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The REMIND-R model: the role of renewables in the low-carbon transformation—first-best vs. second-best worlds

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Abstract Can near-term public support of renewable energy technologies contain the increase of mitigation costs due to delays of implementing emission caps at the global level? To answer this question we design a set of first and second best scenarios to analyze the impact of early deployment of renewable energy technologies on welfare and emission timing to achieve atmospheric carbon stabilization by 2100. We use the global multiregional energy–economy–climate hybrid model REMIND-R as a tool for this analysis. An important design feature of the policy scenarios is the timing of climate policy. Immediate climate policy contains the mitigation costs at less than 1% even if the CO_2 concentration target is 410 ppm by 2100. Delayed climate policy increases the costs significantly because the absence of a strong carbon price signal continues the carbon intensive growth path. The additional costs can be decreased by early technology policies supporting renewable energy technologies because emissions grow less, alternative energy technologies are increased in capacity and their costs are reduced through learning by doing. The effects of early technology policy are different in scenarios with immediate carbon pricing. In the case of delayed climate policy, the emission path can be brought closer to the first-best solution, whereas in the case of immediate climate policy additional technology policy would lead to deviations from the optimal emission path. Hence, technology policy in the delayed climate policy case reduces costs, but in the case of immediate climate policy they increase. However, the near-term emission reductions are smaller in the case of delayed climate policies. At the regional level the effects on mitigation costs are heterogeneously distributed. For the USA and Europe early technology policy has a

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positive welfare effect for immediate and delayed climate policies. In contrast, India looses in both cases. China loses in the case of immediate climate policy, but profits in the delayed case. Early support of renewable energy technologies devalues the stock of emission allowances, and this effect is considerable for delayed climate policies. In combination with the initial allocation rule of contraction and convergence a relatively well-endowed country like India loses and potential importers like the EU gain from early renewable deployment.

1 Introduction

The transformation of the global energy system towards de-carbonization is identified as a key challenge for the 21st century. Following historical trends of de-carbonization is not sufficient to meet stringent climate change mitigation targets as well as major objectives related to environmental protection and economic development, see e.g. Nakicenovic and Riahi (2002). Renewable energy technologies have been identified as an essential option for the transformation of the energy system to meet climate change mitigation. The main driver triggering the recent deployment of renewable energy technologies has not been carbon pricing but dedicated support for renewable energy technologies. May convert the logical relationship into the opposite direction: high renewable deployment contains the costs for achieving stringent climate policies and, hence, increases the social acceptability and economic affordability of such long-term goals. The present paper aims at gaining insight on the role of renewable energy technologies in the transformation of the global energy system and on how they interact with global and regional mitigation costs, if climate policy is delayed.

The issues of climate change mitigation and renewable energy technology (RET) deployment are high on the political agenda. An international agreement on binding caps on greenhouse gas (GHG) emissions is yet not implemented and it is expected that it will take some years before such agreement will enter into force at the global level. The fifteenth Conference of the Parties (COP) 2009 to the UN Framework Convention on Climate Change (UNFCCC) in Copenhagen was expected to make a great step into this direction, but it failed to meet these expectations. However, the Copenhagen Accord called for long-term co-operative action, recognizing the scientific view that the increase of global mean temperature should not exceed 2°C. This is an important outcome in making Art. 2 of the UNFCCC more operational that formulated the ultimate objective of stabilizing GHG concentrations at a level that prevents dangerous interference with the climate system. Though the international negotiation process arrived at a more concrete long-term target, there is no internationally binding agreement on how to deal with emissions in the short-term. Rogelj et al. (2010) reviewed the pledges to the Copenhagen Accord and concluded that according to the pessimistic interpretation the emission cap in 2020 “is nearly equal to the business-as-usual [emissions].”

The growth of CO_2 emissions during the last decade was the highest ever reported, which was mainly triggered by the increasing use of coal. This trend is expected to continue over the next decades, if no effective climate policies are implemented. The global economic crisis of 2008 is not expected to make a huge difference; see e.g. IEA-WEO (2010).

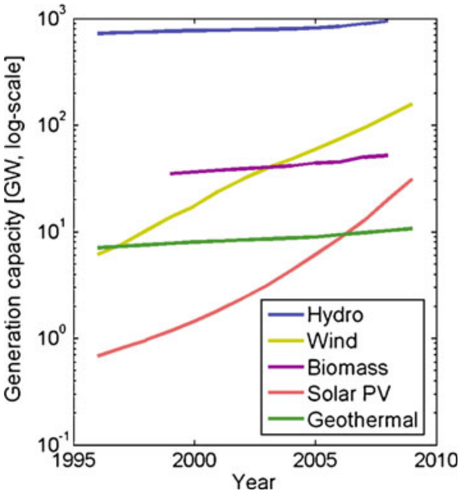


Fig. 1 Global generation capacities of RETs in the electricity sector 1996 to 2009. Sources: GWEC (2010), IEA WEO various issues, REN 21 various issues, Jäger-Waldau (2009)

At the same time, RET deployment is pushed forward by many national governments, for a number of reasons, including climate change mitigation. Feed-in tariffs, renewable energy quotas and other measures triggered a boom of RET, especially in the electricity sector. The recent recession did not interrupt the development. Green Recovery Programs—see e.g. Edenhofer et al. (2009)—are accelerating the development. Jäger-Waldau (2009, p. 10) notes that the major part of the various national fiscal stimuli for renewable energies have not yet been spent, but are going to become effective in 2010 and 2011.

Figure 1 reports the global generation capacities of electricity producing RETs in log-scale. The global cumulative capacity for Wind has been increasing at an annual rate between 21% and 37%; for solar PV the cumulative capacity has been growing at 20% p.a. in the late nineties and by more than 40% p.a. in the period 2005 to 2008. Jäger-Waldau (2009, p. 103) concludes that "the photovoltaic industry is developing into a fully-fledged mass-producing industry." Hydro, geothermal, and biomass were only slowly increasing, but started at relatively high levels in the 1990s. It should be noted that the capacity additions of hydro in 2008 are reported at 35GW, which is still larger than the sum of wind and solar, amounting to 32.5GW. The capacity additions of wind and solar are rapidly growing and, hence, are expected to exceed the new installations of the more traditional renewable electricity technologies within the next few years.

The recent boom of RET over the first decade of the 21st century outpaced all earlier expectations.[1] Policies already in place and recent observations of market developments confirm the expectation that RET deployment will keep on rapidly growing in the near-term future, see e.g. GWEC (2010, p. 15), Jäger-Waldau (2009, p. 17).

[1]For example, IEA-WEO (2002, p. 412) expected the wind power capacity in 2010 at 55GW. The realized value in 2009, however, is 159GW.

In summary, the present situation is ambivalent. The need for limiting climate change is accepted but no emission limitations are implemented at the global level, and renewable energy sources as well as coal use grow at very high rates. From an economic point of view these ambivalent developments raise two sets of research questions:

1. Assume the implementation of global climate policy is delayed until 2020. Is the near-term RET deployment reducing or increasing the mitigation costs of delayed climate change mitigation policies? How is this related to the global CO_2 emissions in 2020? What are the mitigation cost impacts for different regions?
2. For comparison, assume that RET deployment is varied and a global cap-and-trade system for CO_2 emissions is implemented immediately. How do deviations from the optimal RET deployment scenario change the time path and the regional distribution of mitigation cost? What is the impact on global CO_2 emissions?

To answer the first set of questions is the main objective of the present study. The complex interplay of climate and technology policies leads to various effects. To provide a clear understanding of the forces at work, the second set of questions is elaborated.

The methodological approach addressing these questions is to design and to analyze a set of first- and second-best scenarios using the energy–economy–climate model REMIND-R. This is in line with the general philosophy of the RECIPE project; see Luderer et al. (2011, this issue). Previous contributions to the economics of climate change mitigation have intensively applied this methodology for designing scenarios to assess mitigation costs. Manne and Richels (2004) discuss the impact of endogenous technology learning-by-doing on the optimal emission path and the costs for achieving a given stabilization target. They find that technology learning has little impact on the optimal emission path, but significantly reduces the costs for achieving the stabilization target. The International Model Comparison Project assessed the contribution of induced technological change to meeting atmospheric stabilization of GHGs at the lowest possible costs; see Edenhofer et al. (2006). The EU ADAM project mainly focused on the significance of having available specific low-carbon technologies; see Edenhofer et al. (2010). The 22nd round of the Stanford Energy Modeling Forum focused on the impact of delayed mitigation policies and the significance of temporary over-shooting of the stabilization targets; see Clarke et al. (2009).

We extend the methodology in two directions focusing especially on the timing of climate and technology policies. The first set of questions suggests the comparison of two different second-best scenarios: delayed climate policy and early RET deployment are combined. Up to our knowledge the comparison of two second-best scenarios is an innovation to the methodology and extends the debate on the economics of climate change mitigation and technology deployment. The resulting impact of early technology deployment on the mitigation costs is considerable. For improving our understanding we formulate the second set of scenarios which analyze the impact of weaker versus stronger technology development in combination with immediate climate policy. This is also different to common technology second-best scenarios, where the availability of technologies is limited below the optimal case. In the present study the deployment of RET is constrained to deviate negatively as well as positively from the first-best solution.

The analysis of second-best scenarios is related to the discussion about the optimal timing and coordination of policies in the context of climate change mitigation; see Sorrell and Sijm (2003). Böhringer et al. (2009) evaluate the simultaneous application of a cap-and-trade system and renewable penetration targets in the EU using a computable general equilibrium model. They find that the additional costs of the technology policy are small and the CO_2 permit price is decreased. Kverndokk and Rosendahl (2007) discuss the optimal choice of emission taxes and technology subsidies for limiting cumulative emissions in the presence of spill-over effects due technology learning-by-doing. The highly stylized partial model covers the electricity sector of a single region. The study analyzes delays in choosing carbon taxes and technology subsidies. The paper finds that delaying the optimal carbon emissions tax has little impact on welfare. In addition, its effect is smaller than delaying the optimal technology subsidy. Similar studies on first- and second-best policies with explicit representation of policy instruments to address multiple and interlinked externality problems have been undertaken on the coordination of technology R&D and emission taxing policies; see e.g. Gerlagh et al. (2009). Also other market failures could be considered, but like the issue of technology R&D this is not the focus of this paper.

The present study applies a multi-regional model covering the total energy system, the macro-economy and the climate system. It computes first- and second-best scenarios to quantify the economic, technological, and environmental effects of climate and technology policy. The first- and second-best scenarios are implemented by imposing constraints on environmental variables (i.e. atmospheric CO_2 concentration) and on technology related control variables (i.e. investments). The approach to design second-best scenarios by constraining investment variables is different to the second-best policy analysis as has been studied by Kverndokk and Rosendahl (2007), who imposed constraints on policy variables that aim at changing the investment decisions of autonomous private agents.

The remainder of the paper is organized as follows. Section 2 introduces the REMIND-R model that is the numerical tool for assessing the research questions. Section 3 introduces the design of the scenarios and how they are related to the research questions. Section 4 presents and discusses the results. Section 5 concludes and points to promising fields for future research.

2 The REMIND-R model

The Refined Model of Investment and Technological Development (REMIND) is used as the numerical tool to address the research questions raised above. The model is documented in literature; see Bauer et al. (2009) and Leimbach et al. (2010). In the following the general structure of the model and the role of renewable energy is elaborated as it is important for the sake of this paper.

Figure 2 provides a generic overview on the model structure. REMIND-R is an inter-temporal, general equilibrium, multi-regional energy–economy–climate model.

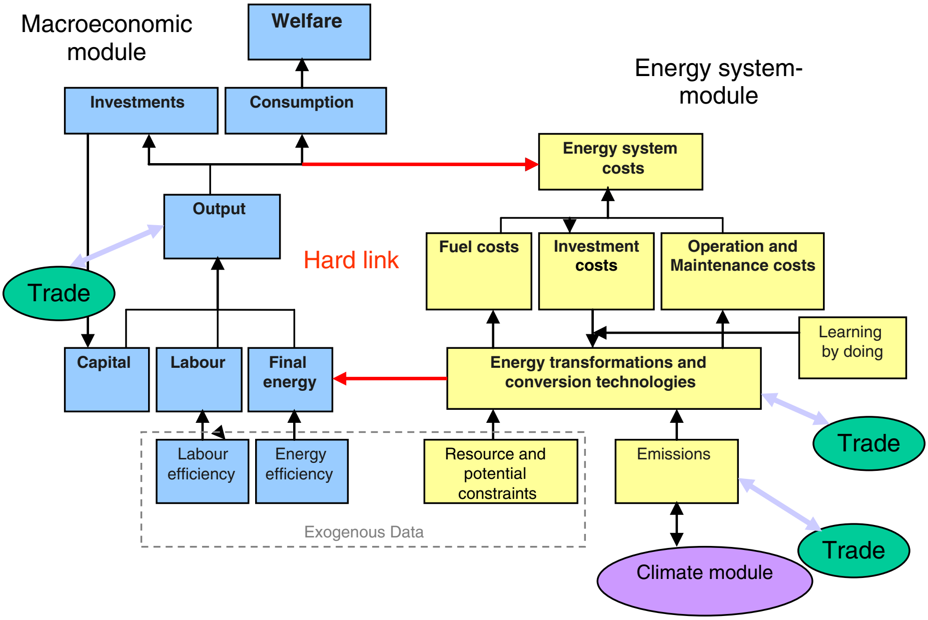


Fig. 2 Overview of the REMIND-R model framework. *Blue boxes on the left* are related to the macroeconomic growth model, *yellow boxes on the right* denote elements of the energy system model. The *red arrows* highlight the hard-links between models. The *light-colored arrows* indicate trade relationships

In each of the eleven world regions[2] a Ramsey-type growth model represents the macro-economy. The energy sector model is embedded into the macro-economic growth model. Both models interact by financial and energy trade flows. A social optimum for each region is computed by maximizing the inter-temporal, social welfare subject to economic and technological constraints as well as prices for internationally traded goods. In each region a hard-link between the macro-economy and the energy system guarantees simultaneous equilibrium on all markets for final goods, capital, labor and energy; see Bauer et al. (2008). The Negishi-approach is applied to compute the Pareto-equilibrium of trade between the regions; see Manne and Rutherford (1994) and Leimbach and Toth (2003). International trade comprises the generic macro-economic good, coal, oil, gas, uranium and emission permits.

Climate policy is imposed by setting a constraint on the atmospheric CO_2 concentration. The resulting CO_2 emission path minimizes the mitigation costs for the world economy by fully exploring ‘when’- and ‘where’-flexibility of mitigation measures given the full tradability of emission permits and inter-temporal equilibrium of the international capital market. The emission permits are distributed to the regions according to an allocation rule, based on the contraction and convergence scheme.

[2]In the present study we have focus on the US (USA), Europe (EUR), China (CHN), and India (IND). The other countries are summarized in the two aggregates Rest of Annex-1 (RAI), which comprise those countries committed to reduce emissions under the Kyoto Protocol and Rest of Non-Annex-1 (RNAI), which are all the other countries that have not agreed on reducing emissions.

The allocation to the regions follows a two step approach. First, the global emission path is optimized. Second, each region receives a share of this aggregate according to the allocation scheme.

The energy sector represents the conversion of energy carriers by various linear production technologies. Each technology is described by a set of techno-economic characteristics. Energy conversion requires the availability of capacities that are extended by specific investments and decreased by technical depreciation. Table 1 gives an overview of all available technologies and conversion routes from primary to secondary energy. Primary energy is distinguished in exhaustible and renewable energy carriers. The former are subject to extraction costs that increase in cumulative extraction. The tradable endowments are owned by the region where they are located. The latter are non-tradable and subject to potentials that are differentiated by grades that capture the decreasing quality of different locations. Secondary energy carriers are delivered to the macro-economic sector that uses them in combination with capital and labor to generate macro-economic output using a nested CES production function.

Renewable energy carriers are an option to supply the rapidly growing demand for electricity. The renewable energy technologies solar PV and wind turbines are learning technologies with learning rates of 20% and 12%, respectively. Learning-by-doing can reduce the investment costs of wind turbines from 1200$US per kW to a minimum of 883$US per kW. The assumptions for solar PV are 4900$US per kW and 600$US per kW, respectively. The fluctuating nature of both primary energy sources is addressed by imposing constraints that imply the need of storage facilities and excess capacities, both, depending on the technologies' share in the generation mix; see Pietzcker et al. (2009) based on techno-economic assumptions from Chen et al. (2009).

Biomass is notable for the supply of other secondary energy carriers. Currently biomass is mainly used in solid form for satisfying basic needs using traditional biomass technologies. With growing income and growing demand for modern energy carriers traditional biomass utilization fades out of the system. The supply for modern ligno-cellulosic biomass utilization is growing to a maximum of 200EJ p.a. in 2050; see van Vuuren et al. (2009) for an assessment of this assumption. Biomass can also be utilized in combination with carbon capture and sequestration (CCS) for the production of electricity, hydrogen and transportation fuels. Hydrogen could be produced from low-carbon electricity sources like renewables or nuclear vie electrolysis (not shown in Table 1). More direct conversion routes for hydrogen production from renewables and nuclear are discussed in Magné et al. (2010).

3 Scenarios

The development of the scenario set-up in this study follows a five step approach. Table 2 summarizes the scenario assumptions that are elaborated in more detailed next. The first step is to compute a case without climate policy constraints, denoted as the BASELINE scenario.

The second step is to compute three first-best climate change mitigation scenarios. The scenarios are constrained to stabilize CO_2 concentrations at 410, 450, and 490 ppm by 2100 with temporary over-shoot. In each scenario the CO_2 concentration

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

Secondary energy carriers	Primary energy carriers						
	Exhaustible				Renewable		
	Coal	Oil	Gas	Uranium	Solar, wind, hydro	Geo-thermal	Biomass
Electricity	PC[a], IGCC[a], CoalCHP	DOT	GT, NGCC[a], GasCHP	TNR, FNR	SPV, WT, Hydro	HDR	BioCHP, BIGCC[a]
H2	C2H2		SMR[a]				B2H2[a]
Gases	C2G		GasTR				B2G
Heat	CoalHP, CoalCHP		GasHP, GasCHP			GeoHP	BioHP, BioCHP
Liquid fuels	C2L[a]	Refin.					B2L[a], BioEthanol
Other liquids		Refin.					
Solids	CoalTR						BioTR

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 methane 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

[a]These technologies are also available with carbon capture

Table 2 Overview of scenarios

	Climate policy (CO_2 only)	RET deployment	Comment
Baseline	None	Optimal	
POL^x	Starting in 2010 × indicates the stabilization at 410, 450, 490 ppm by 2100	Optimal	First-best scenarios
POL^{DEL}	Delayed (**DEL**) until 2020 450 ppm by 2100	Optimal subject to delayed climate policy	Second-best: Delayed climate policy
$POL^{D\&R}$ (s/m/w)	Delayed (**D**) until 2020 450 ppm by 2100	**R**ET deployment is strong (**s**), medium (**m**) or weak (**w**) Until 2020	Second-best: Delayed climate policy and exogenous RET deployment
POL^{RET} (s/w,20/30)	Starting in 2010 450 ppm by 2100	**RET** support strong (**s**) or weak (**w**) Until 2020 or 2030	Second-best: Immediate climate policy with exogenous RET deployment

is allowed to exceed the target by a maximum of 4.5%.[3] Non-energy CO_2 emissions are assumed to follow an exogenous path; see Luderer et al. (2011, this issue). The emission permits are consistent with the optimal emission path and distributed among regions according to the convergence and contraction scheme achieving equal per-capita allocation in 2050; see Den Elzen et al. (2008) and Leimbach et al. (2010). The scenarios are denoted POL^x, where x indicates the stabilization target.[4]

In the third step climate policy is delayed. The climate policy starts in 2020. Until the beginning of climate policy all investment paths are constrained to the BASELINE scenario. This scenario is denoted POL^{DEL}.[5]

In the fourth step the delayed climate policy is combined with early RET deployment constraints. For this purpose in all regions the RET deployments of the three POL^x scenarios until 2050 are given as exogenous constraints in a scenario without any climate policy. The resulting three scenarios provide different development paths for the entire energy–economy system. These three developments until 2020 are used as exogenous constraints for all stock variables, i.e. until the period, when climate policy becomes active. Hence, the delayed climate policy is combined with weak, medium and strong scenarios for early deployment renewables. These scenarios are denoted $POL^{D\&R}$. The three deployment scenarios (**w**eak, **m**edium, **s**trong) are indicated in parentheses. The three scenarios are compared with the POL^{450} and the POL^{DEL} scenarios to address the first set of questions raised above.

In the fifth step immediate climate policy is combined with four non-optimal RET deployment paths to achieve the 450 ppm stabilization level; i.e. the capacity values

[3]This degree of overshooting is the same as assumed in A1_CC_Overshoot in Luderer et al. (2011, this issue). To maintain consistency across scenarios the same overshooting is allowed for the scenarios POL^{410} and POL^{490}.

[4]The scenario POL^{450} is the same as the scenario A1_CC_Overshoot in Luderer et al. (2011, this issue). The scenario POL^{410}, however, is stricter than the scenario A1_CC_410 because the permissible overshoot is smaller.

[5]This scenario is the same as the scenario C8_DELAY2020 in Luderer et al. (2011, this issue).

of all technologies as given in the renewable columns of Table 1. For this purpose **s**(trong) and **w**(eak) RET deployments are considered as exogenous scenarios. The assumptions for the exogenous RET deployment pathways are taken from POL^{410} for the scenario strong scenario and from POL^{490} for the weak scenario. Furthermore, the deployment assumptions are fixed for two time horizons until (20)**20** and (20)**30**. This set of second-best scenarios is denoted POL^{RET}. A specification in parentheses distinguishes the intensity and the duration of the exogenous RET deployment assumptions. The benchmark for comparison is the first-best POL^{450} scenario. The analysis addresses the second set of questions raised above.

The design of the $POL^{D\&R}$ scenarios is based on model outcomes for the period 2010 to 2020 because this approach provides different levels of RET deployment. The alternative would be to base the assumptions on deployment targets announced by governments. It is, however, not the aim of the present study to assess the various renewable policy targets, but to assess the significance of a range of RET deployment assumptions. Deriving the assumptions from scenarios computed by the same optimization model implies that the deployment paths are implicitly tailor-made for the model. The technology policy assumptions are, thus, not subject to the critique of failing to 'picking the winner', which means that the portfolio of the technology policy is not a mis-allocation, but suits the needs of the energy sector represented in the model.

4 Results

4.1 First best solutions—BASELINE and POL^x

The BASELINE and the POL^x scenarios are the starting point for the analysis. The POL^{450} scenario serves as a point of reference for the second-best scenarios introduced in the following sub-sections. Furthermore, the POL^x scenarios provide RET deployment paths that are used as constraints for second-best scenarios below.

Figure 3 shows the global CO_2 emissions from the energy sector for the four scenarios. BASELINE emissions increase to 21GtC p.a. in 2050 and remain approximately at this level. The rapid increase of CO_2 emissions is mainly triggered

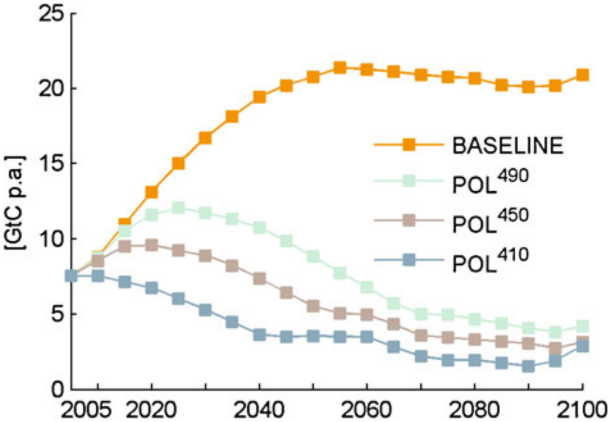


Fig. 3 Global CO_2 emissions 2005 to 2100 from the energy sector for the scenarios BASELINE and POL^x

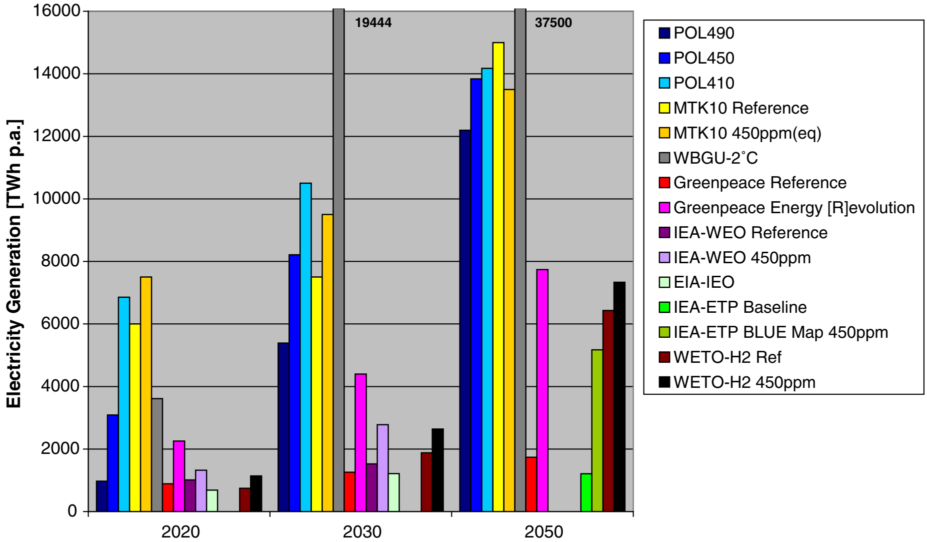


Fig. 4 Electricity generation from wind power turbines in the three POL^x scenarios computed with REMIND-R and results from other publications. Sources: WBGU (2003, p. 138), Magne et al. (2010, p. 93), Greenpeace (2008, p. 190 and 191), IEA (2009, p. 229 and 623), IEA (2008 p. 85), EIA (2009, p. 67), WETO is EC (2006, p. 120 and 129). IEA-WEO and EIA-IEO consider only a time horizon until 2030; IEA-ETP reported numbers only for the year 2050

by the supply of huge amounts of cheap coal. The three POL^x scenarios cover a wide range of different emission pathways. To achieve the 450 ppm target, CO_2 emissions deviate from the BASELINE immediately, peak in 2020 below 10GtC p.a. and decrease to 3.6GtC p.a. in 2070 to stay at this level afterwards. The less ambitious 490 ppm target allows the emissions to peak in 2025 at a much higher level (12GtC p.a.). The emissions start to deviate from the BASELINE path after 2015. In the longer run emissions stabilize at 5GtC p.a. To achieve the much more ambitious 410 ppm target emissions need to decrease immediately and stabilize at 2GtC p.a. in 2070.

The deployment of RET in the three POL^x scenarios also varies over a large range. In the following, the deployment of wind and solar for electricity production are analyzed in depth and compared with scenarios from the literature. The choice for these two technologies is due to the significant deployment computed with REMIND-R and the rapid growth experienced in recent past.[6] Finally, remarks on other RET that are subject to the technology deployment policies will be added.

Figure 4 shows the electricity generation from wind power turbines in the years 2020, 2030 and 2050. The three POL^x scenarios computed for this study show significant sensitivity regarding timing of deployment of wind power turbines. The largest relative differences are observed in 2020, but in 2050 all three paths converge

[6] It is worth to note that only few studies provide results on differentiated global renewable electricity generation. It is common practice to report figures that contain an aggregate on “Other Renewables”, which does not give insight into the contribution of wind, solar, etc.

to quite similar levels. For the scenario POL^{410} the growth is most significant in the coming decades, whereas for the POL^{490} scenario growth accelerates significantly after 2030.

The future wind electricity production of the three scenarios can be compared with simple extrapolation of the historical time series given in Fig. 1 above. Assuming a constant growth rate of installed capacity until 2020 would result in a capacity of 3000GW. Assuming an annual average of 2000 full load hours, which is a relatively low number, would result in an output of electricity of 6000TWh p.a. Comparing this number with the results in Fig. 4 indicates that for the scenario POL^{450} future growth rates could even decrease from their historical levels. For the case POL^{410} the growth rate of installed wind turbine capacity might need to increase above historical rates.

For the comparison with other studies it is useful to distinguish two groups. The first group comprises modeling studies that are similar to the present REMIND-R study. They apply inter-temporal energy-economy models with optimization under perfect foresight. Magne et al. (2010) use the model MERGE-ETL (denoted MTK10) and WBGU (2003) uses the model MESSAGE (denoted WBGU-2°C). Both studies show—like the REMIND-R scenarios—high wind power generation. MTK10 provides two scenarios: the reference case does not consider any climate policy and the 450 ppm scenario[7] considers all GHGs and, thus, is more stringent than the POL^{450} scenario of the present study. In the near-term wind power generation is higher in the 450 ppm scenario than in the reference scenario, but in 2050 the ranking is reversed. This can be explained with the absorptive capacity for fluctuating electricity sources that decreases in the policy scenario because the total electricity generation decreases. The WBGU scenario is supposed to limit the increase of global mean temperature to not more than 2°C above pre-industrial levels. Wind power generation is the highest of all scenarios.[8]

The second group of scenarios is mainly motivated by energy issues and the underlying models are not using inter-temporal optimization with perfect foresight. The scenarios show much lower deployment of wind power. Even the Greenpeace Energy [R]evolution scenario is much lower in 2050 than the scenarios belonging to the first group.[9] The lowest scenario is provided by the US Energy Information Administration (EIA) that does, however, not consider a climate stabilization target. The smallest difference between the reference case and the climate policy case is provided by the WETO-H2 study.

Figure 5 shows the corresponding graph for electricity production from solar sources in log-scale. For all scenarios solar electricity generation in 2030 is less than for wind. In 2050 this ranking is reversed in some of the scenarios. Solar electricity production increases by two orders of magnitude—and even more for few scenarios—within three decades. Regarding the timing of deployment the three

[7]The scenario allows for over-shooting the concentration target.

[8]It should be noted that this scenario is subject to limited possibilities for using alternative technologies in the power sector. Nakicenovic and Riahi (2002) provide an in-depth analysis of the MESSAGE model. For a broad range of scenarios wind power generation is significantly lower than in the present scenario. However, the figures for electricity production are not reported.

[9]It should be noted that the Energy [R]evolution scenario assumes considerably higher increases of energy efficiency than the other scenarios, hence, electricity demand is lower. Therefore, the share of wind power in the overall generation mix is higher than for the other scenarios.

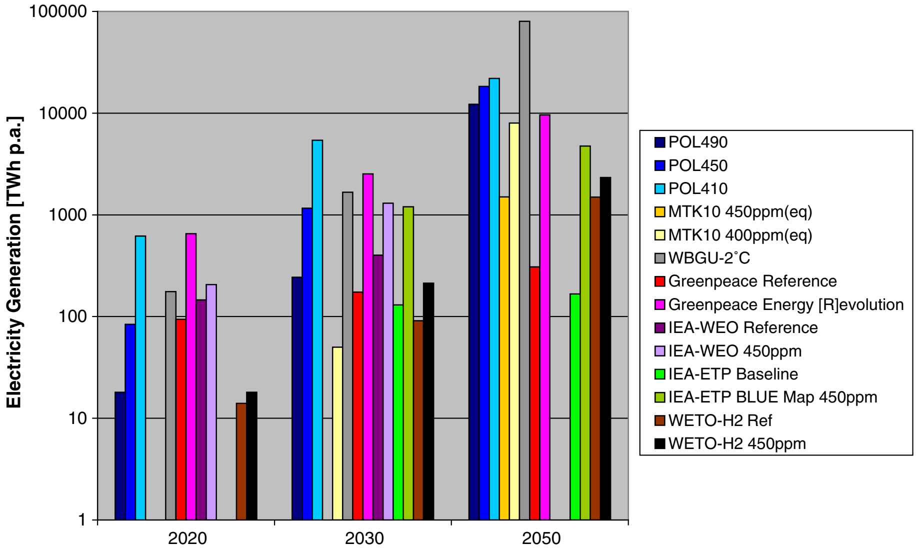


Fig. 5 Electricity generation from solar technologies in the three POL^x scenarios computed with REMIND-R and results from other publications. Note the log-scale. Sources: WBGU (2003, p. 138), Magne et al. (2010, p. 93), Greenpeace (2008, pp. 190 and 191), IEA (2009, pp. 229 and 623), IEA (2008 p. 85 and 367), EIA (2009, p. 67), WETO is EC (2006, p. 120 and 129). IEA-WEO and EIA-IEO consider only a time horizon until 2030; IEA-ETP do not report numbers only for the year 2020

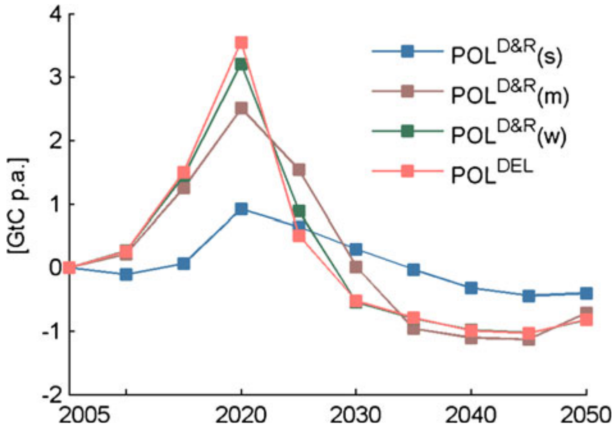
POL^x scenarios show a similar behavior as in the case for wind power production. MTK10 shows lower deployment for solar power. Also the same sensitivity as for the REMIND-R model can be observed regarding timing of deployment as the stabilization target is tightened from 450 ppm(eq) to 400 ppm(eq). The WBGU-2°C scenario again shows much higher figures than REMIND-R. The scenarios of the second group exhibit relatively small differences compared with the first group in 2030. For example, the POL^{450} scenario shows nearly the same solar electricity production as the WEO 450 ppm scenario and the ETP BLUE map scenario. Only in the longer term in 2050 the POL^x scenarios are much higher than the Greenpeace, the ETP and the WETO-H_2 scenarios.

The four scenarios imply different investment costs in the year 2020 as they depend on technology deployment according to the dynamics of learning by doing. Table 3 presents the investment costs in 2020 for the wind and solar PV technology. The lower investment costs for the stricter climate policy targets are a direct consequence of the social optimal deployment of technologies shown above. This result is important for the analysis below.

Table 3 Investment costs of wind and solar PV technologies in 2020 for the four scenarios BAU and POL^x

Technology	Unit	Scenario			
		BAU	POL^{490}	POL^{450}	POL^{410}
Wind	$US/kW	1144	960	917	901
Solar PV	$US/kW	4900	3823	2548	1543

Fig. 6 Impact of delayed climate policy and different assumptions of near-term RET deployment on annual global CO_2 emissions from the energy sector from 2005 to 2050. The lines indicate absolute differences of the POL^{DEL} and the three $POL^{D\&R}$ scenarios with respect to the POL^{450} scenario



Biomass is the most important other RET that is used in the POL^x scenarios. In all three scenarios the maximum potential of 200EJ p.a. is utilized in 2050. It is mainly converted into synthetic natural gas and transportation fuels—the latter partly with CCS. In the scenario POL^{450} biomass with CCS is deployed from 2030 on.

Finally, the mitigation costs of the three POL^x cases are assessed. Mitigation costs are measured as the cumulative discounted consumption losses for the 21st century relative to the BASELINE case. For discounting we used the interest rate that is computed endogenously in the REMIND-R model.[10] For the medium case POL^{450} the losses are 0.5%. For the less ambitious POL^{490} the losses are only 0.3%, but increase to 0.8% as the stabilization target is tightened in the POL^{410} case.

4.2 Delayed climate policy and early RET deployment—POL^{DEL} and $POL^{D\&R}$

The assumption of an immediately established global cap-and-trade system is flawed because the international negotiations take more time. The POL^{DEL} scenario analyses delayed climate policies by freezing the development of all stock variables until 2020 on BASELINE levels. Measures to support renewable energies are not reflected in this near term development. This design feature is added in the $POL^{D\&R}$ scenarios, which combine delayed climate policies and early RET deployment. The design of $POL^{D\&R}$ scenarios captures the current situation with large renewable deployment initiatives but missing global climate policy.

Figure 6 shows the impact on global CO_2 emissions from the energy sector. The graph depicts the absolute differences compared with the POL^{450} case (see Fig. 3 above) until 2050. In the year 2020 the emissions in the POL^{DEL} case are 3.5GtC p.a. higher. This difference can be significantly reduced by imposing the RET

[10]The interest rate in REMIND is time-variable. The steady state value is 5.5% that is approached starting from 8%. It is common practice to apply a constant discount rate to compute net present values of consumption and GDP differences. In the present case the differences between the policy scenarios and the BAU scenario are non-trivial because of multiple intersections. This implies that a fixed discount rate can lead to counter-intuitive rankings of the scenarios; i.e. a second best scenario performs better than a first best scenario. If we apply the endogenous time variable interest rate, the rankings of scenarios are sound.

deployment. If the deployment from the original POL^{450} scenario is assumed until 2020, the difference in emissions reduces to 2.5GtC p.a. During the following decades the differences change sign because the 450 ppm concentration target has to be met in all scenarios. In the scenario POL^{DEL} the rapid and enormous decreases of emissions after 2020 are mainly achieved by abandoning new fossil investments and heavily investing into biomass with CCS. Higher deployments of RET reduce the emission level in 2020 and therefore do not require such massive changes after 2020 because the peak is lower and, hence, this reduces the need to go quickly below the optimal emission path of the POL^{450}. These smoothed changes reduce the mitigation costs.

The mitigation costs for the different scenarios are of particular interest because *a-priori* it is unclear whether the costs of delayed climate policy increase or decrease, if early RET deployment is additionally assumed. It is valid to say that the POL^{450} scenario implies the lowest mitigation costs of the five scenarios considered here. The costs of the POL^{DEL} scenario are expected to be higher, because the energy–economy system can not choose the cost-minimal timing of mitigation measures. The key question is, whether political measures for early deployment of renewables are justified as long as the global climate cap-and-trade system has not yet entered into force to achieve a common CO_2 concentration target.

Figure 7 shows the global and regional mitigation costs measured as the cumulative discounted consumption differences relative to the BASELINE scenario. At the global level it turns out that early RET deployment reduces the additional mitigation costs of delayed climate policy. The additional costs of the POL^{DEL} case can be reduced by 0.23%-points, if RET deployment that originally was optimal in the POL^{450} scenario is triggered by support measures; i.e. the scenario $POL^{D\&R}$(m). However, the cost reducing effect is bound by the mitigation costs of the POL^{450} case.

The distributional effects are heterogeneous among regions. For the US and the EU the cost reducing effect of early RET deployment is in the same direction as at the global level. The same is also true for China, if only the medium and strong deployment scenarios are considered. For India and the RNAI region the effect is of the opposite sign.

The net effect of the mitigation costs for the different regions can be explained by analyzing the different components. The differences of mitigation costs are

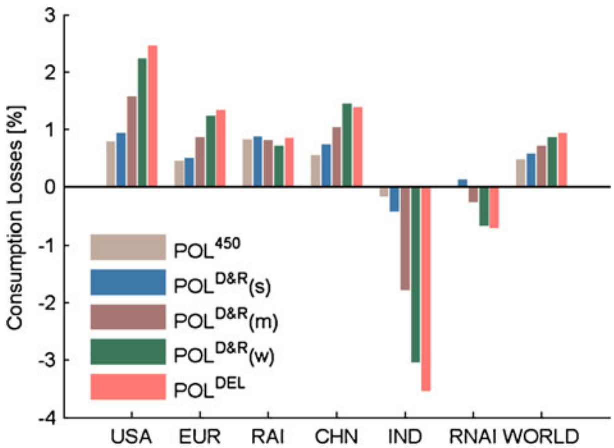


Fig. 7 Global and regional mitigation costs for the POL^{450}, the $POL^{D\&R}$ and the POL^{DEL} scenarios. Mitigation costs are measured as the cumulative discounted consumption losses relative to the BASELINE case for the time horizon 2005 to 2100. The indices in the parenthesis indicate **s**(trong), **m**(edium) and **w**(eak) of RET deployment. The time varying endogenously computed interest rate is used as the discounting rate

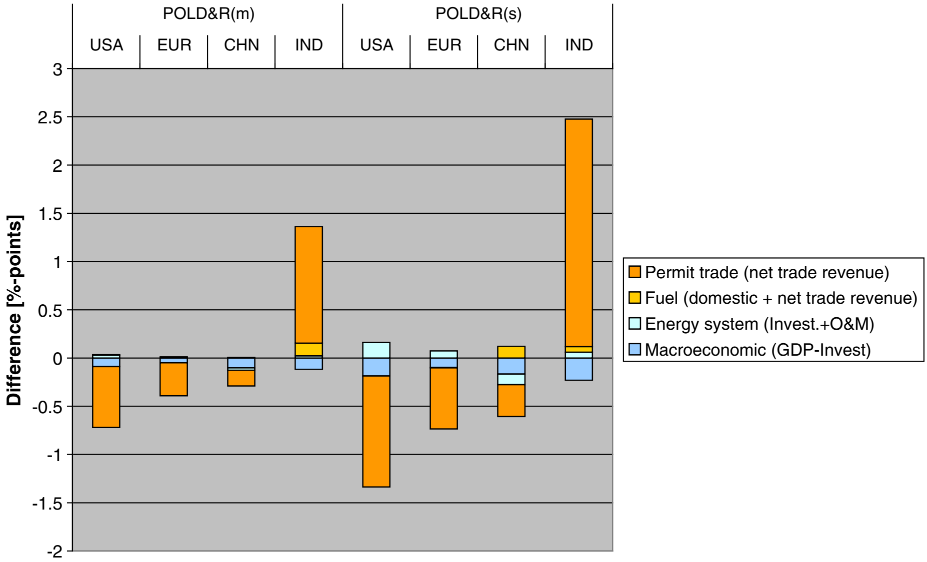


Fig. 8 Impact of various effects on the mitigation costs of the US, Europe, China and India for the $POL^{D\&R}(m)$ and $POL^{D\&R}(s)$ scenarios compared with the POL^{DEL} scenario. Negative (positive) values indicate mitigation cost reductions compared with the POL^{DEL} scenario. Note: the relative differences are relative to changes of GDP, whereas mitigation costs are relative to consumption differences

explained by changes in (a) macroeconomic variables of GDP and investments in the macroeconomic capital stock (b) non-fuel energy system costs consisting of investment and O&M costs, (c) fuel costs including net export revenues and (d) permit trade. The methodology for deriving the single components from the results of the optimal inter-temporal solution is provided by Lüken et al. (2009).

Figure 8 shows the differences with respect to the POL^{DEL} scenario. Negative (positive) values indicate cost reduction (increases) with respect to the POL^{DEL} scenario. The sum of positive and negative components equal the difference that can be observed in Fig. 7 above. By far the most prominent influence is the emission permit component. For the net permit importers US, Europe and China early deployment of renewables is profitable because the cost escalating influence of emission permits in the delayed climate policy scenario can be reduced. The opposite line of argumentation works for the net permit exporter India. The redistribution effect is stronger the more ambitious the RET deployment scenario is.[11]

The other three components are negligible compared with the permit effect. Hence, early RET deployment in case of delayed climate policy is mainly affecting the value of tradable emission permits, which in turn affects the redistribution among regions related to the permit effect proportionally. The reason is that early RET

[11]Moreover, the regional redistribution of the value of permits scales almost linearly with the total value of permits. For example, the total permit value of the $POL^{D\&R}(m)$ scenario is 40% less than in the POL^{DEL} scenario. This reduces the permit effect in each region by about 40%. This result is independent of the sign of the permit effect.

deployment decreases the CO_2 permit price in 2020. In the case POL^{DEL} the price amounts to 92\$US/tCO_2, which is reduced to 53\$US/tCO_2 for the medium RET deployment scenario.

In summary, the increase of mitigation costs due to delayed climate policies can be decreased by early RET deployment. The most important factor that decreases the mitigation costs is the devaluation of emission permits that is explained by three reasons. First near-term emissions are decreased and therefore less of the cumulative emissions are consumed and the emissions must be decreased from less than the baseline level; see Fig. 6. Second, early deployment of renewables increases the capacity of carbon free energy technologies; see Figs. 4 and 5. Third, learning-by-doing decreases the costs of additional deployment of renewable energy technologies; see Table 3. The regional distribution impact of the devaluation of emission permits, however, is very different and depends on the difference between the initial and the market allocation; i.e. the closer the initial allocation of permits matches the efficient market allocation the less emphasized would be the permit trade effect.

4.3 Early renewable deployment and immediate climate policy—POL^{RET}

For understanding the factors better that led to the huge cost decrease in the previous section, we also provide another set of scenarios. In these scenarios deviations from the optimal RET deployment are assessed for achieving the 450 ppm CO_2 stabilization target. The exogenous variation of RET deployment shed light on the impact on emissions and mitigation costs, if the renewables penetration is weaker or stronger relative to the first best POL^{450} case. The deviation from the optimal deployment path *a-priori* implies higher global mitigation costs and changes in the emission time path. The open questions are whether on the global level early or deferred RET is worse, what the effect on the regional distribution of mitigation costs is and how the time-path of mitigation costs varies as the renewable deployment is changed?

Figure 9 shows the impact on CO_2 emissions for the four POL^{RET} scenarios with strong and weak RET deployment until the years 2020 and 2030. The graph depicts the absolute differences with respect to the POL^{450} scenario until 2050. The graph shows that deviations from the optimal path of renewable deployment to achieve the 450 ppm target imply near and long-term changes in CO_2 emissions. The variation of RET deployment leads to an intuitive temporal reallocation of CO_2 emissions. For the scenarios with stronger than optimal RET deployment—i.e. POL^{RET}(s,20) and POL^{RET}(s,30)—coal use in the electricity sector is partially replaced in the near term that allows higher emissions in the longer term; *et vice versa* for the scenarios with weaker than optimal RET deployment. The pattern of deviations is more distinct for the short-term deviations of RET deployment and levels out for the longer-term deviations, since the stabilization target is the same. In general, the deviations from the optimal CO_2 emission path of the POL^{450} scenario are assessed to be small compared with the changes in the effects observed in the $POL^{D\&R}$ scenarios. The maximum deviation of −1GtC p.a. in 2020 for the scenario POL^{RET}(s,20) is relatively small compared with the differences of emissions reductions between the POL^{410} and the POL^{450} cases; see Fig. 3 above. Hence, high penetration levels of RET are not expected to replace fossil energy carriers on a one-to-one basis in a climate policy

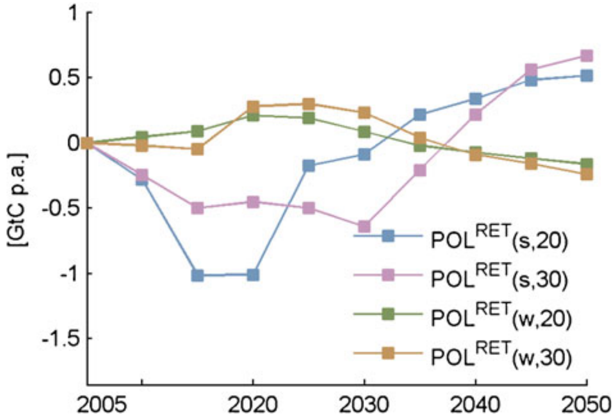


Fig. 9 Impact of deviations from the optimal RET deployment path on annual global CO_2 emissions from the energy sector from 2005 to 2050. The lines indicate absolute differences of the four POL^{RET} scenarios with respect to the POL^{450} scenario

regime, which is due to an emission rebound effect in the energy sector, see also Bauer et al. (2010).

The impact of non-optimal RET deployment on mitigation costs is shown in Fig. 10. The graph depicts the mitigation costs in the optimal POL^{450} scenario as a reference and the mitigation costs of the four POL^{RET} scenarios. The results confirm the a-priori expectation that deviations from the optimal RET deployment path increase mitigation costs, though the differences are quite small. The penalty on mitigation cost is little higher for the two cases with RET deployment stronger than the optimal path. Thus, at least on the global level the timing of RET deployment is of minor importance for the mitigation costs.

Figure 11 presents the components that explain the difference between the POL^{450} and the two second-best scenarios that fix the RET deployment until 2030. The methodology is the same as for Fig. 8 given in the previous sub-section.

In all regions the positive (or negative) effect of strong (or weak) renewable deployment on the macroeconomic component is offset by higher (or lower) energy system expenditures. In the scenario POL^{RET}(s,30) the negative effect of non-fuel energy system costs exceeds the positive macroeconomic effect. In the scenario

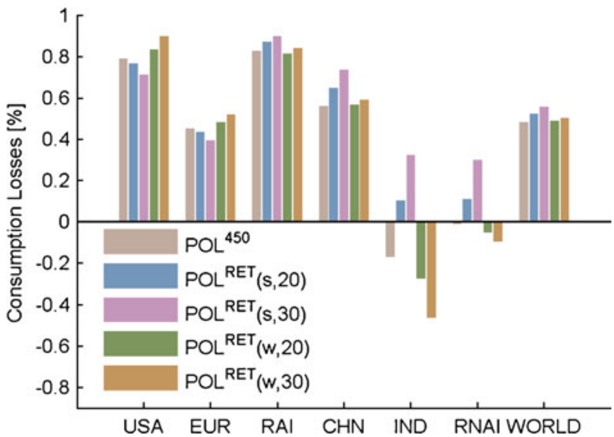


Fig. 10 Global and regional mitigation costs for the POL^{450} and the POL^{RET} scenarios. Mitigation costs are measured as the cumulative discounted consumption losses relative to the BASELINE case for the time horizon 2005 to 2100. The indices in the parenthesis indicate the deviation from the optimal RET deployment path: the intensity **s**(trong) and **w**(eak) and the duration (20)**20** and (20)**30**. The time varying endogenously computed interest rate is used as the discounting rate

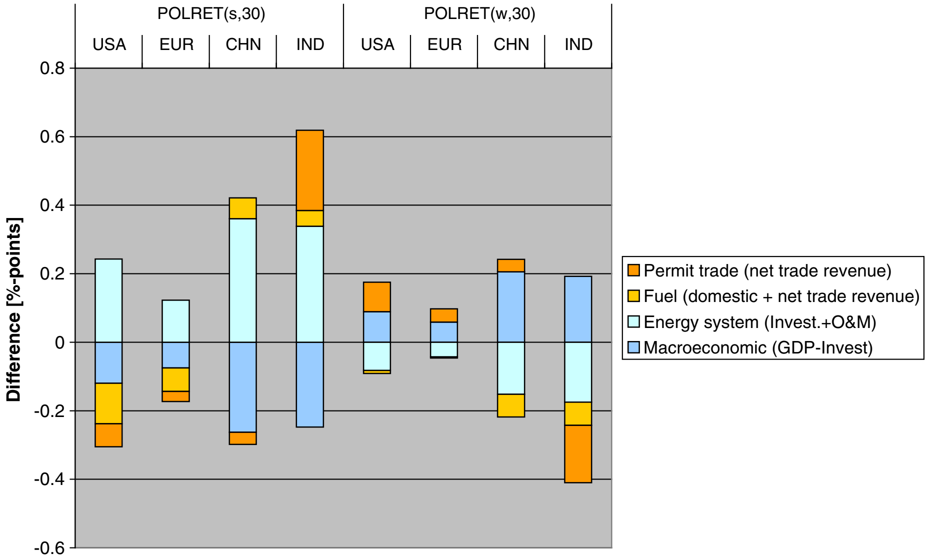


Fig. 11 Impact of various effects on the mitigation costs of the US, Europe, China and India for the POL^{RET}(s,30) and POL^{RET}(w,30) scenarios compared with the POL^{450} scenario. Note: the relative differences are relative to changes of GDP, whereas mitigation costs are relative to consumption differences

POL^{RET}(w,30) the signs of these two effects is reversed. In the US and Europe the fuel cost effect in the scenario with stronger (or weaker) than optimal RET deployment reduces (or increases) the mitigation costs because less fuels are produced domestically and imported. The opposite holds for China and India.[12] The permit effect is most important in the case of India, where strong RET deployment leads to smaller permit export revenues because of a smaller export at lower prices *et vice versa* in the case of weak RET deployment. The other regions however profit from this effect, though the importance is smaller as they have a larger overall GDP.

The small differences of mitigation costs between the first-best and the four POL^{RET} second-best scenarios are mainly the net effects of larger redistribution between economic activity and de-valuation of emission permits as well as energy trade. The de-valuation effect, however, is much smaller than in the case of delayed climate policy. The macro-economic and non-fuel energy system effects are the same for all regions because the economy is supplied with more energy, but the fuel cost and permit trade effect vary between the regions. Whether a region suffers or gains from deviations from the optimal RET deployment depends on the direction and magnitude of the latter two effects. The differences in the permit trade effect, which is much smaller in the POL^{RET} than in the $POL^{D\&R}$ scenarios, is due to the relatively smaller impacts on the CO_2 prices because the renewable mitigation option substitutes alternative options leading to only small CO_2 price changes. Also the impact on the CO_2 emission path is smaller in the POL^{RET} than in the $POL^{D\&R}$

[12]We do not elaborate the energy trade effect more here, because the complex interplay of prices and quantities for the various energy carriers is not the focus of this study.

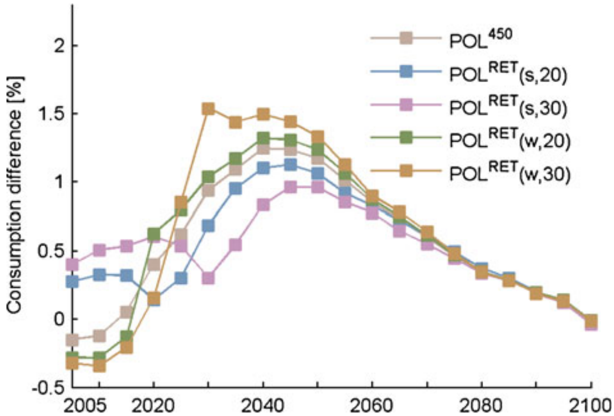


Fig. 12 Time paths of consumption differences 2005 to 2100 relative to the BASELINE case for the POL^{450} and the POL^{RET} scenarios. The indices in the parenthesis indicate **s**(trong) and **w**(eak) and the duration of RET deployment; i.e. (20)**20** and (20)**30**

scenarios shown in Figs. 6 and 9. Hence, the price and the quantity effect lead to a decrease of the overall permit trade effect.

Since the transformation of the energy system is a challenge for the present as well as the following generations, the time paths of mitigation costs of the scenarios are analyzed next. Figure 12 depicts the time paths of consumption differences of the POL^{450} as well as the four POL^{RET} scenarios relative to the BASELINE case. The optimal case POL^{450} shows a path that increases until 2040 peaking at 1.24% p.a. and decreases towards zero afterwards.[13] The four POL^{RET} scenarios show significant deviations from this path. Strong RET deployment until 2030 (POL^{RET}(s,30)) leads to an even flatter time path that already starts at 0.4% p.a. but does never exceed 1% p.a.. The two low deployment scenarios instead exhibit a much more emphasized peaking behavior. They start with some moderate gains, which are due to lower overall investments allocated to the energy system, but the maximum is higher. This is especially the case for the POL^{RET}(w,30) scenario, in which the weaker than optimal RET deployment lasts until 2030 peaking at 1.5% p.a. in 2035.

The comparison of the first-best climate mitigation scenario with the second-best scenarios shows that deviations from the optimal RET deployment paths only imply small changes in the optimal emission time paths and the global cumulative discounted mitigation costs. The regional distribution of the mitigation costs is heterogeneous and depends on the intensity of the RET deployment scenario as well as the contribution of various economic influences affecting the regions. Also the time path of mitigation costs is changed significantly for the different RET deployment scenarios. The cumulative discounted mitigation costs do not reflect the shape of these time paths.

5 Discussion and further research

Early deployment of renewable energy technologies reduces the global costs for achieving a 450 ppm CO_2 concentration target, if climate policy measures are

[13] The shape is not unusual for climate change mitigation assessments with stabilization targets; see Edenhofer et al. (2010, p. 32).

delayed. The cost reduction is due to the devaluation of emission permit that can be explained by three effects. First, early RET deployment replaces some fossil fuel utilization and leaves more emissions for the rest of the 21st century. Second, if large capacities of RET are available in 2020 the negative effect of significantly reducing new fossil fuel investments and increasing the utilization of biomass with CCS is contained. Finally, additional investments in RET will be cheaper post-2020 as early deployment will reduce the investment costs due to learning-by-doing. The global mitigation costs, however, cannot be reduced below the first-best scenario with optimal timing of all mitigation measures.

Similar results can be expected for other energy–economy models since Jakob et al. (2011, this issue) and Clarke et al. (2009, p. S77) report significant increases of carbon prices and mitigation costs as climate policy is delayed. The effectiveness of technology policies for reducing the emissions in the near term and triggering improvements of low carbon technologies is the crucial link to reduce the costs of delaying climate policies. Emission rebound effects can turn out to be serious obstacles to the positive impact of technology policies. Bauer et al. (2010) quantified the emission rebound effects of various mitigation options. The debate about the Green Paradox is even more pessimistic about technology policies, because fossil fuel extraction is expected to increase in the near term as fossil fuel owners anticipate future devaluation of their resources; see e.g. Sinn (2008).

Deviations from the optimal RET deployment path in the case of immediate climate policy increase the global mitigation costs compared with the first-best solution. The impacts on global emissions and discounted global mitigation costs are quite small, which confirms the finding of Böhringer et al. (2009) in the context of European climate and energy policy. Hence, the optimal timing of renewable investments is of minor importance from a global point of view. The impact on the time path of mitigation costs over the entire century, however, is significant. The optimal time path of mitigation costs follows an inverted U-shape with a peak around the middle of the century. Higher than optimal deployment of RET flattens the curve, but less than optimal deployment increases the peak of mitigation costs. This inter-temporal reallocation is not reflected in the discounted mitigation costs. The intergenerational re-distribution of mitigation costs due to different renewable energy investments is not discussed so far in the scientific literature. This issue is not addressed in the present paper and left to future research. An additional argument for stronger RET deployment (scenario $POL^{RET}(s)$) is that it serves as a hedging strategy against the case that in the future it might become necessary to achieve a lower stabilization target than initially chosen, e.g. decreasing the CO_2 stabilization level from 450 to 410 ppm. The significance of technology policies for hedging against climate risks has not been explored yet and seems an interesting field of future research.[14]

The impact of variations of RET deployment on global mitigation costs is larger in the case of delayed than in the case immediate climate policy. This result is in contrast with the finding of Kverndokk and Rosendahl (2007), who stated that the delay of carbon pricing is less significant than the delay of technology subsidies. The difference of results can be related to a number of factors. Kverndokk and

[14]The authors would like to thank an anonymous reviewer for this suggestion.

Rosendahl (2007) only reflect the electricity sector, in which learning technologies are very important, but the present study deals with the total energy sector, where learning technologies are less important. Moreover, Kverndokk and Rosendahl (2007) allow for optimal adjustment of the subsidy in case of delayed climate policy, but the present study only considers exogenous variations of RET deployment paths. Moreover, in case of a delayed technology subsidy the carbon tax in Kverndokk and Rosendahl (2007) would need to increase significantly to achieve any emission reduction (beyond demand responses) because besides two carbon-free learning technologies there is only one fossil generation technology considered. The REMIND model instead considers a large variety of different electricity generating technologies and renewables are differentiated by quality grades, which implies a smoothed transition.

The interregional distribution of mitigation costs is heterogeneous in both cases of immediate and delayed climate policies. At the regional level the US and Europe would gain from strong worldwide deployment of RET in both climate policy regimes. China would gain from strong and medium early deployment, if climate policies are delayed, but in case of immediate climate policy China would lose from strong RET deployment. India and all other non-Annex 1 regions lose from early RET deployment in both climate policy regimes.

In case of delayed climate policy variations of early RET deployment have significant impact on the global mitigation costs as well as the regional distribution. The main factor is that the total value of emission permits allocated to the regions decreases as early RET deployment is imposed on the system. This has a negative effect on regions, which receive relatively plentiful assignments and export these permits. Conversely, net importers gain from early RET deployment.

The main conclusion for policy making from this study is that early deployment of renewable energy technologies can reduce additional global costs of delayed climate policy. High income regions and China can reduce the costs of delayed climate policy by inducing this transformation of the global energy system. Especially the US and Europe would also profit from strong world-wide renewable deployment in case of immediate climate policy, thus, making this option a robust strategy for these regions. Low-income regions may not experience this cost reducing effect. In both cases of immediate and delayed climate policy low-income countries are found to lose from ambitious renewable deployment policies.

The present study only analyzed the influence of early RET deployment, but also other technology related policies should be studied. Most promising to us seem energy efficiency, fossil CCS, gas for coal substitution, and nuclear. The present study also showed that it is important to study the factors that determine the mitigation costs. As the value of carbon permits appears to have a significant influence on the results, future research should aim at identifying the reasons for changing mitigation costs as technology policy is imposed in case of delayed climate policy. Furthermore, the scenario space may also be extended to the land-use sector asking for scenario assumptions that reduce GHG emissions other than CO_2 from the energy sector. Following this line of research would broaden the perspective on alternative scenarios limiting and reducing GHG emissions by different policies.

The method of developing second-best scenarios is appropriate to explore the range of alternative future developments and the implications on costs providing guidance to policy makers and supporting international negotiations. However, the major interest of policy makers is the assessment of international agreements, optimal policy instruments and their coordination in a policy mix. The contributions of Kverndokk and Rosendahl (2007) and Gerlagh et al. (2009) address this challenge, but need much more improvement. The extension towards higher technological resolution and multi-regional frameworks requires additional theoretical foundation and more powerful numerical algorithms to solve these models.

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