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Low-Stabilisation Scenarios and Technologies for Carbon Capture and Sequestration

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Abstract

Endogenous technology scenarios for meeting low stabilization CO_2 targets are derived in this study and assessed regarding emission reductions and mitigation costs. The aim is to indentify the most important technology options for achieving low stabilization targets. The significance of an option is indicated by its achieved emission reduction and the mitigation cost increase, if this option were not available. Quantitative results are computed using a global multi-regional hard-linked hybrid model that integrates the economy, the energy sector and the climate system. The model endogenously determines the optimal deployment of technologies subject to a constraint on climate change. The alternative options in the energy sector comprise the most important mitigation technologies: renewables, biomass, nuclear, carbon capture and sequestration (CCS), and biomass with CCS as well as energy efficiency improvements. The results indicate that the availability of CCS technologies and espec. biomass with CCS is highly desirable for achieving low stabilization goals at low costs. The option of nuclear energy is different: although it could play an important role in the primary energy mix, mitigation costs would only mildly increase, if it could not be expanded. Therefore, in order to promote prudent climate change mitigation goals, support of CCS technologies reduces the costs and – thus – is desirable from a social point of view.

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Keywords: Low-stabilization; Carbon Capture and Sequestration, Biomass, Hybrid Models

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1. Introduction

The United Nations Framework Convention on Climate Change aims at stabilizing greenhouse gas concentration in order to avoid dangerous impacts on the society. Several actors engaged in the international negotiations of climate change mitigation policies have proposed stabilization levels and/or emission reduction targets. During the last years the aim of achieving a relatively low stabilization level has gained support. The most prominent testimony of this shift has probably been the EU's proposal of limiting the increase of the global mean temperature above 2°C.

The first question regarding low stabilization goals is whether they are feasible given a set of technological options that are subject to constraints. The second question is about the technology choice among the different technology options. Third, the costs of emission mitigation policies give an indication of the economic impact of a

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stabilization goal. Finally, the costs vary if technology options are excluded from the portfolio of available alternatives. The differences between the mitigation costs of the full potfolio compared with the costs of the reduced portfolio – that we term option values – indicate the ranking of technological options; i.e. the option value indicates the additional costs of not having available the corresponding technology. The issues above are addressed by employing the global multi-regional hybrid-model *ReMIND*.

The study contributes to a growing literature. Early pieces dealt with low-stabilization scenarios using models that were similar from a conceptual point of view, but less detailed with respect to technologies; see e.g. Gerlagh and van der Zwaan (2000), Kypreos (2003), Manne and Richels (2004), Bauer et al. (2005), Edenhofer et al. (2005). Roehrl and Riahi (2000) used a large scale energy system model, while Klepper and Springer (2003) used a computable general equilibrium model. These studies are summarized in Bauer (2005, Ch. 4). More recently a variety of models were compared for assessing low-stabilization scenarios and the significance of induced technological change; see Edenhofer et al. (2006).

The remainder of the paper is organized as follows. In Sec. 2 we introduce the model *ReMIND*. In Sec. 3 the specific research questions and the scenarios are explicated. The results are reported and discussed in Sec. 4. The final Sec. 5 concludes the study.

2. The Model *ReMIND*

In this section the numerical modeling framework is introduced in two steps. First, we provide a general introduction of the model structure and the solution concept. It serves as a basis for the understanding and interpretation of the results. Second, we provide more specific information on the technologies that are assessed in this study using the model framework.

ReMIND is the acronym for Regional Model of Investment and Development; see also Leimbach *et al.* (2008). It comprises nine world regions[†] that are interacting via trade and emissions that contribute to global warming. Within each region a social intertemporal welfare function is maximized that depends on consumption that in turn is the residual of the economy wide income – measured in market exchange rates – after accounting for savings and variable costs of the energy sector. The savings are allocated to the macroeconomic capital stock and investments into stocks of the various technologies in the energy sector. Among the technology alternatives there are some that only make sense in case of climate change mitigation policies; espec. technologies with carbon capture and sequestration (CCS). The generation of income requires capital and labour as well as energy that demands financial and natural means for its production.

The energy sector and the macro-economy are coupled via a hard-link that guarantees simultaneous equilibrium on the capital and energy markets. The energy market equilibrium is characterized by the price that equals demand and supply of energy in physical units. The capital market equilibrium is characterized by the interest rate that equals demand and supply for financial means. Moreover, the own rate of return of the macroeconomic capital stock and for all alternative energy technologies that are competitive are equal to the interest rate. If the own rate of return for an investment alternative falls short of the economy wide interest rate, this alternative is not competitive. The simultaneous capital and energy market equilibrium implies efficient – i.e. cost minimal – allocation of investments. For a more detailed analysis of the hard-link see Bauer *et al.* (2008).

The nine regions are engaged in trading energy carriers (coal, oil, gas and uranium), emission permits and a generic good. The solution for the trade equilibria is computed by the Negishi approach that allows for the use of optimization algorithms; see Negishi (1961). The method guarantees a Pareto equilibrium between all regions that is characterized by a set of price paths that equal supplies and demands for the traded goods. This reflects the economic idea of exchange: a region exports a good, if and only if it receives sufficient imports of another good in turn. The equilibria on the trade markets guarantee efficient – i.e. cost minimal – use of the endowments and production technologies. Endowments can either be due to natural conditions like in the case of natural resources or they are subject to political agreements as in the case of emission permits. In both cases it is important to note that the efficient allocation induced by the trade equilibrium is consistent with the second theorem of welfare economics: the efficient allocation of goods on the market is separable from the distribution of the initial endowments, if

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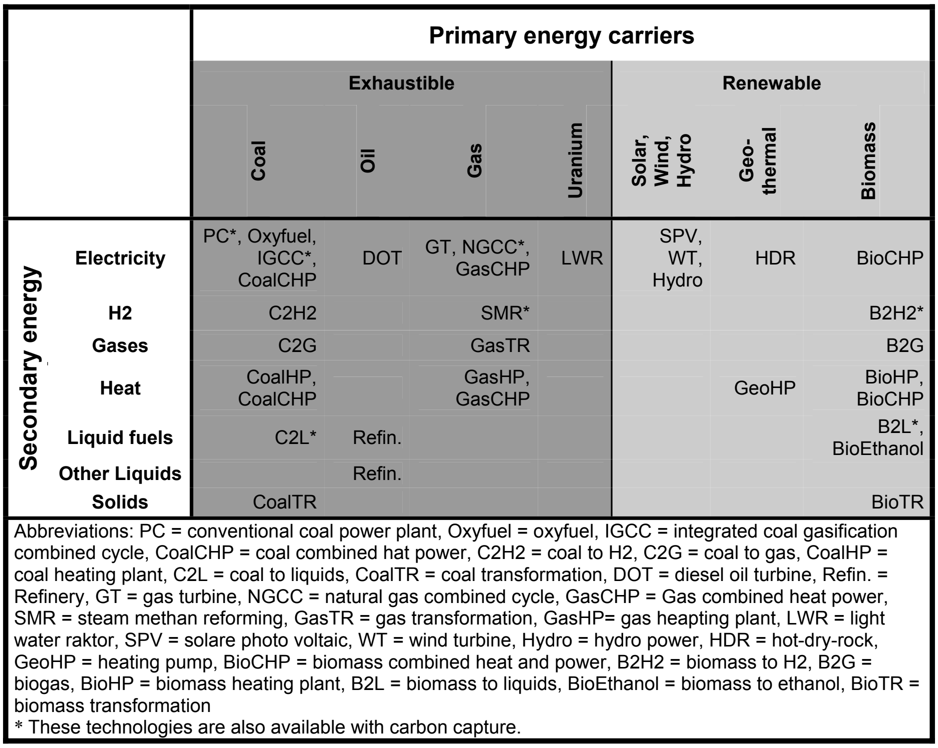
[†] UCA (USA, Canada, Australia), EU-27, Japan, Russia, Middle East and North Africa, China, India, Africa, Rest of the World.

markets work efficiently. This means that – assuming efficient markets – no special emphasis has to be put on the particular institutional framework of an international climate mitigation framework except for the stabilization goal, if one aims at analyzing the global costs of climate change mitigation; see e.g. Manne and Stephan (2004).

The model represents energy conversion technologies with respect to essential economic and engineering characteristics. The primary energy demand and CO_2 emissions are determined by capital structure of conversion technologies. Emission mitigation is achieved by restructuring the capital stock or by changing the demands for secondary energy carriers. The emissions of CO_2 could be reduced through these two reallocation mechanisms or by investing in carbon capture and sequestration, which increases the capital costs and reduces efficiency. Table 1 summarizes the alternative routes and technologies for converting primary into secondary energy carriers.

Primary energy carriers are either exhaustible or renewable. The former are characterized by extraction costs that are increasing with cumulative usage, while the latter are subject to a constraint on annual production potential that is differentiated by various grades. The harvest of biomass leads – additionally – to costs that are accounted for in the budget constrained of the economy.



		Primary energy carriers						
		Exhaustible				**Renewable**		
		Coal	**Oil**	**Gas**	**Uranium**	**Solar, Wind, Hydro**	**Geo-thermal**	**Biomass**
Secondary energy	**Electricity**	PC*, Oxyfuel, IGCC*, CoalCHP	DOT	GT, NGCC*, GasCHP	LWR	SPV, WT, Hydro	HDR	BioCHP
	H2	C2H2		SMR*				B2H2*
	Gases	C2G		GasTR				B2G
	Heat	CoalHP, CoalCHP		GasHP, GasCHP			GeoHP	BioHP, BioCHP
	Liquid fuels	C2L*	Refin.					B2L*, BioEthanol
	Other Liquids		Refin.					
	Solids	CoalTR						BioTR

Abbreviations: PC = conventional coal power plant, Oxyfuel = oxyfuel, IGCC = integrated coal gasification combined cycle, CoalCHP = coal combined hat power, C2H2 = coal to H2, C2G = coal to gas, CoalHP = coal heating plant, C2L = coal to liquids, CoalTR = coal transformation, DOT = diesel oil turbine, Refin. = Refinery, GT = gas turbine, NGCC = natural gas combined cycle, GasCHP = Gas combined heat power, SMR = steam methan reforming, GasTR = gas transformation, GasHP= gas heapting plant, LWR = light water raktor, SPV = solare photo voltaic, WT = wind turbine, Hydro = hydro power, HDR = hot-dry-rock, GeoHP = heating pump, BioCHP = biomass combined heat and power, B2H2 = biomass to H2, B2G = biogas, BioHP = biomass heating plant, B2L = biomass to liquids, BioEthanol = biomass to ethanol, BioTR = biomass transformation

* These technologies are also available with carbon capture.

Table 1: Overview on available alternatives to convert primary to secondary energy carriers. If a technology appears in two columns, it is a technology with joint production. Technologies marked with a "*" are available also in a variant with carbon capture.

Biomass and coal are general purpose energy carriers and can be converted in nearly all secondary energy carriers. Moreover, some technologies can be augmented by CCS in order to reduce CO_2 emissions at the expense of higher capital costs and lower conversion efficiency. Crude oil and natural gas are currently mainly used to produce liquid fuels and gases, respectively. Both can be substituted by coal and biomass. The new renewable energy sources wind, hydro, solar and geothermal are preferably used to generate electricity. However, the annual potential to exhaust these sources is limited by natural availability and other factors.

In the following we will put more emphasis on the technologies with the option to capture carbon. Table 2 summarizes the main techno-economic assumptions for biomass and coal fuelled technologies with carbon capture that will be discussed next. Note that a major difference between coal and biomass is that the latter cannot be converted into electricity with carbon capture. The alternatives of converting biomass into liquid fuels or hydrogen can be augmented with this alternative. Here, the main difference is that the efficiency of capturing carbon is higher for the production of hydrogen than for liquid fuels using the Fischer-Tropsch approach, since the former secondary energy carrier does not contain any carbon, but the liquid fuel incorporates large part of the carbon that was originally contained in the biomass. Hence, hydrogen with carbon capture is more effective in removing carbon from the atmosphere. Note that the investment costs are at the higher end of asssessments in the literature.

		Primary energy carriers								
		Coal					**Natural Gas**		**Biomass**	
		PC*	Oxyfuel	IGCC*	CH2*	C2L*	NGCC*	SMR*	BioH2*	B2L*
Investment costs	$US/kW	1900	1700	1800	712	1040	1350	380	1700	3000
Efficiency	%	35	34	42	57	40	47	70	55	41
Capture rate	%	90	99	90	90	70	90	90	90	50

Table 2: Techno-economic parameters of technologies with option of carbon capture. Abbreviations are the same as in Table 1. For coal and natural gas technologies; see Bauer (2005, Ch. 5) for an overview. For biomass see Iwasaki (2003), Hamelinck (2004), Gül *et al.* (2007), Ragettli (2007), Takeshita and Yamaij (2008).

Coal fuelled plants augmented with the carbon capture option are mainly relevant for electricity production. The three options to add carbon capture to coal power plants considered in the engineering literature are available in the model: post-combustion and oxy-fuel in conventional condensation power plants and pre-combustion in IGCC plants. The main argument for the oxy-fuel approach in the light of low-stabilization scenarios is that it has the highest capture rate compared with the two alternatives which are characterized by higher efficiency and lower capital costs.

In summary, the model *ReMIND* comprises the essential sub-systems of energy, economy and climate. The interaction between the energy sector and the remaining macroeconomy is characterized by a simultaneous equilibrium on the capital and the energy markets. Moreover, the trade in goods and energy carriers between regions is in equilibrium. The investments are allocated in order to supply the economy with quantities of energy that balance the scarcity of capital and the demand for energy. If climate change is constrained to obey a certain upper level like a maximum temperature, the investments are reallocated in order to use the remaining carbon emissions at the lowest achievable burden.[‡] At the international level this is achieved by introducing a cap-and-trade system, where the market for tradable permits is also in equilibrium.

3. Research Questions and Scenarios

The present study tries to address the following research questions regarding the transition towards a sustainable energy system achieving low-stabilization goals:

1. What are the differences in energy use and the structure of energy demand relative to a case without climate change mitigation policies?
2. What are the most prominent emission mitigation options?
3. What are the costs of reaching low-stabilization goals?
4. How do the costs change if a technology is not available beyond the scenario without climate mitigation policies?

These questions were answered by performing a number of scenarios with the *ReMIND* model, that vary assumptions on climate change mitigation goals and the availability of technologies:

a. **BAU** Business-as-usual: no climate change policy imposed; there are no restrictions on emissions.
b. **POL** Climate change mitigation: The temperature increase above the pre-industrial level must not exceed 2°C. The CO_2 emissions of the energy sector are reduced accordingly. The CO_2 emissions from land-use

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[‡] This kind of method is also known as cost-effectiveness analysis.

change and land-use and forestry follow the B2 scenario, while the other greenhouse gas emissions are assumed to remain constant at the levels of 2005.

c. **noCCS** the same as POL, but CCS technologies are not available.
d. **noBCCS** the same as POL, but biomass technologies with CCS are not available.
e. **fixNUK** the same as POL, but nuclear energy is restricted to follow the BAU path.
f. **noNUK** the same as POL, but nuclear fades out completely.

The differences are always related to the BAU scenario. Note that this is a problem in the NoNUK scenario because here the policy scenario has available less possibilities than the realized technology path way in the BAU scenario.

4. Results

The results are presented in two steps. First, we characterize the BAU scenario regarding the general storyline. Second we show the differences as the climate change stabilization goal is imposed with the full as well as the restricted portfolio of technology options. Below we will refer to cost indicators. These are differences of GDP and consumption cumulated over the 21st century relative to the BAU scenario.

4.1. The Business-As-Usual Scenario

The BAU scenario is characterized by medium growth of population reaching 10.04billion people in 2100. The world GDP grows from 47trillion $US up to 417trillion $US in 2100; i.e. the average per-capita increases from 7200$US to 41000$US. The developing countries converge towards the per-capita income of industrialized countries, but the differences are assumed to remain considerable. For example, the poorest region is sub-Saharan Africa (without South Africa) that reaches only 2% of the per-capita income of the high income region UCA (USA, Canada, Australia) in 2005. This figure reduces to 9.3% in 2100, which is still a considerable gap.

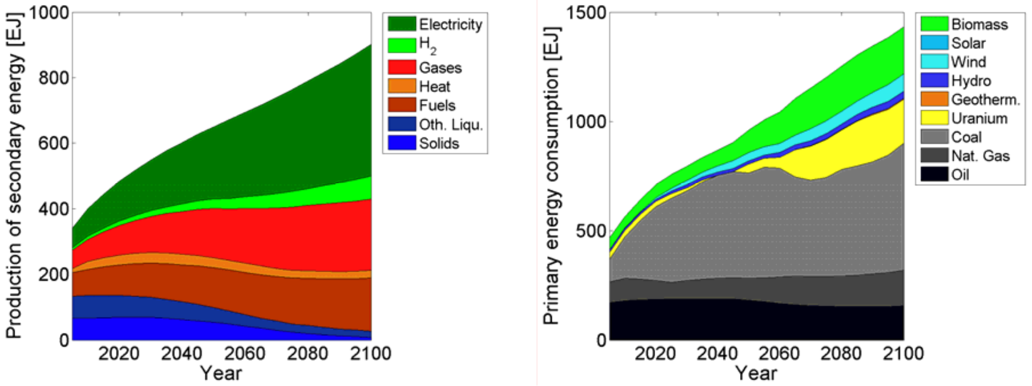

Figure 1: Global secondary production (left) and primary energy carrier (right) consumption in the BAU scenario.

The energy demand of the economy is expected to grow, but the structure is changing towards an increasing share of higher quality energy carriers – especially electricity – and away from low quality energy carriers like solids for cooking purposes; see the left panel of Figure 1. The shift is more emphasized in developing than in industrialized countries. The primary energy input shown in the right panel of Figure 1 is also expected to grow, however here we observe the converse behavior: the system is going to rely more and more on lower quality primary energy carriers. The shares of coal, biomass, and renewables are increasing and the relative contribution of natural gas and oil is decreasing in the near to mid-term. Solar energy technologies are not used at all. Hence, the energy sector is going to convert more and more primary energy carriers of low quality into secondary energy carriers of high quality. This is achieved by increasing the use of capital. The rapid growth of coal – unfortunately – implies rapidly growing CO_2 emissions.

The primary energy mix exhibits three interesting features that shall be explained in more detail next. First, the simultaneous growth of coal as well as biomass and renewables is a feature worth to explain in the present context. The exhaustion of coal leads to increasing extraction costs, which is anticipated in present decisions. Renewables and biomass are potential substitutes for coal, but they are gradually constraint by annual production potentials. In order to supply increasing energy demand, it is optimal to add renewable and bio-energy sources to reduce the growth of coal consumption. If the market would forego this strategy, the economy would have used up the coal too quickly and afterwards the renewables could only supply a very limited amount of energy. For a formal treatment see Amigues *et al.* (1998).

The second feature is that oil and gas extraction remain nearly constant over time. The utilization is prolonged over the entire century and beyond. The reason is that exhaustible hydrocarbons mainly deliver energy carriers that are difficult to substitute; due to limited potential biomass can only partially replace the liquid and gaseous secondary energy carriers. Though coal is a general purpose energy carrier, it cannot be used for all purposes all the time, since it is also subject to intertemporal scarcity. In summary, the BAU scenario already uses renewables and biomass at a considerable extent in order to prolong the use of exhaustible energy carriers. These renewable energy potentials are not available to contribute to the mitigation of climate change. However, their deployment reduces the growth of BAU CO_2 emissions.

The third feature is that nuclear power initially fades out of the system and starts to regain share around the middle of the century. Initially, nuclear replaces some of the coal consumption, but then coal consumption again increases without replacing the use nuclear. The system experiences a phase during which both exhaustible energy carriers are competitive; see Chakravorty *et al.* (2005) for a rigorous analysis.

As a consequence the CO_2 emissions increase sharply until the middle of the century up to 18GtC. This is mainly triggered by the increasing use of coal in the power sector that is gaining share in the secondary energy mix. Afterwards the emissions remain roughly constant with a slightly increasing tendency at the very end of the century when they are going to exceed 20GtC.

4.2. Policy Scenarios

The 2°C constraint is feasible. The impact on the global energy system by introducing a stringent climate policy goal is shown in Figure 2. The left hand panel shows the absolute differences in secondary energy production compared to the BAU scenario, while the right hand side shows the the differences for primary energy consumption. The changes in secondary energy production show that less gases, solids and fuels are produced, but the production of hydrogen and electricity increases. This means that less energy carriers are produced that emit CO_2 where it is finally used, instead higher quality energy carriers that do not emit CO_2 are increased in production.

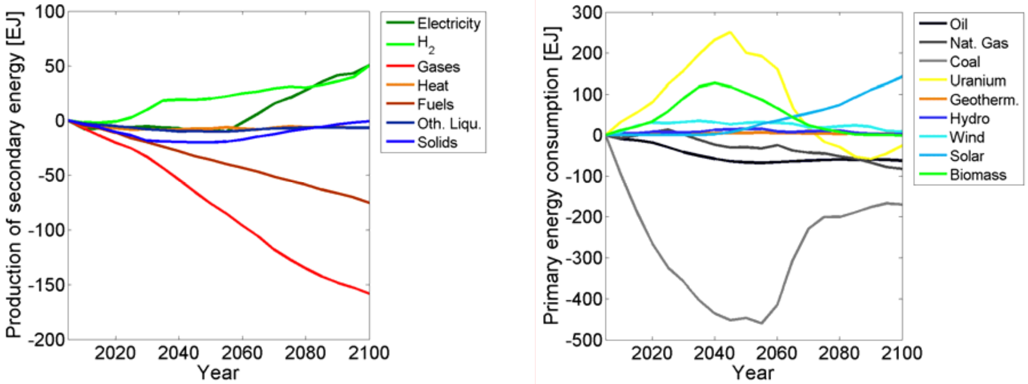

Figure 2: Differences between the POL case and the BAU scenario for global secondary energy production and primary energy consumption.

The changes in the primary energy consumption mix are more emphasized and they are most significant around the middle of the century. To bring the CO_2 emissions down, the most efficient solution is to reduce the consumption of coal in the short to mid-term and to substitute it by nuclear power, biomass, wind and hydro. Smaller reductions are also undertaken regarding the use of hydrocarbons. In the long-run the increased utilization of solar sources and coal combined with CCS are the most important changes in the primary energy mix. The increase of biomass use is augmented by reallocating the biomass towards the production of hydrogen with CCS that is continued until the end of the century. This means that the production of gases and fuels from biomass is reduced. Consequently, the reduction of secondary energy gases and fuels is more emphasized than the reduction of primary energy natural gas and oil. However, the availability of biomass with CCS allows additional emissions from natural gas and oil that produce secondary energy carriers that are difficult to substitute with low emission. Figure 3 shows this in the gross CO_2 emissions and the captured CO_2 differentiated by primary energy carriers in the left panel.

Although a mix of all available options is preferable, each option is subject to the uncertainty whether it will be available. This issue will be treated next. It was shown that in terms of energy quantities the cost-minimal solution in the near to mid term is to increase nuclear and to reduce coal; after 2050 increasing coal use is augmented by CCS. We ask the question whether the short term availability of nuclear is more important than the long term option of CCS. For this purpose we compare the noCCS with the fixNuk, which does not allow for the flexible deployment of nuclear in time. Moreover, it is important to ask whether the availability of nuclear at all is important. We compare the case fixNUK with the noNuk scenario, which does not allow for new expansion of nuclear power plants. Finally, we ask for the significance of biomass with CCS and the CCS option as whole by comparing the scenarios noBCCS and noCCS. Instead of comparing the energy mixes, we measure the impact of reducing the portfolio of technological options by measuring the costs of achieving the climate constraint in the different scenarios.

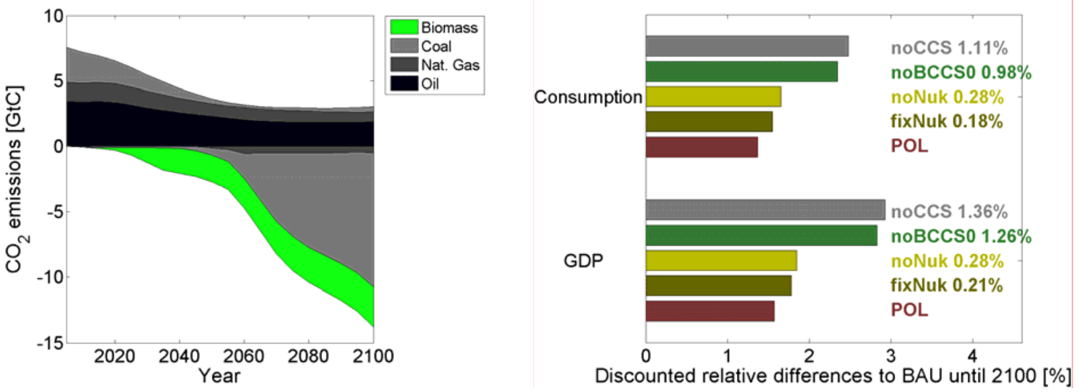

Figure 3: Net CO_2 emissions from the energy sector (positive values) and CO_2 captured (negative values) differentiated by primary energy carriers (left panel) and discounted cumulative consumption and GDP losses relative to the BAU scenario (right panel). The numbers in the graph are the option values in percentage point differences compared to the corresponding value of the POL scenario.

The results are shown in the right hand panel of Figure 3. The graph shows for GDP and consumption the cumulative difference of a policy scenario relative to the BAU scenario discounted with 3%p.a. The numbers in the graph are the option values, i.e. the percentage point differences compared to the value of the POL scenario. At first, both indicators show roughly the same magnitudes; measured in GDP the mitigation costs are mildly higher. The highest option value is attributed to the reduced portfolio of noCCS and the lowest to the fixNuk scenario. Hence, the availability of CCS is more important than the large scale near-term expansion of nuclear power. If the longer-term expansion of nuclear power is also excluded and nuclear power is not available at all (noNUK), the option value is increased by about a third to half. Most surprising is that the option value of biomass with CCS is nearly as high as for the CCS option as a whole. The reason is that biomass with CCS removes carbon from the atmosphere, which allows higher CO_2 emissions from oil and natural gas. In the electricity sector – the domain of all other CCS technologies that only avoid carbon emissions – the availability of renewables and nuclear are sufficient to reduce CO_2 emissions. Therefore, biomass with CCS is important, though the contribution to emission reductions in physical terms is low.

5. Discussion and Conclusion

The goal to limit global warming not to exceed a 2°C increase of global mean temperature above pre-industrial levels is feasible in a growing world economy. However, the energy system requires fundamental restructuring compared to a development in which climate change mitigation is not pursued. The energy transformation sector is going to be more affected than the energy using economy. Having available all mitigation options is the most preferable alternative, but this is subject to the uncertainty whether these options will be indeed available. This uncertainty is addressed by excluding particular options from the overall portfolio in order to compare the mitigation costs of the corresponding scenarios. It turned out that CCS is the most important option we studied and that the availability of CCS in combination with biomass is essential, though the achieved emission reductions are relatively small. The significance arises from the fact that biomass CCS removes carbon from the atmosphere and therefore allows additional emissions from using secondary energy carriers derived from oil and natural gas. We note that information on biomass with CCS in the electricity sector was very little in the scientific literature. However, electricity could be a superior energy carrier compared with hydrogen. The near term availability of nuclear power turned out to be not so important in terms of mitigation costs. Therefore, supporting the development of CCS technologies – especially in combination with biomass – turned out to be economically desirable, if stringent climate mitigation goals shall be reached.

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