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Emission Certificate Trade and Costs under Regional Burden-Sharing Regimes for a 2°C Climate Change Control Target

By Tom Kober, Bob van der Zwaan and Hilke Rösler

SEVENTH FRAMEWORK PROGRAMME

Emission Certificate Trade and Costs under Regional Burden-Sharing Regimes for a 2˚C Climate Change Control Target

A multi-model analysis of post-2020 mitigation efforts of five major economies

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Abstract

In this article we explore regional burden-sharing regimes for the allocation of greenhouse gas emission reduction obligations needed to reach a 2˚C long-term global climate change control target by performing an integrated energy-economy-climate assessment with the bottom-up TIAM-ECN model. Our main finding is that, under a burden-sharing scheme based on the allowed emissions per capita, the sum of merchandised carbon certificates yields about 2000 billion US$/yr worth of inter-regional trade around 2050, with China and Latin America the major buyers, respectively Africa, India and Other Asia the main sellers. Under a burden-sharing regime that aims at equal cost distribution, the aggregated amount of transacted carbon certificates involves less than 500 billion US$/yr worth of international trade by 2050, with China and Other Asia representing the vast majority of selling capacity. Restrictions in the opportunities for international certificate trade can have significant short- to mid-term impact, with an increase in global climate policy costs of up to 20%.

JEL classification number: Q54, F53

Keywords: climate policy, energy system, greenhouse gases, emissions abatement, resource versus cost sharing, carbon certificate trade

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1. Introduction

The much anticipated negotiations during the 15th Conference of the Parties (COP-15) of the United Nations Framework Convention on Climate Change (UNFCCC) in 2009 in Copenhagen failed to lead to a new binding agreement as successor to the 1997 Kyoto Protocol, designed to eventually "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". Since then, the climate policy community has generated a fragmented network of national and regional climate change mitigation measures. The main outcome of COP-17 in Durban in 2011 and COP-18 in Doha in 2012 was that by 2015 the negotiation of a new legally enforceable climate change control agreement should be achieved and become effective from 2020 onwards. The fundamental challenge for policy makers and government representatives from developed and developing countries, during multi-lateral negotiations the forthcoming years, will be to resolve the crux of equitable regional burden-sharing. This matter is one of the main research topics of the LIMITS project[1], which researches greenhouse gas (GHG) emission reduction strategies, globally and at the level of the world's major economies, required to limit the anthropogenic atmospheric temperature increase to 2˚C in comparison to the average level in pre-industrial times (UNFCCC, 2010).

This article, produced in the context of the LIMITS project, investigates the cost and carbon certificate trade impacts of different regimes of inter-regional burden-sharing for the allocation of GHG emission reduction obligations needed to reach stringent global climate change stabilisation. In addition to inspecting the technological and structural changes required to adapt the energy systems of the world's main economies, we analyse carbon certificate price effects as well as carbon market capital flows emanating from the introduction of equitable burden-sharing between regions that undertake collective effort in mitigating global climate change. In section 2 of this paper we shortly describe the model that we use to perform our analysis, as well the approach and assumptions adopted for this study. Section 3 presents our main results, in terms of GHG emission reduction pathways and allocation of GHG emission allowances in two different kinds of regional burden-sharing regimes: resource-sharing respectively effort-sharing. In section 4 we investigate the impact of possible limitations in carbon certificate trade opportunities across the world between its main economies, in terms of quantity and timing of permit trade, inter-regional transfers of funds, carbon certificate prices, and overall climate policy costs. In section 5 we report our overall conclusions and proffer thoughts on the implications of our study for policy makers.

2. Approach and socio-economic assumptions

This paper is complementary to, and an extension of, another article on burden-sharing in this special issue, which unlike ours takes a cross-model perspective rather than a single-model view (see Tavoni *et al.*, 2013). Our article

[1] See www.feem-project.net/limits

reports results from the TIAM-ECN model only, and puts sensitivity analyses with this model at centre stage. Moreover, our paper investigates the effects of possible limitations in international carbon permit trade. For details on the set-up and definition of scenarios analysed in our study we refer to Kriegler *et al.* (2013) in this special issue.

2.1 TIAM-ECN energy system model

TIAM-ECN is the TIMES[2] Integrated Assessment Model (TIAM) of the Energy research Centre of the Netherlands (ECN), used for long-term energy systems and climate policy analysis. It has a global scope with a world energy system disaggregated in 15 distinct regions. TIAM-ECN is a linear optimisation model, based on energy system cost minimisation with perfect foresight until 2100. It simulates the development of the global energy economy over time from resource extraction to final energy use. The objective function is represented by the discounted total energy system costs summed over all time periods and across all regions. The main cost components aggregated in the objective function are the investment costs and fixed plus variable operation and maintenance costs for various energy supply and demand options, including emission reduction measures. TIAM-ECN is based on a partial equilibrium approach with exogenous demands for energy services. These services, however, can respond to changes in their respective prices through end-use price elasticities. Hence, savings of energy demand and corresponding overall energy system cost variations are accounted for in our model. TIAM-ECN is operated with a comprehensive technology database that contains many possible fuel transformation and energy supply pathways, and encompasses technologies based on fossil, nuclear and renewable energy resources. Both currently applied technologies and future applicable advanced technologies, such as ultra-supercritical fossil-fuelled power plants, hydrogen technologies, a broad variety of renewable energy options, and carbon dioxide capture and storage (CCS) techniques in power plants and industrial applications, are available in the model's technology portfolio.

TIAM-ECN simulates in detail three main types of GHGs (and does not inspect other GHG species): carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). GHG emissions related to energy conversion and industrial processes are modeled via a process-oriented approach with an endogenous emission calculation. For emissions of CH_4, CO_2 and N_2O that are not related to energy conversion or industrial activities, such as from agriculture, a reference pathway is determined outside the model and postulated as emission profile exogenously to the model. With regard to climate change mitigation measures, however, our model covers abatement options for *all* GHG emissions, i.e. for both energy- and non-energy related sources. For energy-related sources various low-emission technology options are available in the model, while for non-energy-related emissions cost-potential curves for GHG mitigation measures are simulated. More detailed model descriptions and examples of the application of TIAM-ECN can be found in Rösler *et al.* (2011; 2012), Keppo and van der Zwaan (2012), and van der Zwaan *et al.* (2013b), as well as several references therein. Since TIAM-ECN is an energy system model, it allows for analysing GHG reduction pathways over the entire energy supply chain up to end-use energy demand. Horizontal and vertical

[2] TIMES is the acronym for The Integrated MARKAL-EFOM System, a model generator inspired by two bottom-up energy system models: the MARket Allocation model (MARKAL) and Energy Flow Optimization Model (EFOM).

interdependencies and substitution effects of energy supply are thereby accounted for. For instance, the use of hydrogen in the transport sector as climate change mitigation measure depends, evidently, on the availability and price of hydrogen (vertical dimension). The nature and deployment scale of hydrogen production technology in industry has a significant impact on the supply costs of hydrogen, notably for the transport sector (horizontal dimension).

Besides this integrated systems approach, TIAM-ECN features details of energy extraction, conversion and demand, such as available fossil and renewable energy resources, potentials for storage of CO_2, and region-specific (energy) demand developments. Region- and sector-specific demands for end-use energy and industrial products are driven by socio-economic parameters. Globally we assume almost a tripling of gross domestic product (GDP) over four decades, from 68 tln US$ in 2010 to 247 tln US$ in 2050. World GDP increases further to 731 tln US$ in 2100 (see Table 1).[3] The world population is expected to grow rapidly in the first half of the century to reach 9 bln persons in 2050, and to remain at this level until the end of the century. This population development mimics the medium fertility projections of the United Nations (UN, 2011), and is characterised by strong population growth in three of the main economies: Africa to 2.1 bln persons in 2050, India to 1.7 bln persons in 2050 and Other Asia to 1.4 bln persons in 2050.[4] China's population is supposed to peak around 2025 at 1.4 bln people, and to decline afterwards down to 0.9 bln persons in 2100. The population development of most of the countries of the Organisation for Economic Cooperation and Development (OECD) is relatively stable, with a total average increase of 0.1%/yr for the period 2010-2100. In comparison to population growth, the increase of the number of households is more pronounced, as a result of changing living patterns towards smaller household sizes. The total number of households amounts to almost 4 bln in 2050 and 4.4 bln in 2100.

Table 1: Global socio-economic assumptions

	2010	2020	2030	2050	2070	2100
GDP(PPP) [tln US$]	66.7	99.5	137.7	246.7	420.2	730.6
Population [bln persons]	6.9	7.6	8.3	9.2	9.4	9.1
Households [bln households]	1.9	2.3	2.9	3.9	4.4	4.4
Sources: IEA, 2012; World Bank, 2012; UN, 2011; Ironmonger *et al.*, 2000; own calculations.						

2.2 Burden-sharing regimes

[3] GDP in this paper is expressed in terms of purchasing power parity (PPP), if not indicated otherwise. Monetary values are all in US$(2005).
[4] The latter do not include India, China, South Korea, Japan and Central Asian countries (formerly part of the Soviet Union).

Against the background of expected socio-economic developments and in anticipation of international attempts to mitigate global climate change, meeting future generations' energy demand necessitates a fundamental restructuring of the current global energy system over the forthcoming decades. In comparison to an energy supply system not subjected to GHG emission reductions, a decarbonised energy system is more costly, as a result of the required investments in still relatively expensive low-carbon technologies. The additional cost can vary significantly across regions, for resource-potential, infrastructural, political and cultural reasons. For the most cost-efficient global GHG reductions scheme, ideally the least-cost climate change mitigation potentials worldwide are unlocked, independent of where they are geographically located. Undoubtedly significant expenditures are required in all regions, independent of their economic development status, but some regions may be more endowed with low-cost GHG abatement options than others. As a consequence, in order to exploit the least-cost options on a global scale as extensively as possible, some regions may need to disproportionally contribute to global climate change mitigation efforts, for which they would need to be compensated. Various approaches for regional compensation schemes exist that can shift climate policy costs across regions and thereby establish a more equitable distribution of the financial burdens associated with climate change mitigation. Alternative burden-sharing schemes can be based on different socio-economic variables, and/or varying energy- and emission-related parameters or cost factors. These differences determine the equity principle underlying each scheme as well as the way in which it can practically be implemented. Via an exchange of emission allowances on a carbon certificate market, both cost-efficient allocation of GHG emission reductions and financial compensation for more-than-obliged climate change mitigation efforts can be realised. For an overview of recent literature on different burden-sharing schemes we refer in particular to Tavoni *et al.* (2013), in which the two main schemes that we use for the present paper as well as their methodological background and relation to the literature are elaborately described. Comparative assessments of different burden-sharing principles have also been conducted, for instance, by den Elzen *et al*. (2008), Hof *et al*. (2008), Jacoby *et al*. (2008), and Ciscar *et al*. (2013). Subjects like the linkage between trade of emission allowances and technological innovation, as well as the coupling of different certificate markets, have especially been analysed in Driesen (2003), Babiker *et al*. (2004), de Sépibus (2008), and De Cian and Tavoni (2012).

The two different burden-sharing schemes analysed in this article relate to population development (referred to as "resource-sharing" scheme) respectively climate policy costs and economic development (the so-called "effort-sharing" scheme). Under the resource-sharing scheme, emission rights are allocated according to the level of GHG emissions allowed per capita. Through convergence of regional shares in global emission rights and uniform contraction of these global emissions (see Meyer, 2000, for an explanation of the terminology 'contraction and convergence') a transition from status quo regional emission levels in 2020 to a globally reduced average in 2050 is implemented. The regional shares of global emissions are calculated through Eq. 1, which formulates the convergence part of the resource-sharing method.

$$\frac{E_r(t)}{E_w(t)} = \frac{T_2 - t}{T_2 - T_1} * \frac{E_r(T_1)}{E_w(T_1)} + \frac{t - T_1}{T_2 - T_1} * \frac{P_r(t)}{P_w(t)}$$ *Eq. 1*

$E_r(t)$: Regional emissions at time step t

$E_w(t)$: World emissions at time step t

$P_r(t)$: Regional population at time step t

$P_w(t)$: World population at time step t

T_1: Reference year for grandfathering (2020)

T_2: Target year for convergence (2050)

The effort-sharing scheme aims at equalising the mitigation costs across regions, in the sense that all regions should incur the same climate change control costs in percentage terms of their GDP after emissions trading. From 2020 onwards, regional shares of total climate change mitigation costs (including revenues or expenses from carbon certificate trade) should be equal to the world average (see Eq. 2).

$$\left(\frac{C_r}{Y_r}\right)_t = \left(\frac{C_w}{Y_w}\right)_t \qquad \forall t \in \{2020, 2030, \dots, 2100\}$$ *Eq. 2*

C_r: Regional absolute mitigation costs

C_w: World absolute mitigation costs

Y_r: Regional GDP

Y_w: World GDP

The effort-sharing scheme is applied in TIAM-ECN via a pre-optimisation procedure that calculates each region's overall certificate allocation. For every region and period, target policy costs are calculated on the basis of the world total climate policy costs as percentage of global GDP and the GDP of each of the respective regions.[5] The

[5] Policy costs in the context of our bottom-up modelling approach refer to undiscounted costs for the entire energy system, including expenditures for technology investments, operation and maintenance, other variable costs as well as costs associated

difference between all regions' effort-sharing target policy costs and their policy costs under global least-cost climate change mitigation is divided by the global carbon certificate price. The resulting quantity represents for each region and period the amount of certificates that has to be added to the emission level calculated under least-cost mitigation criteria, which equals the regional effort-sharing certificate allocation.

Both burden-sharing schemes are investigated within a climate policy framework and corresponding annual GHG emission budgets apt to meet a long-term stabilisation of the global mean temperature increase at 2˚C with respect to the pre-industrial level. In the 2˚C climate stabilisation scenario without additional burden sharing arrangements, referred to as the 'reference' scenario, the regional allocation of GHG certificates is identical to each region's emissions under the conditions of a global least-cost GHG reduction pathway. The quantity of emission allowances allocated worldwide in each period equals in both burden-sharing regimes the global GHG emissions of the reference scenario. Neither methodology involves banking or borrowing mechanisms between trading periods. According to our model's time resolution, the duration of one trading period is 10 years.

with changing demand patterns. Policy implementation and transaction costs are excluded. Climate policy costs are calculated as the difference between the total costs under certain policy conditions and the costs in the reference case.

3. Results

3.1 GHG emissions reduction without burden-sharing

As reference GHG emissions reduction pathway in this article we take one of the delayed-action scenarios developed in the LIMITS project: RefPol-450 (see Kriegler *et al.*, 2013). In this scenario, after a short period with fragmented weak national climate policies that reflect the unconditional Copenhagen pledges, from 2020 onwards a global treaty is in force that achieves climate stabilisation with a maximum of 2˚C average atmospheric temperature increase. This climate change control target is implemented through a maximum radiative forcing level of 2.8 W/m^2 in 2100[6]. A detailed description of this scenario can be found in Kriegler *et al*. (2013).

In the reference scenario global GHG emissions peak in 2020 at 51 GtCO_2e, decrease down to 21 GtCO_2e in 2050, and become negative to eventually reach -4 GtCO_2e by the end of the 21st century (see left panel in Figure 1). The majority of this large GHG emissions reduction profile materialises through CO_2 abatement, while CH_4 and N_2O emissions (primary from non-energy-related agricultural activities such as food production) decline by about a factor of 2 throughout the century. Agricultural emissions of CH_4 and N_2O develop mostly according to the combination of population growth and availability of mitigation potential in agriculture, for which we make assumptions based on DeAngelo *et al.* (2006) and van Vuuren *et al.* (2006). In the agricultural sector, GHG emissions mitigation arises, for instance, from changes in soil management, adaptations in water control for rice production and advances in the use of fertilisers. The total worldwide mitigation potential we suppose for CH_4 and N_2O in 2100 of 7.8 GtCO_2e (as expressed with respect to our population-driven business-as-usual assumptions) is fully exploited in this reference scenario, that is, we think that the remaining emissions of these gases are virtually impossible to abate. This is in line with a study on long-term non-CO_2 GHG mitigation potentials by Lucas *et al*. (2007), who provide a comprehensive analysis of this subject including abatement measures and costs.

[6] This forcing target refers to all anthropogenic radiative agents with the exception of three agents: nitrate aerosols, mineral dust aerosols, and land use albedo changes. According to our model approach we adjusted the forcing target to be applied to the three GHG emissions represented in the TIAM-ECN.

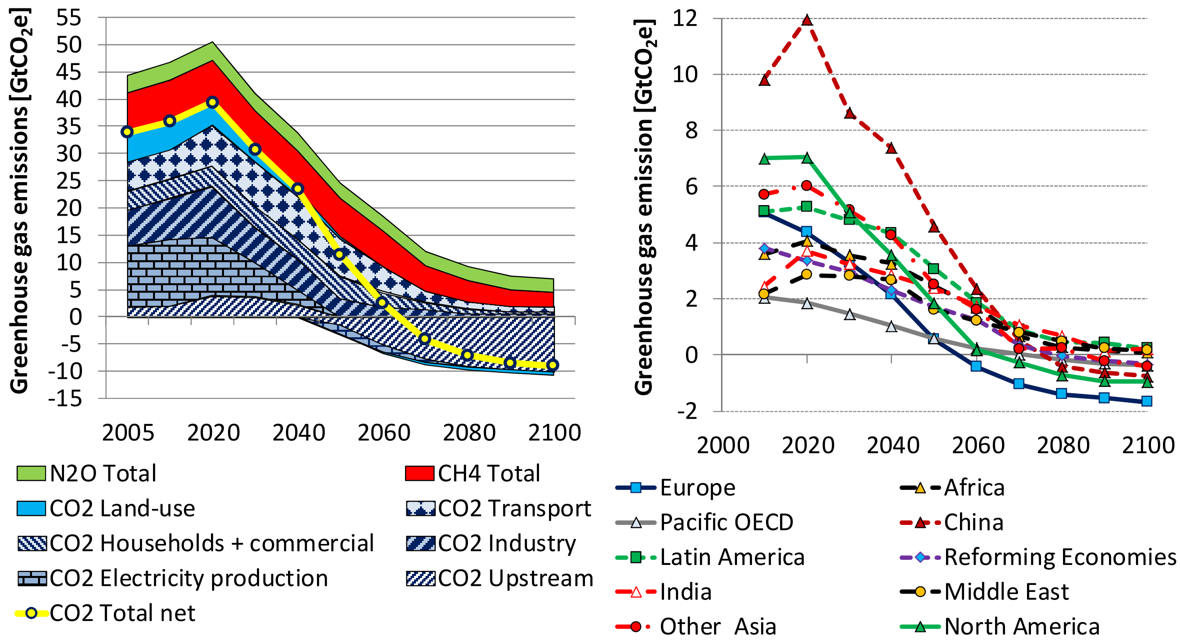


Figure 1: Global GHG emissions by type and sector (left) and by region (right) in the reference climate change control scenario with least-cost long-term GHG mitigation.[7]

Most anthropogenic CO_2 emissions derive from fossil-fuel-based combustion technologies. These emissions are curtailed significantly past 2020. Early emission reductions are notably realised in the power sector, which becomes a negative net GHG emitter on a global level from around the middle of the century. Also the upstream sector experiences a transition from positive net GHG emissions to negative ones around that time, but with eventually much larger quantities of negative GHG emissions. CO_2 emissions from land-use, land-use change and forestry (LULUCF) are eliminated before 2050 and become slightly negative during the second half of the century as a result of the implementation of afforestation measures. These three sectors together largely offset remaining positive GHG emission contributions from other sectors during the last couple of decades of the century, especially CH_4 and N_2O from agricultural activities.

In order to cost-efficiently reach the 2˚C climate change control target, both industrialised countries and emerging economies have to cut their GHG emissions drastically (see right panel in Figure 1). In the Pacific OECD, North America, Reforming Economies, and Europe, GHG emissions never exceed 2010 emission levels. In other regions, mainly those with emerging economies, GHG emissions continue to increase until 2020 due to their economic development, population growth and as of yet limited national climate change mitigation efforts. Past 2020, however, GHG emissions decrease in these regions as well, in most cases rather rapidly. Similar to the off-setting effect between sectors, GHG emissions are levelled out between regions in the long run. In other words, regions that have sufficient mitigation potential to gain a negative net GHG emissions balance, can compensate for regions with

[7] Results are given for the 10 LIMITS 'super-regions', for which our findings for the 15 TIAM-ECN regions have been aggregated.

positive net GHG emissions. Negative net GHG emissions on the regional level occur past 2050 in those regions with significant capacities for afforestation measures and biomass use in electricity generation and hydrogen production (where it is combined with CCS).

In our study we use relatively conservative estimates for global potentials of various types of biomass (representing about 150 EJ in total in 2100), which reflects our judgement that limited biomass may be available when sustainability criteria are accounted for and food price issues are prioritised (GEA, 2012, Hoogwijk *et al*., 2009; Thrän *et al*., 2010). We find that in the reference scenario more than 90 % of all biomass, used in the energy and non-energy sectors combined, is produced within the respective regions of consumption. In other words, unlike is the case for fossil fuel resources, biomass is mostly used domestically, and only relatively modest amounts of biomass are traded internationally. The main explanation for this outcome is our comparably conservative assumption on the availability of biomass resources. With larger biomass potentials, accompanied by excess of supply in certain regions, inter-regional biomass trade could in principle increase substantially in order to match production and consumption cost-efficiently. The costs of large-scale biomass collection within (and transport between) the respective regions, however, would co-determine the extent of such a possible increase. In our reference scenario Europe is one of the regions with the largest biomass net imports of up to 2 EJ/yr. Latin America and Other Asia, on the other hand, are the main biomass suppliers. For an in-depth assessment of the role of biomass at the regional level for reaching ambitious GHG reduction targets, based on a LIMITS multi-model scenario analysis that includes modelling results from TIAM-ECN, we refer to Calvin *et al*. 2013. For insights in the global, regional and sectoral deployment of low-carbon technology more generally (including biomass options) we refer to van der Zwaan *et al.* (2013) and van Sluisveld *et al.* (2013).

The carbon certificate price associated with reaching the 2˚C stabilisation target in our reference scenario, which is determined by the marginal costs of the mitigation options available in all sectors of the global energy system, rises from 70 US$/t$CO_2$e in 2020 via 130 US$/tCO_2e in 2030 to 390 US$/t$CO_2$e in 2050. During the second half of the century the price for emission permits increases substantially further, especially since negative GHG emissions have to be achieved: the certificate price increases to around 2000 US$/t$CO_2$e in 2080 and becomes about 5,000 US$/t$CO_2$e in 2100. The global annual policy costs to reach the 2˚C climate change control target add up to approximately 0.3 tln US$ in 2020, rise to around 4 tln US$ in 2050, and surge to 27 tln US$ in 2100. In total they accumulate to 77 tln US$ for the entire first half of the century, and to almost 1000 tln US$ for the second half of it.

3.2 Allocation of emission allowances under the resource-sharing regime

Along with our population development assumptions for the remainder of the 21st century, GHG emissions per capita (also called 'specific' emissions) for each region in 2020 and the evolution of the global average of GHG emissions (per capita) over the course of the century constitute the key input parameters for the calculation of the allocation of emission allowances according to the resource-sharing method. For the regional specific emissions in 2020 and the global average specific emissions from 2020 until 2100 we adopt those determined under the reference scenario, which are depicted as starting points respectively black line in the left panel of Figure 2. As can be seen in Figure 2, in 2020 North America has the highest specific emissions (19 $MtCO_2e$/capita) and India the lowest (3 $MtCO_2e$/capita), while the global average amounts to around 7 $MtCO_2e$. We observe that, from the regions' respective starting points, specific GHG emissions contract in subsequent decades and converge by 2050, as prescribed by the resource-sharing rule. During this time frame, the global average of specific GHG emissions declines to 2 $MtCO_2e$/capita. During the second half of the 21st century each region's amount of certificate endowments is determined by the region's exogenous population development as well as the further decreasing world average of GHG emissions per capita as calculated under the reference scenario. Against the background of deep global GHG emission reductions at an almost constant world population, the global level of per capita emissions continues to decline after 2050 to reach negative levels from about 2080 onwards.

The development in absolute terms of regional carbon certificate budgets during the course of the 21st century is depicted in the right panel of Figure 2. In early decades, the resource-sharing method favours regions with a high population growth. This can be seen in Figure 2 for Africa and India, for which the number of allocated certificates increases from 2020 to 2030, and for Africa also from 2040 to 2050. All other regions show decreasing certificate allocations from 2020 onwards. In the absence of high population growth rates, the number of emission rights of regions declines especially rapidly when the initially allocated amount of GHG emissions allowances is high, such as for China and North America. For Other Asia the decrease over time of allocated emission rights is clearly less steep, irrespective of their relatively high start, as a result of the initially high population growth in this region.

Scenarios involving negative global GHG emissions in the long run have special consequences for the regional allocation of carbon certificates and its development under the resource-sharing scheme. As pointed out in Figure 1, in order to achieve a 2˚C climate change control target under global cost optimisation criteria, some regions need to reach such a negative net GHG balance during the last decades of the century. The certificate allocation under the resource-sharing scheme in itself does not yield incentives to gain net negative GHG emissions within regions as long as worldwide GHG emissions do not become negative. If negative net emissions are required on a global level, however, as is the case in our reference scenario, the resource-sharing scheme imposes this obligation to all regions, which could as such be effectuated in principle in every region. For the long term, regions with a high population face strongest emissions reduction obligation in absolute terms. Consequently, in the long run the endowment of permits based on resource-sharing deviates from the reference emission levels especially for those regions which have a positive net GHG emissions balance in the reference scenario and a large population (as a result of high population growth in early decades), like India and Africa, and likewise for those regions with significant negative net emissions in the reference scenario and relatively small populations (given *moderate or zero population growth throughout the century), like Europe and North America (compare Figure 1 with Figure 2).*

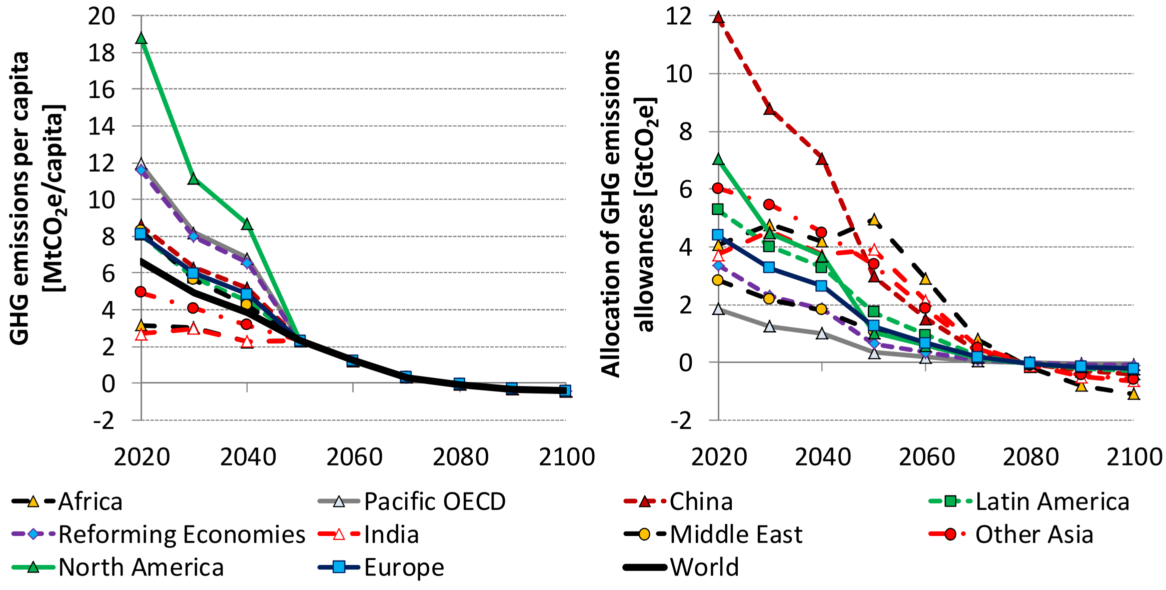


Figure 2: GHG emissions per capita as allowance allocation basis (left) and emission allowances allocation under the resource-sharing regime (right).

Trade of emission allowances occurs based on the allocation of GHG emission rights, on the one hand, and the region's technological potentials to reduce GHG emissions, on the other hand. This trade allows a return to the overall cost-optimal mitigation pathway, if one assumes the existence of a perfect carbon certificate market (as we here do). Trade of certificates in the resource-sharing scheme starts past the year of grandfathering in 2020, the results for which are reported in the left panel of Figure 3). A cumulative amount of certificates equivalent to 250 $GtCO_2e$ is traded until 2100. The total annually traded quantity of emission rights reaches its maximum in 2050, at 5.6 $GtCO_2e$, and decreases down to a value of 2.1 $GtCO_2e$ in 2070. This maximum in 2050, which represents about half of the global GHG emissions in that year, implies a significant divergence of allocated emission rights under the resource-sharing scheme in comparison to the overall cost-optimal mitigation pathway.

During the first half of the century the most important emission certificate selling regions are Africa and India. These two regions combined sell emission rights equivalent to a cumulative amount of 83 $GtCO_2e$ until 2050, which corresponds to about 75% of the total number of certificates sold in this period. Around 80% of the tradable permits in this time frame are bought by Latin America, China, the Middle East and the Reforming Economies, which can be explained by the high economic growth rates (hence rapidly increasing GHG emission levels) and modest or even negative population growth rates in these regions. In the long run, India and Africa become two major certificate-buying regions, because by then they have large economically developed populations but possess few options with which they can attain negative emissions, such as through biomass in combination with CCS. India and Africa buy allowances from regions that do have high biomass-CCS potentials, such as North America and Europe, which consequently become the negative net GHG emitting regions depicted in Figure 1. In 2100 Europe ends up selling carbon certificates up to an amount of approximately 1450 $MtCO_2e$/yr.

Unlike climate policy costs, which involve the sum of all costs required for the implementation of a climate policy target, the carbon capital flow is the monetary transfer associated with the total amount of certificates traded at the price prevailing at the global carbon market. The certificate price is determined by the marginal abatement cost amongst all GHG reduction options partaking in the global carbon market. We report policy costs, capital flows and carbon certificate prices as undiscounted values for their corresponding periods. We find that, as time proceeds, the carbon market capital flow is increasingly determined by the certificate price, rather than by the quantities of traded certificates, as a result of the exponential increase of the former towards the end of the century. The volume of the carbon market capital flow expands from 350-600 bln US$ in 2030-2040 via 2,200-2,600 bln US$ for the period 2050-2070 to about 15,000 bln US$ in 2100 (see right panel in Figure 3).

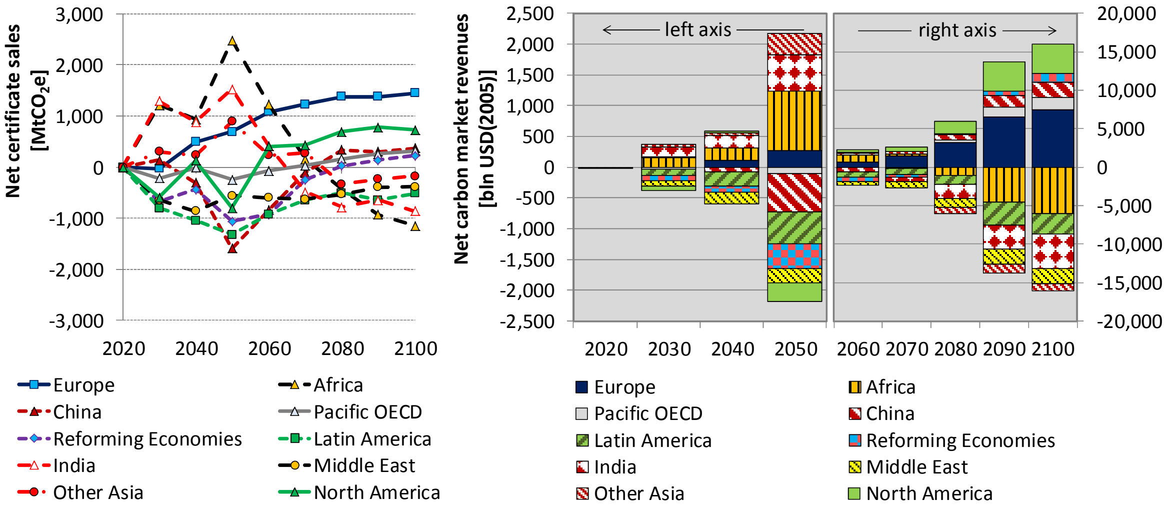
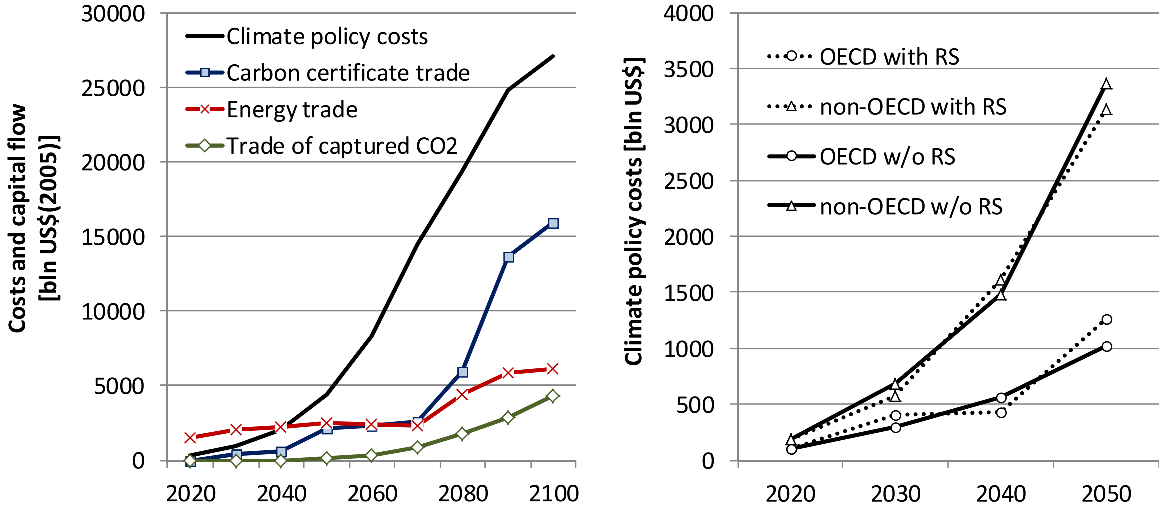


Figure 3: GHG emission certificates trade (left) and carbon market capital flow (right) in the resource-sharing scheme.

A comparison between the annual global capital flows of the carbon certificate market with the costs needed to reach the 2˚C climate stabilisation target reveals several policy-relevant insights. In particular, it shows that the total capital flow of the world carbon market represents between 30% and 50% of the global policy costs associated with this climate target during the first half of the 21st century, and between 20% and 60% after 2050 (see left panel in Figure 4). Figure 4 also demonstrates that the total capital flow for trade of emission allowances reaches the level of energy market capital flows around the middle of the century, and exceeds them by almost three times by the end of it. This outcome underlines the outstanding importance of the carbon certificate market in the future, which within decades could become at least as important as the global energy market.

In terms of regional carbon certificate capital flows versus policy costs, much larger deviations can be observed than in the global case. The case of Africa, for example, shows that the total cumulative revenues of 13 tln US$ from allowances sold during the first half of the century are 2.5 times the cumulative climate policy costs (4.9 tln US$) in the same period. Conversely, the expenses for purchases of emission rights for the Reforming Economies are about 60% higher than their climate policy costs in the reference scenario for the period 2020 to 2050. This latter case indicates that the resource-sharing regime analysed in this study cannot compensate all developing and transition countries at once. Inversely, the former case shows that this scheme might overcompensate the financial efforts of GHG emission reduction measures of selected emerging regions. This overcompensation effect has also been observed in previous studies, e.g. by Jacoby *et al*. (2008), who find that a population-based burden-sharing scheme 'goes well beyond compensating for mitigation costs and turns the GHG mitigation policy into an instrument for global income distribution'.

For the group of non-OECD countries, only marginal effects of the resource-sharing scheme on the reduction of climate policy costs can be observed until 2050 (see right panel of Figure 4). In total 4% of their policy costs can be compensated by revenues from the carbon market during the first half of the century. This is the direct consequence of significant differences among non-OECD countries with regard to their expected socio-economic development and their capabilities to reduce GHG emissions, on the basis of which benefits in the resource-sharing regime are only generated for selected countries within this super-region. Hence, for the entire cluster of non-OECD countries, regional benefits and losses more or less level out, which indicates that the resource-sharing scheme is insufficient for compensating all non-OECD countries for their efforts to mitigate GHG emissions. One reason for this effect, and thereby drawback of the resource-sharing scheme, is the disregard of each region's technological capabilities and economic capacity to implement GHG emission reduction measures. In particular, regions with a moderate population growth and unfavourable GHG mitigation potential are hardly compensated for their climate control efforts irrespective of their macro-economic performance.



N.B. 1: RS: Resource-sharing

N.B. 2: Capital flows are based on trade among the 10 LIMITS regions. Market capital volumes would increase in case of a representation of our results with a higher geographical resolution.

Figure 4: Climate policy costs and capital flows for trade of carbon certificates, energy and captured CO_2 under the resource-sharing scheme.

3.3 Allocation of emission allowances under the effort-sharing regime

For the allocation of emission rights according to the effort-sharing scheme the development of climate policy costs in the reference scenario and the assumed GDP growth paths of each of the regions are the main determinants. Climate policy costs differ among regions, as a result of regional variations concerning the availability of GHG emission reduction options as well as trade patterns for energy and emission certificates. More specifically, drivers for such regional differences may be, for instance, the availability of renewable energy resources, the local feasibility of the diffusion of CCS, and the nature of national policies towards nuclear power. Recent insights vis-a-vis the global versus regional dimensions of technology deployment and diffusion of climate change mitigation measures can be found in studies by e.g. van der Zwaan et al. (2013) and van Sluisveld et al. (2013), both performed as cross-model comparison exercises. The left panel in Figure 5 (black line) depicts for our model the global annual average policy costs required to reach the 2˚C climate change control target, on which the calculation of carbon certificates allocation in the effort-sharing scheme is based. They are expressed in relative terms as shares of GDP: 0.3% in 2020, 1.8% in 2050 and 3.7% in 2100. As can be seen, the world average share of climate policy costs peaks in 2090 at 4.0% of GDP. The regional policy costs can reach up to 0.5% of GDP in 2020 and 6% during the second half of the century. In 2020, China and Latin America face the highest relative policy costs, which result from the large expected increases in their respective energy demands and thus massive investment requirements in renewable energy for power production and energy efficiency improvements on the demand side.

In the long run, effects connected to energy trade and the trans-boundary transport of captured CO_2 for storage abroad gain importance for each region's climate policy costs. Regions that have extensive net fossil fuel exports and possess few local GHG reduction measures, like the Middle East and Reforming Economies, face considerable reductions of these exports and hence the associated revenues when stringent climate policy is implemented. Their climate policy costs therefore increase. Inversely, a reduction of climate policy costs can be expected for regions that have large CO_2 storage capacity or bioenergy resources, if these potentials can be made available for other regions via trans-boundary CO_2 transport or biomass export. Traditional natural gas and oil producing regions can profit from their geological capabilities if their oil and gas fields (depleted or not) are adequate for CO_2 storage. The Middle East and Reforming Economies together hold about half of the estimated global CO_2 storage potential (see Figure 6). In order to make this large storage potential accessible for other regions with less advantageous CO_2 storage sites, CO_2 transport capacities of up to 16 $GtCO_2$/yr for each of these two regions are required under stringent climate change control targets. In that case the trans-boundary transport of CO_2 accelerates during the second half of the century, and then generates significant revenues for these two regions. As a result, the reduction of capital inflow from decreasing fossil fuel exports is compensated by selling CO_2 storage capacity to other regions, and climate policy costs are therefore partly levelised.

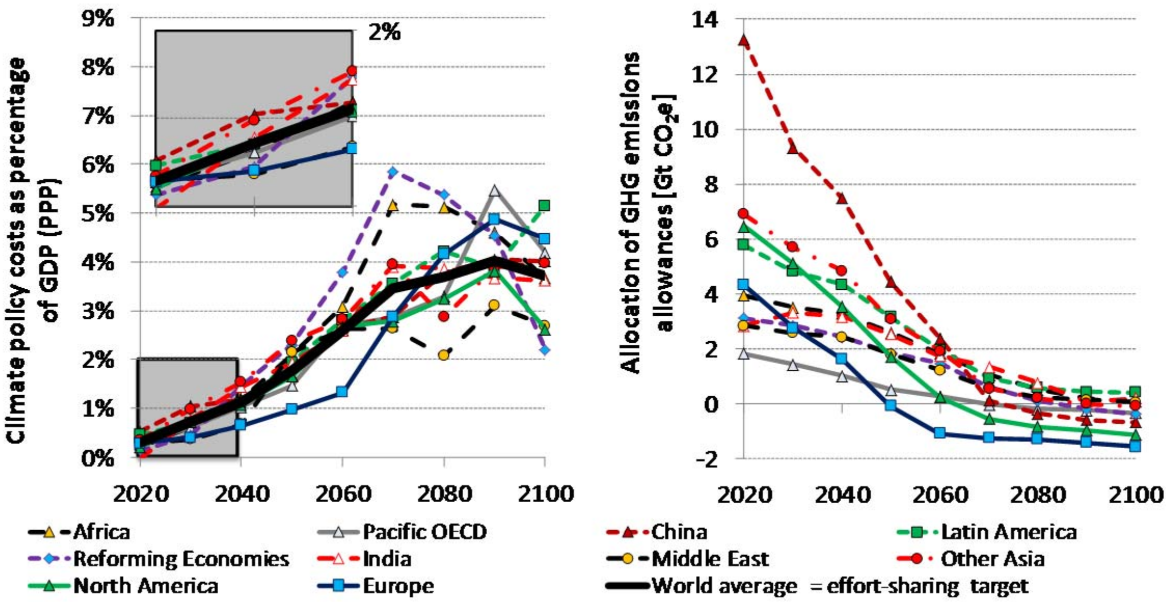


Figure 5: Regional climate policy costs under a global least cost GHG mitigation regime and effort-sharing regime (left) and emissions allowance allocation under this effort-sharing regime (right).

Besides the high climate policy costs observed for fossil fuel exporting regions, costs to mitigate climate change also represent a considerable share of GDP in regions with large GHG reduction potentials but with moderate economic growth, such as Africa and Latin America. For both these regions the share of climate policy costs in terms of GDP exceeds the world's average by up to 1.5%. The climate policy costs relative to GDP for India and China deviate little from the world average during the second half of the century. This outcome can be understood in view of the relatively high economic growth expected for both these countries even during the second half of the century (with average annual rates of, respectively, 4.8% and 1.2%). The absolute capital requirements for GHG emissions reduction in both these countries may thus be significantly higher than in other regions (amounting indeed for these two countries combined only to almost 40% of the global aggregated costs for the period 2050-2100), but in GDP terms they remain close to the global average.

The objective of the effort-sharing regime is to attribute emission rights to regions according to their individual GDP as well as the world's total climate policy costs in terms of global GDP. In this scheme, regions with higher relative policy costs in comparison to the world's average get additional carbon certificates allocated. Revenues from sales of excessive carbon certificates enable regions to compensate (at least partly) their local policy costs, which leads to an equalisation of climate change mitigation efforts across regions. The effort-sharing scheme starts in 2020, without any prior transition phase.

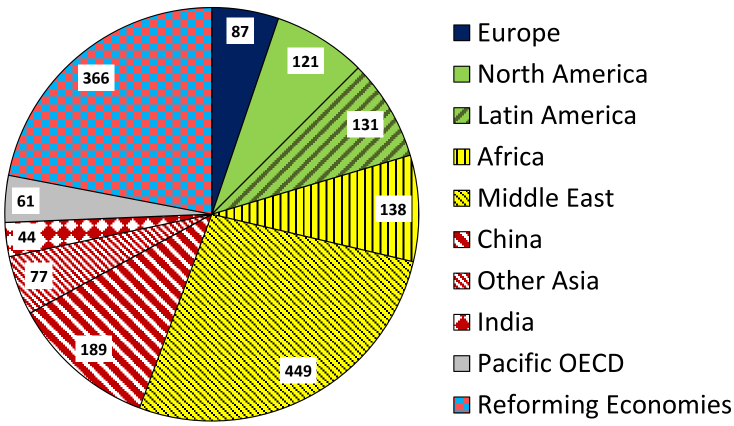


Figure 6: Potentials for CO_2 storage in geological formations by region (in $GtCO_2$), Source: Hendriks et al., 2004.

The cumulative emission rights allocated to China between 2020 and 2050 in the effort-sharing regime equal 256 $GtCO_2e$. This is 14 $GtCO_2e$ (6%) more than the level of GHG emissions in the reference scenario (see right panel in Figure 5). A similar increase applies to India, Latin America and Other Asia, which together profit from additionally available certificates worth about 11 $GtCO_2e$ until 2050. During the second half of the 21st century about 70% (142 $GtCO_2e$) of the total cumulative emission rights are allocated to three regions only: Latin America (53 $GtCO_2e$), India (49 $GtCO_2e$) and Africa (40 $GtCO_2e$). The cumulative certificate endowment of these three regions combined exceeds the GHG emissions level in the reference scenario by 15 $GtCO_2e$ between 2050 and 2100. The Reforming Economies and Other Asia also get allocated additional certificates with respect to their emissions in the reference scenario, worth some 9 $GtCO_2e$ for the period 2050-2100. In comparison to the resource-sharing scheme, the allocation of emission certificates under the effort-sharing regime comes closer to each region's share in a global cost-optimal GHG emissions reduction pathway. Consequently, fewer certificates are traded in the effort-sharing scheme.

Between 2020 and 2100 the cumulative amount of certificates traded under the effort-sharing scheme is 70% (80 $GtCO_2e$) lower than the quantity traded under the resource-sharing scheme (left panel in Figure 7). Annual amounts of carbon certificate trade range from 250 $MtCO_2e$ in 2090 to 2,000 $MtCO_2e$ in 2020, which are lower values in comparison to those observed in the resource-sharing regime. This outcome has a direct influence on the level of financial flows in the carbon certificate market, particularly during the first half of the century: 80% less capital transfer is necessary in the effort-sharing scheme than under the resource-sharing regime. The annual carbon market volume peaks in the first half of the century at 400 bln US$, but increases strongly in the second half of the century up to a value of over 2,000 bln US$ in 2100.

In the near term, the capital flows into certificate selling regions accumulate to 140 bln US$ in 2020, of which China receives 95 bln US$, Latin America 35 bln US$, and Other Asia 10 bln US$. By 2050 Chinese revenues from the carbon market have decreased drastically, to such an extent that China has actually become a net buyer of emission rights. Regions such as India, Latin America, the Middle East, Other Asia, Reforming Economies and Africa receive capital inflows from the carbon market in 2050. During most of the second half of the century, Africa remains a net seller of certificates, with a peak at around 500 bln US$ in 2070 and 2080. Europe undergoes the transition from a net buying region until beyond the middle of the century to being a seller after 2070: it thus generates up to 500 bln US$/yr in 2090 and 2100. This value is less than 10% than that attained in the resource-sharing scheme. Reforming Economies can compensate their decreasing revenues from reduced fossil fuel exports partly by selling emission allowances on the certificate market during especially the second half of the century (while becoming a net buyer of emission rights in 2100). In addition, revenues from selling CO_2 storage capacity for CCS application in other regions increase, which overcompensate the decreasing income from fossil fuel exports. This effect is even more pronounced in the Middle East, where fossil fuel exports reduce significantly under global climate policy (but less so than in the Reforming Economies), while substantial growth takes place of storage of captured CO_2 from outside the Middle East. As a consequence, climate policy costs, and hence the amount of permits allocated to the Middle East, are comparably low for this region. This implies that the Middle East becomes the most important certificate buying region during the second half of the century, with annual expenditures of up to 680 bln US$. Despite these large expenditures, the total net capital balance in the Middle East, based on trade of energy, captured CO_2 and emission certificates, remains positive. In other words, capital inflow for this region stays higher than the outflow.

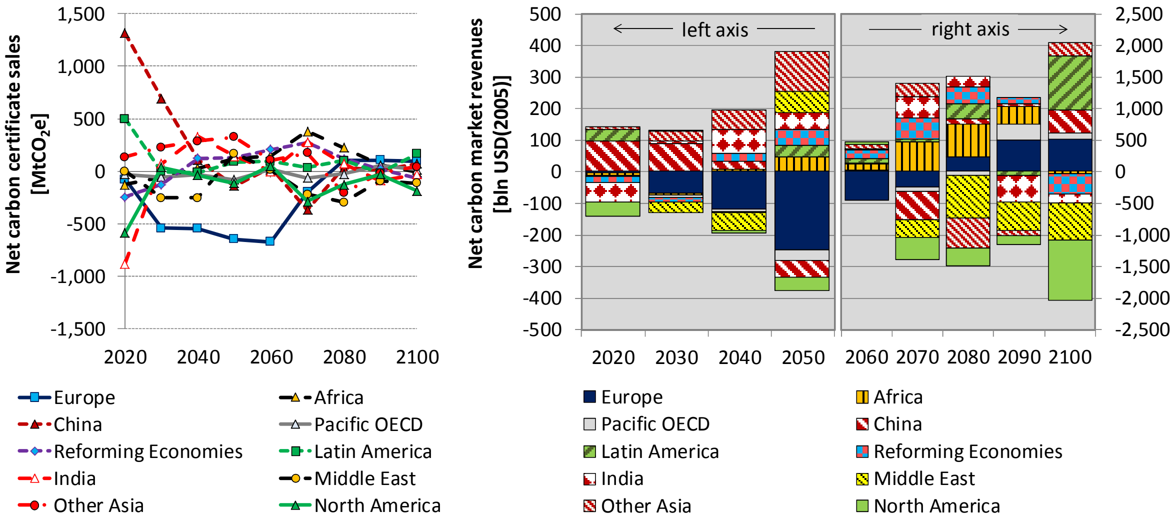
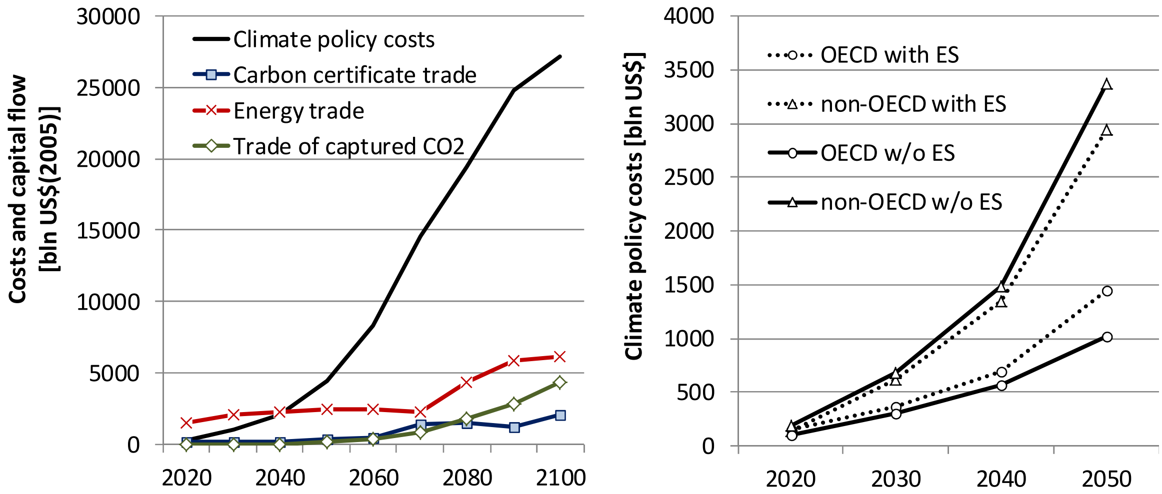


Figure 7: Carbon certificate trade (left) and corresponding market capital flows (right) under the effort-sharing scheme.

The capital volume of the carbon certificate market as percentage of the global climate policy costs declines from 50% in 2020 to 9% in 2050 and remains low for the remainder of the century with values between 5% and 10% (see left panel in Figure 8). By comparing Figure 4 with Figure 8, one observes that the cumulative carbon market capital flow from 2020 to 2100 as share of the total climate policy costs is much lower in the effort-sharing scheme (7%) than under the resource-sharing regime (55%), which reveals much less compensation of regions' climate policy costs in the former than in the latter. In the long run the total capital transferred on the carbon certificate market is significantly lower than the financial transfers involved with energy trade under the effort-sharing regime, unlike in the resource-sharing scheme, where during the last decades of the century the former is substantially larger than the latter. In the effort-sharing scheme, towards the end of the century, the overall value of the carbon market remains so low that even the capital flows associated with the physical transport of CO_2 between regions exceed the aggregated capital flow of emission allowances. For both burden-sharing schemes the main beneficiaries of the CO_2 transportation market are the Middle East and Reforming Economies, given their vast CO_2 storage potentials. As for the carbon certificate market over the next few decades, Africa, India and Other Asia are the main beneficiaries in the resource-sharing scheme, while China, India and Other Asia are so for the effort-sharing scheme. Hence, we find that under either burden-sharing scheme both the CO_2 transportation and carbon certificate markets represent compensation mechanisms for the policy costs associated with GHG reduction efforts incurred by non-OECD economies.

Substantial differences exist between individual regions in terms of the share of their carbon market capital flow of their climate policy costs. In 2020 the revenues from the carbon certificate market cover almost all the climate policy costs for China and Latin America, and one third for Other Asia. Also, the overcompensation observed for Africa under the resource-sharing scheme is less significant under the effort-sharing regime. As can be seen in Figure 8 (right panel) for the effort-sharing regime, for all non-OECD countries combined, about 12% of their climate policy costs can be covered by revenues from the carbon certificate market during the first half of the century, with a maximum of 27% in 2020 and a minimum of 9% in 2040. In comparison to the resource-sharing scheme, the effort-sharing regime is better capable of compensating less developed economies for their costs incurred to mitigate climate change. Indeed, a comparison between Figures 4 and 8 demonstrates that the effect of burden-sharing – generating generally and especially in the long run higher policy costs for the cluster of OECD countries and lower ones for non-OECD countries – is larger for the effort-sharing scheme than the resource-sharing scheme.



N.B. 1: ES: Effort-sharing

N.B. 2: Capital flows are based on trade among the 10 LIMITS regions. Market capital volumes would increase in case of a representation of our results with a higher geographical resolution.

Figure 8: Climate policy costs and capital flows for trade of carbon certificates, energy and captured CO_2 under the effort-sharing scheme.

4. Limitations in carbon certificate trade

The results presented in the previous section indicate that carbon certificate trade plays an important role in burden-sharing schemes to cost-efficiently reach climate change mitigation goals. We so far assumed a perfectly functioning carbon market. It might be hard, however, to establish perfect carbon market conditions, and market distortions of many different types could arise (see e.g. Straub-Kaminski *et al.*, 2013). Carbon market obstacles can result from an inadequate institutional framework, low regulatory transparency, transaction costs, information asymmetry, and other imperfections on financial markets. The objective of this section is to further investigate various aspects of carbon certificate trade, in particular in terms of (1) timing issues, (2) regional implications, (3) certificate price effects, and (4) global climate policy costs. We therefore conduct a sensitivity analysis, and study what may happen to the overall quantities of carbon certificate trade if emission allowances are allocated according to a specific burden-sharing regime but with constrained possibilities to trade permits on an international market. Similar research has been conducted by De Cian and Tavoni (2012), who researched restrictions in carbon certificate trade and their implications for technological innovation and low-carbon technology deployment. Contrary to their study, however, we here assume fixed exogenous technology cost reduction rates and do not assess interdependencies between certificate trade and technological learning. Hence we do not analyse the positive effects on innovation that may result within a region from a (complete or partial) decoupling of its internal market from the global one. The subject of our sensitivity tests is the total cumulative quantity of traded certificates between 2020 and 2100 in each of the two burden-sharing regimes. Under the resource-sharing regime in total about 250 $GtCO_2e$ are traded between 2020 and 2100 among the 10 regions defined in the LIMITS project. Under the effort-sharing regime this figure amounts to around 80 $GtCO_2e$. With as starting point these quantities that apply under perfect trade conditions, different trade (restriction) levels are analysed, in the sense that we constrain the total cumulative quantity of certificate trade while we leave the allocation among regions and the timing of trade endogenous to our model.[8]

4.1 Timing issues

Since under full trade conditions the total number of tradable certificates (cumulatively, as well as at each point in time from 2030 onwards) is more than three times higher in the resource-sharing regime than in the effort-sharing regime, the same trade level restrictions in relative terms represent different reductions of tradable certificates in absolute terms under these two burden-sharing schemes (see Figure 9). We find that the minimal permissible trade level under the resource-sharing scheme (left panel in Figure 9) is 20%. At more stringent trade restrictions, TIAM-ECN yields infeasible results. This trade limitation involves a cumulative amount of traded GHG emission permits until 2100 of 48 $GtCO_2e$, hence about five times lower than under full trade conditions. In the effort-sharing scheme (right panel in Figure 9) the minimal allowable trade level is found to be 30%, which corresponds to a cumulative amount of tradable certificates of 24 $GtCO_2e$, i.e. approximately three times lower than in a world with perfect trade. Under the resource-sharing scheme a limitation of the cumulative amount of tradable certificates down to 20% leads to a world in which the number of available carbon permits is conserved for trade during mostly the last few decades of the century only. This reveals that in this case certificate trade is indispensable in especially the second half of the century, given the depth of GHG emission cuts required after 2050 and the correspondingly rapid increase of mitigation costs by then. In the long run, the global carbon certificate market is particularly important to offset emissions from countries with positive net GHG emissions, by those countries possessing the capabilities to establish a negative net GHG balance. Hence even if stringent restrictions apply on the global carbon market, international trade allows to exploit cost-efficiently the climate change mitigation potentials of all respective regions. In the effort-sharing scheme we observe a different evolution of carbon certificates trade over the 21st century: from a peak in 2020 global trade gradually winds down until the end of the century. The explanation is the fact that under this regime (that is operational from today onwards) national climate policies out-shadow the importance of global climate change control policy, which generates an early reallocation (i.e. trade) of emission permits according to

[8] Another approach could have been to reduce the tradable amount of carbon certificates by equal shares across periods and/or regions. This alternative method, however, which we may still inspect in the future, would by definition have provided less insight with regard to possible shifts in international certificate trade over time and space.

nationally stipulated GHG reduction targets (see also Kriegler *et al.*, 2013). We do not observe this effect under the resource-sharing regime: no certificate trade arises there in 2020, which is a direct consequence of the contraction and convergence procedure applied from only the status quo situation in 2020 onwards.

For the resource-sharing scheme, carbon certificate trade reaches an all-time peak in 2050 for trade levels above 60% (see left panel in Figure 9). Trade patterns in 2050 alter significantly when trade levels are limited from 60% down to 40%. Inversely, the exchange of carbon permits expands substantially in 2050 when trade possibilities increase from a level of 40% to 60%, in which case the traded number of certificates more than doubles from 1.3 $GtCO_2e$ to 3.3 $GtCO_2e$. This strong increase at intermediate trade levels can be interpreted as the high relevance of carbon certificate markets, especially around the middle of the century, and demonstrates the importance of carbon certificate trade in particular under the resource-sharing regime. In the effort-sharing scheme (see right panel in Figure 9), in contrast to the resource-sharing scheme, no particular decade exists with exceptionally high influence of constrained certificate trade. The impact of limited trade under this regime is distributed relatively uniformly from 2030 onwards.

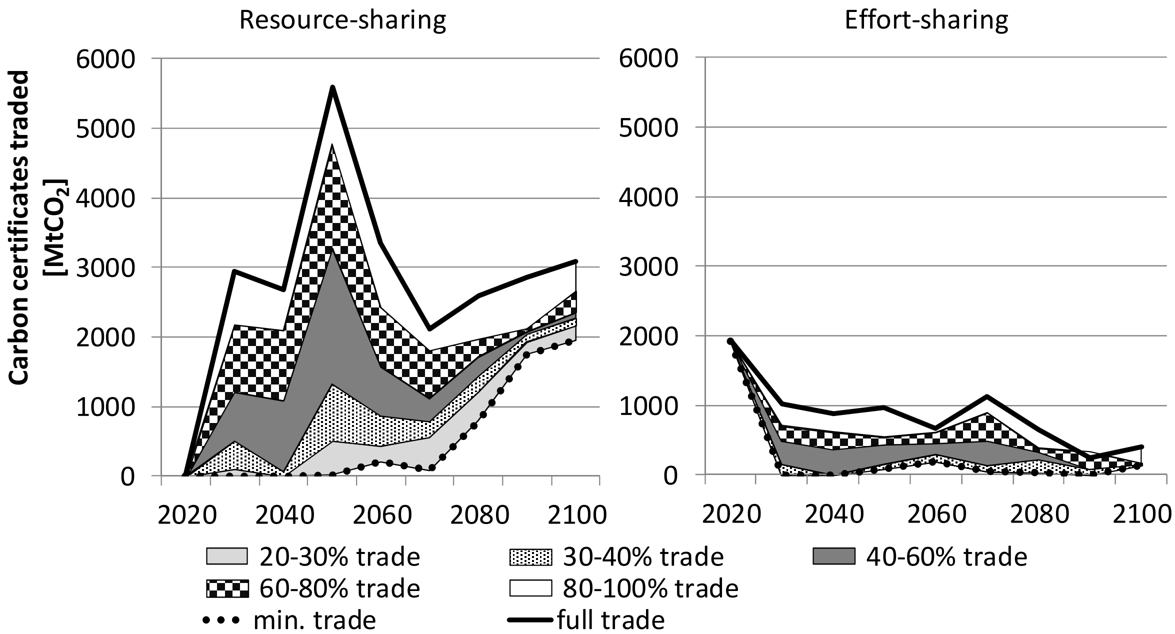


Figure 9: Global number of tradable carbon certificates under different trade levels in the two burden-sharing schemes.

LIMITS

4.2 Regional implications

We find that limitations in carbon certificate trade rarely inverse a region's position on the carbon market within a period, that is, they seldomly switch a region from being a seller to becoming a buyer of emission permits, or vice versa. The amounts of certificates sold or bought on the carbon market, however, may shrink dramatically in response to trade restrictions, and sometimes regions may even entirely decouple from the global certificate market as a result of them. Figure 10 depicts the cumulative net regional sales of carbon certificates between 2020 and 2050 at different trade levels under the resource-sharing and effort-sharing regimes. As can be seen, under the resource-sharing scheme, Africa is in relative terms less affected by trade restrictions in its certificate selling capacity than regions like India and Other Asia. The explanation for this outcome is twofold: 1) Africa gets allocated an excess of carbon certificates under the resource-sharing scheme with respect to the reference scenario GHG emissions; 2) Africa possesses larger domestic GHG reduction potentials than the other two main certificate selling regions. Given its abundant natural gas and renewable energy resources, climate change mitigation can be realised at lower costs in Africa than in regions with less favourable potentials for low carbon energy supply such as India and Other Asia. Adequate institutional, financial and energy policy frameworks would obviously need to exist in Africa to unlock its large GHG emission reduction potentials, and our model assumptions critically hinge on whether these frameworks will be implemented in practice. In absolute terms, Latin America, the Reforming Economies and the Middle East are the largest buyers of certificates, amounting to cumulative purchases of, respectively, 10 GtCO_2e, 7 GtCO_2e and 5 GtCO_2e worth of emission permits, when trade is restricted down to 60%. In relative terms, North America reduces its certificate purchases most, by more than 50% if trade is reduced down to 60%. The reason is that North America possesses domestic climate change mitigation measures with relatively low costs, which allows it to affordably compensate for limitations of certificates on the global carbon market. Domestic GHG mitigation options in the Middle East, on the contrary, are quite costly, so that it only starts significantly reducing its purchases of emission certificates when international trade is almost completely obstructed.

Under the effort-sharing regime limitations in carbon certificate trade reduce in particular the number of certificates sold by China and Other Asia (cumulatively about 6 GtCO_2e for each of these two regions, when trade is restricted down to 40%). Similarly it decreases especially the amount of certificates purchased by Europe and the Middle East (in total about 17 GtCO_2e). The limited availability of emission certificates is compensated in these two regions through the implementation of domestic climate change mitigation measures, such as additional CCS and renewables deployment in the power sector (in Europe) and enhanced CO_2 and CH_4 emissions abatement in the upstream sector (in the Middle East). For Europe we also observe an increased consumption of electricity (+10%) and hydrogen (+15%) in the energy end-use sectors if carbon certificate trade is restricted down to 40%. These developments on the demand side in Europe are accompanied by a reduced CO_2 emissions intensity for the production of electricity and hydrogen in the energy supply sector. In 2050, fossil fuel based electricity generation in Europe is reduced by 60 TWh, while the contribution of renewable energy increases by 450 TWh when carbon certificate trade diminishes down to 40%. For Europe and other oil and gas importing regions, the intensification of domestic GHG mitigation efforts, especially in the transport sector, has a positive impact on their fossil fuel import dependency, and corresponding consequences for global energy trade.

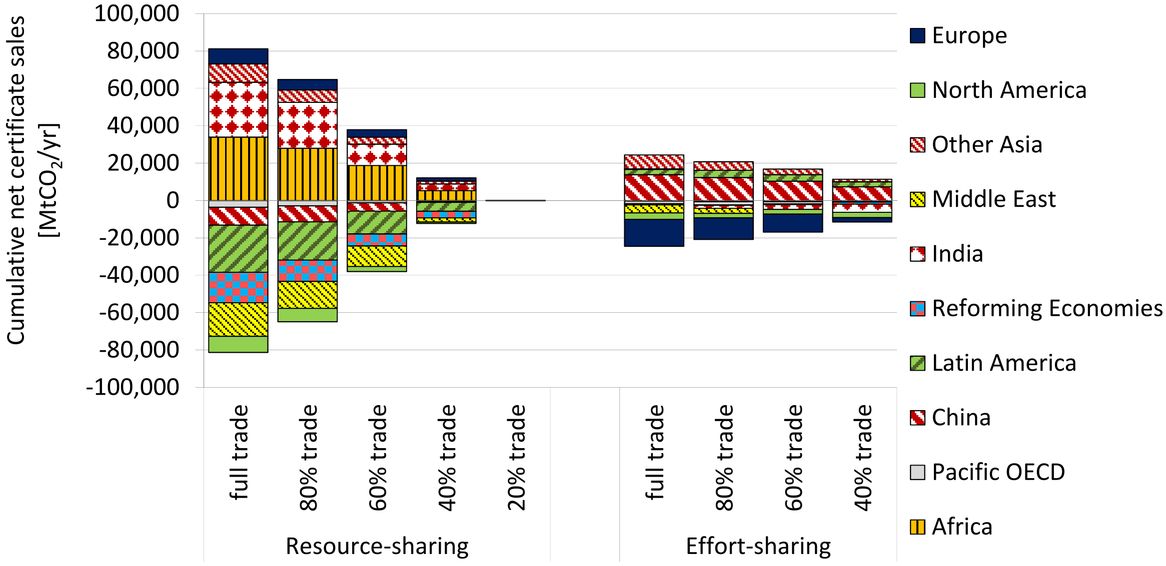
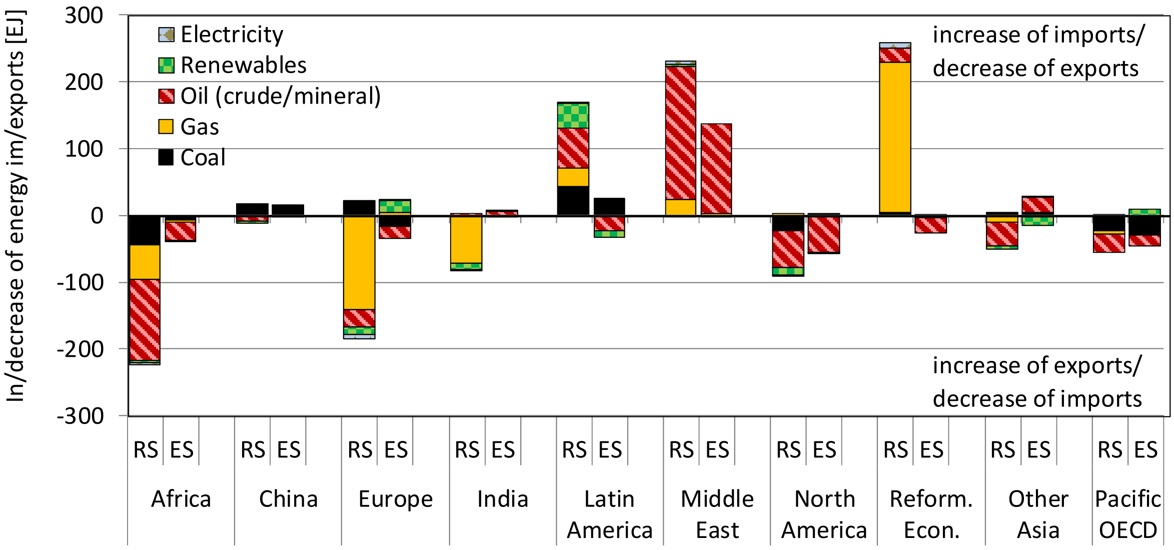


Figure 10: Cumulative net sales of carbon certificates between 2020 and 2050 at different trade levels under the resource-sharing and effort-sharing schemes.

Our model results imply that limitations in the trade of carbon certificates down to 40% reduce global energy trade by 11% under the resource-sharing scheme and by 2% under the effort-sharing scheme. Hence the effect is stronger for the former than the latter burden-sharing regime. Also at the regional level the impact of limited carbon trade tends to be higher under the resource-sharing than the effort-sharing regime, as can be seen in Figure 11 for most regions. The largest changes can be observed in the trade of oil and natural gas. Under the resource-sharing regime global oil consumption declines on average by 2%/yr between 2020 and 2050 if certificate trade is limited to 40%. Consequently oil exports decline, in particular from the Middle East, by a cumulative value of 200 EJ until 2050 (see Figure 11). Inversely, Africa, which is currently also an oil-exporting region and has an excess of emission allowances under the resource-sharing regime, experiences less stringent GHG reduction obligations, can therefore increase its oil production, and is thus able to export more oil (with a cumulative increase of 120 EJ between 2020 and 2050). For the major oil importing regions, i.e. North America, Other Asia, Pacific OECD and Europe, limitations of carbon certificate trade under the resource-sharing scheme lead to a reduction of their oil import dependency, which is mainly driven by a decrease in their oil consumption and partly by a larger use of domestic oil resources. In Latin America, a reduction of available emission certificates on the global carbon market to 40% under the resource-sharing regime obliges the region to implement more GHG emission reduction measures domestically, including fossil fuel savings and especially a reduction of the local production of fossil fuels. As a result, its net imports of fossil fuels must increase during the first half of the century to match domestic demand for these fuels, with 60 EJ for oil, 44 EJ for coal and 27 EJ for natural gas. In the same period exports of biomass products are curtailed drastically in favour of their domestic consumption, e.g. in the form of alternative fuels for the transport sector in Latin America.

Shifts of natural gas trade patterns under the resource-sharing scheme can mainly be observed for Europe and the Reforming Economies. Net natural gas imports to the former decline by about 140 EJ cumulatively until 2050 if carbon certificate trade is restricted to 40%. Since the Reforming Economies are net certificate buyers under the resource-sharing scheme during the first half of the century, a strong limitation of carbon certificate trade opportunities enforces these countries to collectively cut GHG emissions from natural gas production. We find that in the upstream sector in total 1.8 $GtCO_2e$ is reduced between 2020 and 2050 for this region. As a consequence, natural gas prices increase and it becomes less attractive to import natural gas into Europe. Europe's domestic natural gas reserves become thereby competitive and substitute some of the foregone imports from the Reforming Economies. Meanwhile overall natural gas consumption in Europe decreases, which favours an increase in coal demand. In the effort-sharing scheme, on the other hand, we observe negligible shifts in the trade of natural gas under restrictions of the carbon certificate trade. These limitations under this regime influence primarily the imports and exports of crude oil and oil products, with similar regional effects as obtained for the resource-sharing scheme. For the Middle East, the reductions in net oil exports accumulate to 135 EJ until 2050 if the global carbon certificate trade is limited down to 40% under the effort-sharing regime.



N.B. 1: RS: Resource-sharing, ES: Effort-sharing

N.B. 2: Reform. Econ.: Reforming Economies

Figure 11: Decrease of cumulative net energy exports or increase of cumulative net energy imports under carbon certificate trade limitations down to 40% for the resource-sharing and effort-sharing schemes between 2020 and 2050.

Along with shifts in energy trade, capital flows change as well. Our analysis shows that a limitation of carbon certificate trade has, for the period 2020 to 2050, a stronger influence on the worldwide capital transfer on the carbon certificate market than on the total capital involved with energy trade. If the global carbon certificate trade under the resource-sharing scheme is reduced down to 40%, the capital flow on the carbon market diminishes cumulatively by about 18 tln US$ until 2050, while the revenues from energy trade decline by some 8 tln US$ over the same period. Under the effort-sharing scheme the corresponding capital volumes decrease by 4 tln US$ on the carbon certificate market and by 3 tln US$ for trade in energy. On the regional scale, the impact of limited certificate trade appears rather heterogeneous. Regions exist for which changes in the capital flows associated with energy trade are larger than those for carbon certificate trade, such as the Middle East, Latin America, the Reforming Economies and Africa under the effort-sharing scheme. Under the resource-sharing scheme, however, we observe for almost all regions stronger implications for carbon market capital flows than for energy trade flows. Our results for the resource-sharing regime demonstrate that Africa can compensate about 40% of its reduced revenues from the carbon certificate market by increased revenues from energy exports if global certificate trade is limited to 40%. The reverse effect can be seen for the two main fossil fuel exporting regions. As a consequence of the decline in energy trade the revenues from energy exports decrease until 2050 cumulatively by about 3.0 tln US$ for the Middle East and some 2.7 tln US$ for the Reforming Economies, if carbon certificate trade under the resource-sharing regime is reduced to 40%. Simultaneously, these regions' expenses for the purchase of emission allowances reduce, to such extent that the resulting gain compensates for the decline in revenues from energy trade.

4.3. Certificate price effects

Under full trade conditions, regional certificate prices equal the price of permits on the global carbon market at any point in time. In that case these prices are independent of whether the resource-sharing or effort-sharing scheme is adopted, as indicated by the red line in both plots of

Figure 12. Limitations in opportunities for global certificate trade influence the carbon price within regions due to a partial decoupling of regional markets in GHG emission permits from the global marketplace. This decoupling generates certificate price decreases in permit selling regions and increases in permit buying regions. With constrained global trade of emission allowances, GHG reduction measures available within regions increasingly determine each region's carbon certificate price. In other words, domestic climate change mitigation capabilities and their costs are stronger determinants of the locally prevailing carbon price when the global certificate market is limited.

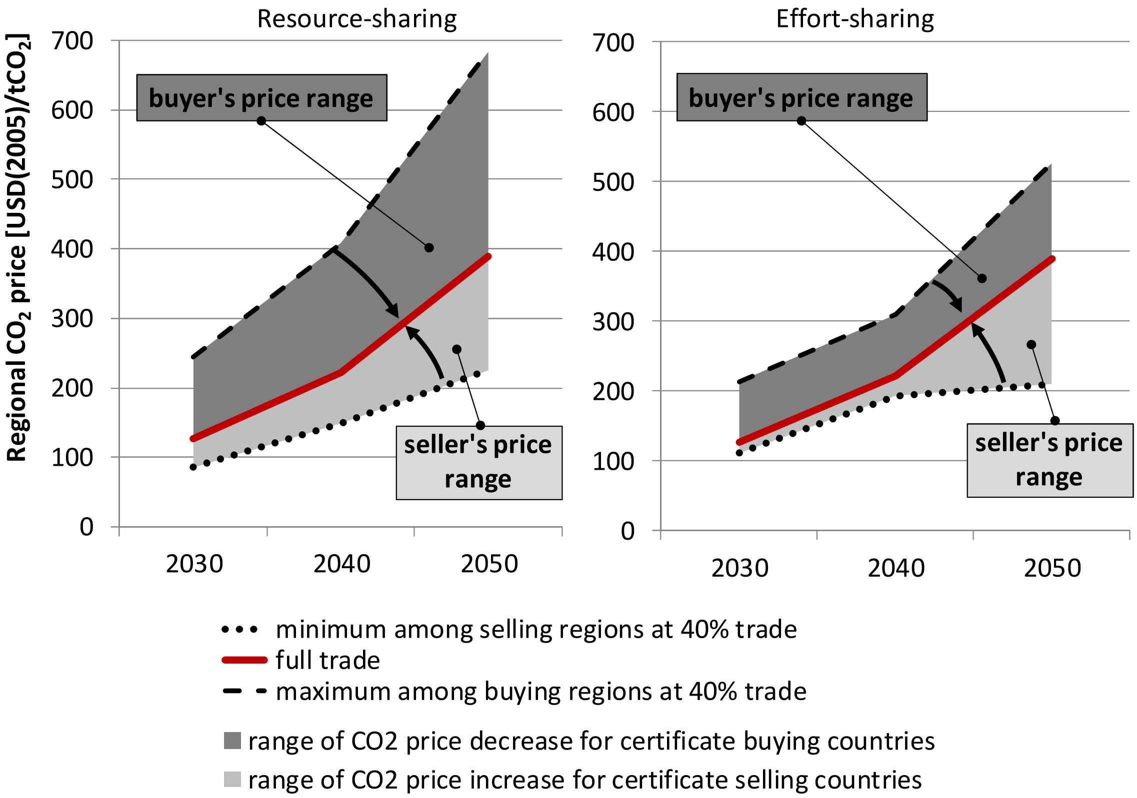


Figure 12: CO_2 price ranges for certificate buying and selling regions at trade levels between 40% and 100% for the the resource-sharing and effort-sharing regimes.

Figure 12 depicts the CO_2 price range under both burden-sharing regimes for total certificate trade levels higher than 40% during the period from 2030 to 2050. Except during the last decade of this time frame in the effort-sharing scheme, the seller's price range is smaller than the buyer's one, which shows that the effects of limited trade on the carbon price are generally more severe in certificate buying than in selling regions. Under the resource-sharing scheme, the minimum CO_2 price of the selling regions at a 40% overall certificate trade level is in 2030 about 40 US\$/tCO_2 below the global carbon price at full certificate trade. In 2050 this difference amounts to about 160 US\$/tCO_2. Our model runs reveal that the minimum CO_2 price of the selling regions is primarily driven by the marginal GHG abatement costs prevailing in Africa. The maximum CO_2 price of the certificate buying regions under the resource-sharing regime exceeds the full-trade global carbon price by about 120 US\$/tCO_2 in 2030 and by some 300 US\$/tCO_2 in 2050 if carbon permit trade is constrained down to 40%. We find that these higher certificate prices are determined by the regional marginal GHG abatement costs in predominantly China, the Middle East, North America and the Reforming Economies.

Under the effort-sharing regime less than one third of the emission permits are traded in comparison to the resource-sharing scheme. Consequently, the maximum CO_2 price of the buying regions at a trade limitation of 40% deviates less from the full-trade global carbon price than the difference we observe for the resource-sharing scheme: 90 US$/t$CO_2$ in 2030 and 140 US$/t$CO_2$ in 2050. This indicates that under an effort-sharing scheme carbon market distortions resulting from reduced certificate trade opportunities have in our model a lower impact on domestic carbon markets of selected regions than in a resource-sharing scheme. The explanation for this finding is that the allocation of allowances in the effort-sharing scheme is closer to the cost-optimal solution in comparison to the allocation under the resource-sharing regime. The outcome of our model runs is that the maximum of the price range of certificate buying regions in the effort-sharing scheme is mainly determined by the costs of GHG mitigation options realisable in Europe. This result supports an enhanced linkage of the European Emissions Trading Scheme (EU-ETS) to other regional markets for GHG emission permits trade, on the basis of which stringent global GHG reduction targets can be achieved significantly more efficiently. For the near term, similar findings are derived by Ciscar *et al*. (2013), who determine a maximum allowance relief of about 50 US$ for the year 2020 if the EU-ETS is fully integrated into an international certificate market.[9] We find that among the certificate selling regions under the effort-sharing regime the lower boundary of the CO_2 price range is set by GHG abatement technologies implementable in Africa, China and India.

4.4. Global climate policy costs

Diminished opportunities to trade emission allowances internationally yield increases in the total costs to mitigate global climate change, since no globally cost-optimal allocation of GHG reduction obligations can be established and costly alternative mitigation measures have to be utilised within regions that otherwise would not have been employed. Contrary to the previously described effects on the regionally prevailing CO_2 certificate price, global climate policy costs are not directly based on marginal GHG abatement costs, but rather reflect additional capital investments, operation and maintenance costs, fuel costs and other energy supply and demand costs such as associated with the transportation of energy carriers. Given the larger amounts of certificate trading in the resource-sharing than in the effort-sharing scheme, trade limitations cause a more extensive deployment of alternative local GHG reduction measures within regions to compensate for a lack of internationally tradable emission permits in the former than in the latter. As a result, as can be seen in Figure 14, incomplete international markets engender a stronger increase of global climate policy costs under the resource-sharing than under the effort-sharing regime.

Under the resource-sharing regime, if global carbon certificate trade is limited by as much as 60%, an extra amount of approximately 200 bln US$ has to be spent worldwide in 2030 on deploying alternative regional mitigation measures in order to reach the 2˚C climate change control target (see Figure 13). This represents a relative increase of global climate policy costs by about 20%. Similarly, in 2050 an additional figure of some 1,000 bln US$ would need to be spent, which corresponds to about 23% of total climate control expenditures in the full-trade scenario. After

9 The number of 50 US$ is based on a conversion factor from €(2012) to US$(2005) of 1.1.

2050 the share of additional policy costs would decrease down to 4% in 2070 (+570 bln US$) and to 2% in 2100 (+610 bln US$). Under the effort-sharing scheme additional climate policy costs amount to around 80 bln US$ in 2030 and 4 bln US$ in 2050 when the trade of emission allowances is restricted down to 40%. In comparison to the full-trade case, this corresponds to about 8% of global climate policy costs in 2030 and less than 1% in 2050. During the second half of the century these shares are roughly equal to those we found in the resource-sharing scheme, that is, about 4% in 2070 and 2% in 2100.

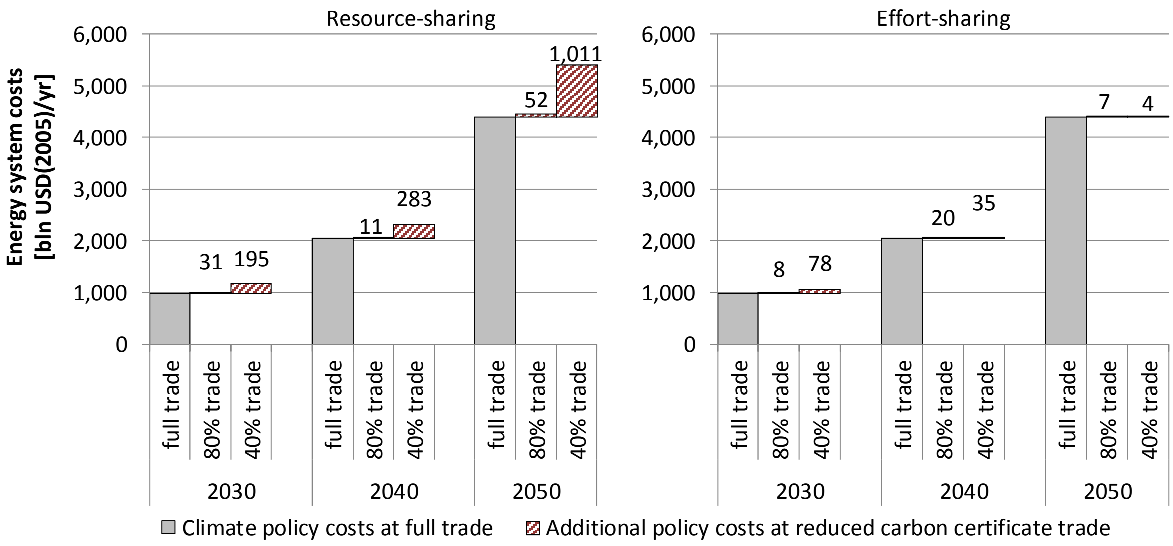


Figure 13: Impact of different carbon certificate trade levels on global climate policy costs, expressed as annual undiscounted energy system costs, under the resource-sharing and effort-sharing regimes.

The additional climate policy costs reported in Figure 14 probably represent a lower estimate of what extra costs could prove to be in reality under the presence of trade restrictions, since we left the timing of trade limitations endogenous to our model, while in practice the timing could be stipulated by political realities as well so that it would need to be exogenously treated in our model. Our model operates under a cost-minimisation paradigm in which the overall optimal certificate trade patterns are determined including in terms of when and between which regions trade of emission allowances takes place. We expect that if we were to limit another degree of freedom of TIAM-ECN by also straight-jacketing the timing of trade limitations, the global climate policy costs would further increase. It is even possible that staying on track of the GHG emissions reduction pathway needed to meet the 2˚C climate change control target becomes significantly curtailed.

5. Conclusions

In this paper we analysed the impacts of two different international burden-sharing schemes in terms of the regional allocation of GHG emission allowances, carbon certificate trade patterns between regions, and the corresponding aggregated carbon market capital flows, in the context of a global climate policy adopted to achieve a long-term stabilisation of the global mean temperature increase with respect to the pre-industrial level at 2˚C. Our first main finding is that, on a global least-cost mitigation pathway, overall GHG emissions must become negative by the end of the century if the 2˚C climate target is to be reached with high (i.e. 70%) probability. In order to compensate for GHG emissions in sectors in which abatement is costly, such as agriculture, industry and transportation, emissions have to become negative for e.g. electricity generation and fuel production from already around the middle of the century onwards. From approximately 2060, total GHG emissions in regions such as Europe and North America will need to become negative in order to balance positive emission levels of, for instance, Latin America and India, where cheap mitigation options deplete more quickly than in the former regions. Under a resource-sharing regime, in which every region's endowment in emission certificates is based on population-related criteria, the allocated emission rights deviate more from the allocation under a least-cost reference mitigation pathway scenario than observed in an effort-sharing scheme, which aims at equal distribution of the economic burden across regions. This translates into a large difference between these respective regimes in the volume of certificates traded on a global certificate market: for the period between 2020 and 2100 the number of certificates traded under the resource-sharing regime is approximately three times higher than under our effort-sharing regime.

The resource-sharing regime favours regions with a strong population growth, such as Africa, India and Other Asia, which assumes a net seller's position on the certificate market with cumulative sales of permits equivalent to 73 $GtCO_2e$ until 2050. This trade volume corresponds to an aggregated capital flow of 18 tln US$, which roughly covers the climate policy costs of these three regions combined until 2050. In the long run (post 2070), Europe and North America become the main certificate selling regions, given their high potentials for reducing GHG emissions. Particularly these two regions manage to realise net negative emissions as a result of their use of biomass plus CCS technologies. The most important certificate-buying regions in the near and medium term are China, Latin America and North America. The explanation for this outcome is their low or even negative population growth. In the long term, Africa and India become the major permit-buying regions, as a result of their relatively low potentials to achieve a net negative GHG emissions balance, against a background of strong population growth rates.

Under the effort-sharing regime, the quantities of regionally allocated certificates are determined by every region's climate policy costs relative to its local economic growth. In the near term (2020), particularly China and Latin America face high climate policy costs, but which they can almost entirely offset (by more than 90%) by selling emission certificates, given their high GDP growth rates. In the long run, climate policy costs are increasingly influenced by changes in fossil fuel trades that occur following global fuel shifts and demand reductions. Especially for the principal fossil fuel exporting regions (Middle East and Reforming Economies) these changes result in substantial reductions of import revenues. These climate policy costs can be offset, however, if revenues can be generated from providing CO_2 storage capacity for CCS applications operating in other regions. The Reforming

Economies are significant carbon certificate sellers under the effort-sharing regime during the second half of the 21st century, and can balance their decreasing revenues from fossil fuel exports partly with annual revenues from the carbon market by up to 340 bln US$/yr. On the contrary, the Middle East becomes one of the main certificate buying regions during the second half of the century, plus loses revenues from decreasing oil and gas exports, which it can both compensate by gaining significant revenues from storing CO_2 capture in foreign CCS installations. China's position on the carbon market changes from being a seller of certificates during the first half of the century to becoming a buyer during the second half of it, as a result of its strong economic growth and comparable advantage in terms of its GHG emissions reduction potential.

Appropriate certificate trading mechanisms need to be in place when functioning burden-sharing schemes are to be established. Full carbon certificate trade enables most efficiently the unlocking of the world's least-cost GHG reduction potentials and GHG emission abatement options, since it allows proffering compensation for some regions' disproportional efforts to implement climate change control measures. Our sensitivity analysis with regard to possible limitations in global trade of carbon certificates has shown that the policy costs required to reach the global 2˚C climate change control target could increase by more than 20% in the short- to mid-term (i.e. around 2030) if carbon certificate trade is significantly restricted (by up to 60%). Substantially restricted carbon certificate trade tends to impose higher additional climate policy costs for the resource-sharing than the effort-sharing scheme, due to the larger amount of certificates traded under the former.

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