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Carbon Markets in a <2 °C World:
What Role May International Carbon Trading Play in, up to and beyond 2050?

Wolfgang Obergassel, Lukas Hermwille, Franziska Jüde, Sascha Samadi and Anna Röhnelt

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Internet
www.carbon-mechanisms.de/en

Contact
Wolfgang Obergassel
Email: wolfgang.obergassel@wupperinst.org

Wuppertal Institute for Climate, Environment and Energy
Döppersberg 19 • 42103 Wuppertal • Germany

www.wupperinst.org

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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 still 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 is an updated Version of the 2016 policy paper "Carbon Markets in a <2 °C World: Will There Be Room for International Carbon Trading in 2050?", which concluded carbon markets would not be obsolete in 2050 and international carbon trading will play a role in the global effort to mitigate anthropogenic climate change.

This policy paper extends and updates that analysis in terms of both the time frame and the sectors examined. While the previous version focused on energy-related emissions, this analysis considers additional sectors including nature-based solutions.

A total of four scenarios were examined for this paper. Two scenarios that are associated with the 2°C target and two scenarios that assume global warming of 1.5°C. It should be noted that the analysis has some limitations: most importantly, the scenarios do not report emissions for the different world regions separately by industry (sub)sector, and they contain little information on abatement costs.

Despite these shortcomings, it can be safely concluded that greenhouse gas emissions are still expected in many sectors 2050 in both the 1.5°C and the 2°C scenarios. It is therefore reasonable to assume that there will be both physical and economic potential for international carbon trading through 2050 and beyond. At the end of the day political decisions will be the decisive factor. Finland has already pledged to achieve net negative emissions by 2035. Such pledges can only be achieved by corresponding acquisitions of mitigation outcomes.

However, emission trading in 2050 and beyond will probably look very different from what we are used to. While the rationale for emission trading has so far been economic efficiency, when approaching zero emissions, transfers of mitigation outcomes may increasingly rather be driven by physical feasibility. The potential to generate mitigation outcomes will increasingly be limited to biological and geological carbon storage. However, this prospect raises substantial cause for concern regarding risks of leakage and non-permanence. Policy-makers should focus on properly regulating these risks to guarantee the environmental integrity of the market for the long term.

1 Introduction

The Paris Climate Agreement established an ambitious long-term goal for mitigating anthropogenic climate change. Parties agreed to aim for

> *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).*

How to achieve this goal is operationalized in Article 4 of the Paris Agreement (PA). Parties 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).

Recent climate science has further clarified what level of emission reductions will be necessary to achieve the long-term goal of the PA. The 2018 special report by the Intergovernmental Panel on Climate Change (IPCC) on the 1.5°C limit considered that global CO_2 emissions need to be roughly halved by 2030 and reduced to zero by 2050 in order to maintain a reasonable chance to stay within the 1.5°C limit.

Achieving such emission reductions will require a fundamental transformation of global energy, industrial and agricultural systems. It has been argued that price-based mitigation instruments[1] provide a tool to efficiently and effectively tackle climate change (see e.g. IPCC, 2014; Schmalensee & Stavins, 2015). Typically, the costs 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 et al., 2015; CDM Policy Dialogue, 2012; Wråke et al., 2012).

On the other hand, the scope for emission trading is limited by the level of reductions necessary to achieve the Paris temperature objectives. 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.

In a previous paper (Hermwille & Samadi, 2016), we analysed the long-term prospects for international carbon trading in 2050. In this new paper, we extend our previous analysis by considering not only the situation in 2050, but also the

[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.

time up to and beyond 2050. In addition, while the first paper focused on energy-related emissions, the new paper aims to extend the analysis to additional sectors, including nature-based solutions. This sectoral extension is subject to the availability of sufficient scenario data.

Section 2 provides an overview of the methodological approach. Furthermore, it includes a discussion of the physical precondition – technical mitigation potentials remain available – and economic preconditions – cost differentials in these mitigation potentials persist – for international carbon trading.[2] The section also includes a brief description of the scenarios and roadmaps utilized for the analysis.

Section 3 analyses the selected mitigation scenarios and assesses whether and to what extent the physical condition for international carbon trading is met or violated in the various scenarios and roadmaps considered.

Unfortunately, the data on cost differentials is much harder to address. The analysed scenarios do not provide direct mitigation cost estimates. Nor do they specify differences with regard to the technical mitigation options utilized in each sector from which one could draw conclusions with respect to the marginal abatement costs. Other scenarios such as the IEA's Net Zero Emission Scenario or Energy Technology Perspectives provide much greater detail on the technologies but lack sufficient geographical granularity. To address the question of the economic condition we therefore have to revert to very rough analogies by looking at differentials in GDP per capita and CO2-intensity of GDP as proxies.

Consequently, this scenario meta-analysis can only provide a rough scoping rather than an in-depth analysis of the remaining potential for carbon trading. However, it can give important pointers as to which areas of our global economies can be expected to participate in international carbon markets either as buyers or suppliers of mitigation outcomes.

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

[2] To note, this paper does not undertake modelling of the potential of international emission trading. Modelling exercises have concluded that global emission trading could vastly cut mitigation costs, or promote additional mitigation if the savings were invested in raising ambition. However, such modelling is often based on simplified assumptions such as perfect markets and that emission trading is the only mitigation instrument used. In this paper, we therefore take a simpler approach by exploring the physical and economic preconditions of emission trading.

2 Methodology and Material

2.1 The Various Forms of International Emission Trading

Emission units may be traded by different actors for different purposes. At the highest political level, national governments may engage in emission trading to achieve national commitments. Emission trading under Article 17 of the Kyoto Protocol allows nation states to trade their endowed emission allowances among each other directly. In addition, governments are able to buy emission reduction credits from the project-based mechanisms Clean Development Mechanism (CDM) and Joint Implementation (JI).

The Paris Agreement does not explicitly provide for emission trading, but 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 Parties 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 (NDC). 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). With its express focus on facilitating private sector engagement, the Art. 6.4 mechanism could become somewhat of a successor of the CDM .

In addition to trading by national governments, a number of jurisdictions have created domestic emission trading systems (ETS) 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. If such an ETS covers more than one country, mechanisms need to be in place to reflect cross-border trades of emission units also in the national balance sheets after the allowances have been surrendered.

Finally, there is the voluntary market where actors may purchase and cancel emission units in order to "compensate" their emissions. This is typically motivated by considerations of corporate social responsibility or individual moral considerations. Currently, there is a rapid increase in pledges by corporations to achieve emission neutrality at some point in time. Some of them purchase emission units to achieve their pledges (Kreibich & Hermwille, 2021).

2.2 Sources of Demand and Supply

In compliance markets, demand for emission trading is determined politically. 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 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. The potential level of demand from a domestic ETS is hence typically derived from the level of ambition of the respective Party.

Demand on international emission markets is therefore a function of the level of ambition of Parties' climate protection goals. This can play out in two ways: (1) emission units purchased 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. 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.

Both, supply and demand on global carbon markets are a corollary of the level of ambition of mitigation activities. In fact, Art. 6 stipulates that Parties may "pursue voluntary cooperation in the implementation of their nationally determined contributions *to allow for higher ambition* in their mitigation […] actions" (emphasis added, UNFCCC, 2016, Art. 6.1). In other words, Art. 6 is supposed to actively drive ambition. But for analysis this means that given the essential role of politics in defining the level of ambition and hence 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.

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.

Demand on the voluntary market is not set politically, but may be strongly impacted by the political decisions discussed above. If political decisions enforced rapid emission reductions, there would be correspondingly little scope for voluntary action. Vice versa, in an environment of low political ambition there is correspondingly more scope for voluntary action. But even in an environment of high political ambition there remains room for private actors to go beyond. For example, Microsoft has pledged emission

[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.

neutrality not only for current and future operations but also for historical operations.

For governments and companies, the highest possible level of ambition is to achieve not only emission neutrality, but to become "emission negative", i.e., to purchase and cancel more units than needed to offset emissions.

2.3 Conditions for International Emission 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 emission trading occurs. However, if these conditions are violated, there is no room for international emission trading whatsoever.

Physical Condition: Untapped Mitigation Potential Remains Available

Emission 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]

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 emission-free technologies generally outcompete emission-intensive alternatives so that any future demand can be expected to be met emission-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, through the use of bioenergy in combination with carbon capture and storage (BECCS), or through directly capturing CO_2 from the air (DAC).

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

Economic Condition: Differentials in Mitigation Costs Prevail

The existence of mitigation potential does not suffice to explain international emission trading. Instead, trading will only occur if significant cost differentials[6] remain between world regions, sectors and / or applied technologies. If

[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.

[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.

abatement costs 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 emission 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 emission 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 market would not result in significant net transfers of mitigation results from one country or region to another.

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.

The four scenarios examined originate from two sources that have projected the development of emissions up to 2050 for both the 1.5 degree target and the 2 degree target. These are two scenarios of the Global Energy and Climate Outlook (GECO) of the Science Hub of the European Commission (Keramidas et al., 2021) and two scenarios developed with the Global Change Analysis Model (GCAM) of the University of Maryland (JGCRI, 2021; NGFS, 2021). The scenarios allow a good comparability among each other, especially with regard to the differences in the temperature targets. This also distinguishes the new version of the present paper from the previous version, in which no scenarios for a 1.5 degree target were examined. Another difference is that the pathway to 2050 was additionally analyzed for all scenarios. While in the previous version the scenarios analyzed the year 2050 only as a single point, the developments in 10-year intervals can now also be analyzed.

Scenario	Publisher	Timeframe analysed
GECO 1.5°C **GECO 2°C**	European Commission, Keramidas et al. (2020)	2010-2050 10-Year steps
GCAM 1.5°C **GCAM 2°C**	University of Maryland, NGFS (2021)	2010-2050 5-year steps

Table 1: Overview of Selected Scenarios.
Source: Wuppertal Institute

There are also differences in the sectors and emissions examined. The previous analysis refers mainly to the sectors energy supply (electricity and heat) as well as the industrial sectors, which were again subdivided into the individual industries. In the updated version, the emission developments of the transport and building sector as well as agriculture and LULUCF were analysed in addition to energy and industry. For the latter sectors, total greenhouse gas emissions were analysed, while the analysis of the energy, industry, buildings and transport sectors focuses on CO_2 emissions from combustion processes. For an overview of the emissions, sectors and time spans analyzed, see Table 1.

Sectors Analyzed	GHG Emissions covered	Regions Covered
Energy Generation and Central Heat Generation (Energy)	CO_2-Emissions from Combustion Processes	Europe *(EU States, UK, Iceland, Norway, Switzerland)*
Industry	CO_2-Emissions from Combustion Processes	North America *(United States, Canada, Mexico)*
Transport	CO_2-Emissions from Combustion Processes	Rest Industrial *(Other Balkans, Russia, Ukraine, Australia, Japan, New Zealand, South Korea)*
		China
Buildings	CO_2-Emissions from Combustion Processes	India
Agriculture	Total GHG-Emissions	Rest of Asia *(Iran, Saudi Arabia, Mediterranean Middle East, Rest Gulf, Indonesia, Malaysia, Thailand, Rest South Asia, Rest South East Asia)*
Land Use Change and Forestry (LULUCF)	Total GHG Emissions	Africa *(Egypt, Algeria & Libya, Morocco & Tunisia, South Africa, Rest Sub-Saharan Africa)*
		South- & Central America (Argentina, Brazil, Chile, Rest Central America, Rest South America)

Table 2 – Key features of the analysed scenarios.
Source: Wuppertal Institute

Scenario description

The 2°C GECO scenario assumes a global greenhouse gas pathway associated with a likely chance of achieving the long-term goal of a temperature increase of less than 2°C above pre-industrial times in 2100. The probability of not exceeding the 2°C scenario by the end of the century is 66%. Like the 2°C scenario, the 1.5°C scenario was developed assuming a global greenhouse gas pathway associated with a likely chance of achieving the long-term goal of a temperature increase of less than 1.5°C above pre-industrial levels by 2100. Based on the 1.5°C scenario, it was designed with a 50% chance of not exceeding this temperature change at the end of the century. The same socioeconomic assumptions and energy resource availability were used in each case to create the scenarios. Thus, the scenarios differ in terms of the climate and energy policies included, which affects the projections of the energy supply and demand system and greenhouse gas emissions.

For more information, please refer to the GECO main report (Keramidas et al., 2021). The GCAM scenarios were developed as part of the Network for Greening the Financial System (NGFS, 2021) scenarios to provide a common starting point for analysing climate risks to the economy and the financial system. The goal of zero global CO2 emissions by 2050 requires an ambitious transition across all sectors of the economy. The NGFS scenarios highlight several important issues, including rapid decarbonisation of electricity, increasing electrification, more efficient resource use, and a spectrum of new technologies to address the remaining emissions that are difficult to avoid.

3 Analysis

The prior preparation of the data enables a comparison of the selected scenarios across all sectors and regions. A look at the scenarios reveals that there is no scenario that projects a complete phase out of global GHG emissions by 2050 (see figure 1). Considering all scenarios, greenhouse gas emissions are still expected in 2050 in both the 1.5°C and the 2°C scenarios. While the GECO 1.5°C scenario forecasts a total of about 7,68 Gt of greenhouse gas emissions and the 2°C scenario even forecasts about 19,98 Gt, the annual emissions expected for 2050 in the GCAM scenarios are slightly higher at about 8,66 Gt in the 1.5°C scenario and over 20,09 Gt in the 2°C scenario.

Due to different types of modelling, the emissions from 2010 (shown here as a blue curve) also differ slightly. For the GECO scenarios, emissions in 2010 reached 47.6 Gt, in the GCAM scenarios 49.28 Gt. For the 1.5°C scenarios, this represents a decrease in emissions of 82% (GCAM) and 84% (GECO). For the 2°C scenarios, the reduction from 2010 to 2050 is estimated at 59% (GCAM) and 58% (GECO). It is also evident that the amount of captured CO_2 plays a larger role in the GCAM scenarios than in the GECO scenarios. However, the difference is offset primarily by the higher CH_4 emissions in the GCAM scenarios, so the amount of total emissions from both scenarios are fairly close.

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 be stated with high confidence that the necessary physical condition for international carbon trading will still not be violated by 2050.

To answer the second research question of the paper "What kind of emissions and emission reduction potentials remain in 2050?", a deeper look at the scenarios is required.

The scenarios differ not only with regard to the absolute simulated greenhouse gas emissions, but also with regard to the shares of different greenhouse gases. In the analysis, the CO_2 emissions from combustion processes were considered; these include the sectors of energy and heat supply, industry, transport and buildings. Further greenhouse gas emissions considered individually in the scenarios are nitrous oxide, methane emissions and chlorofluorocarbons (F-gases). For the Agriculture, Forestry and Other

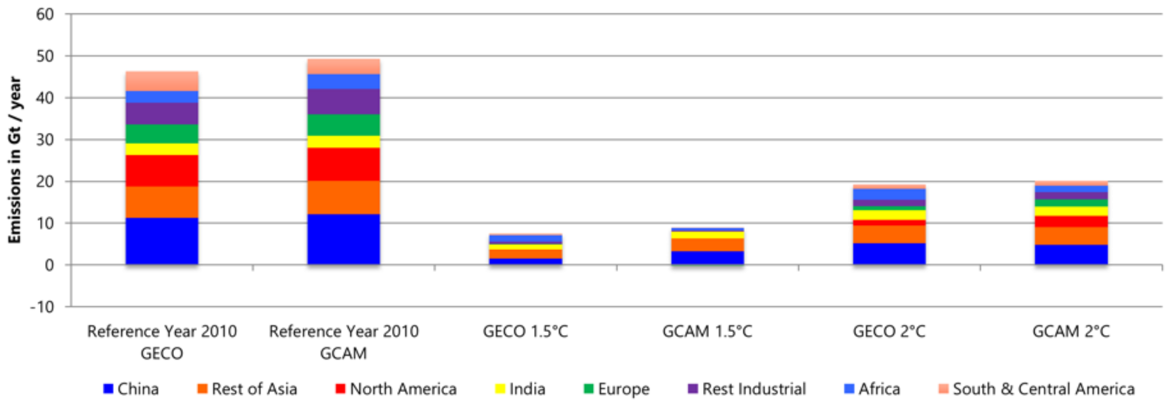


Figure 1: Regional distribution of total emissions in 2050 compared to distribution in reference year (2010) per scenario.
Source: Wuppertal Institute based on Global Energy and Climate Outlook (2021); and Global Change Analysis Model (2021).

Land Use sector (AFOLU), the various GHG emissions are not further differentiated. At this point, it should be noted that there are significant differences in the GHG impact of the different GHGs. Looking at the scenarios, there are also further differences in the shares of different greenhouse gases.

The emissions of F-gases and nitrous oxide across all scenarios are roughly the same amounts. CH_4 emissions as well as GHG emissions from AFOLU are in the same order of magnitude in each of the 1.5°C scenarios and also in the 2°C scenarios. There are clear differences in the simulated CO_2 emissions. These are significantly lower in the 1.5°C scenarios than the quantities projected in the 2°C scenarios.

There are also significant differences between the scenarios in the amount of CO_2 emissions captured. The GCAM scenarios assume significantly higher amounts of captured CO_2. The amount in the GCAM 2°C scenario is therefore also higher than the amount of captured CO_2 in the GECO 1.5°C scenario. In principle, however, negative emissions from carbon removals are included in all scenarios. Section 3.3 provides further information on the carbon removal technologies and the temporal development until 2050.

Figure 2 shows the 2050 scenario emissions by geographic composition. It also shows the geographical emission distribution of the two scenarios from the reference year 2010. Basically, the amount of absolute emissions changes significantly, as can already be seen in Figure 1. The shares of the individual regions differ slightly between the individual scenarios.

For example, the GECO 1.5°C scenario assumes significantly higher emissions in Africa than the GCAM 1.5°C scenario. Nevertheless, the regions China, Asia and North America have the largest shares of total emissions.

3.1 Development of emissions over time

The data of all four scenarios allow a comparison of the temporal development of CO_2 emissions of the different sectors as well as of the total GHG emissions from LULUCF and Agriculture from 2020 to 2050 (see Figure 2). Most striking across all scenarios is the significant reduction in energy-related CO_2 emissions by 2050. For the GCAM 1.5°C scenario, negative emissions are expected shortly after 2040. In all other scenarios,

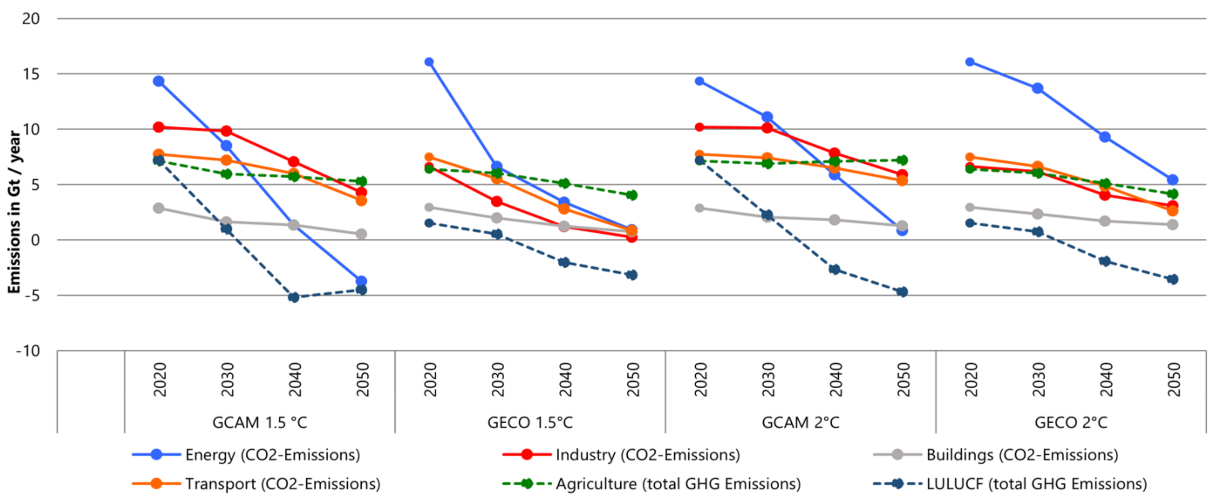


Figure 2: Development of Total Emissions from 2030 to 2050 by sectors and time trends for World Regions.
Source: Wuppertal Institute based on Global Energy and Climate Outlook (2021); and Global Change Analysis Model (2021).

however, energy-related CO_2 emissions remain positive. 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 (see section 3.3).

For the GECO 2°C scenario, the largest share of emissions in 2050 is still projected for the energy sector; in the other scenarios, GHG emissions from agriculture are the main source of emissions; for the GCAM 2°C scenario, emissions here are expected to increase from 2030. For the building sector, similar reduction rates are expected across all scenarios.

For the GCAM scenarios, industry-related CO_2 emissions are higher than transport-related emissions across all years, for the GECO scenarios this can be observed in reverse, only for the year 2050 the GECO 2°C scenario foresees slightly lower emissions from transport compared to industry. In principle, however, these are in similar orders of magnitude.

By far the lowest GHG emissions in all scenarios are from LULUCF, where negative emissions are expected shortly after 2030; in contrast to other sectors, the differences between the 1.5°C and 2°C scenarios are not particularly large here.

Fig. 3 shows the development of total emissions by region over time from 2020 to 2050, depending on the scenario. While China still shows by far the highest total emissions in 2020, these decrease most strongly in each of the 4 scenarios until 2050. The drop is particularly striking in the GECO 1.5°C scenario. Here, emissions in 2050 are actually slightly lower in China than in the rest of the Asian region. In the other scenarios, however, China remains the main source of remaining emissions in 2050. The distribution is also similar in all scenarios. Most emissions come from the Asian regions after China, followed by North America and the rest of the industrialized countries.

While emissions in North America and the rest of Asia are of about the same magnitude in 2020, especially in the GCAM scenarios, North America can reduce its emissions much more by 2050.

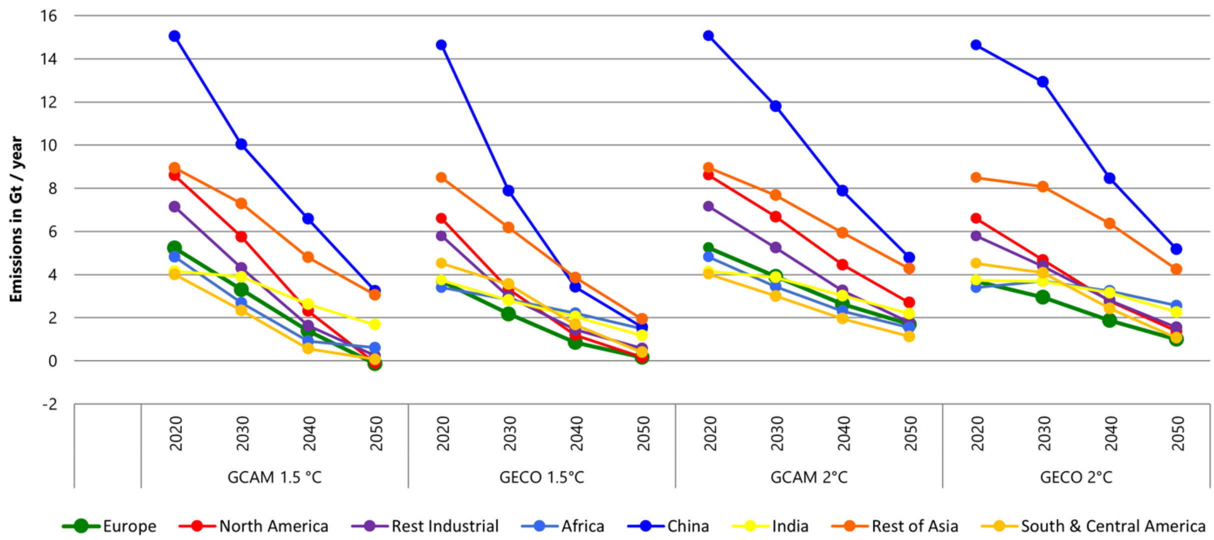


Figure 3: Development of CO2 Emissions from 2030 to 2050 by sectors and time trends for GHG Emissions from LULUCF and Agriculture. *Source: Wuppertal Institute based on Global Energy and Climate Outlook (2021); and Global Change Analysis Model (2021).*

In the GECO scenarios, emissions are particularly low in Europe from 2030 onwards, while the lowest emissions in the GCAM scenarios are found in South America. Emissions in India stagnate or increase in three out of four scenarios from 2020 to 2030 before they also start to decrease here.

3.2 Sectoral Breakdown over Time and Regions

In the following, the time trends of CO_2 emissions from combustion processes and from Agriculture and LULUCF are considered in a more differentiated manner and by region. The figures of the respective subsections show the differences of the emission development of the sector in the different regions (Figure a).

At this point, the scenarios of the Global Change Analysis Model and the Global Energy and Climate Outlook are juxtaposed per region to illustrate the differences for the year 2050 in the 1.5°C and the 2°C scenarios as well as in the regions. Figure b shows the temporal emission development of the respective sector from 2015-2050. In order to map the temporal development in figure b, the GCAM 2°C scenario, the scenario with the highest simulated remaining emissions in 2050, was used.

3.2.1. Power Generation and Central Heat Generation

Figure a) reveals initially clear differences between the individual scenarios and regions. While the GECO 2°C scenario simulates the highest emissions for 2050 in all regions, the GCAM 2°C scenario also projects negative emissions for India, and the 1.5°C scenario for North America, Europe and China. The GECO 1.5°C scenario does not project negative emissions in the energy sector in any region. However, the figure also shows that energy-related CO_2 emissions will be very low in almost all scenarios and regions and are therefore likely to play a less important role in 2050. As described above, the GCAM 1.5°C scenario even assumes negative emissions in China, Europe and North America, while in the GECO 2°C scenario energy-related emissions are still very high, especially in China but also in the rest of Asia. Figure a) reveals initially clear differences between the individual scenarios and regions. While the GECO 2°C scenario simulates the highest emissions for 2050 in all regions, the GCAM 2°C scenario also projects negative emissions for India, and the 1.5°C scenario for North America, Europe and China. The GECO 1.5°C scenario does not project negative emissions in the energy sector in any region. However, the figure also shows that energy-related CO_2 emissions will be very low in almost all scenarios and regions and are therefore likely to play a less important role in 2050. As described above, the GCAM 1.5°C scenario even assumes negative emissions in China, Europe and North America, while in the GECO 2°C scenario energy-related emissions are still very high, especially in China but also in the rest of Asia.

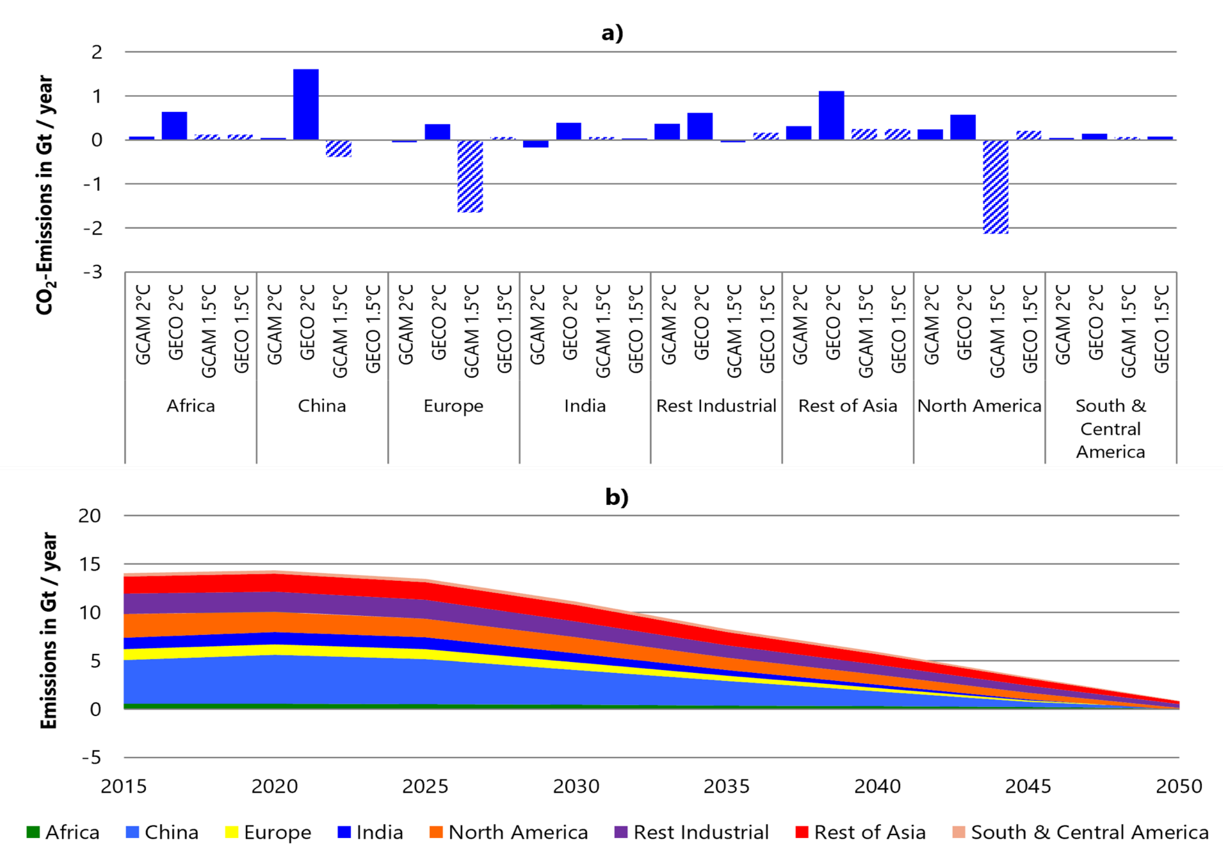


Figure 4: Energy: Breakdown over Regions in 2050 (a) and the projected emissions pathway from 2015-2050 (b) for the GCAM 2°C Scenario. *Source: Wuppertal Institute based on the 2°C Scenario of the Global Change Analysis Model* (2021).

3.2.2. Industry Sector

For the industrial sector, differences between the individual scenarios become apparent in Figure a). The GCAM scenarios assume significantly higher emissions across all regions than the GECO scenarios. Thus, industry-related emissions play a minor role in the GECO scenarios in 2050; according to the GCAM scenarios, they will continue to be important for the market, especially in the Asian region.

The time trend of the GCAM 2°C scenario primarily also shows falling emissions from 2015 to 2050. For the industrial sector, a trend toward falling emissions does not emerge until around 2030, and the sequential rates here are significantly lower than in the energy sector. With a share of more than one third in 2020 to 2030, China is projected to reduce its industrial emissions much more than other countries while the largest share is still recorded in this region.

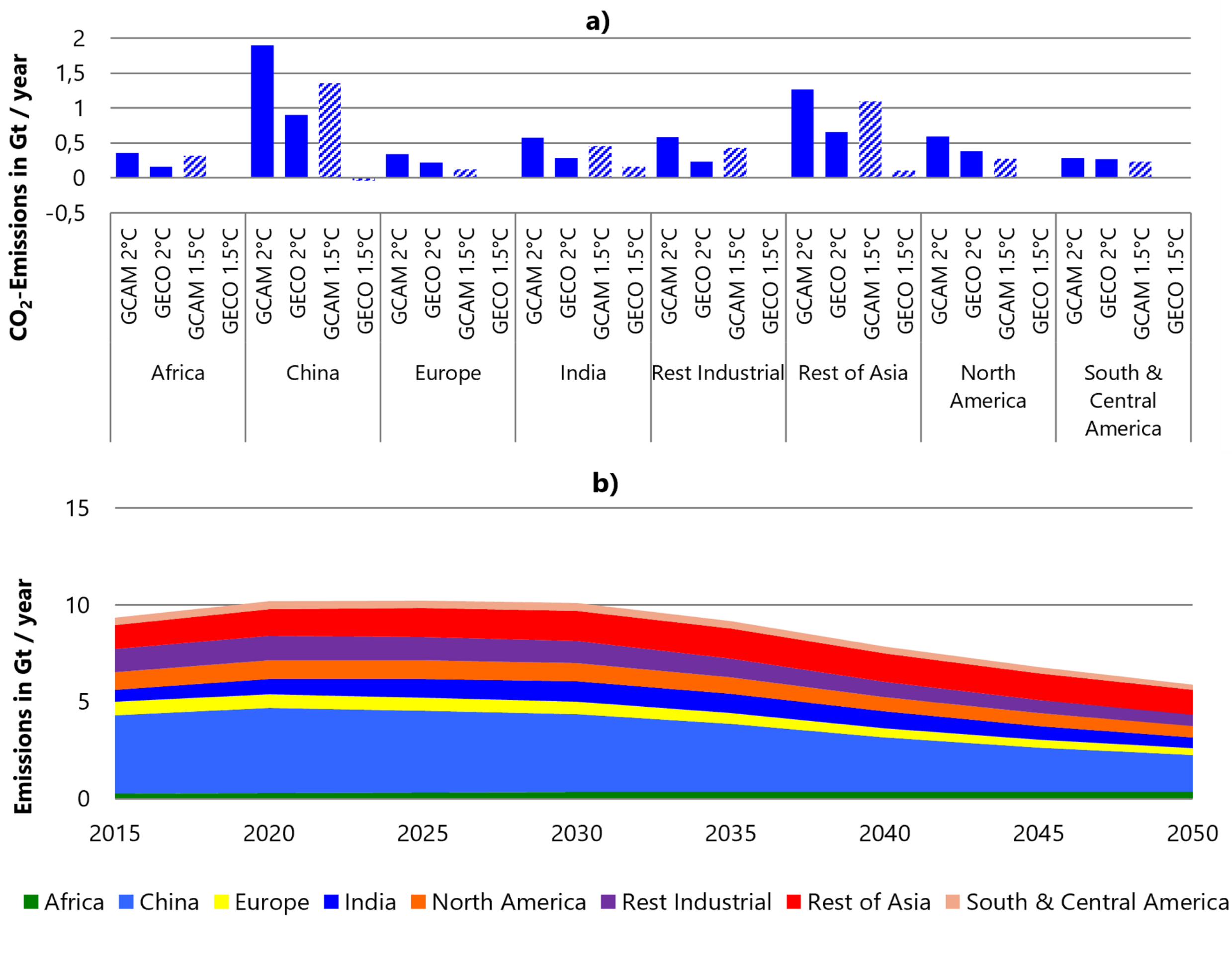


Figure 5: Industry: Breakdown over Regions (a) in 2050 (a) and the projected emissions pathway from 2015-2050 (b) for the GCAM 2°C Scenario. *Source: Wuppertal Institute based on the 2°C Scenario of the Global Change Analysis Model* (2021).

3.2.3. Transport Sector

For the transport sector, the projected emissions in the GCAM scenarios are higher than in the comparable GECO scenarios across all regions. However, they remain positive in all regions; only one scenario (GECO1.5°C) assumes very low emissions across all regions. According to the scenarios, transport-related emissions will be most significant in the Asian region and China as well as in North America. In general, the differences between the GCAM and GECO scenarios are significant. While the GCAM 2°C scenario assumes CO_2 emissions in the order of up to 1.8 Gt (North America), emissions in the GECO 1.5°C scenario remain low across all regions but still positive in 2050. For the transport sector, the largest share of emissions does not occur in China, but in North America and the remaining Asian countries, followed by Europe and China. Emissions are also expected to decrease in the transport sector, but they remain at a high level, exceeding energy-related emissions and staying just below industry-related emissions in 2050.

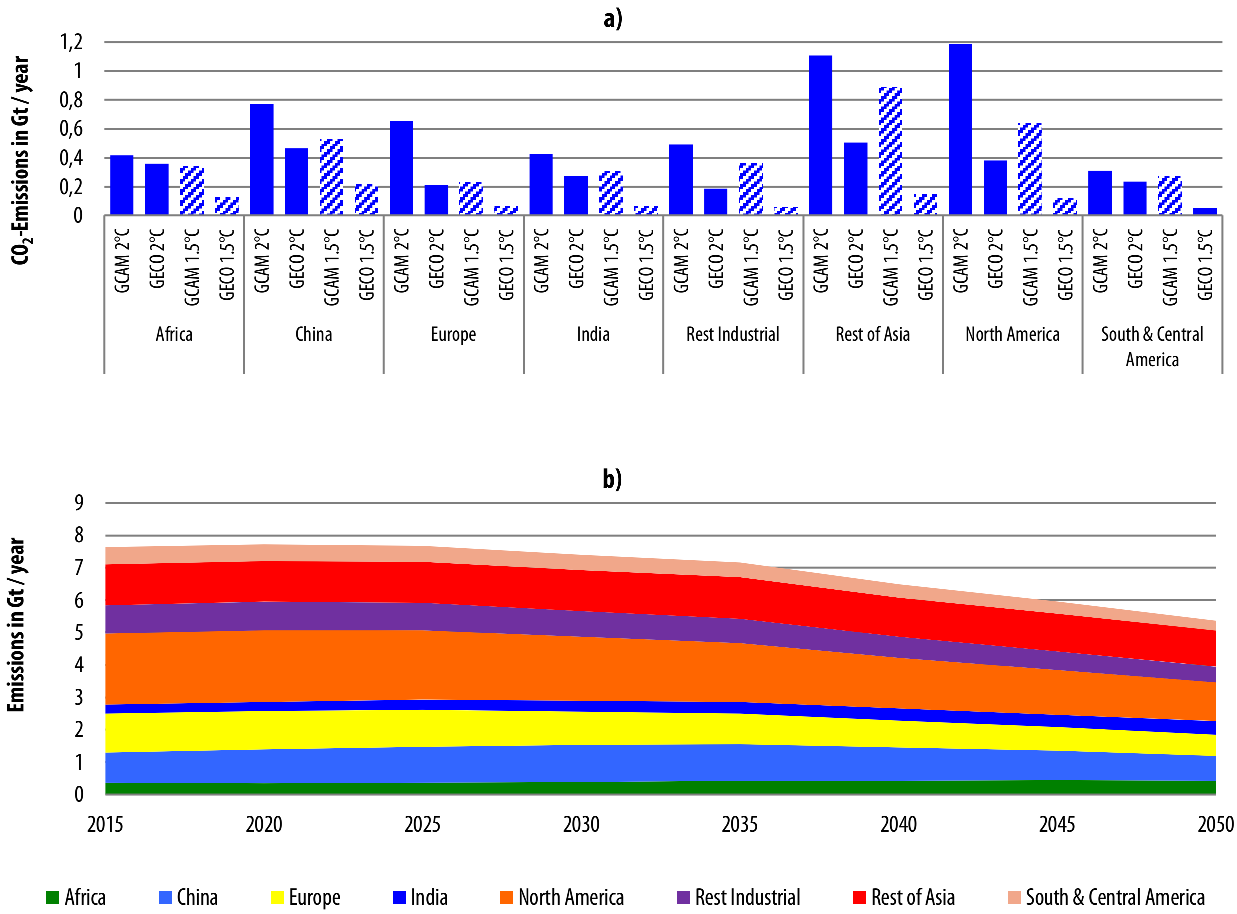


Figure 6: Transport: Breakdown over Regions (a) in 2050 (a) and the projected emissions pathway from 2015-2050 (b) for the GCAM 2°C Scenario. *Source: Wuppertal Institute based on the 2°C Scenario of the Global Change Analysis Model* (2021).

3.2.4. Building Sector

For the building sector, only low CO_2 emissions are expected in 2050, but these are expected to be positive in all regions. The highest values are expected by the 2°C scenarios in North America (3,06 Gt/ year), China (2,8 Gt/year) and the remaining Asian countries (2,6 Gt/year). Only the GCAM scenarios assume very low remaining emissions in India (0,12 Gt/ year for 1.5°C and 0,34 Gt/ year for 2°C) and Africa (0,23 Gt/ year for 1.5 °C and 0,49 Gt/ year for 2°C). Looking at the temporal progression from 2015 to 2050 for the GCAM 2°C scenario shows that strong declines are expected in the building sector in particular in 2020 and 2025, before emissions start to decrease slightly but steadily from 2025 onwards.

The declines in the previously mentioned years are evident across all regions. The India and Africa regions are expected to have minimal emissions from the building sector in 2050, while the largest sources of emissions will continue to occur in China, North America, and Europe.

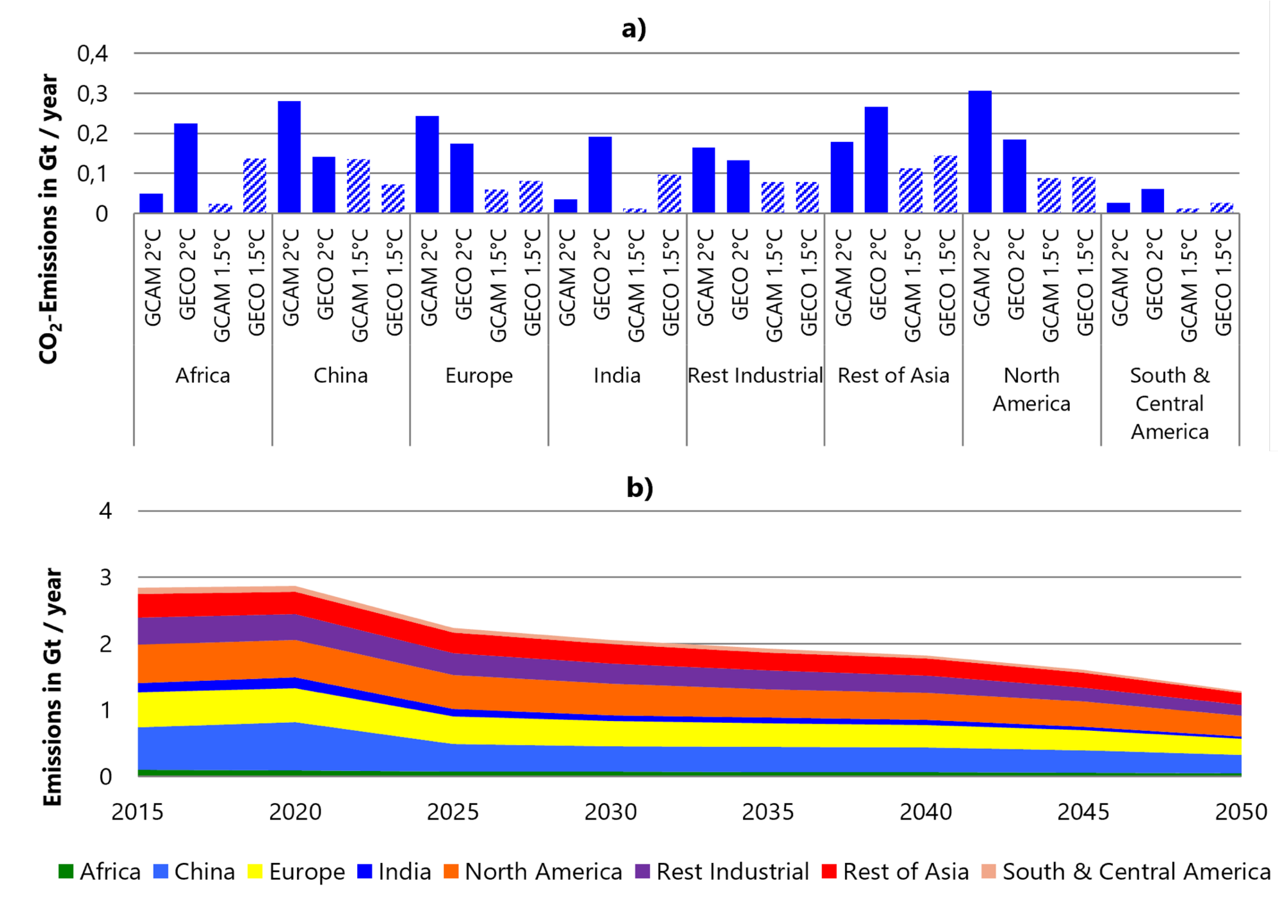


Figure 7: Buildings: Breakdown over Regions (a) in 2050 (a) and the projected emissions pathway from 2015-2050 (b) for the GCAM 2°C Scenario. *Source: Wuppertal Institute based on the 2°C Scenario of the Global Change Analysis Model* (2021).

3.2.5. Agriculture

Detached from the consideration of CO_2 emissions only, the figures in 3.1.5. and 3.1.6. show the regional distribution of greenhouse gas emissions for Land Use, Land-Use Change and Forestry (LULUCF) and Agriculture.

In the agricultural sector, high GHG emissions are expected especially in the GCAM scenarios. There is little difference in projected emissions between the GECO 1.5°C and 2°C scenarios with respect to the agriculture sector. The GCAM scenarios differ somewhat more significantly. Noticeable here is the significantly higher share of agricultural GHG emissions in Europe, projected in the GCAM 1.5° Scenario.

In the other regions, however, GHG - emissions are consistently high there is still potential here in terms of the market in 2050.

For the GCAM 2°C scenario and the temporal progression shown below, Europe's share is significantly lower. In this scenario, the emission sources from agriculture are mainly in the regions of India, China, South and Central America, and the other Asian countries. Basically, no significant decrease in emissions from 2015 to 2050 is discernible here. For the regions of India and China, a slight upward trend is even simulated from 2025 onwards.

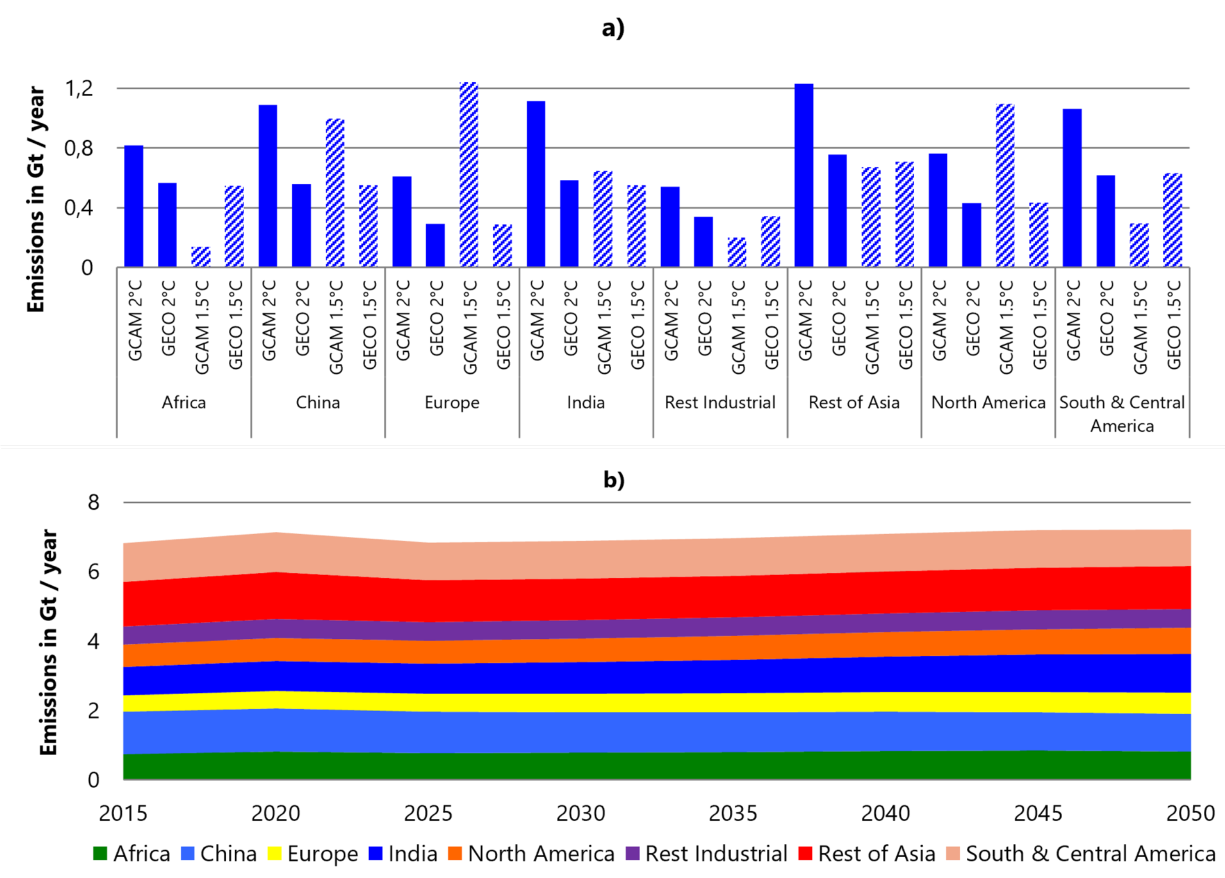
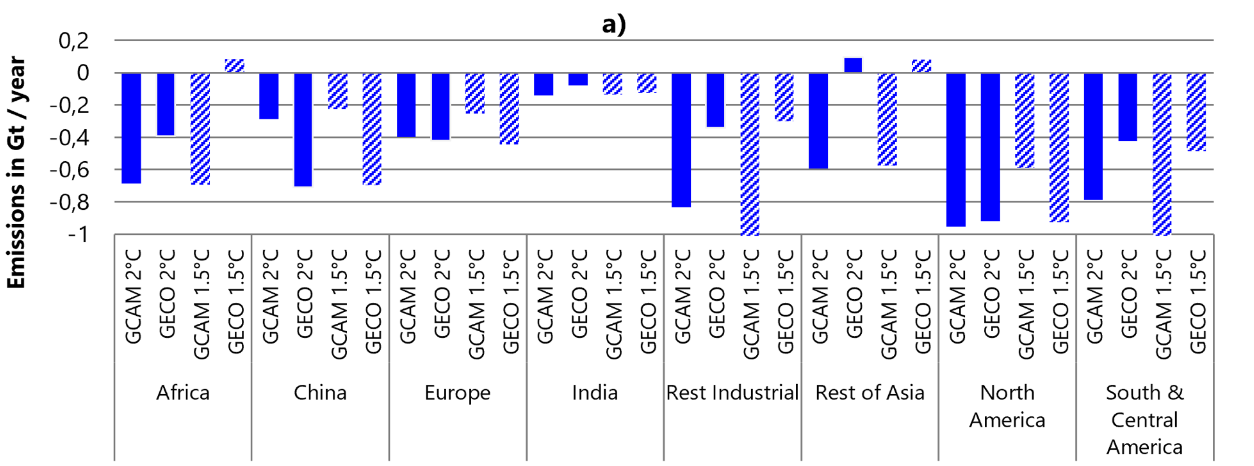


Figure 8: Agriculture: Breakdown over Regions (a) in 2050 (a) and the projected emissions pathway from 2015-2050 (b) for the GCAM 2°C Scenario. *Source: Wuppertal Institute based on the 2°C Scenario of the Global Change Analysis Model* (2021).

3.2.6. Land Use Change and Forestry (LULUCF)

The LULUCF sector is the only one for which almost no positive emissions are estimated in 2050. Only the GECO scenarios assume minimally positive emissions in Africa and Asia. All other scenarios show negative emissions across all regions. Especially in North America and the remaining industrialized countries, the largest sources of reductions are expected across all scenarios. A look at the development until 2050 for the GCAM 2°C shows that while emissions in Africa and some parts of Asia have already been falling since 2015 and will remain unchanged in South and Central America until 2020, emissions in the sector are still expected to rise in the remaining regions until 2020.

However, the emissions will already be negative in the first regions around 2030, and in all other regions by 2040 at the latest. For the year 2045 an end of the further reduction is expected, but until 2050 the emissions will still be negative in all regions.



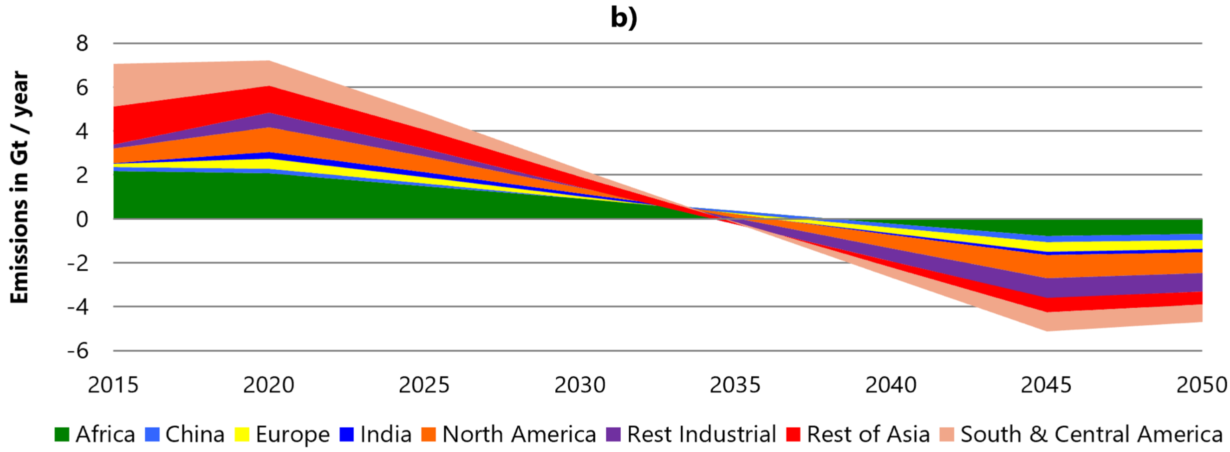


Figure 9: LULUCF: Breakdown over Regions (a) in 2050 (a) and the projected emissions pathway from 2015-2050 (b) for the GCAM 2°C Scenario. *Source: Wuppertal Institute based on the 2°C Scenario of the Global Change Analysis Model* (2021).

Table 3: Overall Overview of Remaining Emissions in 2050. *Source: Wuppertal Institute based on Global Energy and Climate Outlook (2021); and Global Change Analysis Model (2021).*

		CO_2-Emissions in Mt / year				total GHG-Emissions in Mt / year	
	Region	Energy	Industry	Buidings	Transport	LULUCF	Agriculture
GCAM 1.5 °C	Europe	-1647	119	60	231	-254	1240
	North America	-2134	278	89	639	-590	1093
	Rest Industrial	-56	428	79	364	-1027	200
	Africa	117	316	23	342	-695	139
	China	-384	1358	136	524	-227	997
	India	64	454	13	303	-136	646
	Rest of Asia	255	1096	113	890	-576	671
	South- & Middle America	71	235	12	273	-1019	297
GECO 1.5 °C	Europe	73	6	82	60	-444	288
	North America	207	2	91	116	-928	433
	Rest Industrial	164	1	78	59	-302	343
	Africa	119	16	137	124	83	548
	China	9	-43	73	217	-698	549
	India	31	159	97	65	-124	552
	Rest of Asia	254	102	144	150	81	706
	South- & Middle America	76	-11	26	51	-485	630
GCAM 2 °C	Europe	-55	341	243	657	-399	611
	North America	235	592	306	1189	-956	762
	Rest Industrial	373	584	164	491	-834	538
	Africa	77	358	49	415	-688	817
	China	47	1899	280	773	-287	1086
	India	-167	575	35	425	-142	1111
	Rest of Asia	315	1266	179	1107	-594	1228
	South- & Middle America	43	279	27	310	-788	1060
GECO 2 °C	Europe	363	217	174	210	-421	292
	North America	570	380	185	380	-921	429
	Rest Industrial	617	234	133	184	-340	338
	Africa	643	164	224	359	-395	567
	China	1606	901	142	466	-710	558
	India	391	284	191	274	-80	583
	Rest of Asia	1112	655	266	504	96	757
	South- & Middle America	139	266	62	232	-425	617

In addition, Table 3 provides an overall view of remaining emissions in 2050 for all scenarios.

What emerges here at first glance is also evident from the previous graphs. In 2050, negative emissions are expected predominantly in LULUCF and, occasionally, also in the energy sector. In the remaining sectors, all scenarios assume continued positive emissions, especially in agriculture, industry and the mobility sector. A striking feature of the last two sectors is the geographical distribution of emissions in the Asian region.

3.3 Carbon Capture and Storage Technologies - Overview

In order to achieve the goal of the Paris Agreement and to limit global warming to well below 2°C, active removal of CO_2 from the atmosphere is necessary in addition to the reduction of emissions. Data on the development of CCS technologies are available for all selected scenarios. The comparison of the scenarios in **Figure 10** shows that there are differences between the scenarios and that the GCAM scenarios assume significantly higher amounts of captured CO_2 overall. The GCAM 1.5°C scenario assumes 10.5 GT of sequestered CO_2, while the Global Energy Outlook 1.5°C scenario assumes less than half, at about 4.5 GT. Also, the share of CO_2 sequestered by biomass is particularly high in the GCAM 1.5°C scenario. Basically, all scenarios have in common that sequestered CO_2 by direct air capture will play almost no role and the share of captured CO_2 from fossil energy sources is about 2GT.

Figure 11 shows the development of technologies over time for the most ambitious scenario with respect to CCS technologies (GCAM 1.5°C).

Here it can be seen that a steep increase of CCS technologies is expected in general but also with respect to the different CCS technologies. The very low application of Direct Air Capture is also a result of the fact that this technology is only starting to find its way into the academic literature in general and modelling in particular.[7]

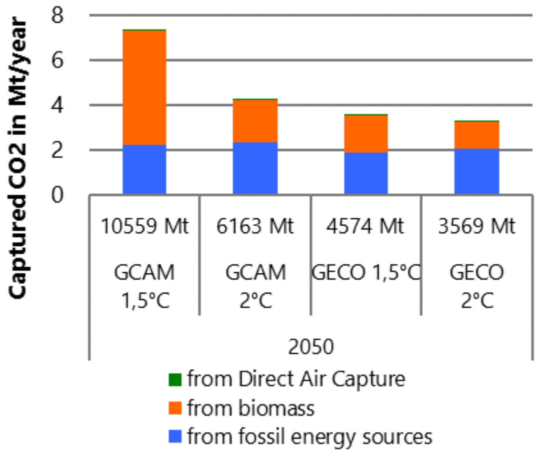


Figure 10: Amount of Captured CO_2 in 2050 - Scenarios in Comparison. *Source: Wuppertal Institute based on Global Energy and Climate Outlook (2021); and Global Change Analysis Model (2021).*

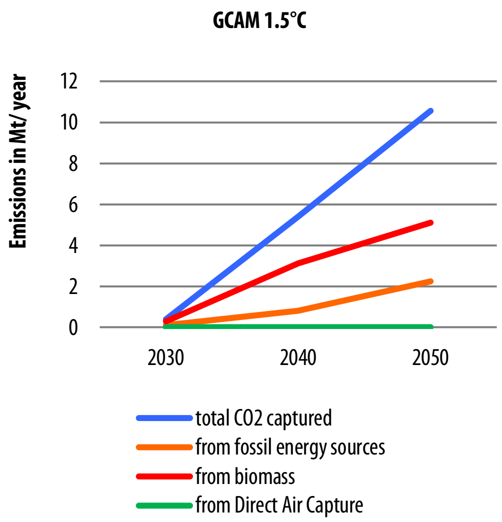


Figure 11: Development of CCS Technologies for GCAM 1,5°C Scenario. *Source: Wuppertal Institute based on Global Energy and Climate Outlook (2021); and Global Change Analysis Model (2021).*

3.4 Differentials in Economic Performance and Costs

As stated above, a key economic conditions for international carbon trading is the permanence of significant differences in realizing mitigation options. From these differentials, cost savings and/or increased mitigation ambition could be realized which are the rationale for the use of carbon markets in the first place (see also IETA et al., 2019). Unfortunately, the scenarios analysed do not provide sufficient information on the relative marginal abatement cost realized in the different sectors or regions. We therefore have to revert to proxies to see whether significant differences persist also over the next 35 years.

In terms of overall economic development, the scenarios project some convergence between world regions, but this will not suffice to close the development gap between world regions. For Europe, North America and the rest of industrialized countries, the GCAM model projects average annual growth rates of ~1.5% p.a. in the 2015-2035 period. China is projected to achieve strong initial growth throughout the 2020s that quickly levels of towards the level of aforementioned industrialized countries after 2035. India and the rest of Asia will feature relatively strong growth throughout with only a slight decrease towards the end of the period (4.48% on average for India and 3.24% for Rest of Asia). Meanwhile, Africa and South- and Central America will see growth rates increasing throughout the 2020s and remain relatively constant thereafter (4.21% average growth rate for Africa, 2.09% for South and Central America).

[7] At a workshop held to present interim results of this study, Prof. Leon Clarke, one of the authors of the GCAM study, pointed out that the potential for direct air captures is not yet fully reflected in his and most other models.

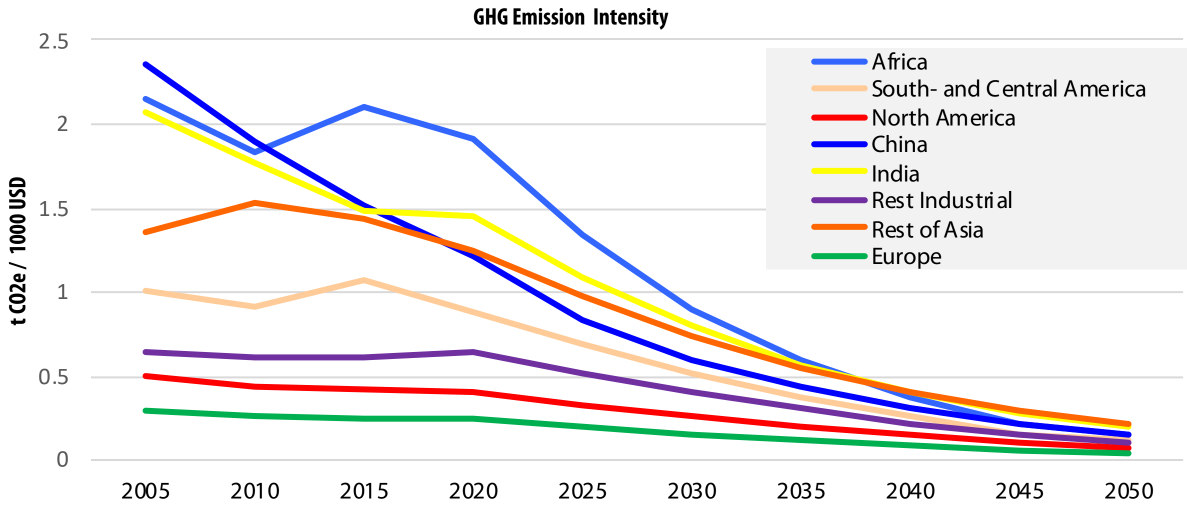


Figure 12: Greenhouse gas intensity of the economy in t CO2e per 1000 USD GDP.
Source: Wuppertal Institute based on the 2°C Scenario of the Global Change Analysis Model (2021).

This convergence can be observed not only in the GDP figures, but also in the GHG intensity of the economy (see **Figure 12**). All regions experience a dramatic reduction in GHG emissions per GDP unit to only a fraction of what it is today. However, this does not mean that regional differences disappear. Surprisingly, the relative standard deviation of the GHG intensity of the economy of the analysed regions remains more or less constant over the 2015-2030 period. In other words, the difference between the worst performing region in 2050 (Rest of Asia at 0.22 t CO2e per 1000 USD GDP in the GCAM 2°C scenario) is still 4.5 times higher than that of the best performer (Europe at 0.05 t CO2e per 1000 USD GDP), but on a much lower level.

Significant regional differences also prevail on a per capita basis, both in terms of GDP per capita as well as GHG emissions per capita. Per capita emissions range between just below zero and 2.4t CO2e in China. And per capita GDP ranges from a mere USD 6430 in Africa to just below USD 60,000 in North America.

4 Discussion and 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 need 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?

A total of four scenarios were reviewed for this paper. It has to be stated that the analysis faces some limitations: 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.

Despite these shortcomings, it can be safely concluded that none of the above-mentioned conditions is very much likely to be violated in 2050. Greenhouse gas emissions are still expected in many sectors 2050 in both the 1.5°C and the 2°C scenarios. The one exception is LULUCF, which achieves negative emissions sometime around 2030 in all scenarios. Another commonality is agriculture, which is projected to still feature about 5Gt CO_2-eq. of emissions in 2050 in all four scenarios. A third commonality is buildings, which features very low emissions in all scenarios across the entire time period.

The performance of the other sectors differs strongly among the four scenarios. In the GECO 1.5°C scenario, nearly all sectors approach zero or even below zero by 2050. By contrast, in the GCAM 1.5°C scenario, the energy sector approaches minus 5 Gt CO_2e. in 2050, while industry and transport stay positive at about 5 Gt CO_2e. In the GECO 2°C scenarios, industry and transport have a relatively similar performance with 2050 emissions of about 5 Gt CO_2e. By contrast, in the GCAM scenario the energy sector approaches zero emissions by 2050 while in the GECO scenario it is still at about 5 Gt CO_2e.

Regional differences also vary widely across scenarios. The two 1.5°C scenarios are extreme cases in this regard. In the GCAM 1.5°C scenario, the traditional industrialised countries as well as China feature substantial negative energy sector emissions in 2050, whereas the other regions approach zero. Industry emissions in this scenario occur mainly in Asia, but smaller amounts also in the other regions. By contrast, the GECO 1.5°C scenario has only little regional differences. It projects near-zero emissions in energy, industry, buildings and transport in all regions. Also, all regions achieve negative LULUCF emissions, except Africa and "rest of Asia", but here emissions are also near zero.

In the period before 2050, international carbon markets might play a bigger role. In the power and heat sector, emissions decrease sharply as of 2025 and hit zero only in 2050. In the most lenient scenario (GCAM 2°C), all industrialized countries as well as India and China see more than 5% emission reductions per annum after 2030 with further increases towards 2050. This seems to be extremely demanding and it is hard to see how this can be accelerated even further to make space for additional mitigation outcomes that could supply international carbon markets (see e.g. Cherp et al., 2021).

Industry emissions remain more or less on current levels until 2030, then decline. Given recent technological advancements e.g. in the steel industry (Bataille, 2020), there seems to be potential to accelerate transformation across the globe and correspondingly supply additional mitigation outcomes for international carbon markets.

On aggregate, the transport sector sees a slow and gradual decline until 2030 and an acceleration only thereafter. However, this development is not uniform across regions. Emissions will decrease earlier in Europe and North America and Industrial countries while China will see a rise in emissions until 2035.

The building sector is projected to achieve some early emission reductions until 2025, particularly from China, but after that, emissions decrease only slowly and this trend only accelerates slightly in the 2040s. Agricultural emissions remain more or less constant through the entire period and LULUCF emissions already turn negative around 2035.

To summarise this, the potential supply for international carbon markets decreases over time. Industry and transport may decrease only slowly in the next 15 years, so there seems to remain some potential for accelerated transformation and hence supply of additional mitigation outcomes for the international carbon market. The same holds for agriculture. But additional supply from the power and heat sector cannot be expected at any significant scale in a Paris compatible development pathway even before 2050.

So which lessons can we draw from the analysis with respect to how we can imagine a global carbon? International carbon markets will look very different from what we used to know. The energy sector that was historically both the largest source of demand as well as supply for carbon credits, will be out of the game in 2050. Moreover, the extremely steep emission reductions projected in the meantime suggest that there is little room to achieve additional emission reductions through a further acceleration of the transformation of the sector. The result that Europe, North America and China achieve even negative emissions in the GCAM 1.5°C scenario is more difficult to interpret. Perhaps, this should prompt us to think that the energy sector in more advanced economies can actually become a source of carbon credits in the period shortly before and after 2050?

The role of industry and transport sectors varies across the studied scenarios, but they might remain relevant for international carbon markets. Given the anticipated remaining differences in purchasing power and differences in emission intensity across regions, we can expect that in industrialized countries these sectors may remain a source of demand for international credits, whereas developing countries may have some potential to accelerate the decarbonization which can be converted into a supply for carbon credits.

Perhaps the most unanticipated finding, though, is that the agricultural sector might play a key role for providing emission reductions for international carbon markets. The agriculture sector may act as a source of demand for emission reductions in industrialized countries and potentially supply from developing countries. However, operationalizing emission reductions from the agricultural sector might be tricky given that many crops are international commodities; international trade could lead to carbon leakage.

Perhaps less surprising is the role of LULUCF sector which shows promise to become a source of supply for carbon credits. But again, it is unclear from the scenarios to what extent global forests can actually deliver on the competing demands. Moreover, questions about the permanence of forest credits have so far impeded more large-scale use of afforestation projects for international carbon markets.

Overall, while the rationale for emission trading has so far been economic efficiency, when approaching zero emissions, transfers of mitigation outcomes may increasingly rather be driven by physical feasibility. According to the scenarios we considered, in particular industry, agriculture and transport may still feature substantial positive emissions in 2050 while the energy and LULUCF sectors may have the potential to achieve significant negative emissions. Also, potentials are not distributed equally globally. Some countries have no potential for biological sequestration and others have no potential for geological sequestration. Transfers would therefore be needed to achieve an overall net-zero outcome.

However, a scenario where carbon storage, whether biological and/or geological, becomes the main source of mitigation units raises substantial reasons for concern regarding risk of leakage and non-permanence. The California forest fires of the summer of 2021 sharply highlighted these risks by destroying several forestry offset projects. Rather than using sequestration to "compensate" for remaining emissions, a safer route may be to account for emissions/ emission reductions and sequestration separately.

Finally, while this paper looked at physical and economic preconditions for trading, at the end of the day political decisions will be the decisive factor. From an equity perspective, the traditional industrialised countries have a higher responsibility than just fully mobilising their domestic mitigation potential. Finland has already pledged to achieve net negative emissions by 2035. Such pledges can only be achieved by corresponding acquisitions of mitigation outcomes. If other industrialised countries follow this example, this would therefore create a long-term demand for mitigation units.

So, in a nutshell, the technical question asked in this paper is straight forward to answer: in all likelihood, there will be both physical and economic potential for international carbon trading up, until and beyond 2050. Carbon markets will not become obsolete any time soon. That is, of course, if there is sufficient political will to utilize them in the first place.

The paper also offered a glance into the crystal ball of how the future of international carbon markets could look like. Admittedly, the gaze is somewhat hazy, but still we were able to identify some rough contours of how and in which sectors international carbon trading may take place. And these contours can guide our attention when designing the governance of international carbon markets today. Particularly, it makes clear that the pre-Paris Agreement legacy experience of the CDM which has focussed strongly on the energy sector may offer relatively limited value for the longer-term future.

Instead, policy makers should pay more attention on regulations related to agriculture and forestry activities as well as potentially negative emission technologies including in the power sector. Overall, international carbon markets will not be gone in 2050, but they will look very different from what we used to know.

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Wuppertal Institute
for Climate, Environment and Energy
P.O. Box 100480
42004 Wuppertal
GERMANY

www.wupperinst.org