction efforts are weakened in the second half of the observation period and by 2050 CO_2 emissions are almost zero at least in the *CLIMATE* scenarios. One reason are more efficient CCS power plants which allow a cost efficient reduction of emissions.

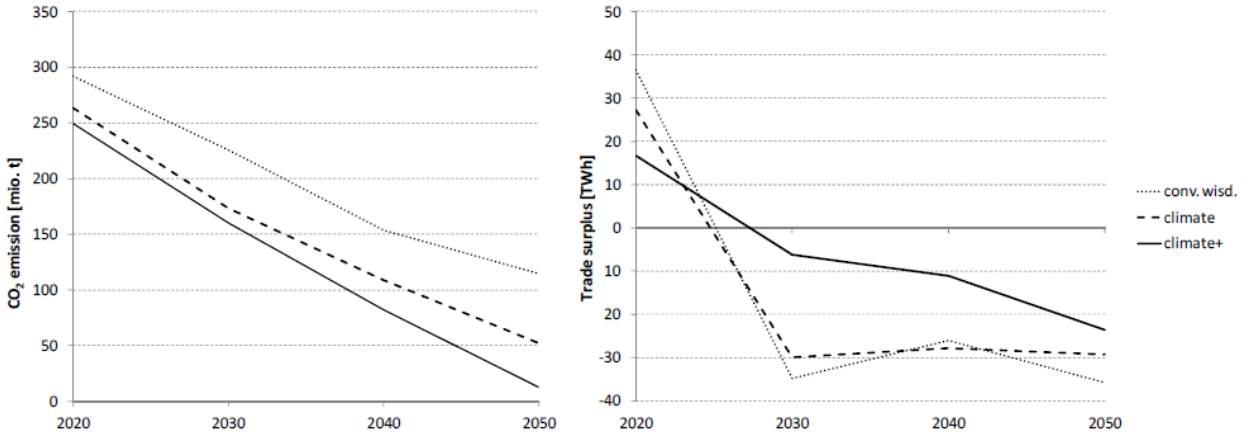

Figure 8: Germany´s CO_2 emissions and trade balance

3.5 CCS investment and CO_2-prices

Investments in CCS power plants occur in all scenarios. One might expect that the highest investments in CCS power plants occur in scenarios with most ambitious emission targets. But analyzing investments in CCS power plants in Germany, they are most substantial in the scenario *CONVENTIONAL WISDOM* (Figure 9). This shows the impact of demand development and existing power plant capacities on the investment decision. The impact of demand developments can even be observed today. Current low CO2 prices are caused by targets which were set in expectation of a stronger economic growth instead of a decline in demand.

In the *CONVENTIONAL WISDOM* scenario, the CO_2 emission target is comparatively low but demand is rather high. In addition, CO_2 emission reduction in the *CONVENTIONAL WISDOM* scenario outside Germany is disproportionately low compared to the other scenarios. A further key aspect is that the potentials of renewables available at low cost are limited. This is notably true for wind onshore. Consequently capacities of renewable energies are quite similar in all scenarios. Correspondingly the residual load is higher in the *CONVENTIONAL WISDOM* scenario. So the necessary CO2 abatement in the fossil sector is higher even though more emission allowances are available. The CO2 price reflects this required abatement in the fossil power sector. In this case the effect on the demand side dominates. As a result CO2 prices are the highest in the *CONVENTIONAL WISDOM* scenario. These high CO_2 prices

together with high full load hours are sufficient to guarantee an economically viable operation of CCS plants and allow them to compete with renewable energies as well as other conventional power plants. In the climate scenarios, CO_2 prices are lower and the operating hours of conventional power plants decrease due to a lower total electricity demand. As a result, operation of CCS-power plants is economically hardly viable.

For that reason, the following analysis focuses on the scenario *CONVENTIONAL WISDOM*. Within this scenario two cases are considered. In the first case storage of CO_2 is possible without any regional restriction (all storage case), in the second case storage of CO_2 is restricted to offshore storage (offshore case). In both cases total storage capacities are considered.

For the all storage case and the offshore case similar investment structures can be observed. Especially in the years 2030 and 2040 investments are dominated by natural gas fired power plants. Because of their low investment costs, their flexibility and their low CO_2 emissions they are especially used as back up technology for fluctuating renewable energies. As a result of the efficiency gains for all power plant technologies during the whole period and interest rate effects, cost intensive CO_2 reduction efforts are postponed to the end of the optimization period. Deployment of CCS power plants mostly differs between climate scenarios and the scenario *CONVENTIONAL WISDOM*. Here, investments are ten times higher. In addition, substantial investments in this technology already occur in 2040 while investments are quite low in the climate scenarios (Figure 9). For the case *CONVENTIONAL WISDOM* all storage CCS power plants become economically feasible from 2040 onwards with 2700 MW of lignite and 3000 MW of coal power plant with CO_2 capture being newly installed in 2040. This lignite capacity increases to 12 GW in 2050, coal fired capacities are even enlarged to 12.3 GW. Gas combined cycle (CC) CCS is not built. In the offshore case investments mainly occur in the year 2050. Here, coal CCS has capacities of 380 MW while lignite fired CCS power plants reach a capacity of 800 MW in 2040. These capacities increase in the year 2050 to 5.1 GW and 7.9 GW, respectively.

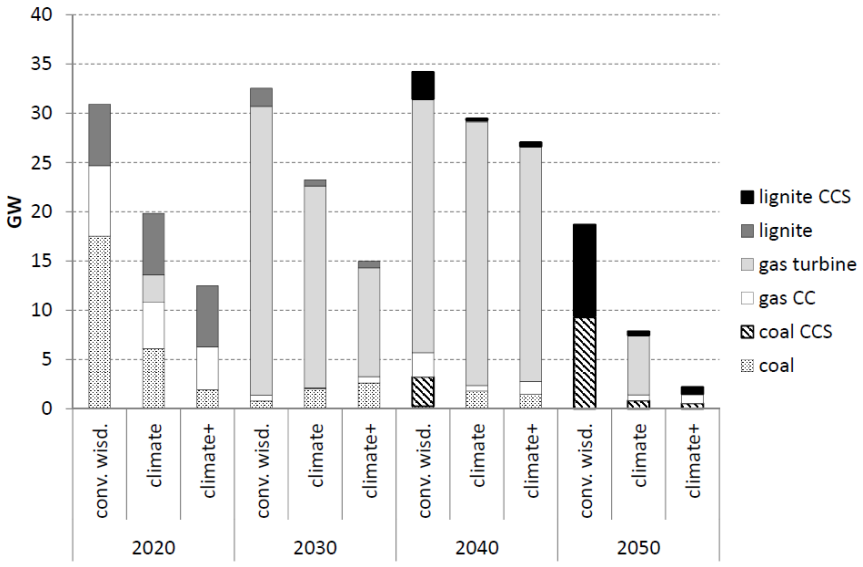

Figure 9: Power plant investments in different scenarios (case all storage)

In comparison to the all storage case, investments in the offshore case have a similar structure but are significantly lower in all scenarios. The reasons are higher CO_2 storage costs in the North Sea and additional costs for CO_2 transport due to longer distances. These higher costs can also be observed in CO_2 prices which are derived from the shadow price of the intertemporal CO_2 emission bound. For the offshore case (*CONVENTIONAL WISDOM*) CO_2 prices are 35 €/t higher compared to the all storage case in the year 2050 (60€/t). CO_2 prices are lower in the climate scenarios with prices of 28 €/t and 36 €/t in 2050, respectively. As a result investments in CCS power plants are low with 1.4 GW (*CLIMATE*) and 1.8 GW (*CLIMATE+*). In the offshore case, these investments are further reduced as a consequence of higher storage costs. CO_2 prices are only slightly increased by 3 €/t CO_2 because of the small share of CCS power plants in total power production.

3.6 CO_2 storage operation

In line with the increased capacities of CCS technologies, the stored amount of CO_2 increases over the years (Figure 10). Thereby it is ensured that CCS power plants have sufficient storage capacity over their lifetime even beyond the optimization period. Storage operation is mainly driven by assumptions on availability and costs. Due to the cost minimizing approach less expensive storage facilities are used first. Costs consist of storage and transport costs. Therefore onshore storage is used in the all storage case being cost efficient compared to offshore storage. As to suitable CO_2 storage sites in Germany, there are two special characteristics that have great influence on the decision where to store CO_2 and which transport routes are preferable. First, the storage sites with the greatest potential are all in the Northern provinces like Lower Saxony and Schleswig-Holstein. Second, Germany has abundant lignite reservoirs in the middle belt of the country – from the Rhineland area in the west to the Lausitz area in the east.

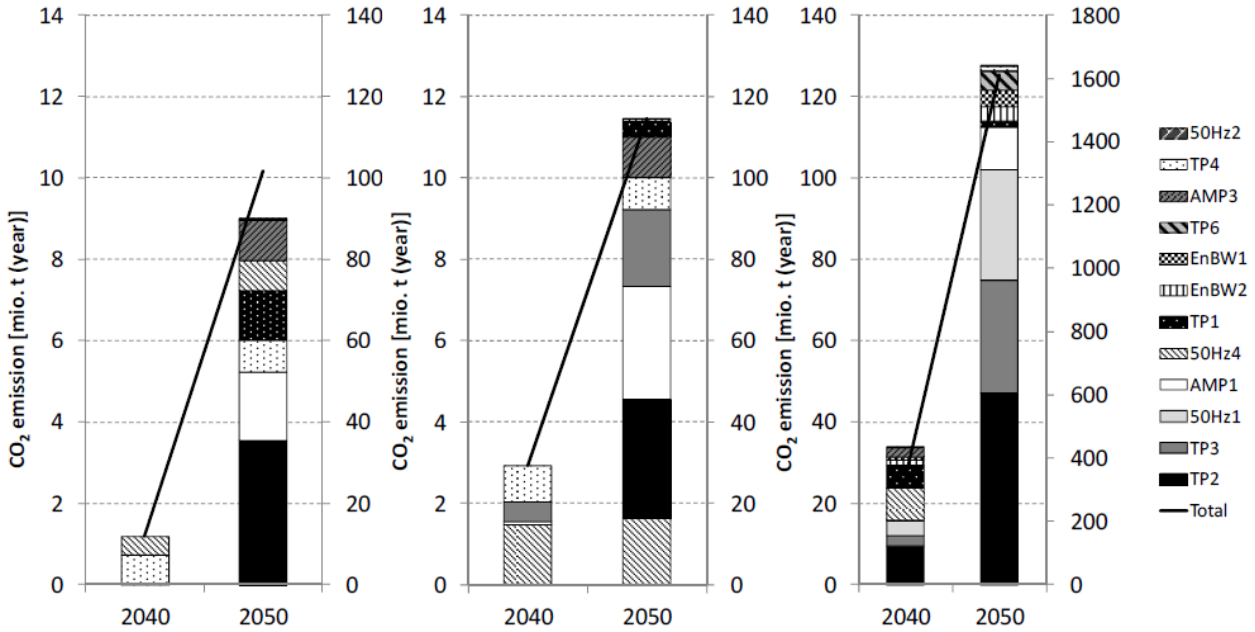

Figure 10: CO_2-storage operation - scenario *CLIMATE* (l), *CLIMATE+* (m) and *CONVENTIONAL WISDOM* (r)

According to the model results the CCS-technology is mostly used for lignite power plants. Due to the fact that lignite cannot be economically transported over long distances, the lignite plants are all linked to the lignite reservoirs. Thus, the CO2 has to be shifted from the lignite regions in the middle of the country to storage sites either in the north or to the offshore-sites in the North Sea (Figure 11).

Compared to a total CO_2 storage potential of about 12 trillion t, only about 10 % of the total storage potential in Germany is used until 2050 in the all storage *CONVENTIONAL WISDOM* case. Having sufficient onshore storage potential, a usage of offshore facilities is not necessary. In the climate scenario utilization of storage capacities is even lower.

For the offshore case a storage bottleneck cannot be observed, either. The amount of stored CO_2 is even lower than in the all storage cases. Notably higher investments in CO_2-pipelines are required because of longer transport distances what makes the CCS technology less profitable.

3.7 CO_2 transport

CO_2 is often not stored in the region where it is captured but is transported to other regions for storage purposes. Thereby it is obvious that CO_2 pipelines are in competition with grid extensions. Due to losses in power transport, power transmission costs mainly depend on the current electricity price. As mentioned in the section before, the results show an extensive use of the CCS technology in lignite plants. Figure 11 emphasizes the prominent transport routes from the lignite reservoirs to the large storage sites in the north. In case of CCS applications to hard coal plants (most notably in Southern Germany), the nearby local potential for CO_2 storage turns out to be sufficient and long range transport is not necessary.

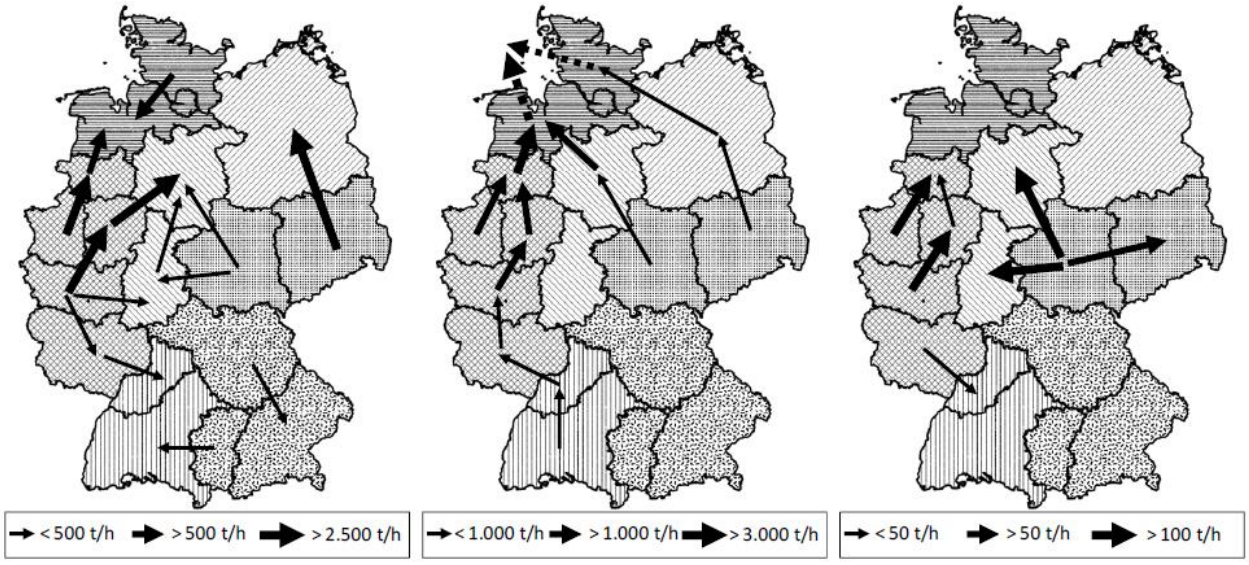

Figure 11: CO_2 transmission capacity in 2050: *CONVENTIONAL WISDOM* all storage (l), offshore (m), *CLIMATE+* all storage (r)

A further point is the need for firm capacity in the different regions which can ensure security of supply and system stability in a system with large amounts of renewable energy infeed. This means that back up capacities have to be considered in addition to a pure trade-offs between CO_2 transport and power transmission. The decision calculus has then to weigh CCS power plants at the storage sites plus power transmission and back-up capacities in the demand regions against CCS power plants in the demand regions and CO2 transport to the storage sites. Therefore CO_2 is captured in areas with high electricity consumption and transported to regions with sufficient storage capacity.

Comparing the all storage and the offshore case, in the latter case the pipeline system has to be developed further in the north (Figure 11). This leads to higher costs for CO_2 reduction and finally CO_2 prices increase. As a result also operation of conventional power plants becomes more expensive.

4 CONCLUSION

This article presented a model framework for the evaluation of CCS with an application to the German power market including district heating. Therefore a bundle of scenarios was developed with different emphasis on climate change mitigation. The computation results show that investments in the CCS technology are strongly dependent on the scenario selected, notably with respect to the development of CO_2 emissions and CO_2 prices respectively as well as residual demand and full-load-hours. Investment costs have another considerable impact on investment decisions. The interdependencies between the CO_2 bound, the CO_2 price and total demand have been identified as the main influencing factors. Only in cases with high CO_2 reduction targets compared to electricity demand, investments in CCS technology become economically feasible. Following the model results, we come to the conclusion that a comprehensive investment in CCS power plants is not likely in the next decades. This corresponds to other studies which do not see a business case for CCS power plants under the current framework conditions in Germany (cf. Viebahn et al. 2012). A crucial point is the extension of renewable energies. Due to subsidies they might reach a market share where an investment in alternative technologies with low CO2 emissions does not make sense from an economic point of view. However, this is not the main driver for non adaptation of CCS in our scenarios. Accordingly, the restricted storage potential for CO_2 is sufficient in these scenarios.

Public acceptance is important besides technical and economical restrictions. Therefore we have investigated a case where storage of CO_2 is restricted to offshore areas. We found out that costs for CO_2 transport increase along with abatement costs. As a result, the usage of CCS power plants is reduced. Again, available offshore storage capacities are no limitation to the diffusion of the CCS technology.

APPENDIX

Nomenclature

Variables

E	transmission flow	*OC*	operating costs
FC	fixed costs	*P*	power production
H	storage level	*SC*	start-up costs
L	capacity	*TC*	total costs
STC	storage cost	*V*	captured emissions

Indices

0	minimal	*op*	Operating
CCS	CCS	*oth*	Other
CO2	CO_2	*r*	Region
cyc	cycling	*pum*	Pumping

fix	fix	*res*	power reserve
FUEL	fuel	*s*	stochastic stage
inv	investment	*stor*	CO_2-storage
life	lifetime	*stu*	start-up
n	node	*t*	time segment
new	new	*t*	final time step
onl	online	*u*	unit type
m	maximum	*y*	year

Parameters

a	annuity factor	*l*	minimum load factor
C	transmission capacity	*b*	life time
c	specific costs	*W*	water inflow
cr	capture rate	η	efficiency
d	duration	ς	fraction of production
D	energy demand	Ψ	occurrence probability
f	frequency	ρ	availability
i	interest rate	τ	transition probability
p	price	ε	emission factor
B	bound		

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