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Global and regional abatement costs of Nationally Determined Contributions (NDCs) and of enhanced action to levels well below 2 °C and 1.5 °C

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ABSTRACT

As part of the Paris climate agreement, countries have submitted (Intended) Nationally Determined Contributions (NDCs), which includes greenhouse gas reduction proposals beyond 2020. In this paper, we apply the IMAGE integrated assessment model to estimate the annual abatement costs of achieving the NDC reduction targets, and the additional costs if countries would take targets in line with keeping global warming well below 2 °C and "pursue efforts" towards 1.5 °C. We have found that abatement costs are very sensitive to socio-economic assumptions: under Shared Socioeconomic Pathway 3 (SSP3) assumptions of slow economic growth, rapidly growing population, and high inequality, global abatement costs of achieving the unconditional NDCs are estimated at USD135 billion by 2030, which is more than twice the level as under the more sustainable socio-economic assumptions of SSP1. Furthermore, we project that the additional costs of full implementation of the conditional NDCs are substantial, ranging from 40 to 55 billion USD, depending on socio-economic assumptions. Of the ten major emitting economies, Brazil, Canada and the USA are projected to have the highest cots as share of GDP to implement the conditional NDCs, while the costs for Japan, China, Russia, and India are relatively low. Allowing for emission trading could decrease global costs substantially, by more than half for the unconditional NDCs and almost by half for the conditional NDCs. Finally, the required effort in terms of abatement costs of achieving 2030 emission levels consistent with 2 °C pathways would be at least three times higher than the costs of achieving the conditional NDCs – even though reductions need to be twice as much. For 1.5 °C, the costs would be 5–6 times as high.

1. Introduction

In December 2015, Parties of the United Nations Framework Convention on Climate Change (UNFCCC) adopted the Paris Agreement to address climate change (UNFCCC, 2015a). Parties agreed to keep the increase in global average temperature to well below 2 °C above pre-industrial levels, and to pursue efforts to stay below 1.5 °C. Many Parties also formulated and submitted Intended Nationally Determined Contributions or INDCs (UNFCCC, 2015b) that outline the post-2020 climate action plans they intend to take under the Paris Agreement. After the Agreement entered into force on 4 November 2016, the INDCs for those countries that have ratified the Agreement, turned into Nationally Determined Contributions (NDCs).[1] Although these NDCs together lead to a significant reduction compared to scenarios in the absence of climate policy, assessments have also shown that their impact falls short of the necessary emission reduction to be consistent with the 2 °C and 1.5 °C climate target (Rogelj et al., 2016).

In this paper, we present projections of direct abatement costs resulting from measures implemented to achieve the NDC reduction targets, both for the world as a whole and for major emitting countries or large multiple-country regions. Furthermore, we compare these costs to the costs of implementing measures to

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[1] As of 12 January 2017, 194 Parties signed and 123 Parties ratified the Agreement. For the countries that have not ratified, we use the reduction targets from the INDCs in our analysis, but we use the term NDCs throughout the paper.

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achieve the enhanced reduction targets in line with meeting the below 2 °C and 1.5 °C target, i.e. keeping the global warming to below 2 °C by 2100 with a 66% or higher probability and to below 1.5 °C with a 50% or higher probability. Such projections are highly relevant, as mitigation costs are an indication of the level of ambition in combating climate change, and as such can be used for the global stocktake of the NDCs that is to be held every 5 years as agreed in the Paris Agreement.

Our analysis is based on a country-level assessment of NDCs. Some studies have already estimated costs of implementing the NDCs on a global scale (Iyer et al., 2015; MILES Consortium, 2015; Vandyck et al., 2016). Some estimates have also been made for individual countries (Brazil, China, EU, Japan, USA) based on national models (MILES Consortium, 2015) and global models (Aldy et al., 2016; Rose et al., 2016). Finally, Fujimori et al. (2016) have assessed the benefit of carbon emission trading on achieving the NDCs and a more ambitious reduction scenario consistent with the 2 °C goal using a general equilibrium model. As far as we know, the latter is the only peer-reviewed study with a comprehensive assessment of the abatement costs of NDCs for regions that together cover the whole world. This study differs and goes beyond the Fujimori et al. study in several aspects:

i) we take into account uncertainty in socio-economic developments and corresponding baseline emission projections by using different Shared Socioeconomic Pathways (SSPs);
ii) we assess the abatement costs of both conditional and unconditional NDCs;
iii) we compare the abatement costs of NDCs to both 2 °C and 1.5 °C scenarios (whereas Fujimori et al. (2016) focused only on unconditional INDCs and 2 °C);
iv) Instead of using a general equilibrium model, our analysis is based on the bottom-up integrated assessment model IMAGE (Stehfest et al., 2014) and hence provides different cost metrics (direct abatement costs instead of welfare change).

Our analysis focuses on the following research questions: (i) What would be the abatement costs and financial flows for reaching the 2030 NDC reduction targets? What would be the impact of emissions trading? (Section 3); (ii) What would be the (additional) abatement costs if countries would take enhanced reduction targets in line with meeting the below 2 °C or 1.5 °C target, assuming cost-optimal reductions over regions? (Section 4).

2. Methods

2.1. Harmonized SSP baselines

Our assessment is based on the reference SSP1, SSP2 and SSP3 scenarios as implemented in the IMAGE model (van Vuuren et al., 2017). The IMAGE model (Stehfest et al., 2014) projects both future energy and land use pathways for 26 world regions (Table S1 of Supplementary material). The SSP scenarios are used as baselines in this study and cover a range of different projections for the future: SSP1 is a scenario with relatively low challenges for mitigation, as sustainable development proceeds at a reasonably high pace and inequalities are lessened. SSP3, on the other hand, has high challenges for mitigation, as emissions are high due to a rapidly growing population, high inequality, and slow technological change in the energy sector. SSP2 represents an intermediate scenario. The calculated baseline emission projections resulting from these different socio-economic developments are harmonized with historical 1990–2010 emission data. For this harmonization, we have used historical emissions data on country-level until 2010. From 2011 onwards, we have used the SSP emissions data trend of the IMAGE region to which a country belongs. While this method does not take into account that countries within one IMAGE region may have different GDP growth projections (and therefore different emission trends), the cost calculations are done at the IMAGE region level, and therefore the differences between countries within one region only marginally affect the costs of the whole region. The historical data was taken from the UNFCCC National Inventory Submissions (Common Reporting Format Tables 2012) for those countries for which this information was available; for other countries, data was taken from IEA (2015) for the energy-related CO_2 emissions and from EDGAR (JRC/PBL, 2014) for the non-energy-related emissions.

The total global emissions were calculated as the sum of the regional emissions, global land-use change CO_2 emissions (Havlik et al., 2014), global international aviation emissions (ICAO, 2013), and global international shipping emissions (IMO, 2014) of the business-as-usual scenario.

2.2. NDC mitigation targets

As a starting point of our costs analysis we use the countries' emissions level in 2025 and 2030 resulting from the full implementation of the conditional and unconditional NDCs based on den Elzen et al. (2016a). They have assessed the mitigation components of 79 of the 161 NDCs (note that the EU28 submitted one NDC for the whole region). The countries which submitted these 79 NDCs were together responsible for about 91% of global greenhouse gas (GHG) emissions by 2012. The NDCs from other countries were not included in den Elzen et al. (2016a), because either (i) their 2012 emission share was less than 0.1%, (ii) there was too much uncertainty in the quantification of their NDC as it consisted only of mitigation actions, not targets, or (iii) the country had not submitted an NDC. For many countries, the GHG emission projections of NDCs were calculated straightforward, as many targets were stated relative to a given base year in the past, or relative to a hypothetical 'business-as-usual' or reference scenarios in the absence of climate policy provided in the NDCs (see Supplementary Material, Table S1). The calculations of emission levels resulting from NDCs were less straightforward for countries with targets related to renewable energy or emissions intensity (i.e., improvements of the ratio of emissions to GDP). China and India are the only G20 economies that belong to this latter category. Both have proposed a combination of targets, including non-fossil energy targets, forest targets, and emission intensity targets. Their combined effect was calculated for the three SSP baseline scenarios using the TIMER energy model (van Vuuren et al., 2014) for energy- and industry-related emissions, using the methodology as described in den Elzen et al. (2016a), den Elzen et al. (2016b).

For all mitigation scenarios, it was assumed that countries follow the average of their unconditional and conditional 2020 reduction targets up to 2020 ("Copenhagen pledge"; UNFCCC, 2009). For countries with only an unconditional pledge, the Copenhagen pledge is assumed, and for countries with only a conditional pledge, the average of the conditional target and national BAU trends is assumed. For countries without a Copenhagen pledge, or with pledges which would lead to a higher emission level than the assumed baseline, we assumed baseline emissions until 2020.

Given the large uncertainty in LULUCF CO_2 emissions and the costs to reduce these emissions, we have only assessed the costs of achieving the NDC targets excluding LULUCF $CO_{2.}$ For some countries (such as Canada, Japan, and South Korea), LULUCF CO_2 emissions are not included in the NDCs. For NDCs from countries that explicitly specify targets to include LULUCF CO_2 emissions (e.g. Argentina, Australia, Brazil, Indonesia, Mexico, and the USA), an estimate of LULUCF CO_2 emissions was made, allowing calculating

Table 1
Greenhouse gas emissions of the baseline and NDC scenarios ($GtCO_2eq$).

	2010	2030			2030			2030		
		Baseline			Unconditional NDCs			Conditional NDCs		
		SSP1	SSP2	SSP3	SSP1	SSP2	SSP3	SSP1	SSP2	SSP3
Global emissions excl. LULUCF and international aviation and shipping	42.7	53.2	58.0	60.2	48.1	50.8	51.7	46.5	48.9	49.7
International aviation and shipping emissions	1.1	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
LULUCF emissions	2.9	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Global emissions	46.8	56.1	60.9	63.1	51.0	53.6	54.6	49.4	51.8	52.6

required reductions including and excluding LULUCF CO_2. The estimate of LULUCF CO_2 emissions was based on the following information sources (in order of priority): (i) the NDCs, (ii) national communications, (iii) country reports, or (iv) independent model estimates of current policy projections (see Supplementary material for more detail).

Important assumptions for NDCs in the calculations are:

- The NDC of China only covers CO_2 emissions and the NDC of India excludes agricultural GHG emissions. Therefore, we have assumed no reductions in non-CO_2 emissions for these countries (i.e., their NDCs are achieved by reductions in CO_2 emissions only).
- For countries with projected emission target levels of NDCs above baseline levels, we have assumed baseline emission levels.
- The target of the United States (26%-28% reduction relative to 2005 levels, by 2025) has been extrapolated to a 36%-38% reduction by 2030, assuming a linear pathway towards the country's long-term goal of 83% reduction by 2050.
- We have assumed a linear emission pathway between the assumed 2020 emission level and the 2030 NDC target.
- For those countries for which the NDC emission levels were not assessed by den Elzen et al. (2016a), we assumed baseline emissions.

Several countries have submitted an NDC for which the reduction target is a range. In some cases, the less ambitious end of this range is defined as an unconditional target, while the more ambitious end of the range is contingent on ambitious action from other countries, realization of finance and technical support, or other factors. For this reason, we have defined an unconditional and a conditional NDC scenario. For countries whose NDC included unconditional targets only, we assumed the same emission level in the unconditional and conditional scenarios. For countries whose NDC included only conditional targets, we assumed the SSP baseline emissions for the unconditional NDC scenario. Of the ten highest emitters, the Russian Federation and the United States specified ranges without specific conditions; the ranges are specified separately in Section 3.1 but in subsequent sections the less ambitious end of the range is assumed for the unconditional NDC scenario and the more ambitious end for the conditional NDC scenario.

The estimation of abatement costs was done at the level of the 26 IMAGE world regions. In many cases, IMAGE regions (mostly) consist of only one country (Canada, USA, Mexico, Brazil, Russian Federation, South Africa, Central Asia (Kazakhstan), Turkey, India, China region, Indonesia, and Japan). For the other regions, the countries' NDC emission levels were aggregated to the IMAGE world regions (see Table S1 in Supplementary material). Europe is modelled as one geographical region, including some non-EU28 Member States, such as Norway, Switzerland, Iceland. However, in terms of total GHG emissions the EU28 and the IMAGE Europe region are very close: the difference is about 0.25 $GtCO_2eq$ (about 5% of total EU emissions) in 2012 (JRC/PBL, 2014), and as such this will only have a small effect on the results.

2.3. Abatement costs

We have assumed a cost-optimal achievement of the NDC emission target levels via a regionally differentiated carbon tax, accounting for the fact that some GHGs are not covered by the NDCs (notably non-CO_2 GHG emissions from China and India). The abatement cost analysis was done with the FAIR policy model (den Elzen et al., 2013; den Elzen et al., 2014; Hof et al., 2016) using the information on emissions and costs of the other components of the IMAGE framework (Stehfest et al., 2014). The marginal abatement curves costs curves in FAIR are based on (1) the IMAGE energy model TIMER for energy-related CO_2 emissions (van Vuuren et al., 2014), and (2) MACs for non-CO_2 GHG emissions as described in Lucas et al. (2007). Some recent updates were made based on Schwarz et al. (2011) and EPA (2013), see Hof et al. (2016) for more detail. The non-CO_2 MAC curves were made consistent with the SSP scenarios.

The MAC curves for energy-related CO_2 emissions were constructed to take into account past efforts by defining a wide range of carbon tax pathways as input for the TIMER model, and recording the induced reduction in CO_2 emissions (see van Vuuren et al., 2007). FAIR captures the time- and pathway dependent dynamics of the underlying TIMER model. by scaling the MAC curves based on the reduction effort from the previous years.[2] These dynamics are the result of technology learning and inertia related to capital-turnover rates. The TIMER model dynamics are mainly determined by the substitution processes of various technologies based on long-term prices and fuel preferences. These two factors drive multinomial logit models that describe investments in new energy production and consumption capacity. The demand for new capacity is limited by the assumption that capital goods are replaced not sooner than at the end of their economic lifetime (which is influenced by the carbon tax). The long-term prices that drive the model are determined by resource depletion and technology development. Resource depletion is represented by long-term cost-supply curves and technology development by endogenous learning curves or through exogenous assumptions. Emissions from the energy system are calculated by multiplying energy consumption and production flows by emission factors. A carbon tax can be used to induce a dynamic response, such as the increased use of low- or zero-carbon technologies, energy efficiency improvements, and end-of-pipe emission reduction technologies. As such, the costs capture the direct costs of emission reduction, but not the macroeconomic implications of these costs. As mentioned above, reducing CO_2 emissions from LULUCF were excluded from the cost calculations.

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[2] The model limits the MAC curves to 4000 US$/tCeq (1091 $/tCO2eq), as the underlying TIMER model provides little additional emission reductions above this value.

3. Abatement costs resulting from the implementation of the NDCs

3.1. NDC emission levels

The SSP2 baseline leads to a global emission level of 58.0 $GtCO_2eq$ (after harmonization with historic emissions), excluding emissions from international aviation and shipping and land use, land-use change and forestry (LULUCF; Table 1). This is 36% above the 2010 emission level of 42.7 $GtCO_2eq$. The SSP1 and SSP3 scenario lead to 53.2 and 60.2 $GtCO_2eq$ respectively (25 and 41% above 2010). In the SSP2 scenario, full implementation of the unconditional NDCs leads to a global emission level of 50.8 $GtCO_2eq$, and for the conditional NDCs of 48.9 $GtCO_2eq$, again both excluding emissions from international aviation and shipping and LULUCF (see Table 1 for results under SSP1 and SSP3). Overall, the NDCs are projected to lead to a reduction in emissions by 10% (in the unconditional SSP1 case) to 17% (conditional SSP3 case) below the baseline levels.

NDCs are projected to lead to larger reductions in OECD90 countries as a group (countries which were member of the OECD in 1990 excluding Turkey: USA, Canada, Europe, Japan, Australia and New Zealand). Fig. 1 shows the NDC emission levels relative to the SSP2 baseline for the largest ten emitters in 2010 and for the total of OECD90 and non-OECD90 countries (Tables S2 and S3 in the Supplementary material provide detailed results for all regions and scenarios). The bars indicate the full range of outcomes for the SSP1, SSP2 and SSP3 scenarios. For OECD90 countries as a whole, the reductions of the conditional NDCs are 22%, 27% and 29% relative to baseline under respectively the SSP1, SSP2 and SSP3 scenarios, and 9%, 12% and 14% for non-OECD90 countries as a whole.

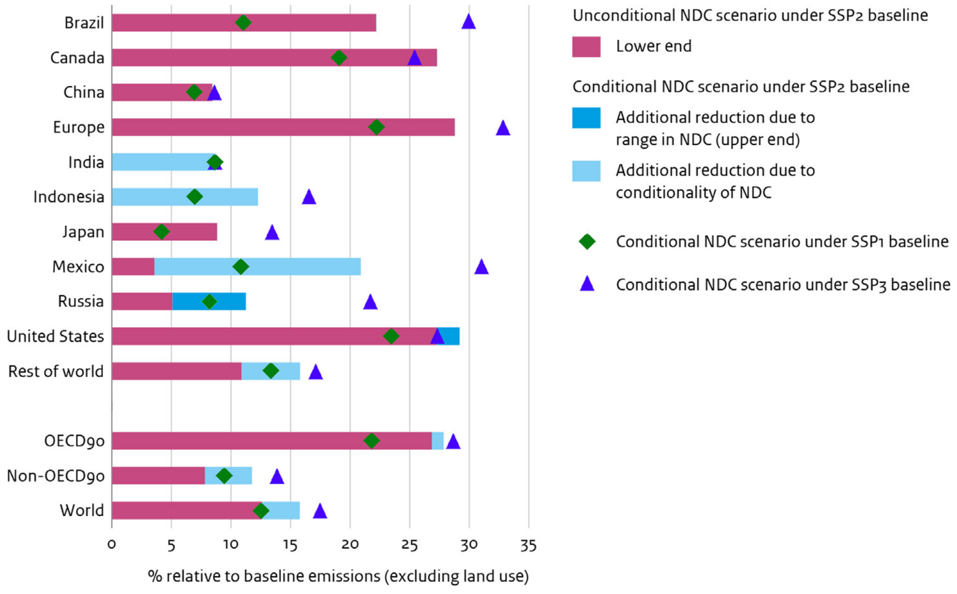
For some non-OECD90 countries, such as Mexico, Indonesia, and India, there are large differences between the unconditional and conditional NDC emission levels. For countries with large differences between SSP1 and SSP3 baseline emissions (such as Brazil, Mexico, Russia and Japan) the reduction targets relative to baseline are very uncertain. Exceptions are China and India, as the absolute emission targets of these countries depend on baseline assumptions (higher baseline emission levels lead to higher absolute emission targets).

3.2. NDC abatement costs

Table 2 (third column) shows the abatement costs of full implementation of the unconditional NDCs for the ten highest emitters in 2010, assuming that all reductions are achieved domestically. As explained in Section 2, the costs of reducing CO_2 emissions from LULUCF are not included here. Globally, abatement costs are projected at 58–135 billion USD in 2030 (undiscounted values, range representing the differences between the three baselines). Under SSP3 assumptions, the costs are the highest, as baseline emissions by 2030–and therefore the required reductions to achieve the NDC targets – are the highest in this scenario. The largest share of these costs (67%-74%) take place in OECD90 countries, largely because of the higher reductions compared to baseline.

The costs of achieving the additional reductions of the conditional NDCs is estimated at about 39–56 billion USD, of which 33–46 billion in non-OECD90 countries (final column of Table 2). The latter range can be regarded as the part of the NDC which is subject to international financing. About one-third of the difference in non-OECD90 abatement costs between the conditional and unconditional NDCs is due to the difference in costs in South Africa, which has a very large range in their NDC reduction target.

Global abatement costs as share of GDP are projected at 0.09% under SSP1 to 0.20% under SSP3 for the conditional NDCs (Fig. 2 and detailed results in Table S3 of the Supplementary material). The differences in costs between the three baselines are larger than the differences in emission reductions, as the shape of the marginal abatement cost curves is convex. For almost all regions, the abatement costs as share of GDP are very sensitive to baseline assumptions. For instance, in Brazil the costs range from 0.06% under the SSP1 baseline to 0.77% under the SSP3 baseline and in Mexico the costs range from 0.02% to 0.43%. The higher costs as share of GDP under the SSP3 baseline for almost all regions can be explained by the combination of relatively low GDP and high



Source: PBL FAIR/TIMER model

Fig. 1. Greenhouse gas emission reduction targets (excluding LULUCF emissions) for NDCs by 2030, relative to baseline levels.

Table 2
Regional and global abatement costs (excluding costs of reducing CO_2 emissions from LULUCF) for the conditional and unconditional NDCs scenarios.

	Unconditional NDCs, domestic only		Conditional NDCs, domestic only (additional to unconditional)	
	Reduction relative to harmonized SSPs ($MtCO_2eq$)	*Costs (billion USD)*	*Additional reduction relative to unconditional NDCs ($MtCO_2eq$)*	*Additional costs (billion USD)*
Brazil	153–522	1–15	0	0
Canada	123–197	2–6	0	0
China	985–1374	6–10	0	0
Europe	1010–1725	14–45	0	0
India	0	0	0	0
Indonesia	0	0	98–261	1–2
Japan	46–162	0–1	0	0
Mexico	0–144	0–1	75–136	2–6
Russian Federation[1]	48–507	0–3	168	1–4
USA	1367–1880	20–37	129	5–7
Rest of World	1330–2168	14–25	557–652	21–25
OECD90	**2770–4064**	**42–90**	**140**	**6–9**
non-OECD90	**2292–4436**	**15–45**	**1468–1882**	**33–46**
World	**5062–8500**	**58–135**	**1609–2023**	**39–56**

The bold values are aggregate regions (they are the sum of (some of) the above-mentioned regions).

[1] INDC, as Russia has not ratified by January 2017.

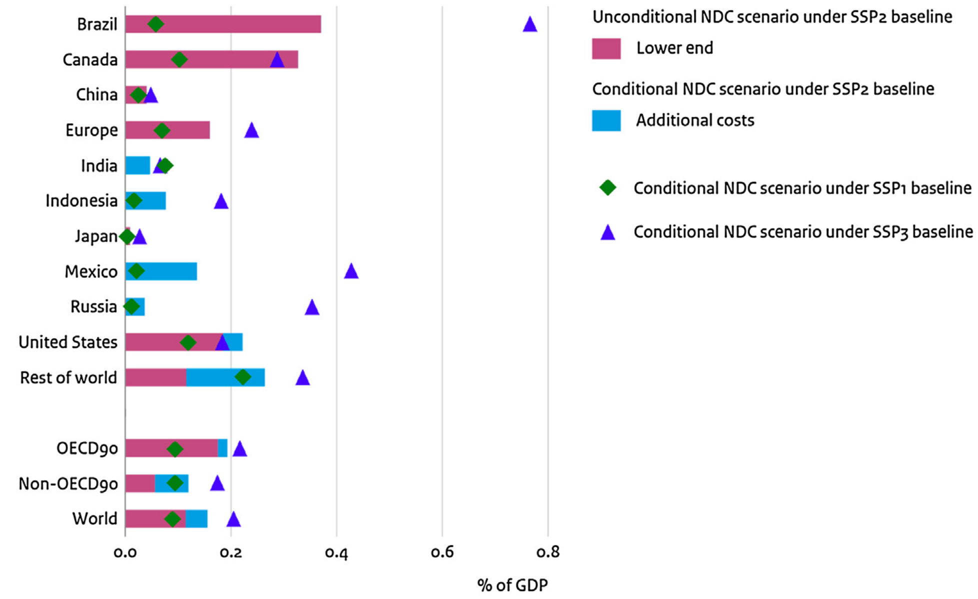


Fig. 2. Regional and global abatement costs for NDCs, excluding costs of reducing CO_2 emissions from LULUCF, 2030.

emissions in SSP3. As an indication: compared to SSP2, global GDP is 8% lower under SSP3 and 8% higher under SSP1 by 2030, while global GHG emissions are 4% higher under SSP3 and 8% lower under SSP1. It should be noted that some of the socio-economic assumptions of the SSP1 baseline will not emerge free of costs – but these costs do not appear as abatement costs as they already occur in the baseline.

Abatement costs of India and China are less sensitive to baseline assumptions, as their NDC emission target level depend on baseline developments, i.e. under higher economic growth assumptions, India and China have higher NDC emission target levels.

3.3. Effect of emissions trading

In the calculations above, we have assumed that all reduction targets for the NDCs are achieved domestically, as the mitigation actions submitted by most Parties relate to domestic reductions only.[3] Allowing for flexible mechanisms between regions could reduce global costs substantially, as countries with relatively high marginal abatement costs can partially achieve their target by paying for emission reductions in regions with relative low costs. Global costs can be reduced by almost 56% in the unconditional NDC scenario and by 44% in the conditional NDC scenario by reducing emissions wherever it is cheapest to do so (Fig. 3). This is in line with Fujimori et al. (2016), who found that emissions trading in the implementation of emission reductions consistent with the NDCs could reduce welfare losses by 75%. The reduction in costs is larger in the unconditional NDC scenario, as in this scenario the regional emission reduction targets are less evenly distributed

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[3] However, within IMAGE regions, we had to assume full flexibility in emission reductions (i.e., we have assumed cost-optimal mitigation across sectors and between countries within an IMAGE region).

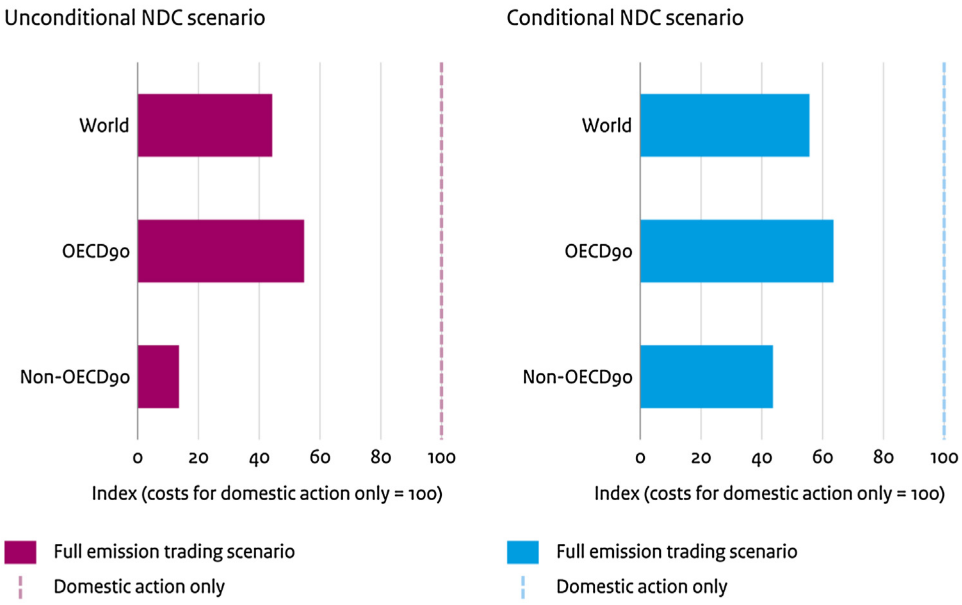

Fig. 3. Impact of full emissions trading on abatement costs for NDCs under the SSP2 baseline.

(see Fig. 1). Countries without a substantial reduction target relative to baseline (India, Indonesia, Japan, Mexico, Russian Federation) or with large low-cost mitigation potential could profit by reducing emissions domestically and selling emission credits. But in general, both OECD and non-OECD countries could benefit strongly by allowing flexibility mechanisms in their NDC.

4. Abatement costs resulting from staying below 2 °C and 1.5 °C temperature increase

The global 2030 emission levels that correspond to emission pathways that limit temperature increase to 2 °C with a likely chance (probability of 66% or higher) are in the order of 42 GtCO$_2$eq (median level), with a range of 31–44 Gt CO$_2$eq (UNEP, 2015). A 2030 emission level of about 39 Gt CO$_2$eq would correspond to a 1.5 °C scenario, according to the same UNEP study. For the 1.5 °C target, there are no published scenarios that meet the target with a likely chance, only with a 50% or higher probability.

The 2030 emission level of the SSP2 baseline is 60.9 GtCO$_2$eq, including 1.1 GtCO$_2$eq LULUCF emissions and 1.8 GtCO$_2$eq emissions from international bunkers (the numbers for SSP1 and SSP3 are 56.1 and 63.1 GtCO$_2$eq). In the conditional NDC scenario, global emissions are projected to reach a level of about 51.8 GtCO$_2$eq (49.4 and 52.6 for SSP1 and SSP3). Although the NDCs lead to a reduction of 9.2 (6.7–11.5) GtCO$_2$eq, there remains an emission reduction gap by 2030 of about 10 (7.4–10.6) GtCO$_2$eq to stay on track to meet 2 °C and about 13 (10.4–13.6) GtCO$_2$eq for 1.5 °C (Table 3). To close this gap, it is assumed that international shipping and aviation could reduce emissions from 1.8 to 1.3 GtCO$_2$eq by 2030, based on Cames et al. (2015) and own model calculations. LULUCF emissions are assumed to be reduced to net zero by 2030, from baseline levels of 1.1 GtCO$_2$eq. Under SSP2, this leaves a remaining gap by 2030 of 8.5 GtCO$_2$eq for 2 °C and 11.5 GtCO$_2$eq for 1.5 °C. The numbers for SSP1 and SSP3 are respectively 6.1 and 9.3 GtCO$_2$eq for 2 °C and 9.3 and 12.3 GtCO$_2$eq for 1.5 °C.

The abatement costs of our *2 °C scenario* (in which full emission trading is allowed and a global emission level of 42 GtCO$_2$eq is achieved in 2030) amounts to 0.31% of global GDP in SSP1 and to 0.64% of global GDP in SSP3 in 2030. These numbers are comparable with the IPCC AR5 WGIII report, which includes a median level of about 0.6% and a 25th–75th percentile range of 0.25% −1.17% (Clarke et al., 2014).

This implies that the global cost level is 3–3.5 times the costs of the conditional NDC scenario without emissions trading, even though the additional emission reductions are less than twice as much. This is due to the steep increase in marginal abatement costs in the 2 °C scenario. For the 1.5 °C scenario, costs are even 5–6 times as high. In absolute terms, the additional global abatement costs for 2 °C (relative to the Conditional NDCs scenario) range from 234 billion USD under SSP1 to 400 billion USD under SSP3 (Fig. 4). For 1.5 °C, the additional costs are about twice as high. Not all countries, notably Europe and Brazil, have higher costs under SSP3 assumptions. This can be explained by (i) lower cost-optimal 2 °C emission levels under SSP1 than under SSP3 assumptions (see Table B1), and (ii) steeper marginal abatement cost curves under SSP1 assumptions, as some low-carbon measures are already taken in the baseline.

Under SSP2, the global GHG emission level of the conditional NDC scenario is 20% (14% under SSP1 and 22% under SSP3) above the "2 °C level" of 42 GtCO2eq – assuming mitigation efforts in

Table 3
Emissions of the NDC, 2 °C and 1.5 °C scenarios (in GtCO$_2$eq).

	2030			2030	2030
	Conditional NDCs				
	SSP1	SSP2	SSP3	2 °C	1.5 °C
Global emissions excl. LULUCF and international aviation and shipping	46.5	48.9	49.7	40.7	37.7
International aviation and shipping emissions	1.8	1.8	1.8	1.3	1.3
LULUCF emissions	1.1	1.1	1.1	0.0	0.0
Global emissions	49.4	51.8	52.6	42.0	39.0

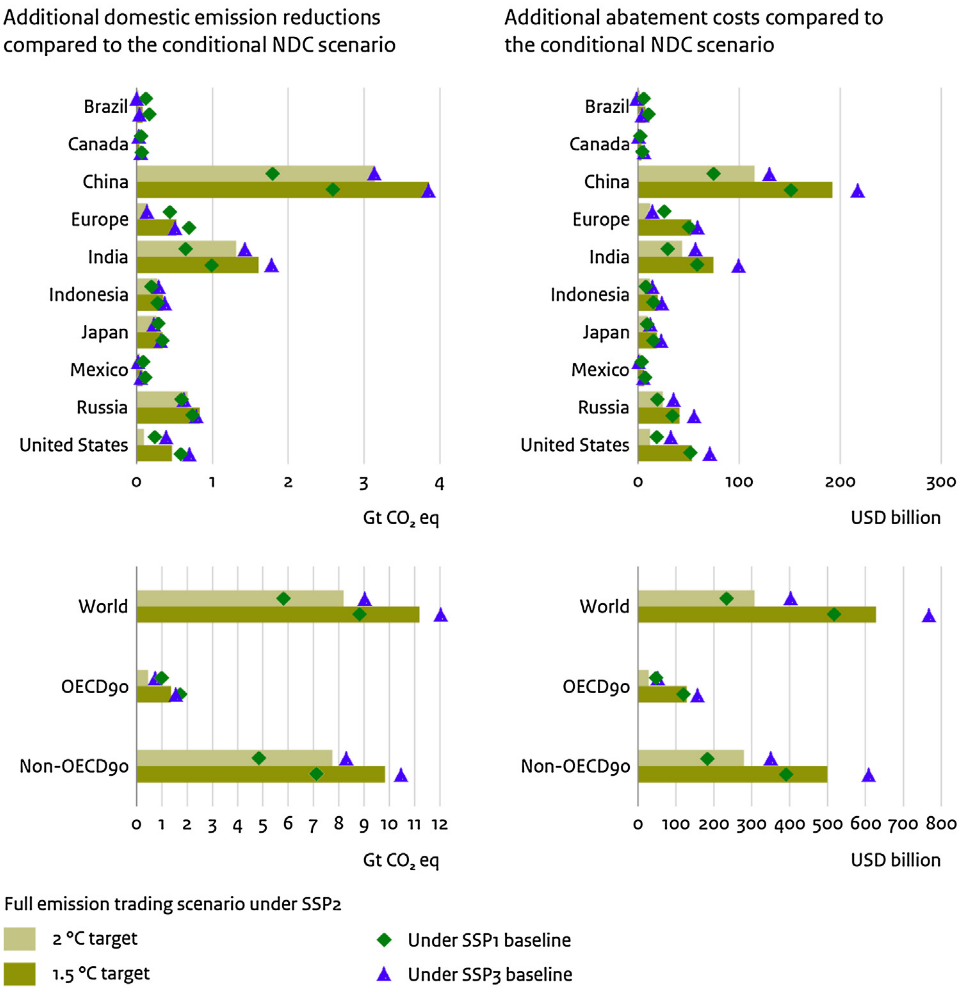

Fig. 4. Impact of meeting the 2 °C and 1.5 °C target on emissions and abatement costs.

LULUCF and international aviation and shipping. If emission reductions are distributed cost-optimally among regions (least-cost pathways), cost-optimal emission levels per country can be calculated. Under SSP2, the conditional NDCs of Brazil, Canada, the EU, and the USA lead to emission levels which are very close to their cost-optimal 2 °C level (4% or less difference). Under SSP1, this is also the case for Mexico.

Overall, the potential for additional emission reduction is larger in non-OECD 90 countries, and therefore the group of non-OECD90 countries has the largest increase in domestic abatement costs in the 2 °C and 1.5 °C scenarios (Fig. 4). This is again under the assumption of cost-optimal emission reductions, and without financial transfers or effort-sharing combined with trading of emission credits, both of which would help to alleviate the burden on non-OECD countries. Compared to the conditional NDCs scenario, domestic emissions are especially lower – and abatement costs higher – in China, India, and Russia. Of the 5.8–9.0 $GtCO_2eq$ difference in global emissions (excluding emissions from international aviation and shipping and LULUCF) between the conditional NDCs scenario and the 2 °C scenario, 1.8–3.1 $GtCO_2eq$ is from China, 0.6–1.4 $GtCO_2eq$ from India and 0.6–0.7 $GtCO_2eq$ from Russia. These countries have a relatively large potential to reduce emissions relative to their conditional NDCs. For China and India in particular by reducing non-CO_2 emissions which are excluded in their NDC (Yao et al., 2016). Naturally, this will lead to large increases in abatement cost as well (75–130 billion USD in China and 29–57 billion USD in India).

Fig. 5 provides a more detailed comparison of relevant indicators (GDP per capita, GHG emissions per capita, and abatement costs as share of GDP) by 2030 under the conditional NDC, 2 °C and 1.5 °C scenarios. The graph illustrates the variation in these indicators between countries. In the conditional NDC scenario, broadly four groups of countries can be distinguished: those with

i) high (>10tCO_2eq) per capita emissions and high (>30,000 USD) GDP per capita: USA and Canada);
ii) high per capita emissions and low (<20,000 USD) GDP per capita: China and Russia;
iii) low (<10tCO_2eq) emissions per capita and high GDP per capita (Europe, Japan);
iv) low (<10tCO_2eq) emissions per capita and low GDP per capita (India, Mexico, Indonesia, Brazil).

Both the global and non-OECD90 average are in group iv. Somewhat surprisingly, no clear relation is visible between abatement costs as share of GDP and the above grouping.

In the 2 °C scenario, countries with relatively low GDP per capita have in general much higher abatement costs than in the Conditional NDC scenario, indicating the importance of

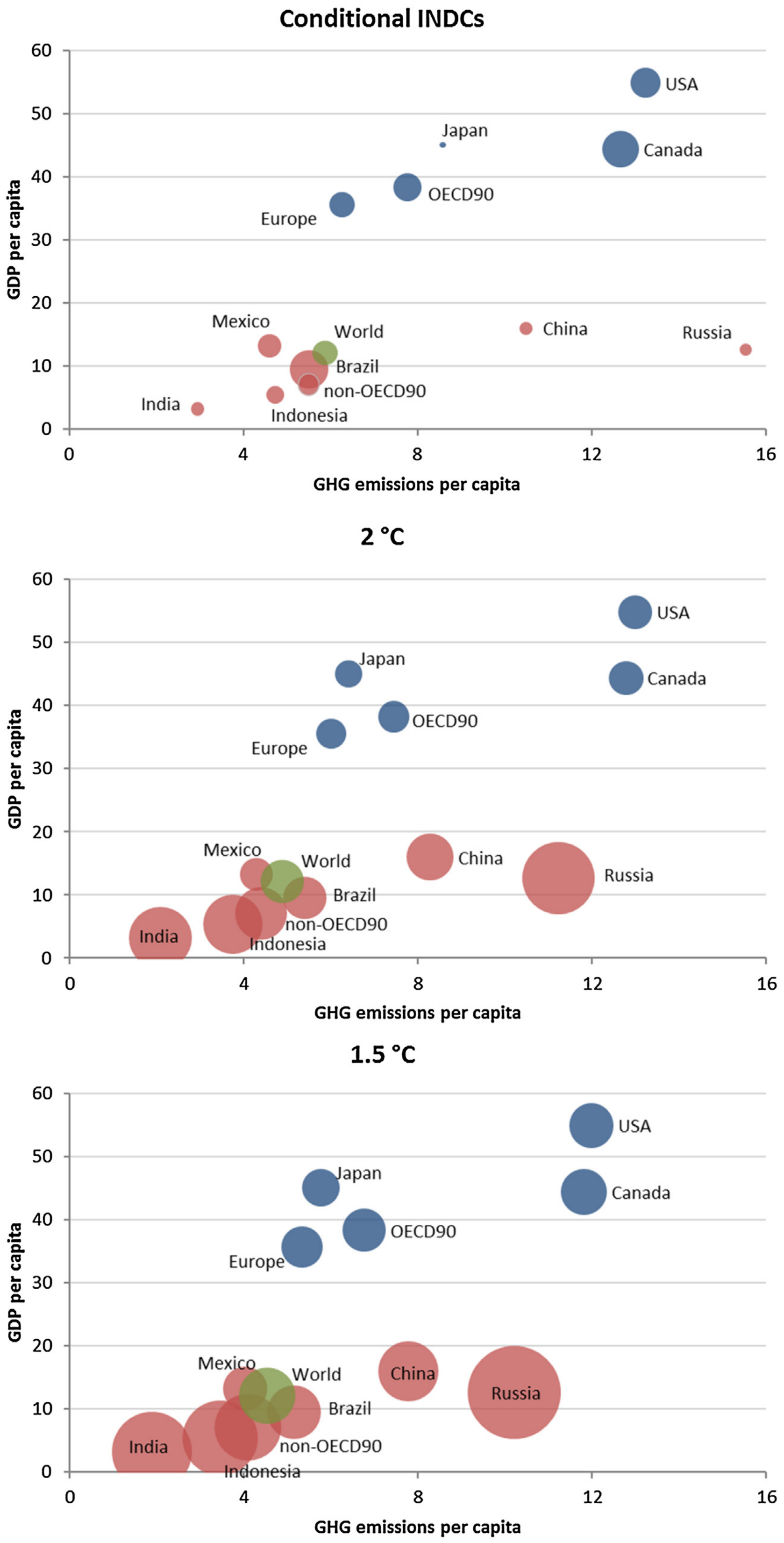

Fig. 5. Greenhouse gas emissions per capita plotted against GDP per capita, 2030. The size of the bubbles indicates abatement costs as share of GDP. All the bubbles are scaled to the region with the highest costs in the 1.5 °C scenario.

international finance. Especially Russia and China, countries with high emissions and low GDP per capita, show large differences with the conditional NDC scenario. Countries with high GDP show relatively small differences between the Conditional NDC scenario and the 2 °C scenario, except for Japan. The increase in the size of the bubbles in the 1.5 °C scenario shows the substantial additional effort that is needed in all countries to go from 2 °C to 1.5 °C.

5. Discussion and conclusions

In this study, we estimated the abatement costs of achieving the GHG emissions levels of the NDCs and more ambitious scenarios in 2030. These more ambitious scenarios aim at meeting the Paris climate targets (to keep global warming well below 2 °C and "pursue efforts" towards 1.5 °C), and distribute emissions reductions cost-optimally among regions (least-cost pathways). The annual abatement costs are calculated relative to different SSP baselines, all harmonized to historical greenhouse gas emissions data.

There are several uncertainties in our cost calculations. Key uncertainties covered explicitly in our calculations include the role of emissions trading, the conditionality of NDC targets and baseline assumptions. Another major uncertainty relates to the model used (and especially to its assumptions regarding marginal abatement costs). As shown by Clarke et al. (2014, abatement cost estimates strongly differ between models: the full range of global abatement costs of 2 °C scenarios ranges between less than 0.3% and more than 1.5% of GDP in 2030, depending on the model and scenario.

A multi-model exercise, such as provided by Aldy et al. (2016), provides some insight in the level of uncertainty related to model differences. In Table 4, we have compared relative abatement costs among the regions provided by Aldy et al. with our study. As reference, the USA was chosen, as Aldy did not provide global cost estimates. For instance, Table 4 shows that according to our study, the costs of achieving the NDC is 28% lower for Europe than for the USA, with a total uncertainty range from the studies included by Aldy and our own of −33% to +40%. The results show that for all the regions reported by Aldy et al., our study would be either the median estimate or is very close to the median estimate of the in total five model estimates (including our own). However, it also shows that the uncertainty in costs is very large. Of the five model studies, our study projects the lowest costs for most regions. In other words, while the relative costs levels across regions in our study is close to the median of a range of other studies, our absolute cost projections are relatively low. This is in line with Kriegler et al. (2014, who showed that of the four partial equilibrium models participating in the AMPERE multi-model study, IMAGE projected the lowest costs.

Apart from the finding that the IMAGE model projects relatively low costs compared to other IAMs, there are several other reasons why our projections may underestimate abatement costs:

- We have not considered the costs of reducing CO_2 emissions from LULUCF. A previous study has estimated that the costs for reducing deforestation emissions in Brazil are about 1.5 billion USD by 2020 (den Elzen et al., 2011), which means that including these costs could significantly increase the costs for Brazil. For Indonesia, estimates of the costs of REDD were in the same order of magnitude.
- We have assumed that emissions in sectors that are not explicitly covered in the NDCs follow the harmonized SSP baseline trend. This may lead to an overestimation of the projected emission levels, and likewise to an underestimation of costs for NDCs.
- We have assumed a cost-optimal implementation of emission reductions, whereas in reality some of the implemented measures will not be cost-optimal, as other considerations such as political and societal acceptance play a role. For instance, some countries may exclude the option to reduce greenhouse gas emissions by increasing their nuclear capacity.
- For our 1.5 °C and 2 °C scenarios, full emissions trading is assumed, and countries and regions are collaborating from 2020 onwards. Delay in participation of regions and sectors would increase costs.

Keeping in mind the above uncertainties, caveats, and assumptions, we come to the following main conclusions.

Allowing for emission trading could decrease global costs substantially, by more than half for the unconditional NDCs and almost by half for the conditional NDCs. Finally, the required effort in terms of abatement costs of achieving NDC2030 emission levels consistent with 2 °C pathways would be at least three times higher than the costs of achieving the conditional NDCs – even though reductions need to be twice as much. For 1.5 °C, the costs would be 5–6 times as high.

Abatement costs of achieving the NDC targets are very sensitive to the assumed socio-economic assumptions

Under SSP1 socioeconomic developments, annual global abatement costs to achieve the unconditional NDC targets are projected at 58 billion USD by 2030, compared to135 billion USD under SSP3 socioeconomic developments. Global abatement costs under SSP2 are projected at 114 billion USD by 2030.

The additional abatement costs of achieving the conditional NDC targets range from 40 to 55 billion USD

Several non-OECD90 countries have provided a conditional and unconditional target, the conditions being often related to international finance. The difference in abatement costs between achieving the unconditional and conditional NDCs of all non-OECD90 countries together is estimated at 33–46 billion USD by 2030 (of which 11–14 billion USD in the Republic of South Africa), which can be regarded as the part of the NDCs which is subject to international financing. For OECD90 countries the additional costs mainly come from the implementation of the more ambitious end of their NDCs.

Table 4
Abatement costs as share of GDP relative to the USA for this study and for four integrated assessment model studies (DNE21C, GCAM, MERGE and WITCH), as reported by Aldy et al. (2016).

Abatement costs relative to the costs of the USA	*This study*	*Median estimate of five studies*	*Average estimate of five studies*	*Minimum estimate of five studies*	*Maximum estimate of five studies*
EU	−28%	−28%	−8%	−33%	40%
China	−82%	−82%	−11%	−148%	157%
India	−79%	−79%	−69%	−100%	−22%
Japan	−96%	−53%	−47%	−96%	12%
Africa	143%	136%	144%	−99%	402%
Russia	−83%	−91%	−124%	−268%	−45%

On average, the costs of achieving the conditional NDCs are higher as share of GDP for OECD90 countries, but there are large differences between countries

For the unconditional NDCs, about 70% of global abatement costs take place in OECD90 countries and for the conditional NDCs this is between 50% and 60%. Of the ten major emitting economies, Brazil, Canada and the USA are projected to have the highest cots as share of GDP to achieve the conditional NDC target, while the costs for Japan, China, Russia, and India are relatively low.

Abatement cost could be reduced substantially by allowing for global flexible mechanisms in achieving the NDCs

As illustration: full emissions trading could reduce global abatement costs of achieving the unconditional NDCs by about 55%, while for non-OECD90 countries the decrease could even be as high as 85%. This finding is in line with Fujimori et al. (2016), who concluded that welfare losses could be reduced by 75% when emissions trading were allowed.

Globally, the costs of achieving 2030 emission levels consistent with least cost-pathways to 2 °C are 3–3.5 times higher in 2030 than the costs of achieving the conditional NDCs

Although the conditional NDCs already halve the gap the difference in the global emission level in the baseline and least cost-pathways to 2 °C (with a more than 66% probability) by 2030, in terms of abatement costs there remains still a large difference. For least cost-pathways to 1.5 °C (with a more than 50% probability), the costs are even 5–6 times as high. This implies that a substantial increase in effort is needed to keep the 2 °C target within reach. In a cost-effective 2 °C scenario, large additional reductions and therefore abatement costs are projected in China, Russia, and India – which indicates the importance of international finance.

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Appendix A. Supplementary data

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