
Technologies, Policies and Economics of Global Reductions of Energy Related CO₂ Emissions

An Analysis with ReMIND

Abstract

The present study analyzes the deployment of technologies to reduce CO₂ emission in the global energy sector and the implied costs using the energy-economy-climate model ReMIND. The results depend on the policy chosen for inducing changes of investments. Climate policies price emissions and therefore induce changes of investments. The mitigation costs of less than 1% of GDP are relatively small. Targeted technology policies enforce investments for subsets of technologies but do not implement emission pricing. The costs are lower than for climate policies, but the climate target is missed significantly because these policies are subject to CO₂ emission rebound effects. The high flexibility of the energy-economy system modeled in ReMIND implies low mitigation costs of climate policies and high rebound effects of technology policies. Technology policies are not sufficient to achieve the climate change mitigation target because coal remains competitive. Climate policies are necessary that target emissions directly.

1. Introduction

The energy sector contributes about 65% to the total emissions of greenhouse gases (GHG), which have been identified as the main causes of climate change. Energy demand is increasing with economic growth and can be met in very different ways. Fossil fuel reserves and resources are sufficiently plentiful to satisfy the bulk of this demand over the 21st century, but

if the generated CO₂ is emitted into the atmosphere, large-scale effects on the climate system are to be expected. Climate change in such a scenario is considered to negatively affect ecosystems, economic activity and human well being; see Lenton et al. (2008) and Smith et al (2009). Several emission mitigation options regarding the energy sector are available to solve the problem; see IPCC WG3 (2007). These include renewables, nuclear, biomass and fossil fuels with carbon capture and sequestration (CCS) as well as increasing energy efficiency.

The deployment of such mitigation options requires policies to alter investment behavior. Policy assessment focuses on the (i) emission reductions achieved and (ii) mitigation costs incurred. The result of the assessment depends on the available technologies and the economic dynamics induced by policies.

In the following we oppose two policy approaches which both aim at reducing CO₂ emissions from the energy sector; for the sake of clarity we strongly emphasize the differences. The *economic approach* proposes climate policy instruments that target emissions directly –taxes and cap-and-trade systems – and indirectly induce changes in the way energy is produced and used by re-evaluating investments in alternative technology. The *engineering approach* focuses on direct development and deployment of technological solutions that allow for energy production and thereby reduce emissions indirectly.

The economic approach views technological choice as the reaction of investments induced by price changes due to policy measures like a cap-and-trade system; technologies as such are not the main research interest.¹ Price changes are considered to have economy wide effects that work through the market mechanism. The engineering approach puts aside the economic

¹ Emission mitigation cost functions that summarize technology choice in aggregate parameters reflect the consequences of this approach.

aspects and discusses the problem of emission reductions as the need to replace high emission technologies by alternatives with lower emissions. The sensibility of climate policies is generally questioned: the “fossil fuel greenhouse effect is an energy problem that cannot be simply regulated away”; see Hoffert et al. (2002, p. 986). Scholars following the engineering approach implicitly assume that technology deployment reduces emissions by replacing those technologies with high CO₂ emissions, and this first order effect is not off-set by second order *rebound effects*; see also Pacala and Socolow (2003). These second-order effects are highlighted by Sinn (2008), who emphasized that the challenge of emission reduction is a problem of unregulated fossil fuel supply.

The term “rebound effect” is common in the field of energy efficiency policies. It measures how much of the initial gain from energy efficiency improvements is lost due to increased deployment of the energy in the same or in alternative activities. The higher the flexibility of the economy to find alternative ends for using the energy that is saved, the smaller is the economy-wide energy demand reduction; see Birol and Keppler (2000).² Empirical estimates in the US residential sector suggest an energy efficiency rebound effect of 0-50% for 100% increase of end-use efficiency; see Greening et al. (2000).

For the purpose of the present study the concept of rebound effects is extended to the CO₂ emissions of the energy supply sector. Policies following the engineering approach that enforce the utilization of specific low-carbon technologies affect investment decisions regarding fossil fuel using technologies only indirectly through market signals, but do not replace these investments automatically. This phenomenon is presently observed: investments in renewable energy technologies like wind turbines are rapidly increasing, but also coal power plants

² Acemoglu (2002) provides basically the same arguments.

remain competitive. For example, from 2005 to 2007 China increased the renewable power capacity by 36GW and at the same time the fossil power capacity increased by 165GW; see SPERI (2008, p. 47).

Next, we turn to the effects of the on the relationship to technology choice and climate change mitigation costs. For the engineering approach the present study will derive the economy wide costs of enforcing certain technologies of a mitigation option into the system. Following the economic approach policies targeting emissions generally imply an efficient market solution of technology choice that minimizes the economy wide emission mitigation costs. The higher the flexibility of the energy-economy system to react to emission constraints the lower the mitigation costs. The flexibility of the economic system depends on the availability of technologies. Hence, a model with high technological flexibility implies high rebound effects of technology deployment policies and low mitigation costs of climate policies. Moreover, reducing the flexibility to react to emission constraints of climate policies by switching off mitigation options will increase the costs of climate change mitigation.

For discussing the interrelationship of policies and technologies as well as quantifying the various effects a numerical modeling framework is required that (i) integrates long-term developments of energy, economy and climate and (ii) renders possible the analysis of the emission reduction options for the two policy approaches. Hence, below the model ReMIND will be introduced that fulfills both requirements. The present study contributes to the existing literature in two ways. First, the systematic comparison of climate and technology policies quantifies the emission reductions and the social values of the availability of various mitigation options. Second, the emission rebound effects of mitigation options in the energy conversion sector can be derived from these results. Both contributions add to the literature on the

economics of climate change mitigation; see e.g. Edenhofer et al. (2006) and Bauer et al. (2009). More generally, the present paper calls for an integrated perspective that combines technology characteristics, policies and system wide economic effects.

The remainder of this paper is organized as follows. In Section 2 the model framework ReMIND is introduced. Results are presented in Section 3. The study concludes in Section 4 with a discussion and gives hints to future research.

2. The ReMIND Model

The Refined Model of Investment and Technological Development (ReMIND)³ is an extension of the MIND model; see Bauer (2005) and Edenhofer et al. (2005). It was improved in all parts, though the basic structure is maintained. The present section aims at introducing the model in detail.⁴ The next sub-section first provides a generic overview of the ReMIND model framework, the macroeconomic growth model (MGM), and the energy system model (ESM). The climate system model (CSM) is not discussed here.

2.1. Overview

The ReMIND model is an integrative framework that embeds a detailed energy system model into a macro-economic growth model and a climate system model that computes the effect of GHG emissions. Figure 1 provides an overview of the model structure. The ReMIND model is completely hard-linked and solves the three integrated models simultaneously considering all

³ See: <http://www.pik-potsdam.de/research/research-domains/sustainable-solutions/remind-code-1> for the technical documentation of the code.

⁴ Bauer et al. (2009) and Leimbach et al. (2009) already introduced the model at a more general and less technical level.

interactions with perfect foresight. The present study uses a global single region version. This is equivalent to a multi-regional model with completely integrated markets and zero transportation costs that would lead to full price equalization of all traded goods.

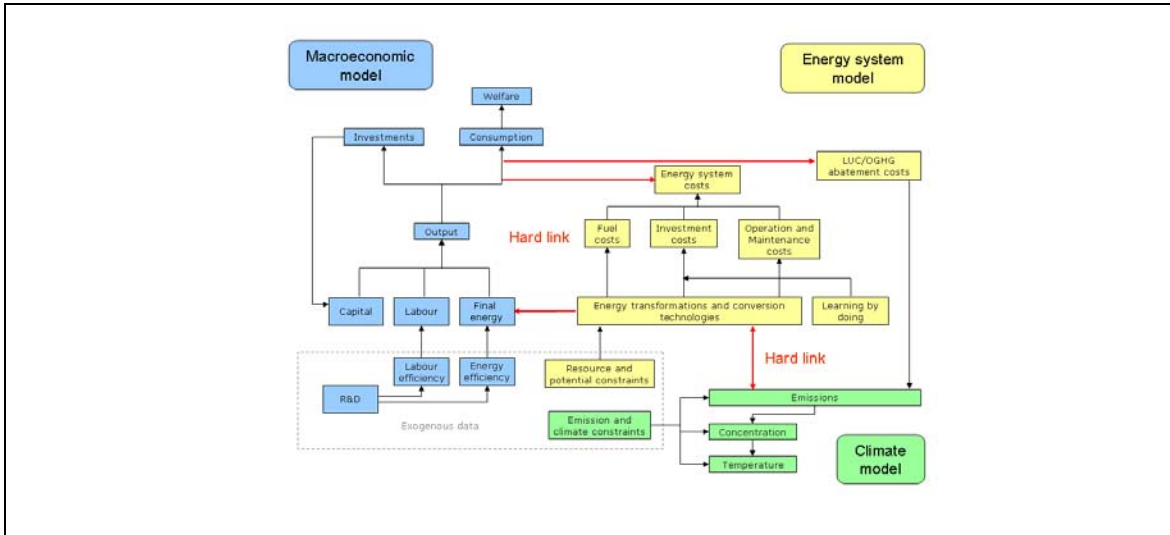


Figure 1: Overview of the ReMIND model framework. Blue boxes on the left are related to the macroeconomic growth model (MGM), yellow boxes on the right denote elements of the energy system model (ESM), and green boxes indicate elements of the climate system model (CSM). The red arrows highlight the hard-links between models.

The MGM of the Ramsey-type is the backbone of the ReMIND model. It solves a general equilibrium problem by maximizing inter-temporal social welfare of the household sector with perfect foresight subject to constraints of the macroeconomic, the energy and the climate system. This approach is well-established in the literature on climate change mitigation; see e.g. Manne et al. (1995), Edenhofer et al. (2005) and Nordhaus (2008).

The household sector owns all production factors – labor, resources, capital stocks and emission permits – that are supplied to the economic sectors, which in turn pay factor prices that make up the income of households that they allocate to consumption and saving. The macroeconomic production sector demands aggregate capital, labor and various types of final energy to produce an aggregate economic good. The value of this aggregate good is completely exhausted to pay the household sector for the production factors.

In the ESM, the energy sector demands financial means for investments, operation and maintenance, and primary energy in order to produce final energy carriers that are supplied to the macroeconomic production sector. The energy sector comprises a large number of energy conversion technologies – i.e. a heterogeneous capital stock – that convert scarce primary energy carriers into final energy carriers that are supplied to the macro-economy. Some energy technologies improve endogenously from accumulating experience known as learning by doing. The emission reductions of other GHG and land-use related CO₂ emissions are integrated into the model structure via marginal abatement cost functions; see Lucas et al. (2008).

The macro-economy and the energy sector interact via energy and capital markets. The hard-link between the ESM and the MGM solves for a social optimum that establishes a simultaneous equilibrium on these markets as has been shown in Bauer et al. (2008). Hence, the ReMIND model considers all interactions between the various markets and investments change accordingly.

For the CSM the ACC2 model has been used; see Tanaka and Kriegler (2007). It considers the accumulation of CO₂ and other GHG and computes the global mean temperature (GMT). ACC2 is computationally efficient and reproduces sophisticated carbon-cycle and atmosphere-ocean general circulation models very well.

Climate policies are analyzed by limiting the increase of GMT to a certain level. The model then computes the first-best cost-minimal solution for keeping the climate system within this limit regarding the emission pathway in general and the investments in particular. *Technology policies* are introduced into the model by setting constraints on investments of particular subset of technologies, without taking into account the climate change mitigation target.

2.2. The Macroeconomic Growth Model

The MGM consists mainly of the household sector and firm sector that produces an aggregate good. Both sectors are interrelated by the demand and supply of goods and factor payments.

The inter-temporal social welfare function is the sum of discounted utility of the world population that depends on the per-capita consumption of an aggregate good. The utility function in each period is logarithmic, which implies an inter-temporal elasticity equal to one. The pure rate of time preference is set to 3% p.a. The time horizon spans from 2005 to 2150 in five year time steps.

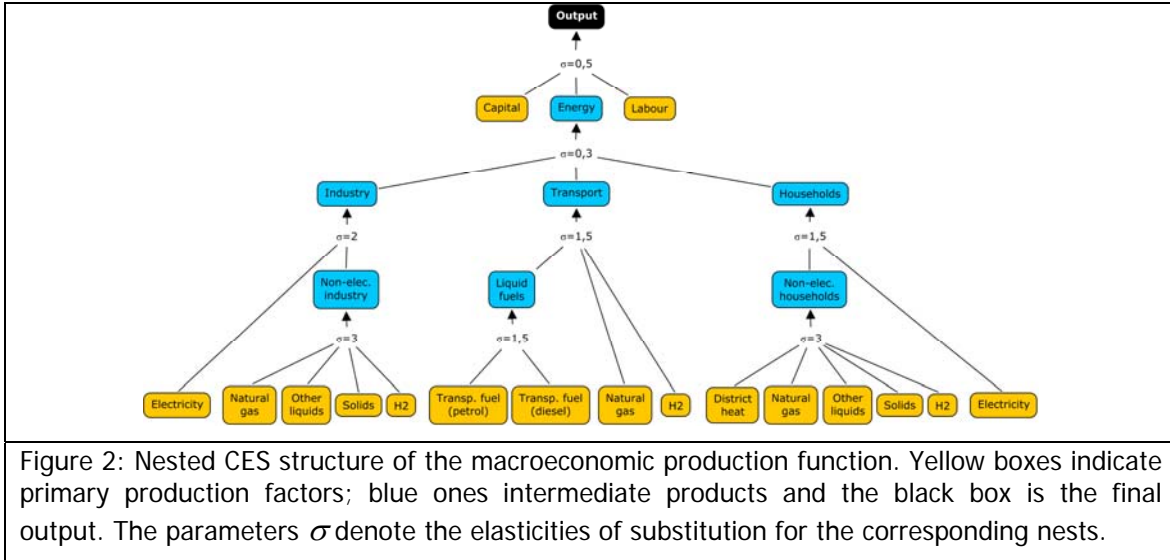
The household sector's budget equation balances in each period the macroeconomic income, which equals world gross domestic product (GDP), and the sum of consumption, savings that equal investments in all capital stocks for the macroeconomy and the energy sector, and other energy related expenditures.

The firm sector's macroeconomic production function applies the concept of nested CES (constant elasticity of substitution) production functions. The nesting structure applied in the ReMIND model is given in Fig. 2. Outputs of all CES aggregations are measured in monetary terms; i.e. also the intermediates (blue boxes). The primary production factors (yellow boxes) are measured in various units: labor in the number of workers, macroeconomic capital in monetary units and energy in physical units. At the top-level the overall GDP is generated. The sub-nest of the energy intermediate is quite elaborate and aims at reproducing the sectoral differentiation of the economy in industry, services&residential and transportation. The differentiation between the various final energy carriers is located at lower levels of the nesting structure. This is a point of departure with respect to other energy-economy models using nested CES structures. MERGE and WITCH do not represent the sectoral differentiation and

only aggregate different final energy carriers; see Manne et al. (1995) and Bosetti et al. (2006). ReMIND pays particular attention to the different services fueled by final energy carriers and therefore the prominence of the transport sector is highlighted: its services are hard to substitute and transportation fuels are difficult to de-carbonize. The macroeconomic production function is essential for the policy assessment of this study because it implies endogenous energy demand that is in turn related to the generation of GDP.

In the initial year the overall nested CES production function is calibrated to convert the production factors into GDP, which is 47.1tril.\$US. For labor the number of workers is equaled to world population. In the context of the present study this assumption is justified because labor is supplied inelastically with respect to the wage rate and the work force is assumed to grow proportional to population. The macroeconomic capital stock in 2005 is estimated at 104tril.\$US. The elasticities of substitution σ are reported in Fig. 2. The choice of the values is based on a literature review; see Bauer (2005, p. 103), Jones (1996) and Urga and Walters (2003). The process of capital accumulation in the macroeconomic sector follows the perpetual inventory assuming exponential depreciation with an assumed rate of 5%.

The growth engine comprises exogenous scenarios of population and development of efficiency parameters. For population we assume a medium scenario in which population reaches 8778 million people in 2050 and 9776 million people in 2100. For the efficiency parameters scenarios are assumed that generate a GDP growth that leads to a 3.3-fold increase until 2050 and a 8.8-fold increase until 2100. For energy demand efficiency parameters are chosen in order to reproduce income elasticities that are consistent with historical data. Since efficiency parameters are dimensionless numbers this point will be revisited in Sec. 4.1, in which the BAU scenario is presented.



2.3. The Energy System Model

The energy sector is represented by a detailed model of technologies and energy carriers that are characterized by their techno-economic attributes. The demand of primary energy carriers and the emissions of CO_2 are determined by the structure and size of the heterogeneous capital stock that is made up of the composition of technologies. The future development of the energy sector's capital stock depends on investment decisions that in turn depend on the development of primary energy and CO_2 prices, technological improvements, energy demand and the interest rate of the economy.

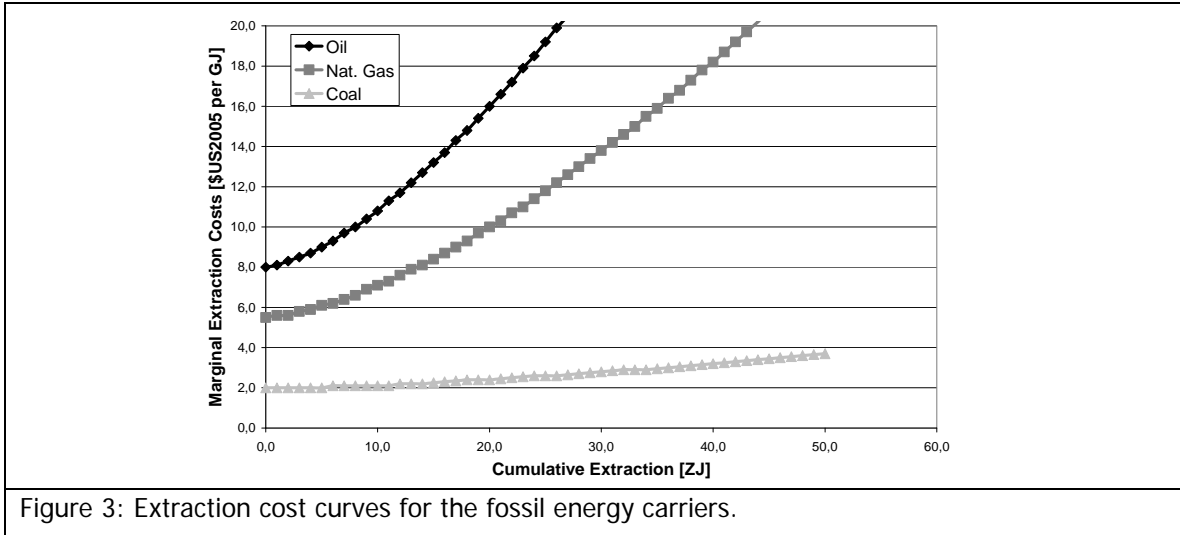
The most notable part of the energy system model is the conversion of primary energy into secondary energy by applying specific technologies. The alternative conversion routes and the availability of alternative technologies is the *conditio sine qua non* for the rebound effect in the energy conversion sector because it determines the flexibility to use fossil fuels with different technologies to generate a variety of valuable energy carriers. Table 1 provides an overview of all technologies that convert primary in secondary energy carriers.

Table 1: Overview of primary energy carriers, secondary energy carriers and the technologies for conversion.

		Primary energy carriers						
		Exhaustible				Renewable		
		Coal	Oil	Gas	Uranium	Solar, Wind, Hydro	Geo-thermal	Biomass
Secondary energy carriers	Electricity	PC*, IGCC*, CoalCHP	DOT	GT, NGCC*, GasCHP	TNR, FNR	SPV, WT, Hydro	HDR	BioCHP, BIGCC*
	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, IGCC = integrated coal gasification combined cycle, CoalCHP = coal combined heat 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 heating plant, TNR = thermal nuclear reactor, FNR = Fast nuclear reactor, SPV = solar photovoltaic, WT = wind turbine, Hydro = hydro power, HDR = hot-dry-rock, GeoHP = heating pump, BioCHP = biomass combined heat and power, BIGCC = Biomass IGCC, 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.

Primary energy carriers are distinguished into renewable and exhaustible energy carriers. Exhaustible energy carriers are subject to extraction costs that increase with cumulative extraction. The concept of extraction cost curves reconciles the idea that low cost deposits are exhausted first and higher cost deposits are used later in a rational sequence; see e.g. Herfindahl (1967). Figure 3 presents the fossil fuel extraction cost curves that are used for the present study. The data was mainly based on the study by Rogner (1997). The original costs reported in Rogner started at about 2.5\$US per GJ for oil and gas and 1.5\$US per GJ for coal, which are much lower than market prices in 2005. The initial extraction costs were corrected up-wards to meet current market prices. Brecha (2008) provides a rationale why the strict sequence of extracting the deposits should indeed be corrected upwards.



Extraction costs for uranium are based on NEA (2003). Uranium extraction costs increase from initially 30\$/kgU to 300\$/kgU at a cumulated extraction of 15.8MtU.

Renewable energy carriers are subject to constraints on the potential output per year that is differentiated by various grades. For solar, wind, hydro and geothermal energy the grades differ in the maximum output and the capital utilization factor due to the fact that highly attractive locations are relatively scarce. The left hand panel of Figure 4 presents these potentials. For geo-thermal Hot Dry Rock a small potential of only 1EJ p.a. is assumed; Turkenburg (2001) reported a maximum electricity production potential of 43EJ p.a., but a final assessment is difficult to make because HDR is highly site dependent. The right hand panel of Figure 4 presents the biomass production costs that also change with time until 2050.

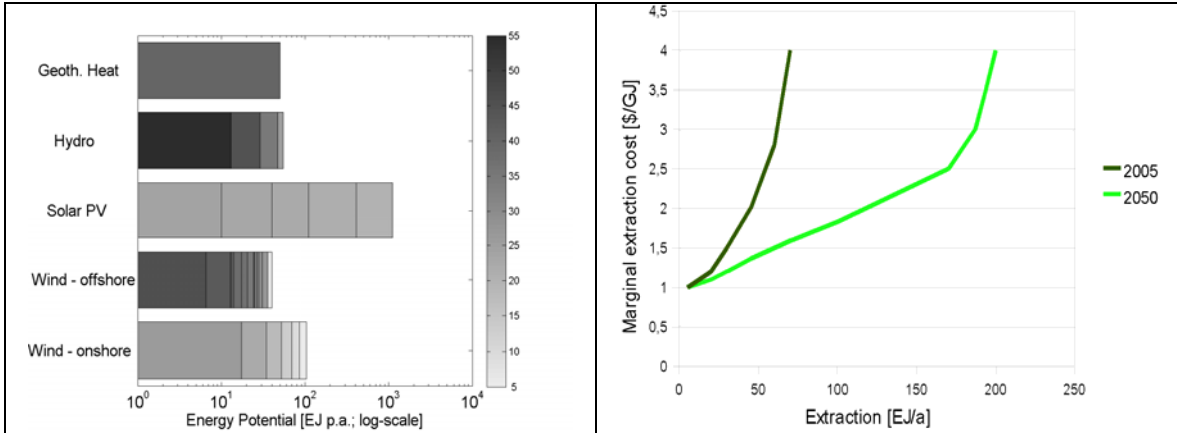


Figure 4: Availability of renewable energy carriers. Left panel: energy production potentials differentiated by technologies and grades. The gray color indicates the capacity factor as the fraction per year a technology is available. Right panel: biomass harvesting costs at different points in time. Sources: ENERDATA (2006), Trieb et al. (2009), Hoogwijk (2004), Sims et al. (2007).

Regarding biomass the model only takes into account lingo-cellulosic biomass. Hence, land competition for food production is not as severe as for first generation biofuels and the direct greenhouse gas emissions from fertilization need not be modeled explicitly because the co-emissions are relatively small; see e.g. Farrell et al. (2006). The additional indirect GHG emissions of nitrous oxide (N₂O) from overall land use intensification over the 21st century that result from the production of 200EJ p.a. lingo-cellulosic bio-energy by 2050 are 6% of the carbon contained in the biomass; see Popp et al. (2009).

Secondary energy carriers are distinguished into modern (electricity, hydrogen, district heat), de-central (gases, transportation fuels) and traditional (other liquids, solids). The technologies for producing secondary energy carriers will be introduced next.

Table 2: Techno-economic characteristics of technologies based on exhaustible energy sources and biomass (cf. Iwasaki (2003), Hamelinck (2004), Bauer (2005), MIT (2007), Ragettli, (2007), Rubin et al. (2007), Schulz et al. (2007), Uddin and Barreto (2007), Takeshita and Yaaj (2008); Gül et al. (2008), Brown et al. (2009), Chen and Rubin (2009), Klimantos et al. (2009). All \$US values refer to 2005 values. Original literature values are normalized to this value taking into account general inflation, the CERA (2009) power plant price index and – if necessary – exchange rates.

		Techno-economic Parameters				
		Life-	Investment costs	O&M costs	Conversion	Capture

		time					efficiency		rate
		years	\$US/kW		\$US/GJ		%		%
			No CCS	With CCS	No CCS	With CCS	No CCS	With CCS	With CCS
Coal	PC	55	1400	2400	2.57	5.04	45	36	90
	Oxyfuel	55		2150		4.32		37	99
	IGCC	45	1650	2050	3.09	4.20	43	38	90
	C2H2*	45	1264	1430	1.65	1.87	59	57	90
	C2L*	45	1000	1040	1.99	2.27	40	40	70
	C2G	45	900		0.95		60		
Gas	NGCC	40	650	1100	0.95	1.62	56	48	90
	SMR	40	498	552	0.58	0.67	73	70	90
Biomass	BIGCC*	40	1860	2560	3.95	5.66	42	31	90
	BioCHP	40	1700		5.06		43.3		
	B2H2*	40	1400	1700	5.27	6.32	61	55	90
	B2L*	40	2500	3000	3.48	4.51	40	41	50
	B2G	40	1000		1.56		55		
Nuclear	TNR	35	3000		5.04		33~		

*) these technologies represent joint processes

~) thermal efficiency

Abbreviations: PC – conventional coal power plant, Oxyfuel – coal power plant with oxyfuel capture, IGCC – integrated coal gasification combined cycle power plant, C2H2 – coal to hydrogen, C2L – coal to liquids, NGCC – Natural gas combined cycle power plant, SMR – steam methane reforming, B2H2 – biomass to hydrogen, B2G – biogas plant, B2L – biomass to liquid, TNR – thermal nuclear reactor, SPV – solar photovoltaic, WT – wind turbine, Hydro – hydroelectric power plant.

Note: technologies marked with a * are joint production processes; for these technologies, capturing does not necessarily result in higher investment costs and lower efficiency in producing the main product.

Techno-economic details for most exhaustible and biomass fueled conversion technologies are provided in Table 2. Over the last few years the more pessimistic assessment of coal fired IGCC plants was the most important shift. The assumptions take this more careful interpretation into account: without CCS investment costs for IGCC are lower than for conventional pulverized coal (PC) plants, and the advantage in the case with CCS is greatly reduced. The general assessment to be found in the literature about electricity plants fueled with gas did not change that much over the last few years. The assumptions used here are generally in line with the literature. For biomass IGCC with and without CCS the parameters are chosen based on a broad literature review for a plant size of 100MW electrical output. Less

optimistic assessments about the investment costs than those applied in the present study are provided by Faaij (2006) and IEA (2008a).

Coal and biomass can also be converted into gases, liquids and hydrogen based on gasification. The conversion of coal, gas and biomass into liquid fuels and hydrogen can be augmented by carbon capture. The values for biomass technologies are at the pessimistic end of the range to be found in the literature. Those for coal and gas are in the medium range.

Table 3: Techno-economic characteristics of technologies based on renewable energy sources and biomass. For details see Neij (2003), Nitsch et al. (2004), IEA (2008a), Junginger et al. (2008), Lemming et al. (2008).						
	Lifetime	Investment costs	Floor costs	Learning Rate	Cumulative capacity 2005	O&M costs
	Years	\$US/kW	\$US/kW	%	GW	\$US/GJ
Hydro	95	3000	-	-	-	3.46
Geo HDR	35	3000	-	-	-	4.2
Wind onshore	35	1200	883	12	60	2.9
Wind offshore	35	2200	1372	8	1	4.7
SPV	35	4900	600	20	5	10.33

The techno-economic parameters for renewable technologies producing electricity are given in Table 3. Hydro power has investment costs of 3000\$US per kW. The exact number is highly site-dependent; see IEA (2008a). For wind power stations we distinguish on- and off-shore locations separately because both technologies are very different with respect to costs and other technological features. The floor costs are derived from cost projections for the year 2050.

Table 4: Techno-economic parameters of storage technologies; based on Chen et al. (2009) and expert interviews.				
	Units	Daily variation	Weekly variation	Seasonal variation
Technology		Redox-Flow-batteries	H2 electrolysis + combined cycle gas turbine	

Efficiency	%	80	40	Capacity penalty to secure supply
Storage capacity	Hours	12	160	
Investment costs	\$US/kW	4000	6000	
Floor costs	\$US/kW	1000	3000	
Learning rate	%	10	10	
Cumulative capacity in 2005	TW	0.7	0.7	
Life time	Years	15	15	
Cheaper technologies but not included due to limited potential		Pump-storage hydro & compressed air storage	Pump-storage hydro & compressed air storage	

Fluctuating renewable sources for electricity production require storage to guarantee stable supply of electricity; see Pietzcker et al. (2009). The approach implemented into the ReMIND model distinguishes between variations on the daily, weekly and seasonal time scale. Increasing market shares of fluctuating energy sources increase the need for storage to guarantee stable electricity supply. The superposition of variations on the three time scales is completely represented. Daily and weekly variations are compensated by installation of storage plants; see Table 4. Seasonal variations imply a capacity penalty.

The sequestration part of CCS requires equipment and energy for transportation and injection. The investment costs for having available the equipment for injecting one GtC per year are 175 bil.\$US; see Broek et al. (2008) and Kjärstad and Johnsson (2009). The upper limit for cumulative sequestration is 2775GtC; see Benson and Cook (2005) and IEA (2008b). The model does not consider leakage of injected CO₂.

The ESM of ReMIND does not – like many other energy system models⁵ – apply bounds on the investments of energy technologies. ReMIND uses adjustment costs for thermal nuclear reactors. For this technology it is assumed that in 2005 a maximum of 5GW could be installed increasing by 1GW p.a. Each percent investment beyond this limit increases the investment costs by 0.5%. The common critique that without bounds the model would compute unrealistic flip-flop behaviour known as penny-switching is avoided by detailing the energy system sufficiently; see e.g. Chakravorty et al. (2005) for an analytical treatment.

3. Scenarios and Results

For studying the issues raised above with the ReMIND framework three types of scenarios are computed:

1. Business-as-Usual (BAU): this scenario describes the optimal growth path if none of the policies discussed above are implemented. It serves as a reference point for the policy scenarios.
2. Climate Policy Scenario (CPS): optimizes policies to limit the GMT to stay below 2°C compared with the pre-industrial level until 2150 with a 50% probability. Consequently, the socially optimal solution for the scale and timing of mitigation

⁵ Grubler et al (1999, p. 271) noted: “Large-scale technology optimization models, which are widely used to assess the costs of abating various environmental problems, display similar ‘flip-flop’ behavior. Published runs typically do not illustrate such behavior only because additional constraints or restrictions on the rate and pattern of technological diffusion, tuned according to the modelers sense of the historical record, are applied to make the outputs appear more realistic. Like sausage, the final product is evidently wholesome but the method of producing tasty results is best left shrouded in mystery.” The implementation and parameterization of such constraints is usually not documented.

measures is computed. In additional experiments, the deployment of mitigation options in the energy conversion sector fossil CCS, biomass CCS (BCCS), biomass (BIO), renewables (RES) and nuclear (NUC) are constrained to the solution of the BAU scenario in order to assess their mitigation option values; this is indicated by sub-scripts to CPS.

3. Technology Policy Scenarios (TPS): evaluates policies that enforce deployment of technologies related to the five mitigation options in the energy conversion sector. The technology investments related to a mitigation option are fixed to the levels of the CPS. Hence five TPSs are computed that are indicated by sub-scripts. It would also be possible to use other time paths for the technology policies, but choosing the particular ones from the CPS enables the computation of the rebound effects because the deployment of the technology of interest is equal for two different policy approaches.

The CPS with full availability of all technologies is characterized by heavy reliance on solar energy. This standard case is augmented by switching off solar technologies leading to a high use of fossil CCS. There is two reasons for doing so. First, the optimistic potential for technology improvements may either turn out to be flawed or technology policies to develop the particular technology may not be successful. Second, the solution with high fossil CCS deployment is the basis for assessing the corresponding rebound effect of the fossil fuel option. Hence, we indicate with the super-scripts “S” and “C” for the CPS and the TPS which solution is the reference.

Wedges and option values are used to analyze the implications of climate policy scenarios. For the purpose of terminological clarity we keep to the scheme provided in Table 5.

Table 5: Terminology for the analysis tools differentiated by policy approach. The methods for computation are available on request from the authors.

		Policy Approach	
		Climate Policy	Technology Policy
Analysis Concept	Wedges	Mitigation Wedge	Technology Wedge
	Option Values	Mitigation Option Value	Technology Option Value

3.1. The Business-as-Usual Scenario

The BAU scenario is characterized by an annual GDP growth of 2.3% achieving 418tril.\$US in 2100. The annual primary energy demand shown in the left panel of Figure 6 increases to 907EJ and 1266EJ in 2050 and 2100, respectively. Coal is the most prominent primary energy source, accompanied by biomass that is already used up to its maximum potential in the BAU scenario. The price of coal is doubling as shown in the right panel of Figure 6. The use of hydrocarbons remains roughly constant though the price of oil is also doubling and natural gas prices only increase by a third. Renewables only contribute little and no new nuclear capacities are added. The penetration of wind conserves some coal in order to fuel growing final energy demand; see Amigues et al. (1998) for an analytical treatment of this result.

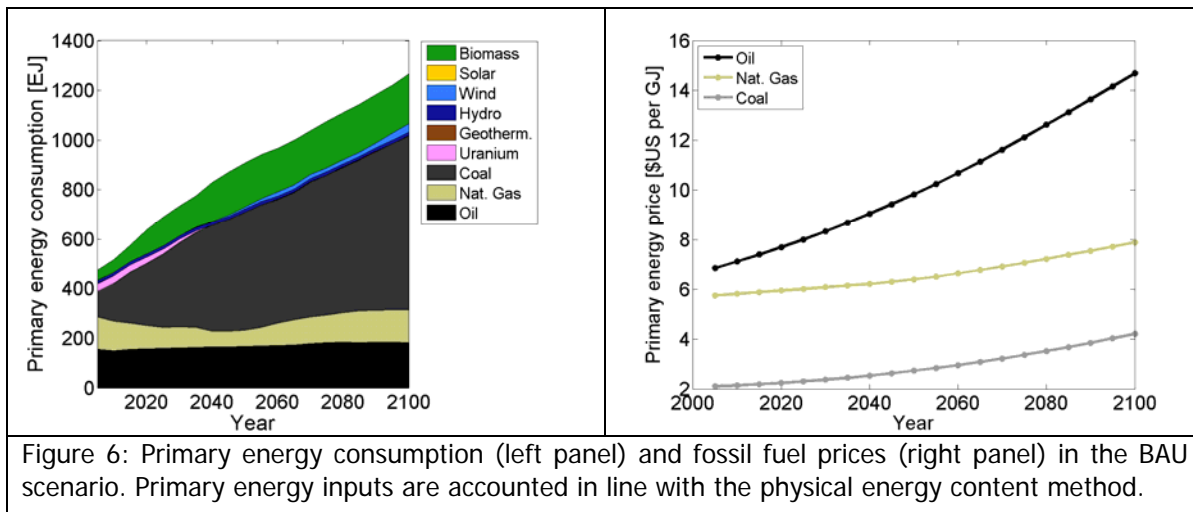
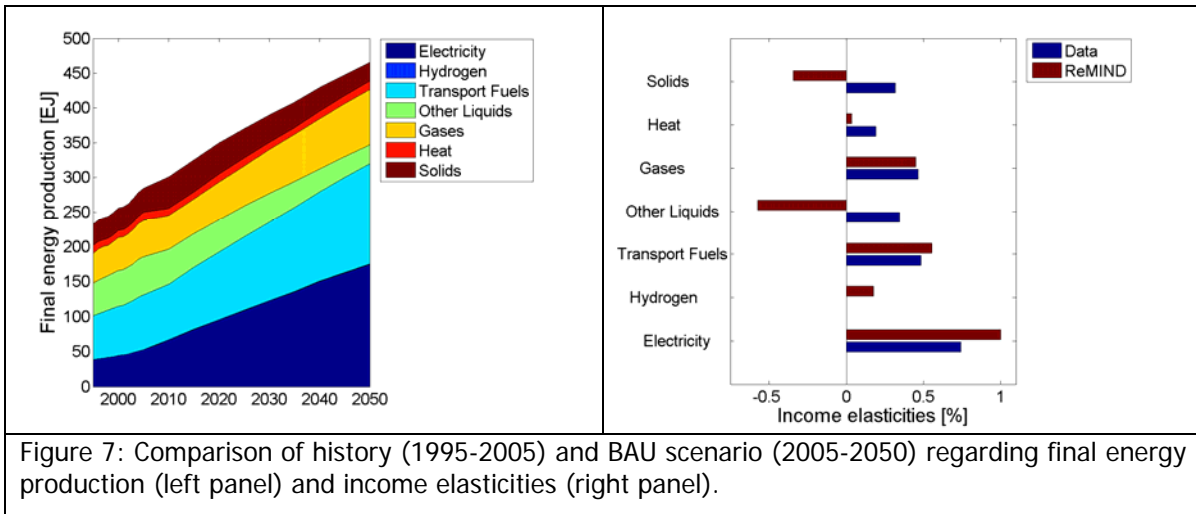


Figure 6: Primary energy consumption (left panel) and fossil fuel prices (right panel) in the BAU scenario. Primary energy inputs are accounted in line with the physical energy content method.

The heavy reliance on coal is due to the high growth of electricity demand – shown in the left hand panel of Figure 7 – that is mainly fuelled with coal. The production of transportation fuels is also increasing, though the consumption of crude oil remains stable. This is feasible because

less other liquids are produced from oil. Additionally, biomass is increasingly used to supply the growing demand, especially during the second half of the 21st century. The demand for gases is decreasing after 2005 in the short term due to the high supply price of natural gas but demand growth recovers quickly. The growing demand is satisfied by synthetic natural gas from biomass that peaks around the middle of the century. Finally, the production of solid energy carriers decreases because of relatively low demand. The right hand panel of Figure 7 shows the comparison of historic income elasticities⁶ of final energy carriers and those implied by the model until 2050; note that these estimates do not account for price changes. The scenario exhibits an accelerated modernization of the energy system: the income elasticity of electricity is highest and the scenario value is higher than the historic. For gases and transportation fuels ReMIND matches well with the historic data. Solids, other liquids and heat exhibit relatively low – and even negative – income elasticities for the scenario.



Consequently, CO₂ emissions from the energy sector increase to 24.0GtC p.a. in 2100, which leads to an atmospheric CO₂ concentration of 803ppm in 2100. In combination with the other

⁶ The income elasticity is the percentage change of final energy consumption for a one percent increase of income.

GHGs the total radiative forcing increases to 6.3W/m^2 that implies a GMT increase until 2100 by 3.8°C above pre-industrial levels.

3.2. Policy Scenarios

As noted above we present results for two main families of scenarios: one with high reliance on solar energy CPS^S and one without solar energy, but high reliance on fossil CCS named CPS^C. The primary energy mixes are shown in Figure 8. The left panel shows the solution with heavy reliance on SPV. The right panel shows the case for high deployment of CCS for electricity production.

There are only small differences between both scenarios until 2030. Both scenarios use considerable amounts of biomass with CCS for producing liquid fuels and electricity starting in 2020. Biomass to liquids with CCS is peaking in 2060 and at the end of the 21st century biomass is nearly completely allocated to biomass IGCC with CCS. Also nuclear, wind and hydro and are considerably extended; the increase is higher in the scenario with high CCS. For the CPS^S scenario investments into solar technologies start in 2020 and become significant in 2030. In the case with high CCS deployment the investments into coal IGCC with CCS start in 2030 and take off in 2060. The investments in NGCC with CCS start in 2050, but decrease after two decades. In both cases the electricity sector is nearly completely de-carbonized. The cumulative use of oil is reduced by 1070EJ and 1230EJ in CPS^S and CPS^C, respectively, compared to the BAU scenario. Natural gas demand remains roughly constant in the CPS^S case, but increases in the CPS^C scenario by 2310EJ compared to the BAU scenario over the 21st century. The increased use of natural gas after 2030 in both scenarios is due to fossil fuel switching in the electricity sector by the deployment of NGCC power plants. Most significant is the reduction of coal consumption: 28ZJ in the CPS^C scenario and 36ZJ in the CPS^S case.

Maintaining the use of hydrocarbons without CCS is rendered possible by the use of biomass with CCS because it allows for positive gross emissions.

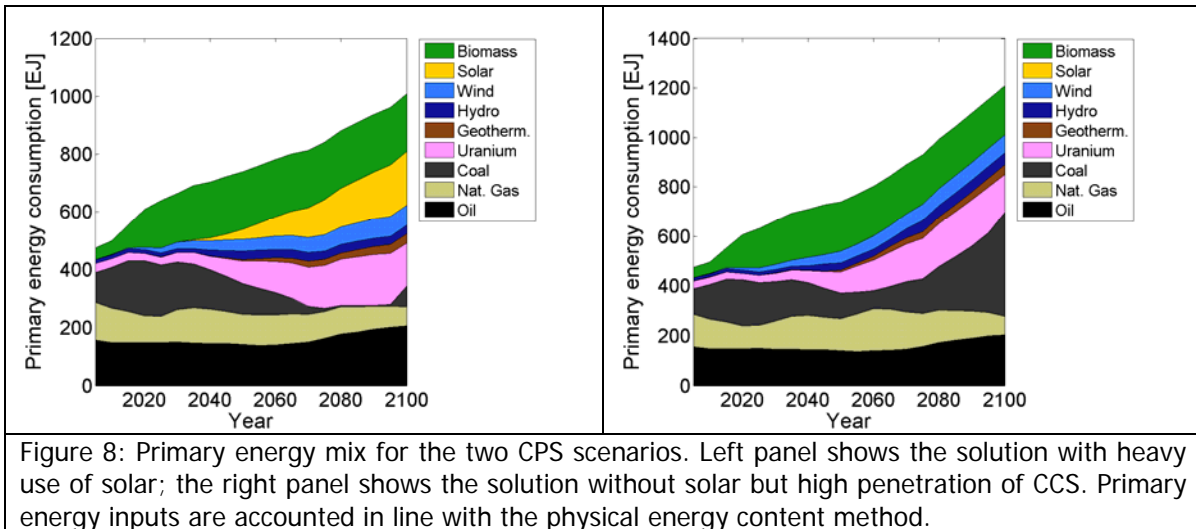
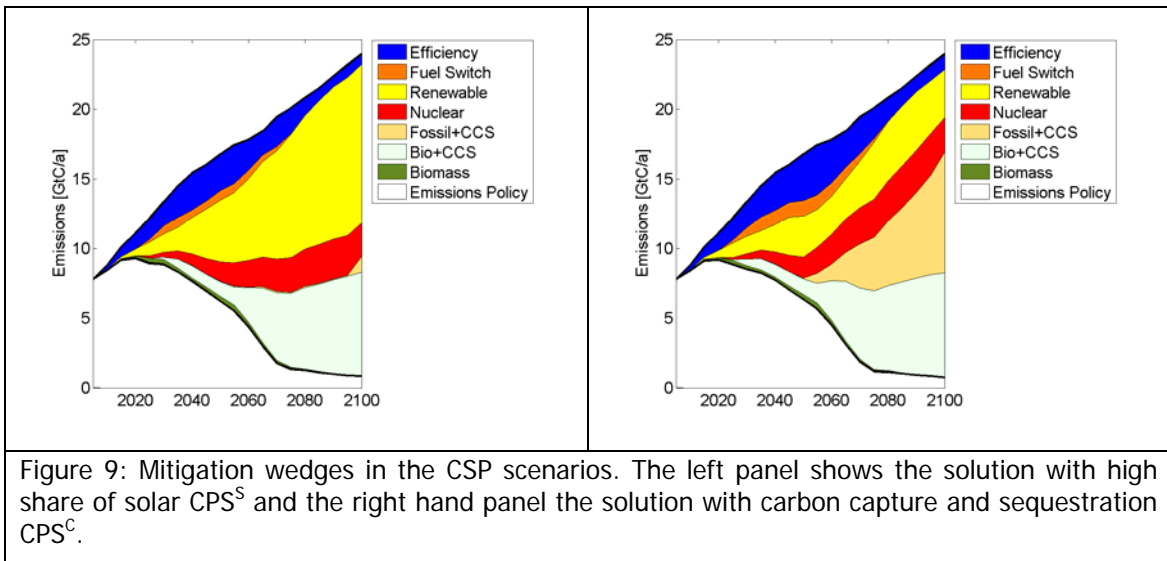


Figure 9 shows the mitigation wedges for the two scenarios CPS^S and CPS^C . The upper boundary shows the emissions in the BAU scenario. The lower boundary is the emissions in the CPS scenario net of the carbon removed from the atmosphere by biomass with CCS. The optimal emissions paths in both CPS cases are approximately the same. The emissions in both policy solutions increase until 2020 up to about 9.2GtC, but they deviate from the BAU case from the very beginning. Afterwards, the emissions decrease sharply, reach a nearly constant level of 1.2GtC p.a. in 2075 and keep on decreasing slowly to 0.9GtC p.a. in 2100. Other GHG emissions are significantly reduced according to the marginal abatement cost functions, but this is not discussed here.

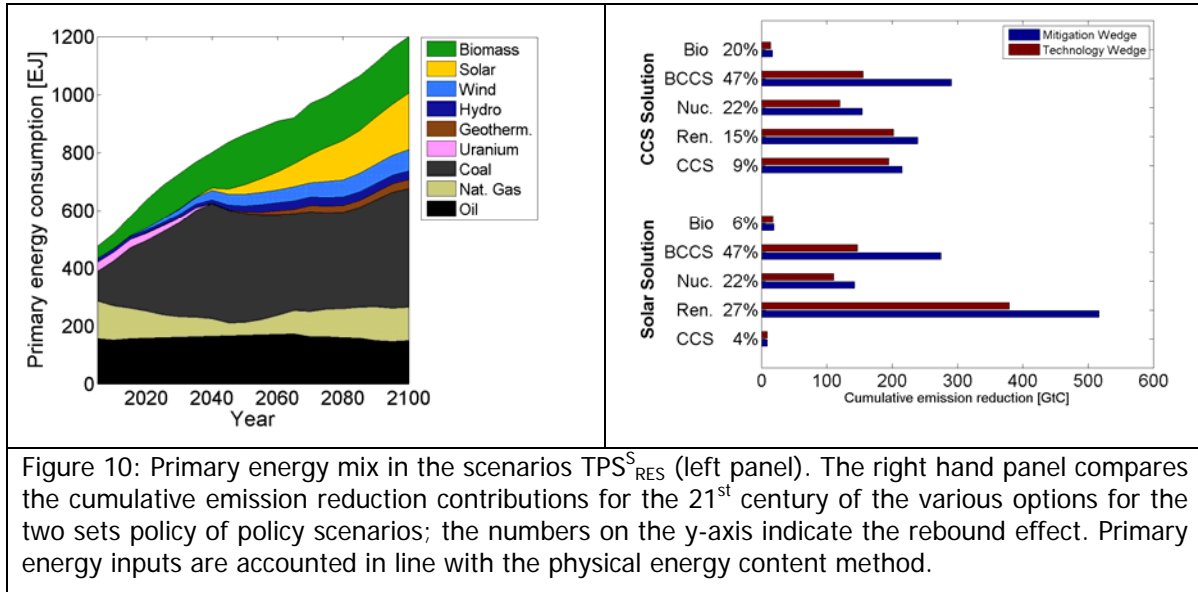
The differently colored patches are the mitigation wedges; i.e. the emission reductions attributed to mitigation options. In the near term the efficiency wedge is most prominent, but it remains relatively small over the mid- to long-term. The other mitigation options kick in one after the other. The huge mitigation wedges for the conversion sector in both cases reflect the

significance of de-carbonizing the electricity sector that makes the deep emission reduction possible. Biomass makes only a little contribution because it is already heavily deployed in the BAU scenario, hence, it does not contribute to additional emission reductions. However, the application of CCS with biomass makes a critical contribution and compensates for the emissions from using oil and natural gas derived products in de-central facilities like transportation vehicles. The use of energy is valued sufficiently high and changes in the conversion sector are competitive so that reductions in energy demand are not very emphasized.



Next, the results of the technology policy scenarios TPS are introduced. The left hand panel of Figure 10 highlights the primary energy mixes of a selected technology policy scenario: TPS^S_{Ren} takes the high renewable contribution from CPS^S as a constraint. It shows that coal is heavily used and not locked out of the system. Coal is also used for various purposes that were not competitive in the BAU scenario like coal-to-gas and coal-to-liquid. However the main reason is that coal is fuelling electricity production in addition to the renewable electricity production. Cumulative electricity production increases for the TPS^S_{Res} scenario by 4.4%

above the BAU scenario over the entire century. However, in the corresponding CPS^S scenario cumulative electricity production has been reduced by 6.5%. This pattern holds for the two sets of policy scenarios in general.



The rebound effect is shown in the right hand panel of Figure 10. It compares the cumulative emission reductions of the energy mitigation options for the two policy approaches and computes the relative rebound effect as given by the percentage numbers on the y-axis. The emission reduction achieved by the application of biomass is very small, hence, this option is not discussed any further. The combination of biomass with CCS has a high emission reduction potential but also a high rebound effect of nearly 50%. Fixing the multi-purpose energy carrier biomass that is limited in its potential to a particular conversion route attracts fossil energy carriers for the alternative purposes that were biomass fuelled in the BAU scenario. The rebound effect for nuclear power is 22% in both TPS cases. For renewables the rebound effect in the TPS^C is only 15% and the effect increases to 27% for the TPS^S case with the huge deployment of solar PV. The rebound effect of CCS in the TPS^C scenario is 9% and therefore

much lower than for the case with high solar PV deployment. The positive rebound effect is due to the additional application of CCS from NGCC plants, which were not applied in the BAU scenario.

The rebound arguments put forward by Sinn (2008) suggest that the rebound is particularly high for renewables and much less for fossils with CCS. Though the suggested ranking of both options is confirmed, the relative differences are not as dramatic as Sinn suggested. The rebound effect is not negligible for CCS. It is significantly higher for renewables and nuclear. However, the rebound effect is high for the CCS from biomass option because related technology policies increase the use of oil and coal.

For a TPS scenario that applies all mitigation options of the energy conversion sector simultaneously the rebound effect implies that emissions increase to 12GtC p.a. until 2040 and never fall below 7GtC p.a. thereafter. This would significantly overshoot the original climate change mitigation target.

Finally, we turn to the economic implications of the policy scenarios. Table 6 shows the results for all scenarios in terms of relative differences of cumulative discounted values for the period 2005 – 2100. The upper four rows summarize the results for the climate policy scenarios; the lower four rows show the results for the technology policy scenarios. The rows in gray show the results for the GDP indicator and those without background color the consumption losses that are a more appropriate welfare measure. Finally, the implications for the solar and the CCS case are separately shown. The columns show first the mitigation costs only for the CPS scenarios, in case that all technologies are fully available. The remaining five columns show the mitigation option values for the CPS scenarios (i.e. cost increase if the option is not

available) and for technology option values for the TPS scenarios (i.e. the costs for enforcing the technology into the system without constraint on emissions).

The mitigation costs in the two main CPS scenarios are 0.55% for the solar solution and 0.75% for the fossil CCS solution. The cost reduction potential of solar PV can reduce the overall costs of an emission pricing policy.

Removing technology options from the mitigation portfolio in the CPS scenarios increases the mitigation costs because the flexibility of the energy-economy system is reduced. The high value for biomass with CCS is notable for both CPS scenarios. Comparing this with the low value for fossil CCS in the scenario CPS_{CCS}^C is surprising. This is due to the flexibility regarding mitigation options in the electricity sector that substitute the missing fossil CCS option in relatively late periods. Non-availability of biomass with CCS has more severe consequences, because less hydrocarbons can be used, the deployment of fossil CCS has to be reduced and hence electricity production as whole decreases more significantly. This leads to a significant change of the optimal CO₂ emission path: it is optimal to reduce emissions strongly in the near term, which increases the discounted mitigation costs. The option value for renewables in the CPS_{REN}^S scenario is high, because the large and early contribution of solar PV is difficult to substitute by other mitigation technologies. The option value of nuclear is low because the emission reduction contribution can be substituted more easily.

Table 6: Cost implications of the policy scenarios; numbers indicate relative differences of cumulative discounted values 2005 – 2100 using a discount rate of 3%.								
Policy	Indicator	Solution	ALL	Option Values				
				CCS	Ren.	Nuc.	BCCS	Bio.
Climate policy	Cons. Losses	Solar	0.55	0.00	0.37	0.03	0.37	0.01
		CCS	0.75	0.07	0.19	0.04	0.46	0.01
	GDP Losses	Solar	0.66	0.00	0.41	0.04	0.62	0.01
		CCS	0.86	0.12	0.22	0.07	0.69	0.01

Technology policy	Cons. Losses	Solar	0.02	0.01	0.02	0.14	0.04
		CCS	0.18	0.02	0.03	0.15	0.04
	GDP Losses	Solar	0.00	-0.15	-0.02	0.02	0.01
		CCS	0.02	-0.06	-0.02	0.02	0.01

For the TPS scenarios the sum of consumption losses that would result from supporting all mitigation options up to the level in the CPS cases would be lower than the mitigation costs of these scenarios. Regarding the specific mitigation options the consumption losses are higher, if one of the two CCS options is supported compared with the renewable and nuclear options. The two CCS options are reasonable to reduce emissions but the energy penalty and the distorted allocation within the energy conversion sector incur costs to the economy. The allocation effect is particularly important for the biomass with CCS option, because the biomass devoted to produce electricity is not available anymore for substituting hydrocarbons. For the renewable and nuclear option there is no energy penalty and the distorted allocation in the energy conversion sector is less important because these primary energy carriers can only be used for electricity production.

A general pattern comparing the GDP and the consumption indicator is that for the CPS scenarios the impact measured in consumption differences is lower than for GDP differences. The opposite holds for the TPS scenarios. Actually, for the TPS scenarios that enforce large amounts of nuclear and renewables into the system the GDP is even higher than in the BAU scenario; hence, low-carbon technology policies can boost the economy, though this is not welfare improving because the impact on consumption is negative.

4. Discussion and Further Research

The analysis in this study assesses technological options for climate change mitigation in two different policy settings within the integrated energy-economy-climate model ReMIND. The study contributes to the debate about two policy approaches that aim at reducing CO₂ emissions from the energy sector. Climate policies following the economic approach aim at emission reductions by pricing emissions. This is effective in order to achieve a certain climate protection target like the 2°C target with 50% probability. However, it does not necessarily lead to the cost minimal solution, if the positive social value of technology learning is not internalized to induce early investments. The engineering approach that aims at direct deployment of technologies through specific support measures would be cheaper than the climate policy, but it suffers from considerable emission rebound effects. Hence, it fails to achieve the climate protection target. The lower costs are due to the high use of fossil fuels – in particular coal – that are not locked out effectively. The continued use of coal increases the production of final energy – especially electricity – and therefore energy prices decrease and economic costs are lower. Hence, deployment of low carbon technologies does not effectively lock out carbon emitting technologies from the energy conversion sector. Climate policies lock out the carbon emitting technologies but this also reduces the production of final energies, which increases energy prices and therefore mitigation costs.

The performance in terms of emission mitigation and costs varies significantly between the mitigation options and heavily depends on the policy approach. The contribution to emission reductions of nuclear and renewables would be reduced by the rebound effect in the technology policy case, though the costs would be low. The renewables option has a high value in the climate policy framework, because mitigation costs would increase significantly if it is not

available. In particular the solar PV technology is essential for achieving the climate protection target at low costs, but the initially high investment costs need to be decreased by technology support that induces early learning investments. However, the emission rebound effect of renewables nearly doubles with the contribution of solar energy. Fossil CCS could replace the contribution of solar PV, but the costs would increase significantly. The support of fossil CCS within a technology policy framework would have higher costs than the renewable option, but it leads to much lower rebound effects. Biomass CCS is indeed a mitigation option that only makes sense within a climate policy framework. It is very valuable in producing final energy carriers and taking up CO₂ from the atmosphere, which allows for the continued use of hydrocarbons. In a technology policy framework the costs would be high and half of the emission reduction would be offset by the rebound effect. Biomass without CCS would not lead to notable additional emission reductions because it is already heavily used in the scenario without any policy addressing climate change.

The high flexibility of the ReMIND model suggests a relationship between the low mitigation costs in the climate policy case and the high rebound effects in the technology policy scenarios. The flexibility of reallocating investments within a broad portfolio of technologies and adjusting demand to price changes is the general reason for the low mitigation costs. The rebound effects are so significant because the energy sector offers many alternatives to use coal that is substituted by the deployment of low carbon technologies. Thus coal is not replaced, but augmented by low-carbon technologies. This finding has an enormous implication for the debate about the economics of climate change mitigation. High rebound effects are consistent with little costs for reducing emissions by market based climate policies. If the rebound effect is found to be negligible, technology support policies would be effective in reducing emissions,

but constraining emissions by climate policies would lead to high costs. However, the argument for market based climate policies should not ignore the use of technology support policies that make low carbon technologies ready by bringing down the costs, because this increases the flexibility of the energy sector to react to increases of carbon prices.

These findings highlight the need to analyze technologies and policies in an integrated manner within a model framework. To improve science in this direction we set out three issues that seem promising for future research. First, economic significance of coordinating technology support policies and climate policies in an integrated framework should be studied intensively; see e.g. Kverndokk and Rosendahl (2007). The available studies only used idealized models of the energy sector. Conceptual research is needed to develop approaches that allow studying second best coordination of climate and technology policies in a perfect foresight framework like ReMIND. Then we could ask for the significance of coordinating policies and whether ill-defined technology support may do more harm than good. Second, the present study only focused on the two policy approaches for reducing CO₂ emissions from the energy sector. However, the same question is worth to be explored regarding other sources of GHGs. In particular, the land use sector, which is the second most important emitter of GHGs, is different in many respects compared to the energy sector because the latter today is fuelled from fossil stock resources but land-use change decisions are annually revised. Moreover, the quest for diet behavior (meat demand, etc.) could turn out as a field that is subject to little rebound effects. Finally, the flexibility of the energy sector can be measured by the elasticity of substitution between the production factors carbon emissions and capital. The numerical model should be analyzed to estimate the elasticity of substitution subject to technology availability, techno-economic parameters and availability of policy instruments. Such analysis would

improve our understanding of the costs of climate change mitigation and could also be applied to other models.

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