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Carbon Markets in a <2 °C World: Will There Be Room for International Carbon Trading in 2050?

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Summary

The Paris Agreement to the UNFCCC does not explicitly establish an international carbon market. Yet its Article 6 provides a legal avenue for the "international transfer of mitigation outcomes". The specific rulebooks and guidelines for how to utilize the options provided in Article 6 are subject of ongoing negotiations under the UNFCCC.

While the rulebook for international carbon trading under the Paris Agreement is in the making, some have argued that it may not be necessary to invest in the development of the necessary institutional framework. Given the dramatic emission cuts necessary to attain the Paris Agreement's 1.5/2 °C objective, some people argue, there is simply no room for international carbon trading.

This Policy Paper sets out to explore this hypothesis. Two conditions for international carbon trading are established: (1) carbon trading is only physically possible as long as further mitigation potential exists; and (2) carbon is only economically viable as long as significant differentials in the level of abatement costs prevail around the globe.

A review of four ambitious long-term emission scenarios and nine sectoral low-carbon roadmaps reveals that substantial emissions and correspondingly substantial mitigation potential will continue to exist in 2050. Also, differences in per-capita GDP, per-capita emissions as well as technology diffusion rates across world regions suggest that also the second condition will continue to be met in 2050.

Unfortunately, the data available in the considered studies does not suffice to provide a reliable estimate on the scale of the remaining mitigation potential and/or the cost at which this potential could be realized.

Still, the analysis demonstrates that the use of carbon markets or "international transfer of mitigation outcomes" is much more a political question than a technical or economical one. There is no reason to believe that carbon markets will be obsolete by 2050 even if the states of the world succeed in implementing the Paris Agreement and bringing the world onto a sustainable low-carbon development pathway. Whether or not international carbon trading will play a role in the global effort to mitigate anthropogenic climate change is a matter of politics and not of economic or physical conditions.

1 Introduction

In December 2015, the Parties to the UNFCCC agreed to a new universal international climate treaty: the Paris Agreement. The Paris Agreement establishes a new international legal framework to combat climate change. It stipulates a new and tightened long-term goal for mitigating anthropogenic climate change. Parties to the UNFCCC have agreed to strengthen their response to climate change by

> *Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change (UNFCCC, 2016, Art. 2.1a).*

This has been further operationalized in Article 4 of the Agreement. Parties have agreed to reach a peak in global emissions as soon as possible and to "achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century" (UNFCCC, 2016, Art. 4.1).

This latter goal will require a fundamental transformation of global energy, industrial and agricultural systems. Industrialized countries will have to take the lead in this transformation and achieve net zero greenhouse gas (GHG) emissions sooner than many developing countries towards the middle of the century in order to leave atmospheric space for less developed countries to catch up.

It has been argued that price-based mitigation instruments[1] provide a tool to efficiently and effectively tackle climate change (see e.g. IPCC, 2014c; Schmalensee & Stavins, 2015). Typically, the cost of climate change impacts are not reflected in the price of consumer products. These costs are therefore referred to as 'external costs'. A carbon price that reflects these costs can help to 'internalize' these costs, i.e. it makes them visible and allows corporations and consumers to reflect them in their routine production, investment, and consumption decision making.

Furthermore, a carbon price can help to identify the cheapest abatement options. If carbon emissions can be traded, either as emission *allowances* or as emission reduction *credits*, this creates flexibility for regulated entities – be they nation states or corporations under domestic climate change mitigation schemes – to attain their mitigation obligation more cost effectively in economic terms. Market-based mitigation instruments such as the EU Emissions Trading Scheme and the Clean Development Mechanism have proved to be effective in leveraging low cost GHG abatement (Bel & Joseph, 2015; Branger, Lecuyer, & Quirion, 2015; CDM Policy Dialogue, 2012; Wråke, Burtraw, Löfgren, & Zetterberg, 2012).

The Paris Agreement and in particular its Article 6 create a legal option for "international transfer of mitigation outcomes", i.e. international carbon trading. Whether or not this option will be actually utilized is ultimately a political question. It requires political will to create the necessary demand for carbon units (emission allowances or mitigation credits) through ambitious political commitments. And it requires political will to use market-based instruments in general – some left-leaning countries have opposed market-based instruments for ideological reasons.

[1] In our understanding this includes all forms of carbon pricing, be it in the form of carbon taxes, allowance based market instruments like emissions trading or certification schemes such as the CDM.

At the current stage, when the rulebook for the international transfer and use of mitigation outcomes is still in the making, it is impossible to make predictions on the political dimension of international carbon trading other than purely speculative ones.

For the ongoing discussions it is nevertheless highly relevant to explore the physical and economic dimensions of international carbon trading. Experiences with international carbon trading were made in times when (low-cost) mitigation potential was relatively abundant. Assuming that the Paris Agreement will be fully implemented, much less mitigation potential will remain in 2050 and thereafter. Economic theory suggests that carbon trading will become obsolete in the long run, at the latest when greenhouse GHG emissions are phased out altogether. It may therefore be questioned whether investing in the development of the necessary institutional setup for international carbon trading schemes is not worth the time and effort.

Along these lines, this JIKO Policy Paper will explore the following hypothesis: **Assuming we take the Paris Agreement seriously and implement it accordingly, there will be no room left for international transfer of mitigation results (carbon trading) in 2050.**

The paper sets out in the first order to falsify this hypothesis. It will do so by specifying the conditions for international carbon trading and exploring them by reviewing existing long-term mitigation scenarios. In the second order, the paper sets out to assess the remaining potential for international transfers or mitigation outcomes.

The paper does not discuss, however, how the world has got onto a climate compatible development pathway in the first place. Even if carbon trading were obsolete in 2050 – and the analysis shows it is most likely not – investing in the development of the necessary institutional setup for international transfer of mitigation outcomes may still be worthwhile. It may even be the case that it is a *conditio sine qua non* for getting to a <2°C world in 2050.

Section 2 provides an overview of the methodological approach. Furthermore, it includes a discussion of the physical and economic preconditions for international carbon trading. The section also includes a brief description of the scenarios and roadmaps utilized for the analysis.

Section 3 analyses the selected mitigation scenarios and additional sectoral roadmaps and assesses whether and to what extent the physical and economic conditions for international carbon trading are met or violated in the various scenarios and roadmaps considered. While the scenarios provide sufficient information on the first order question of this paper – carbon trading will most likely not be obsolete in 2050 – the second order question is much more difficult to address. The scenario meta-analysis can only provide a rough scoping rather than an in-depth analysis of the remaining potential for carbon trading.

Section 4 discusses the results of the analysis in the light of the above mentioned limitations and Section 5 concludes, specifying further research needs.

2 Methodology and Material

2.1 The Various Forms of International Carbon Trading

Different forms of carbon trading have emerged over the past two decades. One distinguishing criterion concerns the entities entitled to trade. Emissions Trading under the Kyoto Protocol for example allows nation states to trade their endowed emission allowances among each other directly.

On the other hand, Emission Trading Schemes (ETS) have emerged under which private corporations are legally obliged to surrender one emission allowance or emission reduction credit for each ton of CO_2-equivalent (CO_2e) they emit in their facilities. The EU ETS is the most prominent example. If such an ETS covers more than one country, mechanisms need to be in place to reflect cross-border trades of emission allowances also in the national balance sheets after the allowances have been surrendered.

The Paris Agreement does not explicitly mention "carbon trading" or "carbon markets" but its Article 6 provides a legal foundation on which a wide range of different carbon trading schemes could be designed (UNFCCC, 2016). Specifically, Article 6.2 provides the option for member states to engage in "cooperative approaches" and to "internationally transfer mitigation outcomes" from one exporting country to another country that may use these mitigation outcomes against its nationally determined contribution. Moreover, in Article 6.4 a mechanism under international oversight is established "to contribute to the mitigation of greenhouse gas emissions and support sustainable development" (UNFCCC, 2016, Art. 6.4). While the modalities and procedures of this mechanism have yet to be developed, it is likely that it will take a form similar to the CDM, potentially expanding and improving it (cf. Marcu, 2016).

2.2 Sources of Demand and Supply

In carbon trading schemes, the amount of potential permits is defined politically via a fixed carbon budget as the amount of allowable GHG emissions. The price of the permits is a resulting variable. Demand for carbon trading of the types relevant for this study is, hence, determined politically.[2] It rests on national obligations to mitigate a country's own GHG emissions or to support other countries in doing so. These obligations can originate from international treaties such as under the Kyoto Protocol or they can be self-imposed. Under the Paris Agreement, all countries have an obligation to prepare and submit "nationally determined contributions" and to take appropriate measures to implement these climate protection goals. While countries face no formal obligation to actually achieve their contributions under international law, many countries including the EU have taken on legally binding obligations under their respective national laws. In some cases this national obligation is (in part) passed onto the private sector as is the case with the EU ETS and other comparable schemes.

[2] At much smaller scale, voluntary carbon markets exist in which corporations or individual buyers purchase carbon credits in order to compensate their own emissions. This is typically motivated by considerations of corporate social responsibility or individual moral considerations.

Linking of emission trading schemes and international carbon trading between private entities

One rationale for the establishment of "cooperative approaches" under Article 6.2 of the Paris Agreement was to create a legal avenue for linking up national emissions trading schemes: for example, this could apply to linking the EU ETS with other systems such as the upcoming Chinese ETS and/or the Korean ETS in the medium or long term.

If two ETSs are linked, trading may occur between companies and across sectors from one country to another. These transactions would have to be tracked and accounted for in the respective national trading systems. Any net transfers would have to be reflected as "international transfer of mitigation outcomes" (ITMOs). Linking two (or more) ETSs should lead to a levelling out of abatement costs in the systems involved. Mitigation units would be transferred from the ETS with lower abatement costs to where mitigation is more costly. After abatement cost have arrived at similar levels on average, trading may still continue as long as cost differentials prevail among different sectors. However, these transactions should approximately balance each other out so that no substantial ITMOs would occur. Nevertheless, a robust accounting system would be necessary to keep track of such private transactions (see also section 2.3.2).

Demand on international carbon markets is therefore a function of the level of ambition of national climate protection goals. This can play out in two ways: (1) carbon units traded from abroad can be used to compensate for excess emissions in the country that imports them (offsetting). (2) Countries may choose to make use of market-based mitigation instruments as a means to support other countries in mitigating their emissions; for example, developed countries could buy carbon credits or allowances from developing countries and count the expenses against their pledged financial contributions[3].

But demand for international carbon trading is not only a function of the level of ambition of mitigation commitments but also a function of the cost and availability of mitigation potential in importing countries, at least this is the case for the demand for offsetting purposes. Why should a country want to import mitigation results if mitigation potential is abundant at low cost within its own borders?

Likewise, supply for international carbon trading is a function of technical mitigation potentials and the level of ambition, this time in the exporting country. If the exporting country exerts highly ambitious mitigation efforts on its own, a smaller share of the technical mitigation potential will remain available for international trading.

Given the essential role of politics in defining the level of ambition of mitigation activities and hence determining both supply and demand, it is impossible to make credible projections on the price levels on international carbon markets. However, the abatement cost in potential ex- or importing countries define a boundary for the expected price ranges.[4] Supply cannot be cheaper than abatement costs in the exporting countries and demand will be zero when prices exceed abatement costs in the importing countries.

[3] In the Copenhagen Accord, industrialized countries pledged to provide an annual USD 100 billion in order to support mitigation and adaptation activities in developing countries from 2020 onwards. In Paris this pledge was reiterated and parties agreed to negotiate a new collective climate finance goal before 2025.

[4] There is not one unique abatement cost in every country but a range of different costs for different abatement options in each country. As a matter of simplification our analysis will not look into the details of abatement costs in different sectors and technologies, but compare overall cost levels on an aggregate level. Trading may still occur between a sector Y with high abatement costs in country A with sector X with low abatement costs in country B.

	2DS	2°C	Energy [R]evolution	Advanced Energy [R]evolution
Publisher	International Energy Agency (IEA)	Joint Research Centre (JRC)	Greenpeace et al.	Greenpeace et al.
Model used	ETP model	POLES	Mesap/PlaNet	Mesap/PlaNet
Regional Resolution	28 to 39 countries and world regions	39 countries and world regions	10 countries and world regions	10 countries and world regions
GHG emissions covered	Energy- and process-related CO_2	All GHG	Energy-related CO_2	Energy-related CO_2
Timeframe considered	2013-2050	2010-2050	2012-2050	2012-2050
Change in energy- and process-related global emissions in 2050 (vs. 1990)	-35% (energy and process emissions, CO_2)	-54% (energy and process emissions, GHG) / -61% (energy emissions, CO_2)	-79% (energy emissions, CO_2)	-100% (energy emissions, CO_2)

Table 1: Overview and comparison of the four scenarios considered. *Source: Wuppertal Institute.*

Therefore, between two countries there will be no trade of carbon units if abatement costs are on par. In fact, carbon trading itself is not for free but comes with substantial transaction costs, for example for monitoring emissions and measuring, reporting and verifying emission reductions. No net flows of mitigation units will occur as long as the price differentials between exporting and importing country are not big enough to cover also these transaction costs (see box "Linking of Emissions Trading Schemes").

2.3 Conditions for International Carbon Trading

As indicated above and as built in in any trading instrument that aims at a steering effect on the traded units, the definition of the conditions for carbon markets is the result of a highly political decision-making process. Whether or not international carbon trading occurs is much more a question of political ambition and preferences then of any hard-wired natural or economic preconditions. In the following, we will nevertheless lay out a set of essential conditions for international carbon trading. As we shall demonstrate below, these conditions are only violated under rather extreme conditions. On the other hand, even if both of these conditions are met, this still does not guarantee that international carbon trading occurs. However, if these conditions are violated, there is no room for international carbon trading whatsoever.

2.3.1 Physical Condition: Untapped Mitigation Potential Remains Available

Carbon trading will only remain possible as long as mitigation potential exists. That is, GHG are still emitted at least in some sectors, and technologies exist that can abate these emissions.[5]

[5] Even if no technologies exist to further reduce emissions per unit of a product produced, the production of that product can be reduced or phased out altogether. Either the product can be substituted with a climate friendly alternative or the phase out comes at the cost of a welfare loss. Whether or not a country is willing to bear that loss, again, is a political question that cannot be addressed here.

Moreover, mitigation potential may exist in the form of avoided increase in future emissions, as long as economic growth and emission growth are not decoupled entirely. The mitigation potential would be exhausted only if carbon-free technologies generally outcompete carbon-intensive alternatives so that any future demand can be expected to be met fossil-free even in a business as usual scenario.

Last but not least, CO_2 can be sequestered for example in reforestation or afforestation projects, in the soil through improved agricultural practices, or through the use of bioenergy in combination with carbon capture and storage (BECCS). Although a majority of the 2 °C compatible scenarios from the IPCC AR5 database entail some form of negative emissions, the analysis in this paper does not consider negative emissions mitigation options; mostly, because these activities typically involve a high degree of uncertainty with respect to the permanence of the mitigation result. Also data availability is poor. Excluding negative emissions from the analysis also does not compromise the analysis with respect to the research question (at least not the first order question). As we shall see, significant positive emissions remain in nearly all scenarios considered. Adding negative emissions would only increase the potential for international carbon trading.

This physical condition can be considered as a necessary condition for international carbon trading. Yet under what conditions would the physical condition for carbon trading cease to be met? It is violated if all abatement options are realized (no remaining potential to reduce existing emissions) and carbon-free technologies become the baseline technologies in virtually every application (no remaining potential to avoid future emissions).

2.3.2 Economic Condition: Differentials in Mitigation Costs Prevail

The existence of mitigation potential does not suffice to explain international carbon trading. Instead, trading will only occur if significant cost differentials[6] remain between world regions, sectors and / or applied technologies. If abatement cost are on par all over the globe, why should anyone trade mitigation outcomes? In this case, the costs to obtain them would be the same everywhere and the profit margin would be zero.

For the subsequent analysis, the economic condition for international carbon trading (at least in the context of international trade of mitigation outcomes as per Article 6 of the Paris Agreement) is deemed to be violated if no significant regional differences in the cost of abatement prevail.

Even without such disparities in abatement costs, this does not strictly preclude a global carbon market. Cost differentials may continue to exist in between sectors and technologies within a given country. If this is the case, private entities may continue carbon trading within a country or region. Linking these domestic markets globally can then still be beneficial in that it creates a bigger market including with better liquidity. However, this global carbon market would not result in significant net transfers of mitigation results from one country or region to another.

[6] It is important not to confuse cost differentials with price differentials. The price is the result of demand and supply. While the supply-curve is co-determined by abatement costs, demand is created politically.

2.4 Comparative Scenario Analysis

In order to answer the overarching research question of the paper, a set of global GHG emission scenarios will be assessed with a view to explore whether and to what extent the necessary physical and sufficient economic conditions for international carbon trading are met and/or violated respectively.

This exercise requires scenarios that have a timeframe of at least until 2050 and provide a resolution that allows to associate emissions both with world regions as well as with sectors. Due to the limited scope of the paper, the analysis will focus on energy supply (electricity and heat) as well as the industrial sectors only . Not only do these sectors account for the lion's share of current emissions, but also they have proved to be particularly suitable for carbon markets. For example, projects in the energy and industry sectors account for the vast majority of projects in the CDM's project pipeline while projects in the agriculture, building and transport sectors are relatively rare (UNEP DTU, 2016).

It is worth noting that the analysis will look at 2050 as a single point in time only. It does not assess how the world embarks on a 2 °C-compatible development pathway. Neither does it discuss the role of international carbon trading in the time before 2050.

2.4.1 Four Scenarios

The analysis will compare the results of four scenarios that are roughly representative to cover the range of 2050 GHG emissions generally deemed to be compatible with the 2 °C target. All four scenarios claim to be in line with 2 °C but vary with regard to their projections of 2050 emissions as well as their cumulative emissions until 2050. This means that the scenarios' probabilities of successfully limiting global warming to 2 °C differ. The following four scenarios from three different studies have been analysed respectively (see table 1 for an overview and comparison of the studies and scenarios):

- "2DS" from "Energy Technology Perspectives 2016" (IEA, 2016)
- "2°C" from "GECO 2016 – Global Energy and Climate Outlook – Road from Paris" (JRC / European Commission, 2016)
- "Energy [R]evolution" from "Energy [R]evolution – A Sustainable World Energy Outlook 2015" (Greenpeace, SolarPower Europe, & GWEC, 2015)
- "Advanced Energy [R]evolution" from "Energy [R]evolution – A Sustainable World Energy Outlook 2015" (Greenpeace et al., 2015)

None of these scenarios were explicitly modelled in light of the 1.5 °C goal. However, the latter two scenarios from the study by Greenpeace et al. are very ambitious (maintaining global mean temperatures below 2 °C with relatively high probability) and may therefore be not too far from scenarios that achieve to halt global warming at or around 1.5 °C above pre-industrial levels (albeit at a higher probability of exceeding the limit). The "Advanced Energy [R]evolution" scenario even entails a complete phase out of energy-related CO_2 emissions in 2050.

It is also important to note that the scenarios selected are all simulation-based scenarios.[7] By contrast, optimization models typically aim to identify a cost optimal selection of technologies under given constraints. This is usually done by applying a common endogenous carbon price. Therefore, these models by design achieve a settlement of marginal abatement costs across the model and thus they inherently assume the

[7] The IEA scenarios combine simulation-based modelling with optimization-based modelling for some sectors.

existence of market forces in the selection of development pathways. Building an argument on whether carbon markets are obsolete in 2050 on model projections that assume their existence would be incongruous.

2.4.2 Cross-check with IPCC AR5 Scenarios

In order to provide a sense of the representativeness of the four selected scenarios, they were juxtaposed to those scenarios of the IPCC AR5 Scenario Database that reliably limit global warming below two 2 °C. This database contains an overall of 1184 scenarios, only 114 of which fall into the IPCC's most ambitious category 1 of scenarios. These scenarios are characterized by a CO_2-equivalent concentration of 430-480 ppm and cumulative total CO_2 emissions of <950 Gigatonnes in the year 2100 (IPCC, 2014b).

Unfortunately, the database does not provide for sufficient resolution to inform the assessment of the conditions for international carbon trading as explained above. The IPCC scenarios as represented in the database specify a breakdown of sectoral emissions only as a global aggregate but not for each world region. Cross-checking with the IPCC scenario database therefore only provides a sense of whether the four scenarios fall within the spectrum of 2 °C compatible scenarios.

2.4.3 Other Greenhouse Gases

The scenarios and roadmaps considered in the analysis are all restricted to CO_2 emissions, some even cover only energy-related emissions. Various other GHGs exist that may further add to the abatement potential identified in the scenarios considered.

Methane (CH_4), for example, is emitted primarily through enteric fermentation processes by livestock farming, waste treatment and rice cultivation. Nitrous oxide (N_2O) emissions are produced in agriculture and certain industrial processes. Various hydrofluorocarbons (HFCs) are produced for example as refrigerants or precursors in the chemical industry.

It is unclear to what extent the abatement potential of these GHGs will be fully realized by 2050. For some of them, particularly the industrial processes, there may be reason to be optimistic that most of the abatement potential will be realized by then. For example, at the recent 28th meeting of the parties of the Montreal Protocol, parties have agreed to phase down HFC emissions (IISD Reporting Services, 2016). On aggregate, however, relevant emissions prevail in nearly all scenarios in the IPCC scenario database (IPCC, 2014a).

Although these emissions cannot be considered quantitatively in the subsequent analysis due to lack of detailed data, this omission does not compromise the analysis with respect to the research question. Much like the exclusion of negative emissions (see section 2.3.1) including non-CO_2 GHGs would only increase the mitigation potential in 2050.

Author(s)	Title	Date	Sector
Cefic & Ecofys	European chemistry for growth – Unlocking a competitive, low carbon and energy efficient future	2013	Chemicals
Cembureau	The Role of Cement in the 2050 Low Carbon Economy	2013	Cement
EUROFER	A Steel Roadmap for a Low Carbon Europe 2050	2013	Iron & Steel
IEA, DECHEMA & ICCA	Technology Roadmap: Energy and GHG Reductions in the Chemical Industry via Catalytic Processes	2013	Chemicals
IEA & WBCSD	Cement Technology Roadmap 2009: Carbon emissions reductions up to 2050	2009	Cement
Lechtenböhmer et al.	Decarbonising the energy intensive basic materials industry through electrification – Implications for future EU electricity demand	2016	various
WSP | Parsons Brinckerhoff & DNV GL	Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 – Cement	2015	Cement
WSP | Parsons Brinckerhoff & DNV GL	Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 – Iron and Steel	2015	Iron & Steel
WSP | Parsons Brinckerhoff & DNV GL	Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 – Chemicals	2015	Chemicals

Table 2: Overview of sectoral roadmaps considered for the analysis. *Source: Wuppertal Institute.*

2.4.4 Additional Information Required

Only part of the information to fully explore the research question of this paper could be found in the considered scenarios. This concerns, for example, a more fine-grained breakdown of emissions of the industrial sector. The scenarios do not provide information of the emissions of sub-sectors such as steel, cement, other metals, paper and pulp, industrial gases, or the chemical industry or do so only on the global level but not with a regional resolution.

Also, the scenarios provide only very limited information with respect to the technologies employed in each sector, let alone the associated (mitigation) costs of these technologies or even marginal abatement cost curves.

To make up for these deficiencies, a series of nine sectoral roadmaps were considered to provide complementary data (see table 2) (Cefic & Ecofys, 2013; Cembureau, 2013; EUROFER, 2013; IEA, DECHEMA, & ICCA, 2013; IEA & WBCSD, 2009; Lechtenböhmer, Nilsson, Åhman, & Schneider, 2016; Parsons Brinckerhoff, WSP & DNV GL, 2015a, 2015b, 2015c).

3 Analysis

A look into the IPCC scenario database (IPCC, 2014a) reveals that there is no scenario that projects a complete phase out of global GHG emissions by 2050 (see figure 1). The scenarios considered for this study fall well within the range of the most ambitious (category 1) IPCC scenarios. Only the "Advanced Energy [R]evolution" scenario prepared by Greenpeace et al. (2015) describes a pathway that leads to zero *energy-related* CO_2 emissions by the middle of the century. However, this scenario does not include any other GHG emissions like those from industrial processes, land-use or the agricultural sector. Furthermore, this scenario was specifically intended to outline an extreme conceivable case.

To answer the first order research question of this paper, i.e. falsifying the claim that carbon trading will be obsolete in 2050, it can been stated with high confidence that the necessary physical condition for international carbon trading will not be violated by 2050.

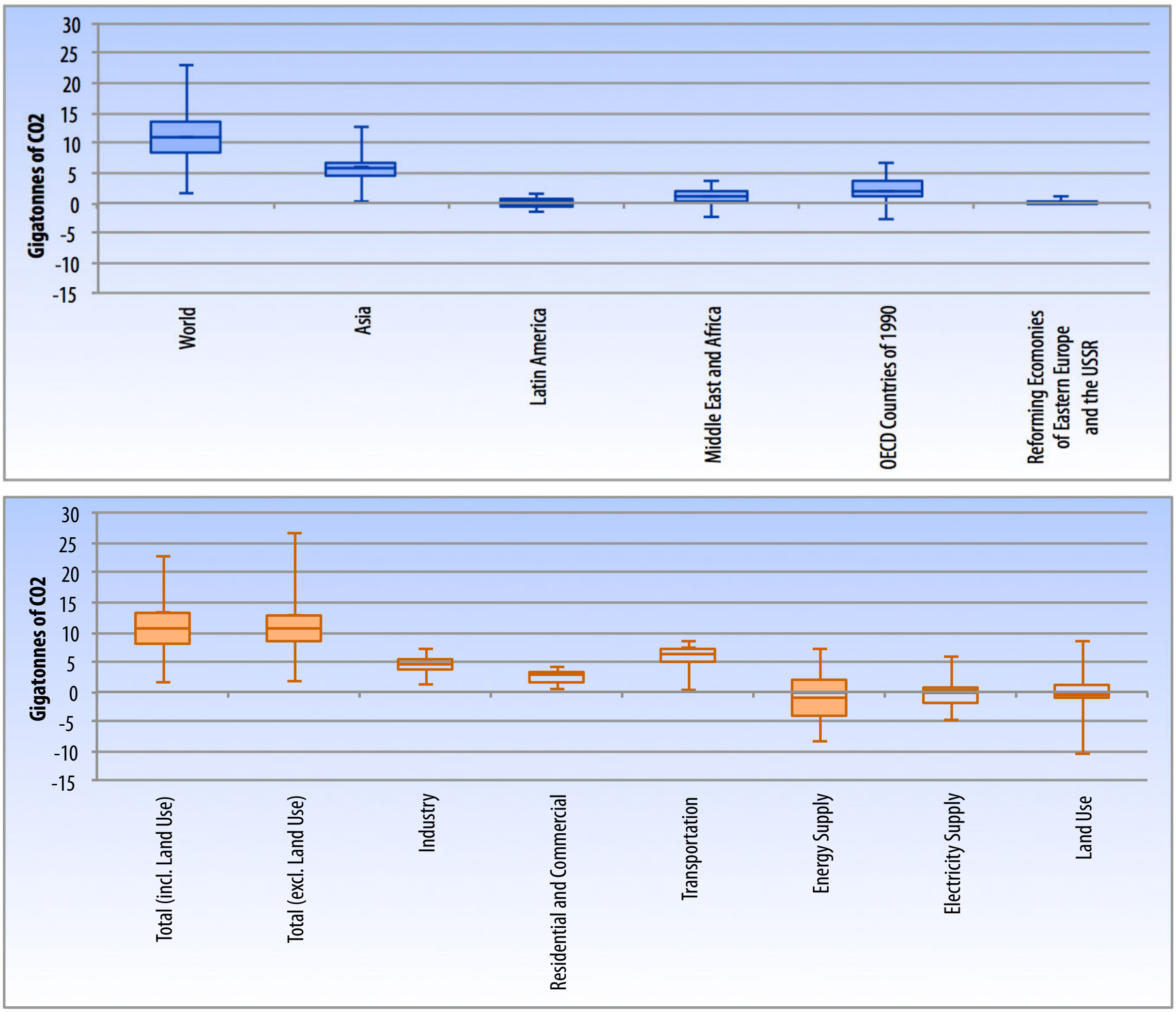

Figure 1: Distribution of projected global CO_2 emissions of the most ambitious IPCC AR5 scenarios (category 1) by region (upper chart) and sector (lower chart). The boxes indicate 1st quartile, median and 3rd quartile of occurrence, with whiskers showing minimum and maximum values .*Source: Wuppertal Institute based on IPCC (2014a)*

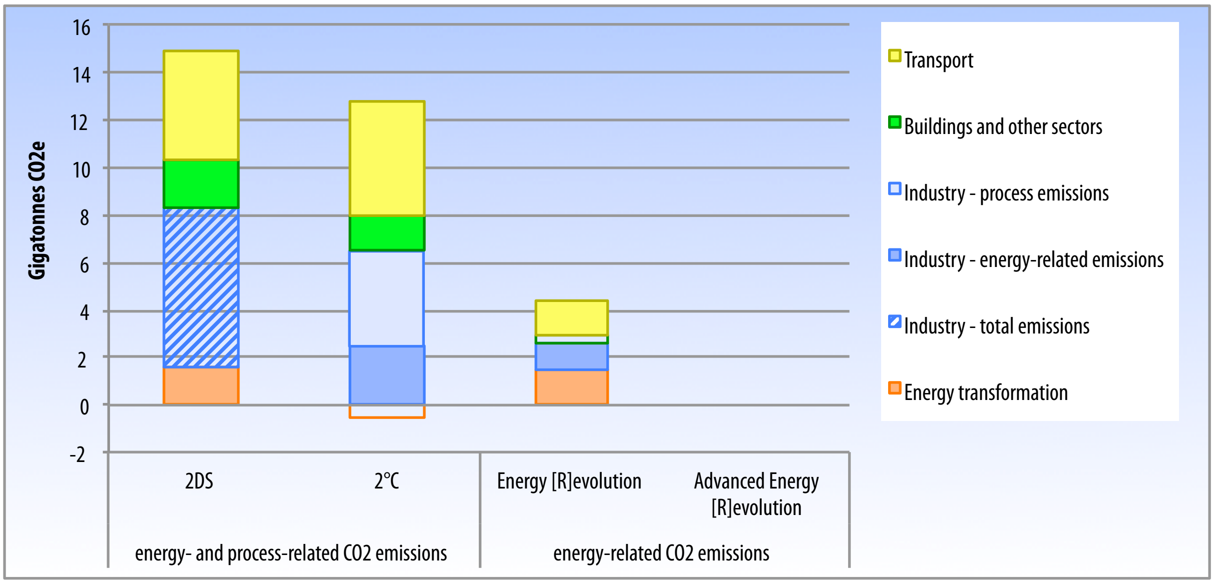

Figure 2: CO_2 emissions in 2050 as projected in the four scenarios, breakdown by sector. Note that the "Advanced Energy [R]evolution" scenario projects the complete phase-out of energy related CO_2 emissions.
Source: Wuppertal Institute based on IEA (2016), JRC / European Commission (2016), and Greenpeace et al. (2015).

Much more difficult to answer is the second order research question: What kind of emissions and emission reduction potentials remain in 2050? In the following, we provide an overview of the regional and sectoral distribution of the remaining emissions in the four selected scenarios as well as a brief outlook on the processes and technologies that are responsible for them.

Figure 2 shows the remaining emissions in 2050 by sector in the four scenarios. The industry sector will likely remain an important source of GHG emissions, it is the sector with the largest energy- and process related emissions in at least two of the analysed scenarios. In the "2DS" and "2°C" scenarios, the industry sector still emits between 6 and 7 Gigatonnes of CO_2e by 2050.

Note that there are methodological differences in the three studies that make a direct comparison of the results difficult. The study by Greenpeace et al. only accounts for energy-related CO_2 emissions whereas the studies by IEA and JRC / European Commission include process-related emissions in the industry sector. The breakdown of industry emissions which is only available in the JRC / European Commission study suggests that energy-related emissions in industry (for example process heat), again, account for only a minor part of the sector's total emissions.

All scenarios have in common that emissions from the energy transformation sector (electricity and district-heat) are substantially reduced. Emissions from the energy transformation sector are therefore likely to play a less important role by 2050, especially if carbon capture and storage (CCS) technologies are available as a mitigation option.

The transport sector is expected to be another sector with relevant CO_2 emissions, at least in the "2DS" and "2°C" scenarios, less so in the more ambitious scenarios by Greenpeace et al.

The scenarios considered by the IPCC in general come to a similar conclusion: apart from non-CO_2 GHG (which are not considered here), 2050 GHG emissions are expected to stem mostly from the transport and industry sector (IPCC, 2014b, figure 6.35).

3.1 Sectoral Breakdown

3.1.1 Energy Transformation Sector

As stated above, the energy transformation sector in all scenarios is projected to be largely decarbonized in all world regions. The JRC / European Commission study assumes that by 2050 still some 23% of global electricity demand is met by fossil fuels including some coal capacities. However, almost all of the remaining capacities will be used with CCS. CCS is also foreseen for the use of biomass so that emissions of the power sector in the "2°C" scenario even become net negative.

Similarly, in the IEA's "2DS" scenario only 5% of electricity demand is met by coal and gas without CCS (and 12% with CCS power plants). The Energy [R]evolution scenario, despite being the most aggressive of the three scenarios that still project emissions, nevertheless predicts that 8% of the electricity demand is met by fossil fuel sources, predominantly natural gas. This can be explained by two of the central premises of the scenario: a quick phase out of nuclear power and non-utilization of CCS technologies.

The power sector is generally expected to provide the widest and cheapest mitigation opportunities (cf. IEA, 2016, p. 69). This is why all scenarios project that these opportunities will be largely realized by 2050. Nevertheless, even the more ambitious scenarios still project the use of fossil fuels without CCS in the power sector. Abating these emissions in the end will be a matter of cost and not of technical feasibilities. Figure 3, below, suggests that the deployment rate of CCS technologies, alongside other factors such as the availability of suitable storage sites, may depend on the developmental state of the host country.

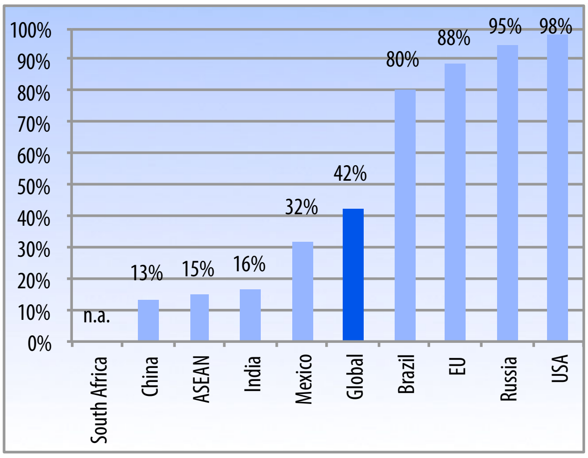

Figure 3: Share of emissions avoided in natural gas power production through the use of CCS by world region as projected by the "2DS" scenario.
Source: Wuppertal Institute based on IEA (2016).

3.1.2 Industrial Sector

As stated above, emissions from the industrial sector include both energy-related emissions and process-emissions, i.e. emissions originating inter alia from chemical reactions in the production process. A comparison of the three studies is difficult because each study takes on a different approach. The IEA aggregates both types of emissions, the study by JRC / European Commission provides separate data on both types of emissions, and Greenpeace et al. only consider energy-related emissions.

A breakdown of industrial emissions in the "2DS" scenario with respect to the most emission intensive sub-sectors is provided in figure 4 below. The chemicals, cement, and iron and steel sub-sectors remain the largest industrial polluters despite realizing substantive and in fact the largest absolute emission cuts of all industrial sectors as compared to the reference scenario.

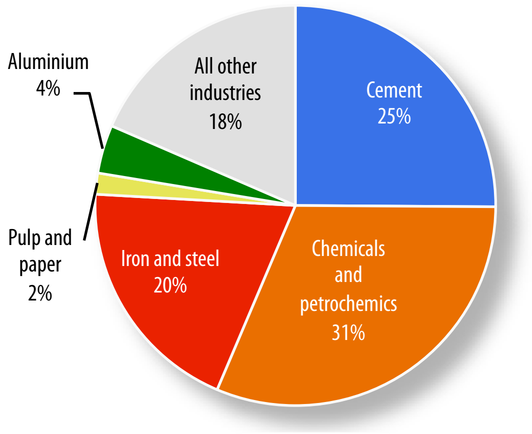

Figure 4: Shares of industrial emissions in 2050 in the "2DS"-scenario by sub-sector.
Source: Wuppertal Institute based on IEA (2016).

Chemicals and Petrochemicals

Sectoral roadmaps show that the technical mitigation potential in the chemical industry may be substantially larger than projected in the "2DS" and "2°C" scenarios. According to a study by Cefic and Ecofys (2013), emissions of the (European) chemical industry can technically be reduced to 90% below 2010 levels with a combination of incremental improvements (energy efficiency measures, fuel switch, N_2O abatement and decarbonisation of power supply) and heavy use of CCS.[8] This is in line with the findings of a study carried out for the UK, which likewise estimates that emission reductions of 80-90% below 2012 levels may be technically possible (Parsons Brinckerhoff, WSP & DNV GL, 2015b).

Both of these studies do not even consider other "breakthrough" technologies such as the utilization of electrolytic hydrogen, synthetic methane or carbon reuse (circular economy). Particularly the use of hydrogen can further reduce carbon emissions from the sector (cf. Lechtenböhmer et al., 2016).

[8] According to the study, this would require CO_2 prices of EUR 200-300 per tonne CO2.

Iron and Steel

The "2DS" scenario estimates that by 2050 CO_2 emissions from the iron and steel sector can be reduced by as much as 66% below 2013 levels. This finding is supported also by a sectoral study focusing on steel production in the UK (Parsons Brinckerhoff, WSP & DNV GL, 2015c). However, in both studies CCS is applied only to a limited extent due to high expected costs.

Moreover, both studies again do not take into account potential "breakthrough" technologies. A study by EUROFER (2013) lists a number of such technologies that currently are at various stages of development but may be technically available before 2050. The most ambitious of those technologies is alkaline electrolysis of iron ore. This technology would virtually eliminate direct process emissions. If 100% renewable electricity is used, this process could slash carbon emissions by as much as 98% even without CCS.

Cement

In the cement sector it is particularly difficult to cut specific CO_2 emissions since the lion's share of emissions are process-related and originate from the calcination of limestone. The only solution in this case would be to substitute limestone as a raw material. However, no proven alternatives exist to date that could be introduced at the required scale (Lechtenböhmer et al., 2016). Consequently, most sectoral roadmaps estimate that emission reductions in the range of only 30% below 1990 levels are possible in 2050 without the use of CCS (Cembureau, 2013; IEA & WBCSD, 2009; Parsons Brinckerhoff, WSP & DNV GL, 2015a). The "2DS"-scenario only estimates emission reductions of 32% below 2013 levels even including CCS. In contrast to that, Cembureau (2013) projects that with CCS, emission reductions of up to 80% should be possible.

3.1.3 Transport

The largest share of the remaining emissions in 2050 as projected by the scenarios result from the transport sector. The sector is and remains the largest source of demand for oil. One key abatement option is the increasing electrification of the sector. However, the scenarios considered (again with the exemption of the "Advanced Energy [R]evolution") do not project a complete substitution of oil-based transport. The share of electric vehicles is projected to increase substantially only for light vehicles, yet all studies (except again "Advanced Energy [R]evolution) project that their share will not exceed 50% of final energy consumed in the sector. The share is substantially lower in all scenarios for heavy duty vehicles as well as in aviation and maritime transport. Even the Advanced Energy [R]evolution scenario achieves zero emissions only by assuming the heavy use of synthetic fuels and liquid biomass. The latter scenario demonstrates that technically, a large mitigation potential remains in the transport sector, however at significant costs.

3.2 Regional Breakdown

In all scenarios, absolute 2050 GHG emissions are highest in China, followed by India. However, the EU and the USA also still have relevant emissions by then. A sectoral breakdown of these emissions is provided by the "2°C" scenario (see figures 5).

From this regional distribution of emissions however, one cannot yet conclude on differences in regional levels of abatement costs. As stated above, such cost differentials are essential for international transfer of mitigation outcomes to occur (at least as a means to offset mitigation obligations in the importing country). Unfortunately, none of the considered scenarios provides cost data of sufficient detail to explore this question in depth. Still, the scenarios do provide us with some leads which we are going to explore in the remainder of this section.

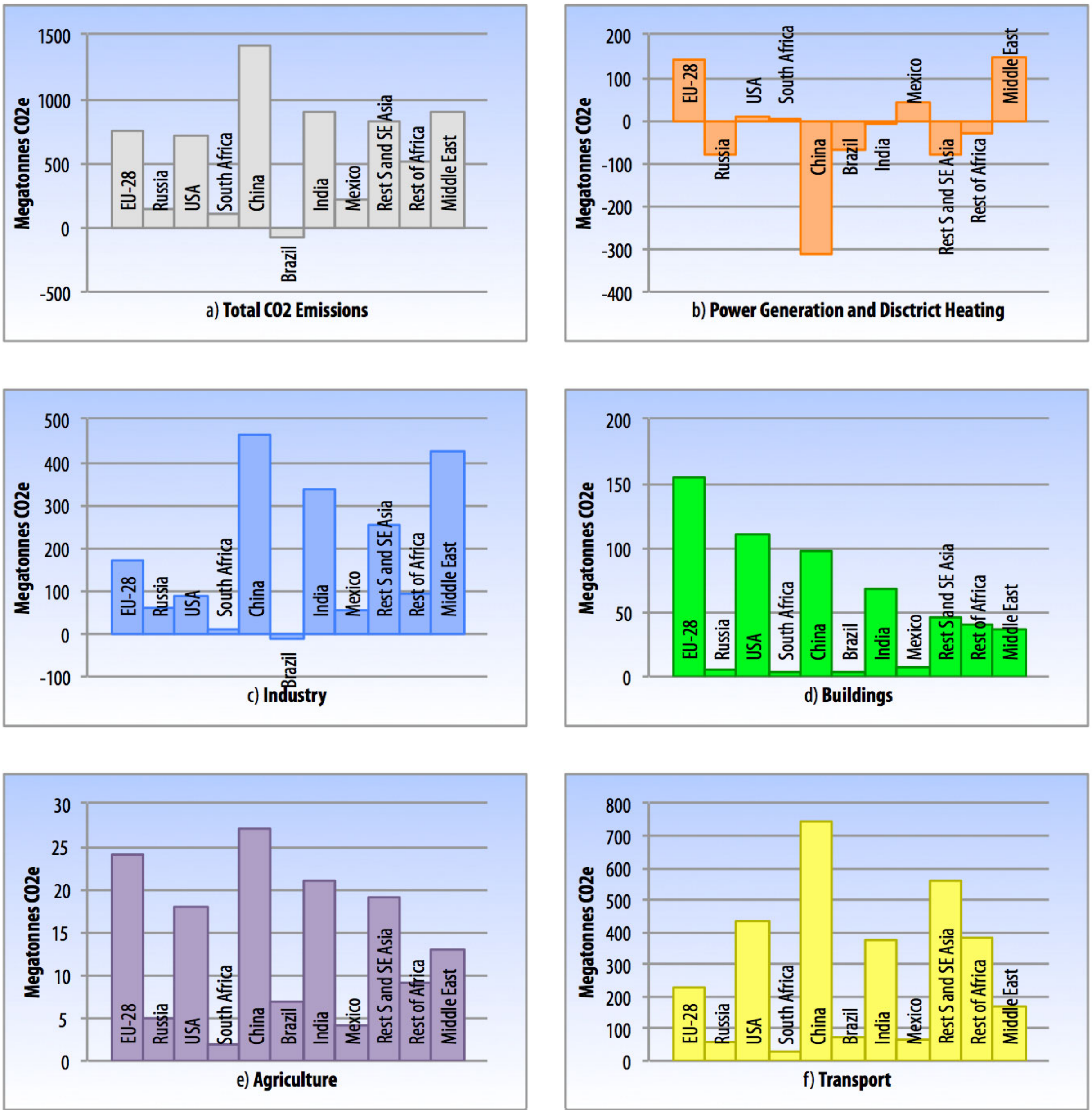

Figure 5: 2050 CO_2 emissions by region in total a) and by sector: b) energy transformation [Use of BECCS explains negative emissions], c) industry, d) buildings, e) agriculture, and f) transport.
Source: Wuppertal Institute based on JRC / European Commission *(2016).*

One very generic assumption is that, all else being equal, mitigation should be cheaper in less developed regions. The argument supporting this claim is that it should be easier to build up low carbon infrastructure from scratch than replacing existing high-carbon infrastructure, especially when this high-carbon infrastructure has to be discarded before the end of its scheduled lifecycle (stranded assets).

If we take this premise for granted, two particular indicators from the scenarios may lead us closer to an answer: per capita GDP (in purchase power parities) and per capita emissions. Figures 6 and 7 show that significant disparities in the state of development prevail in 2050 in all scenarios.

The scenarios concur with regard to the differences in per capita CO_2 emissions by world region in 2050: In all three scenarios that still report emissions by 2050, per capita emissions are expected to be higher than the global average in Europe and especially in the USA (North

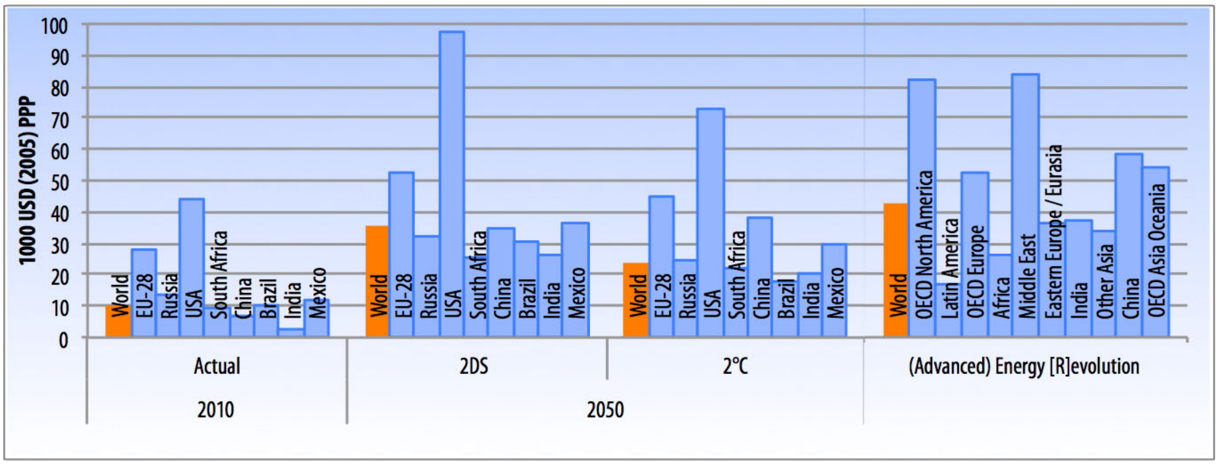

Figure 6: Per capita gross domestic product in 1000 USD (2005) in purchase power parities of selected world regions. Values include actual data for 2010 and scenario assumptions for 2050 from all three studies. Note that Greenpeace et al. use the same assumptions in both "Energy [R]evolution" and "Advanced Energy [R]evolution". *Source: Wuppertal Institute.*

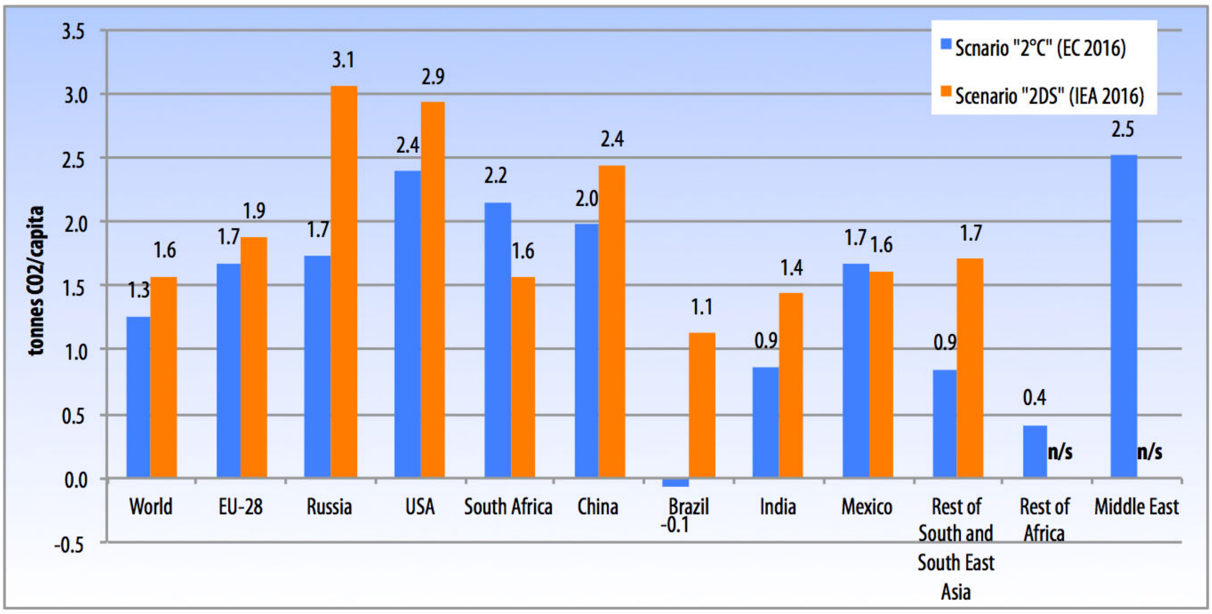

Figure 7: Per capita emissions in selected world regions as projected by the "2°C" and "2DS" scenarios.
Source: Wuppertal Insitute based on JRC / European Commission (2016) and IEA (2016).

America), China and Russia (Eastern Europe/Eurasia), also in the Middle East in two of the scenarios. Per capita emissions are expected to be lower than the global average in Africa. However, notable differences exist in regard to India.

The differences in per capita CO_2 emissions between the world regions are significant in all three scenarios: For example, in the USA in the "2°C" scenario, emissions are about six times higher than in Africa. In the "2DS" scenario, per capita emissions are almost three times as high in Russia compared to Brazil. In the "Energy [R]evolution" scenario, energy-related CO_2 emissions in Eastern Europe/Eurasia are almost 7 times higher than in Africa.

These findings again correspond with the IPCC scenarios. Of those scenarios in the IPCC database that specify regional per capita emissions, only two scenarios (both applied in the Phoenix 2012 model) achieve equalization of per capita emissions. The mean difference between the highest and lowest regional per capita emissions of the most ambitious scenarios in the IPCC AR5 scenario database (category 1) is 2.27 tonnes, the maximum difference is 5.73 tonnes (IPCC, 2014a).

It is therefore safe to say that significant differences in the material wealth will prevail at least until 2050. These differences imply a higher capacity to pay for mitigation technologies. In the absence of a carbon market that would allow for a levelling of abatement across the globe, it can be assumed that more expensive mitigation options will be explored first in more prosperous world regions.

This argument is also supported by differences in the diffusion rates of particular mitigation technologies. Unfortunately, this kind of information is extremely scarce in the reviewed studies. The only exemption is information with respect to the diffusion of CCS technologies. The IEA study does provide some data on this aspect. Figure 3 above indicates that in natural gas based power production, virtually all remaining generation capacity is projected to be equipped with CCS technology in the US, Russia and the EU, whereas for India, China and other South-East Asian (ASEAN) countries below 20% of emissions from natural gas power production are avoided with CCS. Similar disparities are present when it comes to CCS in the industrial sector (see figure 8 below).

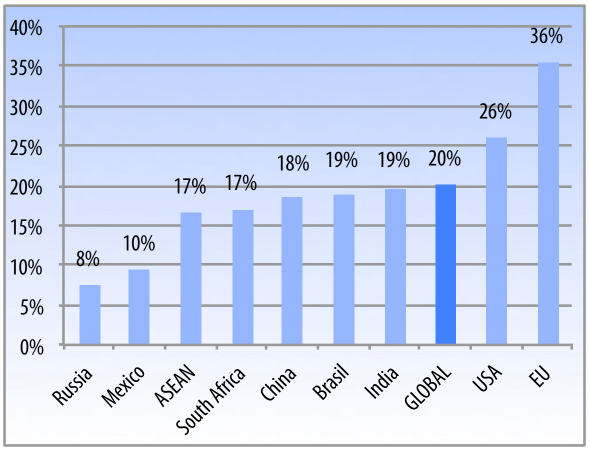

Figure 8: Share of emissions avoided through the use of CCS in the industry sector as projected by the "2DS"-scenario. *Source: Wuppertal Institute based on IEA (2016).*

4 Discussion

The scenario meta-analysis allows us to conclude with respect to the first order question of this study: there is no reason to believe that carbon trading will be obsolete in 2050 on economic or physical grounds.

Reliable estimates with respect to the second order problem this study addresses – the extent, volume or even expected costs of the remaining international carbon trading potential – are much more difficult. The analysis faces some fundamental problems. At the core is a lack of detailed sectoral and regional data in the existing literature. Existing energy and emission scenarios do not provide a level of detail to come to a definitive answer with respect to our research question providing data on the physical and economic potential for carbon markets in the future.

Most importantly, the scenarios do not specify emissions separately for industrial (sub-)sectors for the different world regions and they provide little information on abatement costs. Some studies do not even show a breakdown of GHG emissions from industrial sub-sectors at the global level. Moreover, process-related emissions are not considered by all studies.

The analysis is further hampered by the fact that the existing studies focus on particular CO_2 mitigation options in 2050 and do not discuss mitigation potential and/or cost of those options that have not been considered or that may become available only later on. Even for those technologies that have been considered, no detailed information on abatement costs are provided, generally.

Of course, the studies should not be blamed for this, since they all set out to answer very different research questions. Furthermore, the availability of advanced "breakthrough" technologies is highly speculative, let alone speaking of cost and deployment rates across the globe.

To mitigate this problem, we have reverted to a series of sectoral roadmaps. While these may provide a more detailed insight into the respective sectors, it may come at a cost: It is unlikely that those sectoral studies built on similar assumptions with respect to what technologies are likely to be utilized before 2050 as compared to the global scenario studies. Unfortunately, the lack of detail in the scenario studies does not allow for a direct comparison. Still, the differences in the realized mitigation potential suggests that differences exist.

Nevertheless, the analysis allows to conclude that even in 2050 there is ample mitigation potential left, if breakthrough technologies such as CCS or other technologies that have yet to be fully developed or scaled up (including hydrogen production by electrolysis) are taken into account. From today's point of view it is, however, uncertain whether and at what costs these technologies will mature to realize abatement that achieves the levels of the more ambitious scenarios or, in the light of the 1.5 °C goal, even exceed them. One could even go so far as to say that it seems unlikely that this will happen in the absence of a sufficiently high carbon price.

Despite these shortcomings, the results of the study are quite clear. Every lead points in the same direction: there will still be ample room for international transfer of mitigation results even in 2050. All sectors we have looked at still feature substantial emissions in 2050. However, in the energy transformation sector, a sector which is considered particularly suitable for carbon trading due to its structure of a limited number of large point sources, has relatively little to offer in terms of remaining emissions. While some mitigation potential is predicted for the industrial sector, which comprises large point sources of GHGs as well, it may be necessary that carbon trading will have to revert to sectors and emissions that are more difficult to capture with existing tools and methodologies of measuring, accounting and verifying emissions or emission reductions.

The scenario comparison also reveals that significant disparities in the regional distribution of wealth and emissions will prevail in 2050. This allows to conclude that there is room, both economically as well as technologically, to shift emissions from one world region to another. In other words: there is room for carbon trading in 2050.

All things considered, there is no reason to believe that there is no room for carbon markets by the middle of the century or that they become obsolete by then in a scenario of very ambitious global climate change mitigation efforts. Quite the contrary, a form of carbon pricing may be necessary to achieve those ambitious goals in the first place. One feature of market-based mitigation instruments is the so-called "search function" of carbon markets: putting an effective price on carbon through emission trading (or alternatively a carbon tax) engages new actors to seek rents by identifying and most importantly realizing low-cost mitigation options. Additional revenues can help to overcome technical or institutional barriers e.g. by directing the attention of managers and engineers.

Last but not least, it is difficult to imagine how a levelling of abatement costs on the globe can be realized without harnessing market forces. Levelling abatement costs is equivalent with realizing the cheapest mitigation potentials first. While carbon markets certainly are no silver bullet that can resolve the climate crisis alone, they help to optimize the use of scarce resources and thus enable spending on other climate protection purposes including on adaptation that are less prone to market forces.

The analysis also reveals that, ultimately, the use of carbon markets or "international transfer of mitigation outcomes" is much more a political question than a technical or economical one. It is political in at least two ways: Are countries willing to make use of markets in general? And do countries, in particular the industrialized countries, take on ambitious mitigation commitments, commitments that are in line with their historic responsibility or in fact any measure of equity? The remaining disparities in per-capita-emissions in 2050 (see figure 6) indicate that industrialized countries, in order to do their fair share, need to compensate their higher-than-average emissions by supporting mitigation in lesser developed countries. International transfer of mitigation outcomes is one potentially important tool to organize this contribution on the global scale.

5 Conclusions

This Policy Paper set out to investigate whether any claims that "if we take the Paris Agreement seriously, there is no room for carbon markets" or "carbon markets will be obsolete in 2050" are substantiated. Two conditions have been identified that would technically preclude any international carbon trading: (1) no mitigation potential remains and/or (2) no differences in the cost of the remaining abatement options remain. The first of the two conditions needs no explanation. The second is based on the following rationale: if cost are on par across the globe, why should one country invest in mitigation activities abroad when it can achieve the same within its own borders?

Three studies comprising a total of four scenarios have been reviewed. Despite some shortcomings in terms of the level of detail of the data provided by these studies, it can be safely concluded that none of the above mentioned conditions is very much likely to be violated in 2050. The only exemption is the "Advanced Energy [R]evolition scenario by Greenpeace et al. (2015) which foresees a complete phase-out of energy related emissions by 2050 (process related emissions are not covered in the scenario). This extremely ambitious scenario can serve as an interesting reference point. It demonstrates that a full phase-out of emissions seems technically possible (even if possibly at extremely high cost). From here it can be inferred that the technical mitigation potential remains in all other scenarios.

Also, all scenarios document significant disparities in the distribution of global wealth and emissions. This can be interpreted as a strong indicator that the second condition is not violated either. All scenarios that still feature emissions in 2050 concur that industrialized countries in Northern America and Europe will still feature per-capita-emissions above the global average, in some scenarios very substantially above average. If these countries would like to contribute their fair share to the global climate change mitigation effort – however this share is defined – they will have to assume responsibility for emission reductions elsewhere. International carbon trading and the international transfer of mitigation outcomes can be one tool to organize this compensation cost effectively.

The political aspects of international carbon trading, though, were beyond the scope of this Policy Paper. From our scoping we can conclude that technically and economically there is no reason to believe that carbon trading will be obsolete in 2050. Due to the limited space and the imperfect data provided in the consulted studies, they do not allow us to make any further conclusions on the scale or volume of potential international transfers of mitigation outcomes nor the price levels at which this may (or may not) occur.

To address these questions, further research is required in at least two directions. First, it would be necessary to investigate the political dimension of carbon markets: with respect to estimating potential demand for international carbon trading, it would be interesting in particular to compare the projected (per-capita) emissions in industrialized countries and their fair share according to a range of different equity indicators.

Second, a dedicated modelling exercise could provide data that is not available from the third party scenarios considered in this study and that would enable a much more sophisticated estimate of potential supply. This relates particularly to data with respect to a detailed sectoral and regional breakdown of remaining emissions and emission reduction potentials, diffusion rates of key low-carbon technologies, as well as expected abatement cost levels in the respective sectors and regions.

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