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Uncertainty in Carbon Capture and Storage (CCS) deployment projections: a cross-model comparison exercise

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Abstract Carbon Capture and Storage (CCS) can be a valuable CO_2 mitigation option, but what role CCS will play in the future is uncertain. In this paper we analyze the results of different integrated assessment models (IAMs) taking part in the 27th round of the Energy Modeling Forum (EMF) with respect to the role of CCS in long term mitigation scenarios. Specifically we look into the use of CCS as a function of time, mitigation targets, availability of renewables and its use with different fuels. Furthermore, we explore the possibility to relate model results to general and CCS specific model assumptions. The results show a wide range of cumulative capture in the 2010–2100 period (600–3050 $GtCO_2$), but the fact that no model projects less than 600 $GtCO_2$ indicates that CCS is considered to be important by all these models. Interestingly, CCS storage rates are often projected to be still increasing in the second half of this century. Depending on the scenario, at least six out of eight, up to all models show higher storage rates in 2100 than in 2050. CCS shares in cumulative primary energy use are in most models increasing with the stringency of the target or under conservative availability of renewables. The strong variations of CCS deployment projection rates could not be related to the reported differences in the assumptions of the models by means of a cross-model comparison in this sample.

1 Introduction

CCS is often mentioned as a key response option to mitigate greenhouse gas emissions (Fisher et al. 2007). The technology can be used to reduce emissions from power plants, hydrogen

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production, and industrial facilities and thus forms an alternative to renewables, nuclear power, and bio-energy (without CCS). The strength of CCS compared to some of these options is that relatively little system changes are required. Moreover, costs to reach different climate targets are often projected to be lower if CCS is part of the mitigation portfolio (Azar et al. 2006; IEA 2012; IPCC 2005). Furthermore, CCS can be very important to substantially reduce carbon emissions in some of the most CO_2 intensive industries (steel, cement, etc.) (IEA 2012). Finally, bioenergy with CCS (BECCS) can create negative emissions, allowing to reach even ambitious climate goals (Azar et al. 2010).

However, the technology is still surrounded by uncertainties and questions: 1) integrated CCS systems[1] are barely used on a large-scale (IEA 2012) such that costs and technical challenges are difficult to foresee (Flannery 2011). 2) Storage capacity estimates are uncertain and vary (Bradshaw et al. 2007; GEA 2012; IPCC 2005). 3) CCS may bear risks with respect to leakage (GEA 2012; IPCC 2005), 4) CCS is afflicted with various concerns from the public sphere (GEA 2012), and finally 5) in combination with fossil fuels, the energy system would still rely on non-renewable energy sources. Presumably related to some of these issues, CCS is often mentioned as a “bridging technology” to “buy time” (see e.g. (Bauer 2006; Praetorius and Schumacher 2009; EU 2009)) easing the transition to a renewable-based system (Bauer 2006; Praetorius and Schumacher 2009), while still reducing emissions.

The future role of CCS in the energy system is uncertain. Deployment projections by integrated assessment models (IAMs) can be used to explore the future role of the technologies, based on different assumptions about technology development, climate policy and many other variables. Model comparison studies, like undertaken by the Energy Modeling Forum (EMF), have proven to be an effective tool to explore uncertainties of technologies and the implications for mitigation strategies in different models and to achieve a certain degree of robustness of conclusions (see overview EMF19 Weyant (2004)). So far relatively little explicit attention was paid to different CCS deployment strategies in such studies. A partial exception is the comparison of CCS deployment of the IPCC TAR-scenarios[2] as summarized in the IPCC (2005), but this study included only three models explicitly representing CCS and provided little detail. Still, from individual model studies of the EMF19 interesting conclusions regarding the importance, and uncertainty or sensitivity to techno-economic assumptions of CCS can be drawn (e.g. (Akimoto et al. 2004; Kurosawa 2004; Riahi et al. 2004; Smekens-Ramirez Morales 2004)). The model comparison study EMF27, a consortium of 18 IAMs, pays specific attention to the role of different technologies such as bio-energy and renewables in mitigation strategies (Rose et al. 2013; Luderer et al. 2013). Using the data from this EMF round, the present study is looking into the role of CCS.

What role CCS can play, under which circumstances, and how this is influenced by model assumptions and type, is important to find out for policy makers and modelers. Using the EMF27 outcomes, in this paper we look into the following questions: What is the role of CCS in the different models in this century? How strong is the variation across the model results? Which influence do the mitigation target and the assumptions about renewables have? Is there enough storage capacity available? Which primary energy fuels are applied with CCS in the energy system over time and, in particular, in cumulative electricity production? How is this altered by the target and pessimistic assumptions for renewables? Finally, we try to relate the

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[1] Globally, only about 17 large-scale integrated projects (i.e. covering the whole chain) under construction or in service have been identified by GCCSI (2013) as of January 2013.

[2] An overview can be found in Morita et al. 2000 as cited in (IPCC 2005).

specific model outcomes to model assumptions and model type. The structure of the paper is organized around the questions formulated above.

2 Method

In this paper we use a large set of scenarios from the EMF27 model comparison study, to look specifically into CCS deployment. Below, we briefly discuss the methodology.

An overview of the EMF27 scenarios is provided by Kriegler et al. (2013) and specifically for the technology focus by Krey et al. (2013). All models run scenarios with and without greenhouse gas stabilization targets in combination with different technology assumptions. We only use model runs that project until 2100 and report CO_2 captured (i.e. 12 models). Furthermore, we focus on four scenarios:

- The default technology scenarios (Benchmark-Tech) in combination with greenhouse gas concentration targets of 450 and 550 ppmv CO_2-eq.
- The scenarios with pessimistic assumption about renewables (Low-Renewable) with a greenhouse gas concentration target of 450 and 550 ppmv CO_2-eq.

More detailed information about the EMF27 scenarios can be found in Krey et al. (2013), Kriegler et al. (2013) and supplementary material of Kriegler et al. (2013). Assumptions about availability of nuclear and CCS, as well as energy intensity development are the same in the four scenarios. Benchmark-Tech scenarios further assume high technological progress of wind and solar as well as optimistic (but sustainable) biomass potentials. In contrast, the Low-Renewable cases assume conservative technological progress of renewables and limit bioenergy potentials to 100 EJ/yr. The carbon price in the four scenarios ranges between the models from 96 to 852 (Benchmnark-Tech-450), 174–2000 (Low-Renewable-450), 35–449 (Benchmark-Tech-550), and 85–550 (Low-Renewable-550) USD_{2005}/tCO_2 in 2050 and from 204 to 3348 (Benchmnark-Tech-450), 1898–20000 (Low-Renewable-450), 92–1188 (Benchmark-Tech-550), and 144–2369 (Low-Renewable-550) USD_{2005}/tCO_2 in 2100.

We selected these scenarios: 1) As CCS is only used in mitigation scenarios, 2) to analyze the dependence of CCS deployment on the stringency of the climate target and 3) to look into competition with other low CO_2 emitting options (in particular renewables). For each of these scenarios we look at the development of CO_2 storage rates over time and the total variation of cumulative CO_2 stored. Then, we compare the change in this amount and the share of CCS in cumulative primary energy used between scenarios. Furthermore, we compare projected cumulative storage until 2100 (and simple extrapolations beyond) to global potential estimates. Subsequently, we investigate the differences in fuels used with CCS between scenarios.

Finally, we try to explore whether the variation in the model outcomes can be related to relevant general and CCS-specific assumptions or model types. For this, we compiled an overview of assumptions regarding the way CCS is modeled in the IAMs by consulting the modeling teams (Tables 1 and 2). Moreover, different model types may have tendencies to undervalue, or overvalue, for example, mitigation costs (IPCC 2005). We test this for the results of CO_2 capture projections of these models. Consequently, we classified the models into three different groups on the basis of available model documentation (see supplementary material, Table 1): 1) technology-focus, 2) macro-economic-focus and 3) hybrid models, leaning on distinctions made by Löschel (2002) and Hourcade et al. (2006).

3 Results

3.1 CCS deployment

First, results show that CCS plays an essential role in the CO_2 mitigation scenarios of all models looked at (Figs. 1 and 2). In fact, the cumulative capture in these models is at minimum about 600 and at maximum about 3000 $GtCO_2$ until 2100. The scenario averages across the models are at least around 1160 in the Low-Renewable-450 and at most 1480 $GtCO_2$ in the Low-Renewable-550 scenario. The shares of primary energy used with CCS demonstrate also the relative importance of CCS in the models. In 2050 they range from 9 to 53 % and in 2100 from 15 to 70 %. Across the 42 model runs the average shares are 30 % in 2050 and 41 % in 2100. In electricity production, the average shares are 37 % in 2050 and 34 % in 2100.

Second, Fig. 1 also shows that the majority of the models in all four scenarios have higher storage rates in 2100 than in 2050 (Tables 8 and 9 in supplementary material). This is an interesting result because CCS is often mentioned as a "bridging technology" to "buy time" (Bauer 2006; Praetorius and Schumacher 2009; EU 2009). Apparently, CCS remains competitive throughout the 21st century. Obviously, in the longer time frame physical limits to storage imply that the technology will need to be substituted by other energy forms. Still, the role of CCS as a key contributor to energy supply during the 21st century instead of a bridging technology will possibly have consequences for technology pathways in various regions.

A third observation is that there is clearly a wide divergence across models about the capture rate over time and total projected CO_2 capture. For instance, by the end of the century, GRAPE projects the highest value of about 64 $GtCO_2$/yr, while WITCH projects 12 $GtCO_2$/yr in the Low-Renewable-550 (the overall range is 8–64 $GtCO_2$/yr). Not surprisingly, the calculations of cumulative CO_2 captured also differ widely, ranging from 625 (BET) to 2449 $GtCO_2$ (IMACLIM) within the 450 ppmv scenarios. For the 550 ppmv target, the cumulative capture ranges from 613 (WITCH) to 3061 $GtCO_2$ (GRAPE).

3.1.1 CCS deployment differences between scenarios

Interestingly, Fig. 1 suggests that the overall storage is higher under the less stringent target. It should be noted however, that some models are included in the 550 ppmv and not in the 450 ppmv scenarios. Comparing only the models included in both runs, shows that under the Benchmark-Tech assumptions the tight majority of models (six out of ten models (6/10)) project higher storage rates in 2050 as well as higher cumulative capture (2010–2100) when the target is more stringent. (Note: the differences are often small. Four out of ten models show a difference less than ±1 Gt/yr, similarly for cumulative values).[3] In the Low-Renewable scenarios, half of the models (4/8) project lower 2050-storage rates and lower cumulative CO_2 capture in the 450 ppmv than in the 550 ppmv scenario (again, often small differences). Furthermore, it is not generally the case that pessimistic assumptions about renewables come with higher storage activity. Under the 450 ppmv target the storage rate in 2050 as well as the cumulative CO_2 captured is often higher (4/8 and 6/8 models, respectively) in the Benchmark-Tech than in the Low-Renewable case. Under the 550 target, in contrast, this is in most cases higher in the Low-Renewable case: 10 of 12 models have higher 2050-storage rates and 9 of 12 also higher cumulative capture. Again, often differences are small, but average values confirm this tendency.

Finally, looking at CCS shares in cumulative primary energy provides a more insightful figure than cumulative CO_2 capture values alone: CCS shares in cumulative primary energy

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[3] Precise differences are in Table 2–5 supplementary material.

Table 1 Model assumptions about CCS and cumulative CO_2 capture results from 2010 to 2100

	Model name	BET	FARM	GCAM	GRAPE	IMACLIM	IMAGE	MERGE	MESSAGE	POLES	REMIND	TIAM WORLD	WITCH
	Model type	Hybrid	Macro-focus	Tech-focus	Hybrid	Hybrid	Tech-focus	Hybrid	Hybrid	Tech-focus	Hybrid	Tech-focus	Hybrid
CCS Chain coverage detail	1 = one add on cost 2 = separate capture cost; combined storage & transport cost 3 = Separate capture, transport and storage	2	1	2	3	1	3	1	2[a]	2	3	3	1
CCS sector coverage	*P* = Power sector *I* = Industry LF/H/G = Liquid fuels/ Hydrogen/Gas production (counted as one sector)	P	P	P, I, LF/ H/G	P,LF/H	P,LF/H	P, I, LF/ H	P, I	P, I, LF/H	P, I, LF/ H	P, LF/H	P, I, LF/H	P, I
Number of BECCS sectors	Including Liquid fuels	1	1	3	1	1	3	1	3	4	3	3	1
	Excluding Liquid fuels	1	1	2	1	1	3	1	2	3	2	2	1
CCS power plant life time		40	40	60	30	Coal & Gas:30; Biomass: 50	40	N.a.[b]	30	40	35–40	30–40[c]	Biomass & Gas: 25, Coal 40
CCS power plant early retirement		No	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No
Availability		2020	2020	2020	2020	Always	2005	2020	2020–2030[d]	2015	2020	2030	Always
CCS investment cost development	1 = Exogenous constant 2 = Exogenous declining 3 = Endogenous learning	1	1	2	1	3	1,2[e]	1[f],2	1,2[g]	3	2[h]	1,2[i]	1

Table 1 (continued)

Model name	BET	FARM	GCAM	GRAPE	IMACLIM	IMAGE	MERGE	MESSAGE	POLES	REMIND	TIAM WORLD	WITCH
Model type	Hybrid	Macro-focus	Tech-focus	Hybrid	Hybrid	Tech-focus	Hybrid	Hybrid	Tech-focus	Hybrid	Tech-focus	Hybrid
Cumulative[j] storage 2010–2100 Benchmark-Tech-450 ($GtCO_2$)	730	–	1372	–	2411	1614	1306	1262	1629	947	653	797
Cumulative storage 2010–2100 Low-Renewable-450 ($GtCO_2$)	625	–	1306	–	2447	–	827	–	1232	807	1366	638
Cumulative storage 2010–2100 Benchmark-Tech-550 ($GtCO_2$)	719	1262	1224	2962	1468	1329	1552	1744	1686	866	846	655
Cumulative storage 2010–2100 Low-Renewable-550 ($GtCO_2$)	699	1098	1248	3061	1717	1442	1607	2101	1980	869	1357	613

Personal communication with Bertram, C.; Bibas, R.; Blanford, G.; Calvin, K.; Carrara, S.;Yamamoto, H.; Kanudia, A.; Kitous A.G.; Krey, V.; Kurosawa, A.; Labriet, M.; Rose, S.; Russ, P.; Sands, R.; Sugiyama, M

[a] Separately calculated, but modeled combined

[b] Unspecified—levelized cost formulation with smooth depreciation

[c] Depending on technologies

[d] 2020 OECD regions; 2030 in developing regions; BioCCS 10 years later respectively

[e] Costs are constant over time in the industry and hydrogen sector

[f] Only for cement production

[g] Costs for capture tend to decline over time, but the extent to which this is the case depends on the maturity of the specific capture technology. Costs for transport and storage of CO_2 are assumed to be constant

[h] Fixed exogenous cost, but declining mark up in the first periods

[i] Exogenous and declining cost in power sector, exogenous constant cost in other CCS sectors

[j] Values between 10-year-time-steps are interpolated using an annual compound growth rate

Table 2 Model assumptions about CO_2 storage and transport

Model name	(1) Is there a maximum storage rate	(2) Regional differentiation of storage capacity	(3) Possibility of international trade of CO_2 storage space	(4) Regional differentiation of transport and/or storage cost	(5) Storage and transport cost[a] in $\$US_{2005}/tCO_2$	(6) Number of storage types	(7) Storage cost differ per reservoir type	(8) Storage capacity in $GtCO_2$
BET	No	Yes	No	No	$ 8	No differentiation	No	3538
FARM	No	Yes[b]	No	Yes[b]	$ 13.8[b] - ∞	No differentiation	No	Unlimited[b]
GCAM	No	Yes	Yes[c]	Yes	$ 0.1–$96	2[d]	Yes	7178
GRAPE	No	Yes	No	Yes	$ 12.6–262	4[e]	Yes	~20000
IMACLIM	No	No	Yes[f]	Yes		No differentiation	No	Unlimited[g]
IMAGE	No	Yes	No	Yes	$ -6–50	11[h]	Yes	5856
MERGE	No	No[i]		No	$10	No differentiation	No	Unlimited[j]
MESSAGE	No	No	Yes[k]	No	$ 7–9[l]	No differentiation	No	Unlimited[m]
POLES	No	Yes	No	Yes	$ 10–300	2[n]	Yes	Unlimited
REMIND	Yes	Yes	No	No	$~6	No differentiation	No	3959
TIAM-WORLD	No	Yes	No	Yes[o]	$ 8–57	8[p]	Yes	11600[q]
WITCH	No	Yes[r]	No	Yes[s]	$ 5–10[t] (initial cost) -~ <100	No differentiation	No	Unlimited[u]

Personal communication with Bertram, C.; Bibas, R.; Blanford, G.; Calvin, K.; Carrara, S.;Yamamoto, H.; Kanudia, A.; Kitous A.G.; Krey, V.; Kurosawa, A.; Labriet, M.; Russ, P.; Sands, R.; Sugiyama, M

[a] We convert the cost to $US\$_{2005}$ using the IHS/CERA Upstream Capital Costs Index (UCCI) (IHS 2011). Cost of MERGE are assumed to be in US$2005

[b] Each world region has an implicit supply curve for CO_2 storage during each time step. Storage becomes increasingly expensive within each region as the quantity of stored CO_2 increases· Accumulated CO_2 stored must be calculated and checked for plausibility in each region. Storage and transport cost start at 2004 US$ 12.50 and increase rapidly depending on the regional storage demand

[c] Implicitly because there is a global high-cost off-shore reservoir

[d] Two reservoirs—onshore (region-specific) and offshore (available to all regions)

[e] Aquifer, EOR, ECBM, Depleted gas

[f] Implicitly because there is only one global reservoir

[g] Ex-post verification

[h] On and offshore EOR, depleted gas, undepleted gas, depleted oil, as well as ECBM onshore, and two types of aquifers

[i] Except not permitted in Japan and Korea

[j] Regionally dependent: Infinite in most regions except in Japan, Korea not permitted when modeled separately

[k] Implicitly because there is only one global reservoir

[l] 18.3 $\$_{2005}$/tC for transport and 7.3 $\$_{2005}$/tC for disposal for fossil CO_2 capture and twice this amount for biomass CO_2 capture, assuming that the unit size is considerably smaller

[m] There are no constraints in the model, but its monitored in the scenario development process

[n] Ocean and geologic storage

[o] Only differentiation between big and small regions

[p] EOR, depleted oil and gas fields (onshore and offshore), ECBM, saline aquifers, deep ocean

[q] Decreases to 2000 $GtCO_2$, if aquifers are removed

[r] Indirectly due to regional specific cost supply curves

[s] Indirectly via regional specific cost supply curves

[t] Increasing cost supply curves. Also depends also on region and policy

[u] The CCS cost increases exponentially with the stored amount, which fixes an indirect constraint

use are somewhat higher for the stringent targets (8/10 and 6/8 models under Benchmark and Low-Renewable conditions, respectively). As one would expect, pessimistic assumptions about renewables usually lead to higher CCS shares in 2050 (8/8 and 12/12 models under 450 and 550 ppmv, respectively), and higher cumulative energy use (7/8 and 12/12 models under 450 and 550 ppmv, respectively). Again, the differences are often small.

3.1.2 Mechanisms behind CCS deployment differences between scenarios

An analysis of the change in related variables can help understand why cumulative CO_2 capture rates and CCS shares in primary energy use can be lower in the pessimistic renewable or stringent target scenarios. We can distinguish three groups of models: those with lower cumulative CO_2 capture, but higher CCS shares in cumulative primary energy use (group 1), those with lower values for both (group 2) and models that project—as expected—higher values for both (group 3). In Table 6 and 7 in the supplementary material we try to explain the behavior of these groups by looking at the changes in cumulative primary energy use, the cumulative primary energy use with CCS, and the carbon intensity of the fuel mix used with CCS technologies.

In models of the first two groups, cumulative primary energy use decreases as a result of the increased carbon price. Consequently, cumulative primary energy used *with CCS* often decreases as well.[4] In models of group 1, the percentage decrease of *total* cumulative primary energy used is stronger than the reduction of cumulative *CCS* primary energy used. Therefore, CCS shares increase. In contrast, in models of group 2, the cumulative fuel used *with CCS* decreases faster than the *overall* cumulative primary energy used and thus the shares of CCS decrease.

Also cumulative CO_2 capture decreases because the total amount of primary energy used with CCS decreases in most models of group one and two. Furthermore, it decreases in some models because the fuel mix used for CCS technologies changes to less carbon intensive fuels. Replacement of higher carbon fuels may occur to reduce costs of the remaining emissions as well as storage costs. Both are highest for coal and biomass due to the higher carbon content compared to natural gas and oil.

3.2 Is there enough storage capacity?

Most models are very optimistic on the use of CCS, but clearly this can depend on the assumption about available storage capacity. Estimates of storage capacity are diverging and uncertain (Bradshaw et al. 2007; IPCC 2005) especially for saline aquifers,[5] which make the largest share of the estimates. The model assumptions on storage capacity vary considerably with, in fact, half the models assuming no upper limit (Table 2). Here, we compare the amount of CO_2 stored until 2100 with other storage capacity estimates.

The most recently published summaries of storage estimates are from GEA (2012)[6] and IEA GHG (2011). Their range is comparable while the ends in the GEA (2012) with 5050–

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[4] In some cases there is even an increase in the amount of primary energy used with CCS, although total primary energy used decreases.

[5] According to Bachu et al. (2007), storage capacity in saline aquifers is more difficult to assess because 1) they are less explored than hydrocarbon reservoirs, 2) aquifers are continuous (p. 436), 3) the mechanisms that determine the capacity are very complicated, and require site-specific data (p. 441).

[6] These estimates are acknowledged not to be exhaustive (GEA 2012).

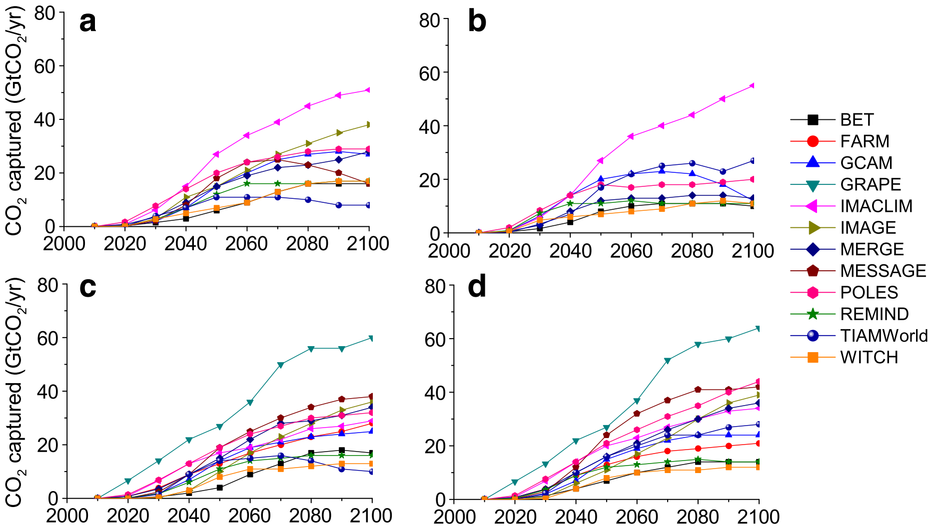

Fig. 1 CO_2 capture rates until 2100. Benchmark-Tech-450 (**a**), Low-Renewable-450 (**b**), Benchmark-Tech-550 (**c**), and Low-Renewable-550 (**d**) scenario

24470 $GtCO_2$ are slightly larger than in the IEA GHG (2011) (4890–20950 $GtCO_2$). The respective ranges without aquifers are around 820–3870 Gt (IEA GHG 2011) and around 1090–1300 Gt (GEA 2012). The model results are within these different resource estimates, certainly when aquifers are included. Without them, under the high estimate of IEA GHG

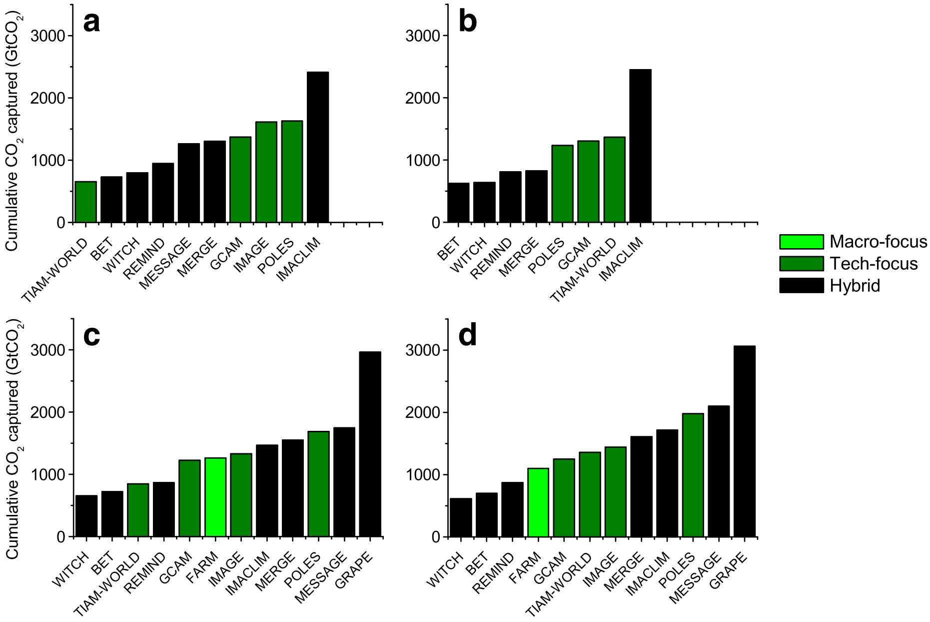

Fig. 2 Cumulative CO_2 capture until 2100 per model and model type (values between 10-year-time-steps are interpolated using an annual compound growth rate). Benchmark-Tech-450 (**a**), Low-Renewable-450 (**b**), Benchmark-Tech-550 (**c**), and Low-Renewable-550 (**d**) scenario

(2011), enough storage capacity is available at a global level until 2100 for all model runs. However, pessimistic numbers from IEA GHG (2011) and GEA (2012) estimates without aquifers would be exceeded in around 65–75 % of model runs of the current scenarios.

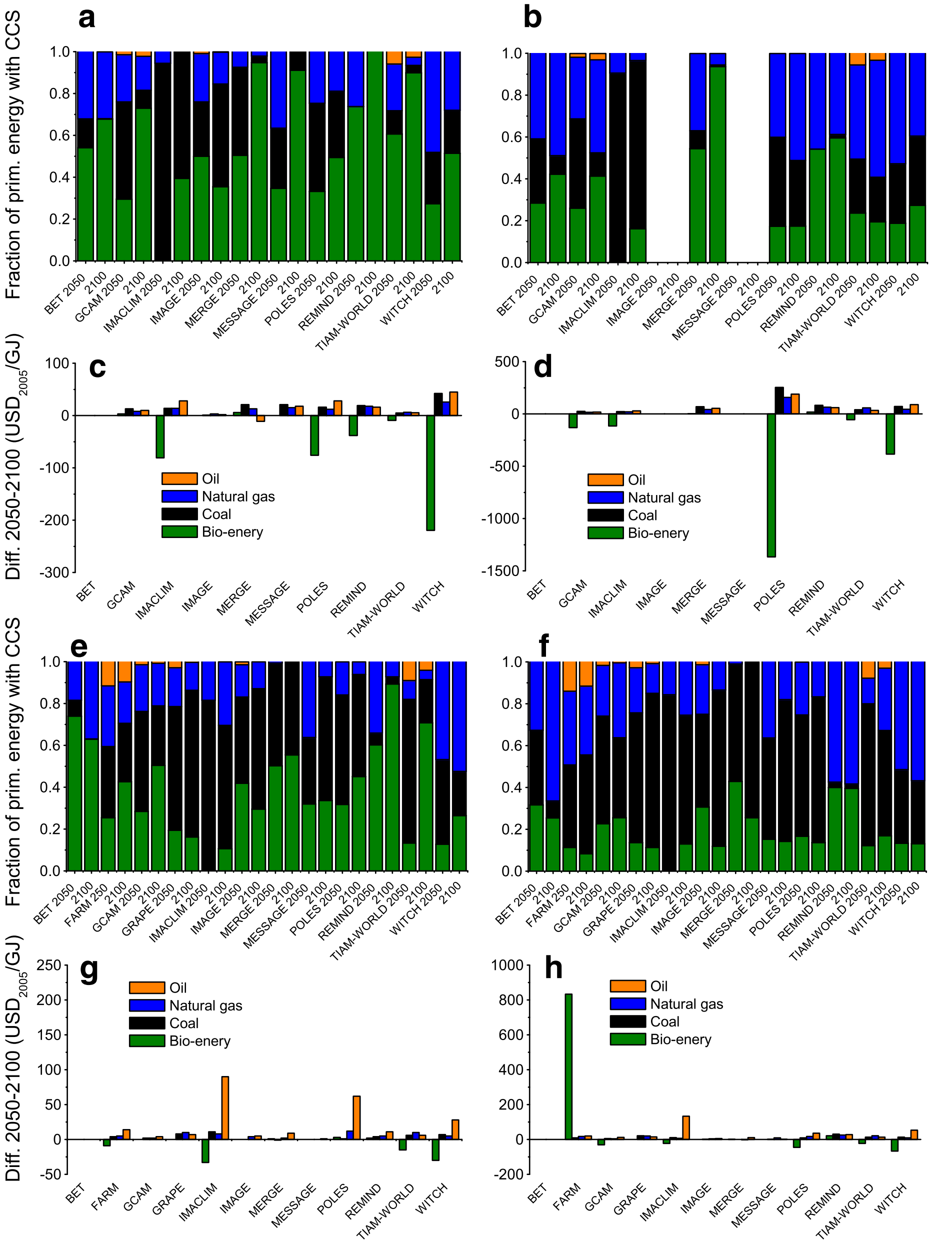

Fig. 3 Share of energy carriers in primary energy used with CCS in 2050 and 2100 and change in price of primary energy between 2050 and 2100. **a**, **b**, and **e**, **f**, show the share of each energy carrier in total primary energy used with CCS in 2050 and 2100 in the Benchmark-Tech-450 (**a**), Low-Renewable-450 (**b**), Benchmark-Tech-550 (**e**) and the Low-Renewable-550 (**f**). **c**, **d**, and **g**, **h**, show the price change in the fuels from 2050 to 2100 including the carbon price for the corresponding scenarios (Note that the scale differs)

Obviously, given the storage rates in 2100, it is important to realize that also storage would be required after. To see for how long the capacity could last, we assume for simplicity constant storage rates after 2100. Using pessimistic estimates including aquifers (4890 $GtCO_2$), the first model exceeds this estimate before 2130. About 30 years into the 23rd century half the model runs exceed this estimate as well. Using optimistic numbers without aquifers from the IEA GHG (2011) (3870 $GtCO_2$) would still give similar results. The first model run exceeds this capacity in 2113, while it takes almost 80 years extra until half of the model runs hit the limit. However, the optimistic estimates excluding aquifers from the GEA (2012) (1,300 $GtCO_2$) are already exhausted by half the models around 2100.

3.3 Fuel shares in CCS deployment

Figure 3 illustrates fuel shares in total primary energy use with CCS over time (2050 and 2100). In the Benchmark-Tech-450, most of the models (9/10) substitute away from either coal, natural gas, or both, to higher biomass shares (14–56 %-point increase/ on average 28 %-points). This fuel-switching towards biomass is less pronounced in combination with pessimistic assumptions about future renewable energy (average +12 %-points) - in particular bioenergy potentials - and for less stringent emissions mitigation targets (average +12 %-points), or both (average -3 %-points). In the less pessimistic renewable case, the results come from the restriction on bioenergy potentials. For the less ambitious climate target, the result likely comes from the reduced importance of “negative emissions” from BECCS.

Figure 4 shows the share of energy carriers in cumulative CCS electricity generation from 2010 until 2100. The preference of CCS power plants for fuel types varies among the scenarios and models. In the Benchmark-Tech-450 scenario, BECCS has the largest share in the portfolio in 7 of 10 models, whereof five have more than 50 % and the highest is up to 70 %. In most models (5/6) this changes to natural gas if the scenarios assume low renewable availability (Low-Renewable-450), such that most often (6/8 models) natural gas dominates the cumulative fuel portfolio. Lowering the target (Benchmark-Tech-550) also leads to less dominance of BECCS in CCS electricity. Instead, coal CCS is more often (6/12) dominating in both 550 scenarios. In the Low-Renewable-550, natural gas dominates the portfolio in the other half of the models. (See supplementary material Tables 10–12 for detailed values of this section).

3.4 Can the model variation be easily explained?

Several factors could potentially cause the large variation in the model results for CCS as they may have an influence on CCS deployment. This includes 1) fuel prices, 2) baseline emissions, 3) the type of model, 4) modeling technology change, and 5) the way CCS is modeled. We test whether such factors—in isolation—can explain the range of model results. In summary, the results show no clear relationships between these factors and the projected CO_2 captured of the models. (Section 4 of supplementary martial and Tables 13 and 14 explain and motivate the investigation in detail).

The model results cannot be related to the type of model (Fig. 2). Results of the hybrid models, for example, can be found over the whole range of reported outcomes. Furthermore, Fig. 5 shows that a relationship between capture and the baseline emissions is not apparent from the current data set. Figure 3 shows the fuel shares in primary energy use with CCS for 2050 and 2100 along with the price change of primary energy (the price includes the carbon tax calculated

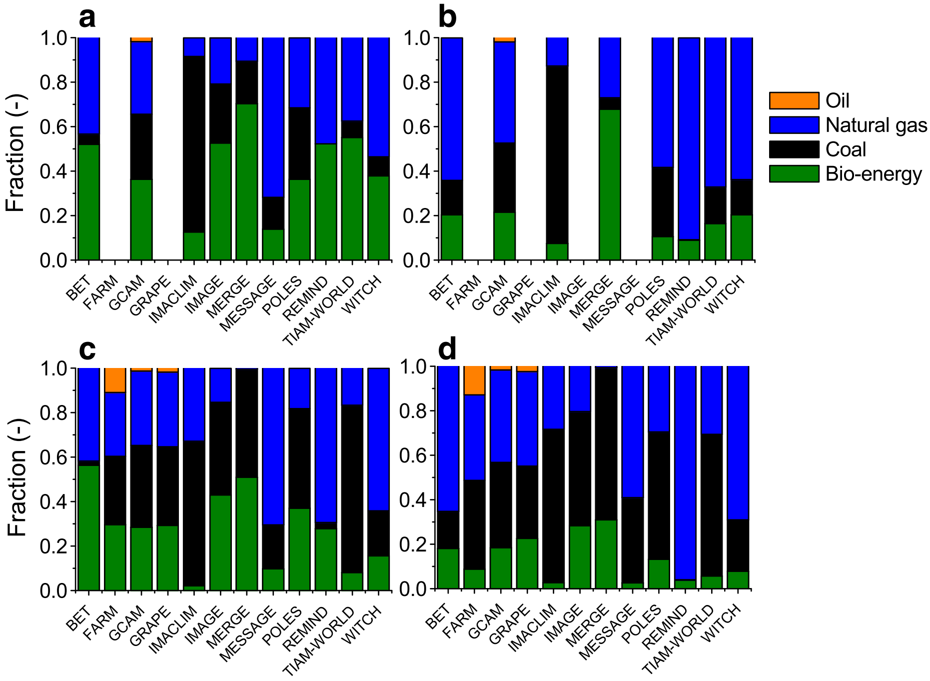

Fig. 4 Share of energy carriers in cumulative electricity production with CCS (2010–2100) (values between 10-year-time-steps are interpolated using an annual compound growth rate). Benchmark-Tech-450 (**a**), Low-Renewable-450 (**b**), Benchmark-Tech-550 (**c**), and Low-Renewable-550 (**d**) scenario

based on the estimated carbon price in the models)[7]. A clear relationship between the fuel price increase/decrease and the substitution of shares is not always present for all fuels in all the scenarios and models.

None of the model assumptions (Table 1) about the detail of CCS in the model, sectoral coverage, amount of sectors where BECCS is possible, power plant assumptions or implementation of technological development in the model can be related unambiguously to the amount of CO_2 captured cumulatively by the models. Similarly, the model assumptions about CO_2 transport and storage as summarized in Table 2 can also not be associated with the model outcomes. Also, no discernible relationship between the storage capacity assumption and the global CO_2 stored can be derived (see also Fig. 1 in supplementary material).

Finally, comparing the levelized cost of electricity (LCOE)[8] for the cheapest CCS option divided by the cheapest carbon-free-alternative,[9] shows that the model with the lowest cost ratio does not have the highest capture rate, or share of CCS in electricity production and vice versa (See Fig. 2 in supplementary material). This implies that even the combined costs for (among others) fuel, operating and maintenance, transport and storage of the CCS power plant cannot explain the variation, when isolated from the remaining model assumptions.

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[7] In order to include the carbon price in the primary energy price we assume a carbon content of 95.3, 56.1, 93.5 and 70.8 $kgCO_2/GJ$ for biomass, natural gas, coal, and oil respectively (de Vries et al. 2001). Furthermore, we assume a capture rate of 85 %. For Biomass we assume that 5 $kgCO_{2\text{-eq}}/GJ$ are indirect emissions of biomass as summarized in van Vliet et al. (2011:256).

[8] LCOE does not include the carbon price.

[9] This was only tested for Europe for nine models in the Benchmark-Tech-550.

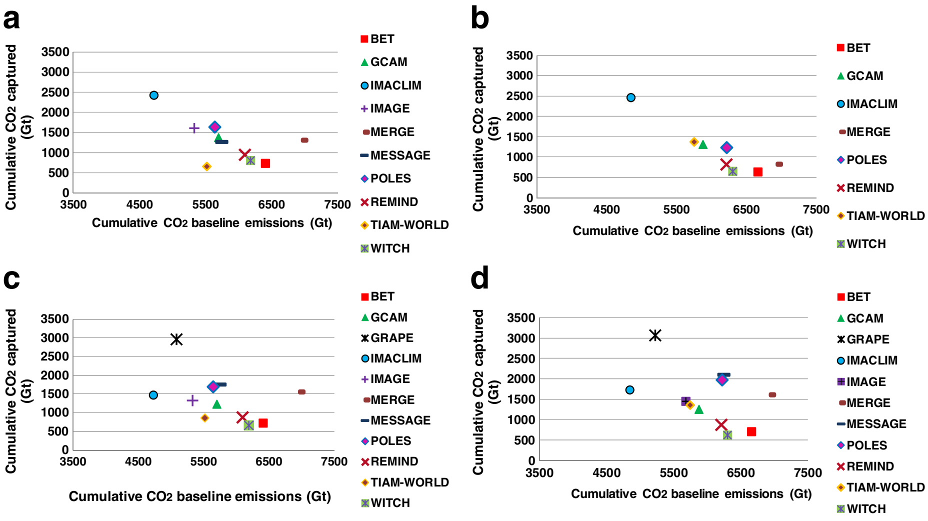

Fig. 5 Cumulative CO_2 baseline emissions in relation to cumulative CO_2 captured (values between 10-year-time-steps are interpolated using an annual compound growth rate). Benchmark-Tech-450 (**a**), Low-Renewalbe-450 (**b**), Benchmark-Tech-550 (**c**), and Low-Renewable-550 (**d**) scenario

4 Discussion

Although the EMF 27 study included 18 models, only a maximum of 12 models projected values for variables of our interest until 2100. In some scenarios the number of participating models is even smaller (for an overview of the amount of participating models per scenario and models that could not find a solution see Krey et al. (2013)). Therefore, the sample size to derive solid conclusions for the CCS assumption analysis is small. Especially with respect to statistical assessments, conclusions should rather be seen as weak indicators, but not as proofs.

Furthermore, many of the conclusions drawn with respect to the scenario comparison and development of CCS should be interpreted as a *tendency* found in model results, since they are often based on the *majority and average values* of results. Hence, other outcomes are possible. Moreover, the conclusion that CCS is more important in model results than suggested by many papers and current investment rates needs to be taken with care. First of all, the model results focus on 2050, i.e. 40 years from now. Second, the models do not include many limitations that are important in reality, like social and political dynamics, or other market barriers (see also IPCC 2005:349,351). Still, the model results suggest that CCS is attractive also in the second half of the century.

Also, we use the amount of CO_2 captured as an indication of CCS deployment which is not a precise measure as natural gas and coal have different carbon contents. However, to summarize different sectors, CO_2 capture is the most suitable indicator. To confirm results, we also often use the share of CCS in the use of primary energy.

We showed that CCS might be deployed beyond the 21st century even under pessimistic capacity estimates with aquifers or the optimistic estimate without aquifers from IEA GHG (2011). However, we only compared the global amount of capacity. This does not take into account that the regional distribution of capacity might pose further limitations, i.e. reservoirs could be too far away for some relevant regions. Therefore, a regionally detailed model analysis of this limitation is necessary.

The classification of model types into three categories is a rather crude exercise. Therefore, the classification of the models can be subject to discussion. However, we have considered different categorizations for some models, (GCAM & MERGE), which did not change the conclusion.

Confounding effects of variables may exist, including many variables not considered in our comparison (e.g. performance of competing technologies). This is likely an important reason for not being able to explain the CCS outcomes based on model characteristics although impacts seem logical. One key factor not included in our comparison is investment costs. Unfortunately, this data was not sufficiently available. Therefore, we focus on the LCOE of the cheapest CCS option versus the cheapest carbon-free-alternative for nine models of one scenario. Although capital costs usually make a large share in LCOE, no relationship with CO_2 captured or CCS shares in primary energy use can be discovered. This indicates that capital costs might also not explain the variation in the cross-model comparison when isolated from other assumptions.

Finally, the fact that we cannot identify a relationship between the model characteristics and the outcomes does not imply that higher detail of models is unnecessary. High detail is still necessary to address specific policy questions. As an example, the regionality of storage potential allows to evaluate the role of CCS on a regional level.

5 Conclusions

This study compared the results of the EMF27 modeling round with respect to the deployment of carbon capture and storage. The rationale behind this inquiry was: (1) to investigate whether general conclusions about the importance and tendencies of future CCS deployment can be drawn, (2) to explore the possibility of relating the wide diversity in model projections to model assumptions. Key conclusions are:

CCS plays a key role in the mitigation portfolio of all models looked at. In the models between 600 and 3050 $GtCO_2$ is captured cumulatively in this century. The share of CCS-related technologies in primary energy use is also high under the 450 and 550 ppmv target looked at. The average of all 42 model runs is 30 % in 2050 and 41 % in 2100. This level contrasts with the small amount of experiments with CCS at the moment.

In most models CCS remains important across the century. While CCS is often mentioned as a bridging technology to advanced renewable energy systems, the models often consider CCS to be important until the end of the 21st century: here, the CO_2 capture rates and the CCS share in primary energy use are higher in 2100 than in 2050 in the majority of the model runs.

There is a large range of outcomes across the models. The projections of CO_2 captured cumulatively until 2100 by the different models diverges strongly. Even using the same target and some common technology assumptions for all models, the range of values (~600–3060 Gt in Low-Renewable-550) is comparable to the range of model averages that was found by the IPCC-TAR-scenario (133–3462 Gt) (IPCC 2005:356) under the same target, but different baselines.

The large variation in results cannot easily be explained on the basis of individual model assumptions. Apparently, CCS use is a result of a complex interplay of several factors in each model. We have explored the possibility to explain the model results on the basis of known model characteristics and assumptions. In nearly all situations, it turned out not to be possible to easily explain model results on the basis of fuel costs, model types, and general or CCS-specific assumptions. These parameters are thus either not the driving forces, or their impact is confounded by other forces such that an external examination cannot identify their impact. Understanding the exact impact of different factors can therefore best be explored in a within-model sensitivity analysis.

Assumed and current estimates of storage capacity do not pose a physical limit on the capture for any model on the global level, as long as aquifers are included. Using the whole range of storage options from the capacity estimates summarized in the literature, shows that there is enough storage potential until the end of the century (and for most models beyond 2100) even when pessimistic estimates are used. However, if we use the pessimistic estimates *and* exclude all potential for aquifers, storage potential estimates are not sufficient for the global CO_2 captured until 2100 in about 65–75 % of the 42 model projections.

Models indicate that under pessimistic technological development of renewable energies, CCS will play a larger role in the primary energy portfolio if one attempts to achieve similar climate targets. Scenario comparisons show that cumulative storage rates are often lower in the Low-Renewable-450 than in the Benchmark-Tech-450. Nevertheless, under the 550 ppmv target the majority of models capture more in the Low-Renewable case. Furthermore, the Low-Renewable cases mostly project higher CCS shares in primary energy use than the Benchmark-Tech cases.

Under the 450 ppmv target CO_2 captured is not necessarily higher than under the 550 ppmv target, but CCS shares in primary energy tend to be higher in the majority of models. The 2050 storage rates in the 450 scenarios are not always higher than in the 550 ppm scenarios. In the Low-Renewable case, only in half the models capture rates are higher under the 450 than under the 550 ppmv target. These results seem to be at odds with the model-average values reported from the IPCC-TAR-scenarios (IPCC 2005). Still, the shares of CCS in primary energy use generally increase in most models for the more stringent targets. Reasons for the seemingly counterintuitive projections of CCS deployment under low renewable assumptions or more stringent targets can mostly be explained by less absolute primary energy used for CCS, a fuel switch within CCS technologies (less CO_2 is captured) as well as substitution between CCS and other energy sources (determines the share of CCS in primary energy use).

BECCS use is especially attractive under stringent targets and no pessimistic restriction on biomass potentials. 90 % of the models substantially increase BECCS use in their CCS fuel portfolio substituting often for coal and, natural gas over time. When targets are less stringent and/or the biomass potentials are restricted in the scenario, the substitution over time is more heterogeneous between models.

Further research to investigate impacts of CCS modeling parameters using *within* model studies is recommended. Although the sensitivity to some CCS parameters has been shown before (e.g. (Kurosawa 2004)), it was not possible to relate the variation in results to the CCS parameters in the cross-model comparison. Therefore, we recommend further research in within-model studies to investigate the impact of techno-economic uncertainty on the CCS deployment projections. This also implies that assumptions like costs and performance of technologies should be published with each study.

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