From NDC to national long-term low greenhouse gas emission development strategies compatible with a 2 °C target

Sandrine Mathy

Abstract

Given the lack of collective ambition resulting from the Nationally Determined Contributions (NDCs) to the objective of the Paris Agreement, countries must submit revised and more ambitious NDCs. Countries are invited to formulate long-term low greenhouse gas emission development strategies that should be designed within the context of other development goals and co-benefits. This article addresses the issues related to the evaluation of national trajectories developed in a cooperative framework aiming at collectively reaching 2°C and based on the integration of development priorities and co-benefits into national trajectories. The national decarbonization trajectories discussed in this article were developed as part of the Deep Decarbonization Pathway Project (DDPP) by the 16 major GHG emitting countries. These 16 bottom-up decarbonization strategies are implemented in the POLES model, a partial equilibrium model of the global energy sector, which is an appropriate tool to provide a harmonized contextual framework for assessing these trajectories. The results make it possible to evaluate the gap between, on the one hand, national DDPP trajectories and NDCs and, on the other hand, national DDPP trajectories and a scenario resulting from a minimization of abatement costs. They allow to feed a discussion on the development of NDCs and the move away from national trajectories of trajectories minimizing the overall reduction cost and produced with IAMs.

Keywords: Climate change; Paris Agreement; National Determined Contributions; co-benefits; Integrated assessment models; bottom-up models

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1. Introduction

The climate objective of the Paris Agreement is holding the increase in the global average temperature well below 2 °C above preindustrial levels and to pursue effort to limit the temperature increase to 1.5 °C (UNFCCC, 2015a - Article 2.1). It relies on Nationally Determined Contributions (NDCs), submitted by Parties and representing voluntary commitments formulated by each country with a 10-15 year horizon (Article 3 and 4.2). These NDCs are to be designed within the context of other development goals defined by national circumstances and developmental priorities such as energy access and security, air quality, poverty alleviation and employment creation (Winkler et al., 2015).

Given the lack of collective ambition resulting from the aggregation of the NDCs to the objective of the Paris Agreement (UNFCCC, 2015b; Rogelj et al., 2016), the co-benefits of climate policies can be a considerable lever to increase the ambition of national policies to reduce GHG emissions (Zenghelis, 2017). *The New Climate Economy Report* in 2014 showed that more than half of emissions reductions required to meet an ambitious target generate co-benefits, such as reducing the costs of air pollution, improving energy efficiency, and creating new export markets in fabricating energy efficient kit and renewables. Air quality co-benefits on morbidity, mortality, and agriculture could globally offset the costs of climate policy (Vandyck et al., 2018).

A number of studies assess at the national level the lack of ambition of NDCs in relation to the long-term objective of limiting global warming to below 2°C. However, these assessments are most often based either on burden-sharing rules to allocate the budget consistent with a 2°C target among countries or on national emission trajectories resulting from a cost-minimisation approach using integrated assessment models (IAMs). But this global IAM approach has limitations that need to be addressed to support the national policy processes envisaged in the Paris Agreement (Stern, 2016). In particular, IAMs rely on aggregate sectoral and regional representations and simplified economic and behavioural assumptions and face structural challenges to represent climate co-benefits or other non-climate objectives (Weyant, 2017). Integrating in IAMs climate co-benefits would lead to different and most ambitious cost-optimal mitigation scenarios, but there are too many of them to be taken into account in IAMs and the co-benefits prioritized in each country are country-specific.

This article thus addresses the issues related to the evaluation of national trajectories developed in a cooperative framework aiming at collectively reaching 2°C and based on the integration of development priorities and co-benefits into national trajectories. The national decarbonization trajectories discussed in this article were developed as part of the Deep Decarbonization Pathway Project (DDPP) by the 16 major GHG emitting countries (Bataille et al., 2016; Waisman et al., 2019). These 16 bottom-up decarbonization strategies are implemented in the POLES model, a partial equilibrium model of the global energy sector, which is an appropriate tool to provide a harmonized contextual framework for assessing these trajectories. The results make it possible to evaluate the gap between, on the one hand, national DDPP trajectories and NDCs and, on the other hand, national DDPP trajectories and a scenario resulting from a minimization of abatement costs. They allow to feed a discussion on the development of NDCs and the move away from national trajectories of trajectories minimizing the overall reduction cost and produced with IAMs.

The first section explores the existing literature on the assessment of NDCs at national level and justifies the integration in the analysisof scenarios from the DDPP study as a robust benchmark for assessing the 2°C compatibility of NDCs. Section 2 describes the modelling methodology and the global scenarios. Section 3 presents the results and section 4 discusses them.

2. Literature review on NDCassessment and description of the Deep Decarbonization Pathway Project

2.1. Literature review on the NDC assessment

The Paris Agreement has given rise to an extensive literature that explores NDCs and their adequacy with the 2°C objective (Benveniste et al., 2015; Boyd et al., 2015; CAT, 2016 ; Climate Interactive, 2015; DEA, 2015; Enerdata, 2016; Fawcett et al., 2015; Fujimori et al., 2016 ; Hof et al., 2015; IEA, 2015; IEA, 2016; Iyer et al., 2015; Kitous et al., 2015; Kitous et al., 2016; PBL, 2015; Robiou du Pont et al., 2017; Rogelj et al., 2016; Spencer et al., 2015; UNEP, 2016; UNFCCC, 2015; Vandyck et al., 2016). All these studies lead to the same general conclusion regarding the global "emissions gap" between NDCs and 2°C trajectories: more efforts are needed to limit global warming below 2°C throughout the century.

Beyond these global level analyses, the evaluation of NDCs at national level requires a conversion of the 2°C global objective into national long-term emissions. To do so, many analyses rely on a "burden sharing" approach that allocates the global budget or emission trajectories from NDCs into 2°C pathways for each country. The CAT (2016) evaluates whether the emission reductions in the NDCs represent a "fair share" of the global effort to limit warming below 2°C, relying on a Fair Share range for each country from the range of fairness criteria from the literature (including considerations of equity such as historical responsibility, capability and equality). It then proposes a "fair NDCs" objective. Robiou du Pont *et al.* (2017) modelfive international equity approaches[1] available in the literature and in the IPCC AR5 that are applied to assess the costs of optimal mitigation scenarios consistent with the Paris Agreement objectives. Then they allocate the emissions dynamically using selected 2°C scenarios from the IPCC-AR5 (2014). Only the GDR approach (Baer et al., 2009) allocates the emission gap between global budget from NDCs into 1.5°C or 2°C pathways to each country (Holz et al., 2018).

Other assessments are based on IAMs that compare implicit carbon values, national costs or welfare losses at the national level for NDCs and for the national declination of 2°C trajectories resulting from a cost-minimisation approach. Aldy et al. (2016) use four IAMs to produce

[1] The five allocation criteria are capability, equality, responsibility-capability-need, equal cumulative per capita and staged approaches according to the IPCC category.

metrics of Paris Agreement pledges, and show differentiated effort across countries. Fujimori S. et al. (2016) evaluate with the AIM/CGE model the benefit of emissions trading under both NDCs and a more ambitious reduction scenario consistent with the 2°C goal. Van Soest et al. (2017) assess emission trajectories and the energy system transition of 11 major economies projected by IAMs for baseline and cost-optimal 450 ppm CO2eq mitigation scenarios and compare the results with the NDCs. Hof et al. (2017) apply the IMAGE integrated assessment model to estimate the sensitivity to socio-economic assumptions of the annual abatement costs of achieving the NDC reduction targets, and of 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.

To deviate from the cost-minimization approach and the resulting global carbon price, which is not *de facto* considered in the Paris Agreement, exogenous assumptions to these global models are necessary to decline national trajectories compatible with a target of 2°C or below 2°C. Vandyck et al.(2016) define a 2°C scenario, relying on the combination of a bottom-up, detailed energy system model (POLES) and a top-down global economic model (GEM-E3) with three corresponding groups of countries for which carbon prices are assumed to converge to high, intermediate or low levels of 53, 45 and 26 US $ (2015) in 2030 in function of their per capita GDP.

At last, some estimates have also been made for individual countries (Brazil, China, EU, Japan, USA) based on national models (Spencer et al., 2015) but these approaches are not able to reconstruct at the global level a set of national scenarios compatible with a 2°C or below 2°C target.

All the approaches mentioned above are not aligned with the bottom-up NDC process that emerged in the negotiations after the failure of the Copenhagen Conference. For this reason, we focus in the following on the national scenarios developed as part of the Deep Decarbonization Pathways Project as better representing the bottom-up approach subsequently adopted.

2.2. Deep Decarbonization Pathways to 2050

With the Paris Agreement, the emphasis of climate change policies has shifted from the top-down "global cap + burden sharing + emission trading" triptych for the design and implementation of national decarbonization plans and policies to voluntary commitments, with national determined contributions. Responding to the new negotiation process, new research methodologies are therefore needed.

In the Kyoto and the Copenhagen negotiation paradigms, IAMswere the preferred tools for assessing the Kyoto Triptych (Criqui and Mathy, 2017). They made it possible to study optimal or cost-effective solutions by introducing unified or harmonized carbon prices and emissions trading systems (Barker *et al*., 2007). In a very different way, the logic of NDCsis based on national constraints and priorities and therefore mobilize other resources for the design of climate policies.

A number of studies document national energy and long-term emissions strategies. In addition, some international studies combine common reporting schemes and the use ofnationally differentiated methods or models. Among them, the Deep Decarbonization Pathways Project[2],launched in 2013 and coordinated by IDDRI and SDSN (Bataille *et al.*, 2016),aimed at providing a vision of what may be a liveable decarbonized future for the 16 largest CO2emitting countries[3](energy and industrial process emissions), including for those that are most dependent on fossil fuels. The 16 countries currently represent 75% of global CO2 emissions.

The project aimed at defining how countries may individually engage in a low carbon transition consistent with a global target of limiting global warming to 2°C. For that purpose, experienced country teams from these 16 countries composed of national research centres and experts, familiar with the specific national circumstances, including social acceptance issues or, in general, the social, technical and economic preferences of the respective societies, have developed their own national low carbon transition scenariosthrough country-specific methodologies.

The starting point of the project was the recognition that national long-term low-carbon strategies must bridge the gap between long-term issues of the Paris Agreement and existing national development priorities and constraints to be useful in informing NDCs. Therefore, each national research institution developed national, sectorally detailed mitigation scenarios consistent with national circumstances and domestic priorities, e.g.: reduction of air pollution in China (Teng et al., 2015); energy access and poverty alleviation in India (Shukla et al., 2015); energy security in Japan (Kainuma et al., 2015); reduction of energy poverty in the UK (Pye et al. 2015); employment and poverty alleviation in South Africa (Altieri et al., 2015).

While country teams shared common assumptions about the global availability and cost of key technologies that require global learning[4], the national DDPP studies were supported by a variety of modelling tools, chosen by the research teams in each context, with varying areas of focus and level of detail. For South Africa, the focus was on poverty alleviation and unemployment reduction, combining an energy system model with a computable general equilibrium model that portrayed disaggregated labour skill classes and their sector employment (Altieri et al., 2015). The DDPP study of Japan analysis focussed on energy security concerns, requiring a detailed energy supply and demand bottom-up model (Kainuma et al., 2015). The DDPP study of China highlighted the air quality co-benefits of mitigation by coupling energy system and air pollution models (Teng et al., 2015). In India the scenario combined analysis of air quality and energy security benefits (Shukla et al., 2015). These examples illustrate how distinct modelling structures can inform key national mitigation and development priorities.

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[2] See the DDPP website and countries publications: http://deepdecarbonization.org/.
[3]Australia, Brazil, Canada, China, Germany, France, United Kingdom, India, Indonesia, Italy, Japan, South Korea, Mexico, USA and South Africa.
[4]e.g. carbon capture and storage (CCS), net-zero homes, non-foodstuff biofuels, vehicle and grid battery storage

The 16 deep decarbonization scenarios produced follow different types of emissions profiles but aggregate energy-related CO2 emissions (excluding LULUCF emissions) in the 16 countries are reduced to 9.9 GtCO2 in 2050, i.e. 56% below 2010 levels[5]. The scenarios take into account country-specific forecasts of future population, which lead to an expected growth of 17% from 2010 to 2050, consistent with the UN medium fertility scenario (2015).

Based on the IEA 2°C scenario (2015), the global emissions (energy sector and process emissions) benchmark is consistent with a 50% likelihood of staying below 2°C,over the 21st centuryand translates into total emissions of 15 GtCO2 in 2050[6].

We consider in the following the 2050 CO2 emission levels in DDPP national scenarios as reflecting nationalconditions and ambitions and, as such, being a good proxy for national CO2 emissions consistent with a 2°C global target (table 1). For the European Union, as there is no EU DDPP scenario, a -80% mitigation target in 2050 (compared to 1990) was considered, in accordancewith IPCC AR5 (2014) for industrialized countries.

3. Methodology

3.1. The POLES model and its reference scenario

The Prospective Outlook on Long-term Energy Systems (POLES[7]) is a long-term recursive simulation model (up to 2100) for energy supply, demand and prices. It is a partial equilibrium bottom-up world model, based on 57 national sub-models, which allows the balance of energy supply and demand with endogenous energy prices. The model allows projections of energy demand and supply in each country or region, as well as the induced CO2 emissions. Economic assumptions are exogenous to the model, while the set of variables that structure the energy demand, supply and prices are endogenously estimated for each country or region and market.

The POLES model produces detailed world energy scenarios and has been used in several European projects, including ADVANCE related to model development and validation for the improved analysis of costs and impacts of mitigation policies (Luderer et al., 2017; Desprès et al., 2015) and AMPERE on the assessment of climate change mitigation pathways and evaluation of the robustness of mitigation cost estimates (Riahi et al., 2015; Criqui et al., 2015).

[5] Several variants have been developed by each team in each country.Across all scenarios, by the year 2050, energy-related CO2 emissions for the 16 DDPP countries were reduced to 9.9-12.1 Gt CO2, or 46-56% below 2010 levels.In the modelling exercise, we consider only those variants that lead to the lowest emission level in 2050.

[6] Cumulative GHG emissions over 2010-50 fell in the range of 1185-1555 GtCO2. This is consistent with the 1166-1566 Gt CO2 range for 50% chance of 2°C (Table SPM.1 WGIII AR5 in IPCC, 2014).

[7] It has been developed at CNRS, the French National Scientific ResearchCenter (currently in the GAEL lab) in collaboration with the European Commission's JRC-IPTS and ENERDATA, a consulting firm specialized in the energy sector.

The POLES model is also used for the economic analysis of CO2 mitigation policies for different energy administrations or companies in Europe, and for the Global Energy and Climate Outlook of the JRC-IPTS.

GDP are considered in purchasing power parity (US$2005) and GDP assumptions are taken from Fouré et al. (2012) for the historic data until 2015 and on forecasts by the OECD Economic Outlook (2013a) and the World Bank (2014). Appendix A provides more details for the description of the model and on these socio-economic assumptions common to all scenarios.

The reference scenario serves as a benchmark for comparison with mitigation scenarios described in the following subsection. The reference scenario does not consider any additional climate policy after 2015 and carbon prices observed in 2015 remain constant until 2030, i.e. only European countries have a non-zero price.

3.2. Mitigation scenarios

We build four global CO2 energy-related emission reduction scenarios:

- The DD2C scenario is a 2 °C scenario integrating the national scenarios of the DDPP project that focus only on CO2 energy-related emissions,

- The 2C scenario is a 2 °C scenario with the same CO2 energy-related emission budget over the period 2010-2050 as the DD2C scenario, but built with a universal global carbon price,

- NDC LOW and NDC HIGH are two scenarios integrating the high (higher ambition and conditional objectives) and low (lower ambition and unconditional objectives) ranges of the NDCs for the countries or regions considered in the DDPP scenario.

3.2.1. The DD2C scenario, a "Deep Decarbonization 2 °C" compatible scenario

The DD2C scenario is a global deep decarbonization scenario based on the national DDPP scenarios and more specifically on national long-term 2050 DDPP emissions levels (table 1).

In the DD2C scenario, we consider the EU28 as a whole, as NDC for European countries is defined at the EU level, while in the DDPP, only four European national teams from Germany, France, Italy and United-Kingdom have developed scenarios. The reduction level considered in DD2C for EU28 is computed from the CO2 energy-related emission reduction levels in these four DDPP national scenarios: France (-74% in 2050 compared to 2010), Italy (-80%), Germany (-88%) and UK (-81%). This corresponds, with the economic growth assumptions considered (Appendix A), to a 50% reduction in CO2 intensity of GDP for these four countries in 2050 compared to 2010. Although the socio-economic characteristics and energy and industrial structures of the other 24 EU countries are far from identical to these four countries, we apply this rate of decrease in CO2 intensity of GDP to EU28 to determine the level of emissions in 2050 in the DD2C scenario. This leads to a decrease in emissions in 2050 equal to 84% compared to 2010 or 86% compared to 1990. Such a level of emission reduction can be considered consistent with figures in Box 13.7 of the IPCC AR4 (2007) that indicates GHG reductions between -95% and -80% in 2050 compared to 1990 required for Annex 1 countries for a concentration stabilisation level equal to 450 ppm CO2 eq. Although non-CO2 energy emission reductions are more costly than CO2 energy reductions and consequently more weight should be given to CO2 energy emission reductions than to other gases, it can be considered that emission reductions for the EU28 of the DD2C scenario are consistent with the range given in box 13.7 of the IPCC AR4.

Table 1: National energy-related CO2 emissions targets for the NDC in 2030 and DD2C scenarios in 2030 and 2050 (MtCO2 excluding LULUCF)

<table>
<tr><th></th><th>NDC HIGH in 2030</th><th>NDC LOW in 2030</th><th>DD2C in 2030 (source: scenario modelling result)</th><th>DD2C in 2050 (source: Deep Decarbonization Pathways Project, 2015 except for EU – see section II.2.1.)</th></tr>
<tr><td>Australia</td><td>356</td><td>366</td><td>254</td><td>106</td></tr>
<tr><td>Canada</td><td colspan="2">491</td><td>207</td><td>53</td></tr>
<tr><td>EU 28</td><td colspan="2">2,777</td><td>1,670</td><td>664</td></tr>
<tr><td>Japan</td><td>891</td><td>905</td><td>447</td><td>179</td></tr>
<tr><td>Russia</td><td>1,911</td><td>2,034</td><td>601</td><td>200</td></tr>
<tr><td>South Korea</td><td colspan="2">510</td><td>228</td><td>76</td></tr>
<tr><td>USA</td><td>4,351</td><td>4,448</td><td>2,212</td><td>785</td></tr>
<tr><td>Brazil</td><td colspan="2">557</td><td>416</td><td>262</td></tr>
<tr><td>China</td><td>12,351</td><td>14,115</td><td>8,413</td><td>5,109</td></tr>
<tr><td>India</td><td>5,030</td><td>5,183</td><td>2,308</td><td>1,871</td></tr>
<tr><td>Indonesia</td><td>726*</td><td>961</td><td>489</td><td>402</td></tr>
<tr><td>Mexico</td><td>432*</td><td>530</td><td>431</td><td>239</td></tr>
<tr><td>South Africa</td><td>344</td><td>526</td><td>423</td><td>241</td></tr>
</table>

At the global level, we consider a global CO2 emission budget between 2011 and 2050 equal to 950 GtCO2. This CO2 budget is within the range of the CO2 emission budget for emission paths with a probability of less than 12-22% of exceeding a 2 °C temperature increase (table 6.3, IPCC AR5, 2014).

3.2.2. The 2C mitigation scenario

The 2C scenario is constructed according to two assumptions. First, the budget for energy CO2 emissions is the same as in the DD2C scenario, i.e. 950 GtCO2 between 2011 and 2050. Second, scenario 2C is built with a universal global CO2 price reflecting equal marginal abatement costs across all the countries.

3.2.3. NDC scenarios

National DDPP scenarios focus on CO2 energy-related emissions, while most NDCs cover all GHG, without explicit distinction between CO2 and non-CO2 gases and between LULUCF and other sectors (see appendix B). The comparison of NDCs to DDPP long-term national objectives thus requires translating 2030 NDCs into CO2 energy-related emissions only. The methodology for the conversion of NDC into CO2 energy related emissions is described in the appendix C.
For most DDPP countries, the NDC does not provide details on sector or technologies that should be prioritized, except for Japan, whose INDC provides a very detailed roadmap for each sector, China and Brazil. We thus develop NDC scenarios relying on each NDC emission reduction target only and thus refer to the CO2 emissions excluding LULUCF:

- The NDC HIGH scenario considers the 16 DDPP countries achieve their higher ambition emission target (including conditional targets).

- The NDC LOW scenario considers that only the lower range of the NDC objective and unconditional objectives are achieved.

Table 1 details CO2 emission targets for each country in these two NDC scenarios. The uncertainties on the evolution of CO2 emissions from LULUCF are considered in four alternative scenarios developed in the Appendix D.

3.3. Modeling protocol: the carbon value as a proxy of CO2 emission mitigation policies

Carbon pricing can have different meanings. While explicit carbon pricing puts a price directly on carbon emissions, like carbon tax and cap and trade, implicit carbon pricing includes policies or instruments that effectively price carbon, such as gasoline taxes (OECD, 2013b). Taxes and other instruments have the effect of putting a price on carbon, some in an obvious way, and others not so obvious: for example, implicit pricing on transportation include tax exemptions on biofuels or other renewables, fuel mandates, and support for electric vehicles. This implicit carbon value is not necessarily a pure price instrument, but should be considered as a proxy of the different instruments and constraints that will impact the energy system.

In the POLES model, an implicit carbon value can be associated to each mitigation objective. This value corresponds to a shadow cost imposed to all CO2 emitting activity. Carbon prices affect the average energy prices, inducing energy efficiency responses on the demand side, and the relative prices of different fuels and technologies, leading to adjustments on both the demand side (e.g. fuel switch) and the supply side (e.g. investments in renewables).

In the model, the carbon value defined at regional or national scales is set according to the carbon constraints in the four scenarios (NDC LOW, NDC HIGH, 2C and DD2C scenarios). We use the assumption of a linearly increasing carbon value (starting from zero in 2015) and identify the national (or regional for EU28) carbon value that is required:

- in the D2C scenario, for each DDPP country, to reach its 2050 emission reduction level while in other countries, a uniform linearly increasing carbon value is adjusted to reach the global CO2 budget over the period 2011-50.

- in the NDC scenarios, for each DDPP country, to reach the NDC emission levels in 2030 while in other countries, we set a carbon value equal to zero[8].

In the 2C scenario, a global linearly increasing carbon value is adjusted to comply with the CO2 budget over the period 2011-50.

This assumption of linearity is of course restrictive as the profile of the optimal carbon value depends upon assumptions related to technological change, anticipation of consumers and productive sectors (Ha-Duong et al., 1997; Goulder and Mathai, 2000). The hypothesis chosen aims at avoiding a delayed action bias that would be introduced by a geometrically increasing carbon value.

We compute total mitigation costs for each country and for each mitigation scenario. To do this, we build marginal abatement cost curves by simulating the impact on each country's emissions of a set of implicit carbon prices. In general, four different types of mitigation costs can be distinguished: direct engineering costs, economic costs for a specific sector (abatement cost; Edenhofer 2010), macroeconomic costs and welfare costs. In the case of the POLES model, as GDP is prescribed exogenously the mitigation costs for the transition of the energy system are provided as the sum of the implied costs of demand reduction through price-effects and of the costs of changing the technology mix according to a merit order that reflects direct engineering costs. These costs will be referred as “mitigation costs” in the following and are reported as a proportion of GDP values.

4. Results

In the following, we analyse results of the scenarios in 2030.

[8] As the focus of the analysis in the article is on the 16 DDPP countries, we consider this assumption for non DDPP countries.

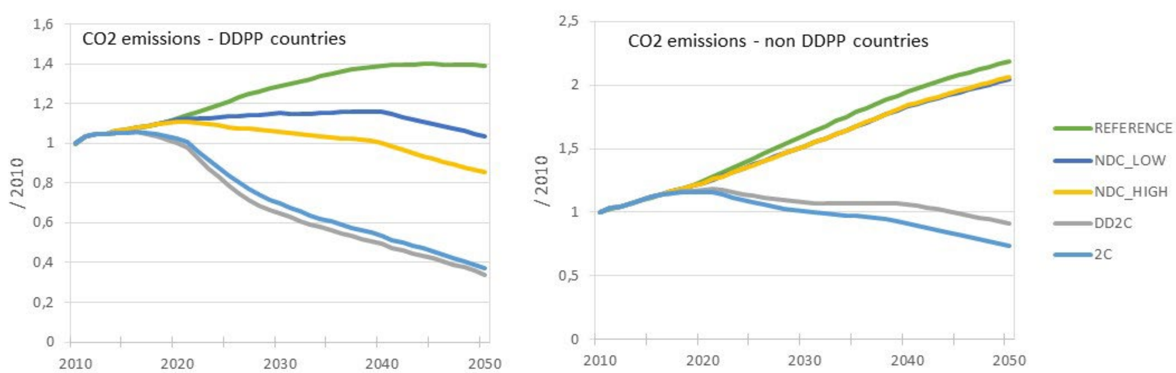
4.1. Global and national energy-related CO2 emissions

In DDPP countries in 2030, energy-related CO2 emissions are 36% lower than in 2010 in the DD2C scenario compared to 30% lower in the 2C scenario (Figure 1). Conversely, at this horizon, in other countries, emissions are higher in the DD2C than in the 2C scenario (+8% vs +1% compared to 2010). Figure 1 also shows the significant bifurcation in emission pathways in DDPP countries of NDCs emissions compared to the reference scenario in 2030[9]. It is nevertheless largely insufficient compared to both DD2C and 2C scenarios to be consistent with a 2 °C objective.

Figure 2 allows a description of the emission reductions in each scenario and in each country with respect to 2010. The NDC HIGH scenario leads to emission levels for Canada, Russia, India and Indonesia very close to those of the reference scenario. The long-term objectives (2050) of the national strategies described in the DDPP lead to very high levels of emission reductions in 2030 compared to 2010 for developed economies. They exceed 60% for Canada, Japan, Russia, South Korea and the USA. In developed economies, these reductions are systematically higher than the emission reductions in scenario 2C. The emission gap is particularly high for South Korea.

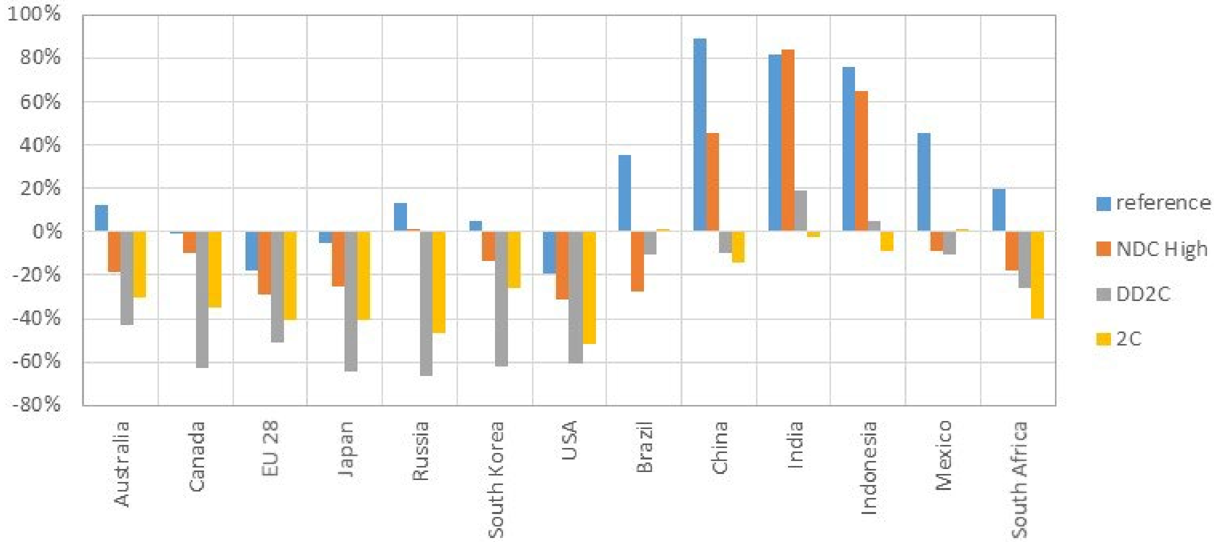
In emerging countries, the opposite is true, except for Mexico, whose NDC HIGH emissions are very close to those of the DD2C scenario and which leads to emission reductions higher than those of the 2C scenario.

Figure 1: Global energy-related CO2 emissions in DDPP and non-DDPP countries



[9] Emission profile in non DDPP countries for NDC scenarios are close to the reference scenario because of both NDC scenario design and modelling assumptions.

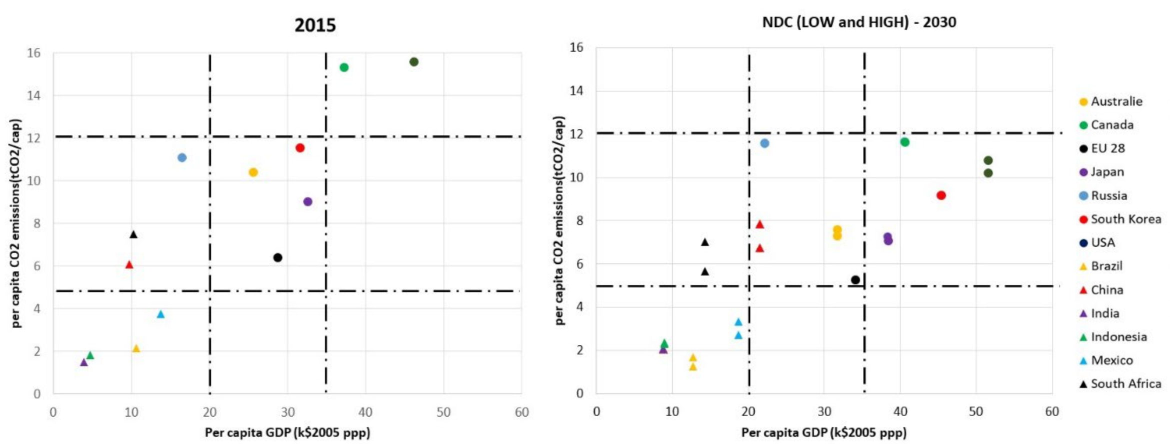
Figure 2: CO2 energy-related emissions in 2030 with respect to 2010 in the reference scenario and in mitigation scenarios for the DDPP countries

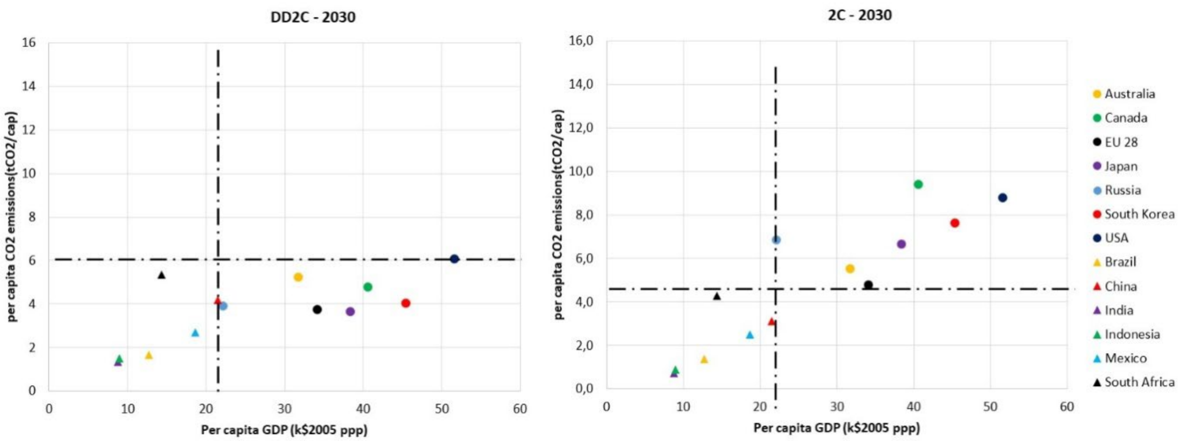


4.2. Per capita emissions in 2030

Figure 3 provides a comparison of GDP per capita and GHG emissions per capita in 2015 and the evolution by 2030 under the NDC (LOW and HIGH) for DDPP countries.

Figure 3: CO2 energy-related emissions per capita (for DDPP countries) plotted against per capita GDP in 2015 and in 2030 for NDC LOW NDC HIGH, DD2C and 2C scenarios





In 2015, broadly four groups of countries can be distinguished with:

i) high (>12tCO2) per capita emissions and high (>35,000 USD) GDP per capita: USA and Canada;

ii) median (<12tCO2 and >5tCO2) per capita emissions and median (<35,000 USD and >20,000 USD) GDP per capita: Australia, South Korea, Europe, Japan;

iii) median per capita emissions (>5tCO2 and <12tCO2) and low (<20,000 USD) GDP per capita: China, Russia and South Africa;

iv) low (<5tCO2) emissions per capita and low GDP per capita: India, Mexico, Indonesia, Brazil.

In 2030, economic growth pulls countries to the right of the graph compared to 2015. Nevertheless, countries from group *iv* and South Africa remain in the group of countries with per capita GDP lower than 20,000 USD while South Korea, Japan, China and Russia jump into the highest GDP per capita category.

NDCs lead to a significant decrease of per capita emissions only for countries that were in group *i* and *ii* in 2015. No countries have per capita CO2 emissions higher than 13tCO2 in 2030. At this date, countries that were in group *iv* (India, Indonesia, Brazil and Mexico) in 2015 remain the only ones with per capita emission below 5tCO2.

The impact on per capita emissions is much more significant in DD2C and 2C scenarios, but very contrasted between the two scenarios (Figure 3). In the 2C scenario, per capita emissions in 2030 appear linearly correlated with per capita GDP; they vary between 0.9 tCO2 in Indonesia and India, the two countries with the lowest GDP per capita at this date among DDPP countries, to 9.4 tCO2 in Canada. Conversely, in the DD2C scenario, in all the DDPP countries per capita emissions are lower than 6 tCO2. In comparison, in the 2C scenario, Australia and

EU28 are the only ones with per capita emission lower than 6 tCO2 and in all developed economies (per capita GDP higher than 22 k$2005 in 2030), per capita emissions are higher than 4.5 tCO2.

In all emerging countries per capita emissions are lower than 4.5 tCO2 in the DD2C scenario and in the 2C scenario. Mexico is the only country among emerging countries with higher emission reduction in DD2C compared to the 2C scenario. Brazil and China emission reductions are very close in both scenarios. India, Indonesia and South Africa have lower emission reduction in the DD2C than in the 2C scenario.

Per capita emissions in EU28, in Japan, Russia and South Korea in the DD2C scenario are close to 4 tCO2, the level that would be reached in China, and lower than the level in South Africa. In this scenario, the ratio between the highest emitting country, and the lowest emitting country would be equal to 4 compared to 13 in the 2C scenario, to 10 in 2015, and to between 7 and 9 in NDC scenarios. The DD2C scenario leads in 2030 to a significant convergence of per capita emission compared to other mitigation scenarios.

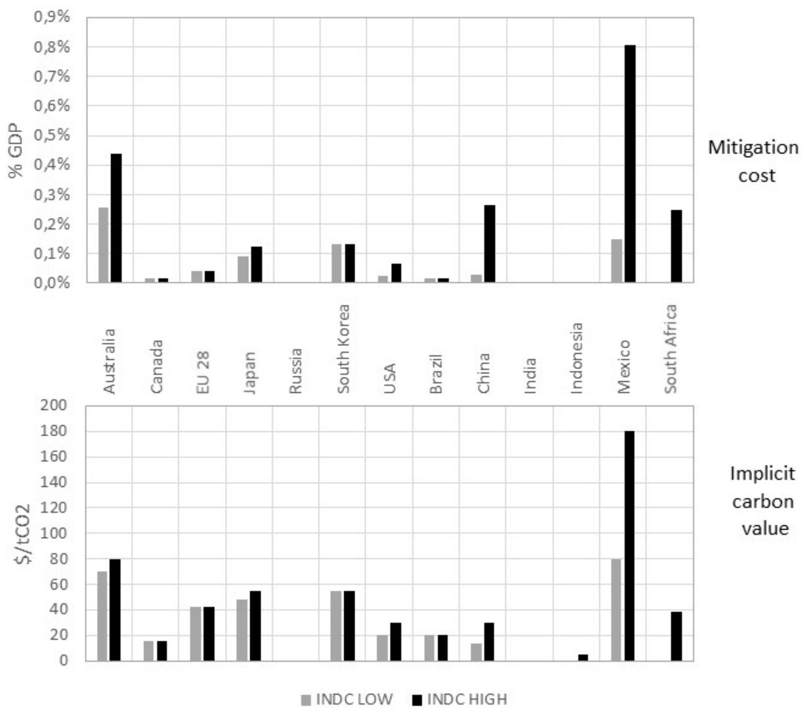
4.3. Implicit carbon values and mitigation costs in 2030

4.3.1. NDC LOW and NDC HIGH

Achieving NDC LOW targets does not require any mitigation efforts for India, Indonesia, Russia and South Africa (Figure 4). This statement is also true for the high ambition targets of India and Russia. Consequently, the corresponding mitigation cost is null. The conditional target of Indonesia is not far from its unconditional target and would be consistent with a low 5 $/tCO_2$ carbon value in 2030.

For industrialized countries (except Russia), all implicit carbon values are at least 15 $/tCO2 in 2030 for the two NDC scenarios. With a carbon value equal to 15 $/tCO2 in 2030, the Canadian NDC comes out as the lowest of industrialized countries considered in the analysis, followed by the USA (20 and 30 $/tCO_2$ respectively for the low and high ambition targets) and the EU28 (42 $/tCO2 in 2030). The Japanese and South Korean carbon values are comparable, with a range of 48-55 $/tCO_2$for Japan and 55 $/tCO2 for South Korea. Finally, the Australian NDC represents the highest carbon value for the industrialized countries considered (70 and 80 $/tCO2 respectively for the low and high NDC targets) and the highest mitigation cost (0.4% of GDP), followed by South Korea (0.2% of GDP) and Japan (0.1% of GDP). NDC mitigation costs compared to GDP for Canada, EU and USA are comparable and low compared to other industrialized countries.

Figure 4: Implicit carbon values and mitigation cost (/GDP) for DDPP countries in NDC scenarios in 2030



Results show a significant range of implicit carbon values across developing countries. While some of them present very low or even null carbon values as mentioned previously, Mexico displays the highest carbon values of all the countries considered. This is true for the unconditional objective (80 \$/tCO2) and still more true for the conditional objective (180 \$/tCO2) which leads to the highest mitigation cost among all the DDPP countries (0.8% GDP). Mexico unconditional objective leads as well to the highest mitigation cost among emerging countries. Notably, the implicit carbon values are quite low in China (13 and 30 \$/tCO2) and Brazil (20 \$/tCO2), but these values are comparable to values computed for USA and Canada. They are the only two other emerging countries with a strictly positive cost for unconditional objectives: between 0.1 % and 0.3 % of GDP for China and <0.1 % of GDP for Brazil. When considering conditional objectives, mitigation cost for South Africa becomes strictly positive (0.2% of GDP).

These results are generally consistent with other modelling exercises (see Appendix E). The results are mainly different for Mexico and South Korea, two countries for which we have found only one value in the literature (from Vandyck et al., 2016). More generally, the differences in results stem from the different models used to carry out these assessments and their own internal dynamics, economic growth assumptions, the inclusion of sectoral climate policies in some modelling exercises that reduce the implicit carbon value necessary to achieve the NDC objectives, the scope of emissions limited to CO2 emissions in this modelling exercise, and uncertainties related to the conversion of GHG emissions including LULUCF to non-LULUCF CO2 emissions only.

4.3.2. Comparison of the DD2C scenario and of the 2C scenario

The universal global carbon value in 2030 corresponding to scenario 2C is equal to 107 $/tCO2 (Figure 5). This value is in the range of the marginal abatement costs in 2030 for scenarios from the IPCC AR5 (2014) database (https://secure.iiasa.ac.at/web-apps/ene/AR5DB) that would limit warming to no more than 2 °C with at least a 50% probability (Aldy et al., 2016).

Results for national carbon values in the DD2C scenario in 2030 are of course more diversified as it does not consider international CO2 emission trading. Two groups emerge among DDPP countries. In the first group composed of seven developed economies - Australia, Canada, EU28, Japan, Russia, South Korea, USA - and an emerging country, Mexico, carbon values are significantly higher than the implicit carbon value of the 2C scenario. The values for Canada, Japan and South Korea are particularly high, above 450 $/tCO2 in 2030. As implicit carbon values in the POLES model are proxies for explicit carbon taxes and other taxes and instruments, complementary policies would lead to a lower and more acceptable explicit carbon price than the implicit value computed by the model (OECD, 2013b; Bataille et al., 2018).

According to the High-Level Commission on Carbon Prices (Stern and Stiglitz, 2017), the explicit carbon-price level that is consistent with achieving the climate objective of the Paris Agreement, assuming a supportive policy environment, is at least US$40–80 tCO_2eq by 2020 and US$50–100 tCO_2eq by 2030, which is lower than the current value of the carbon tax in Sweden. On the other hand, Rockström et al. (2017) have set a roadmap for rapid decarbonisation which calls for “Herculean Efforts” as soon as 2020 on the basis of “carbon pricing across the world starting at $50 per metric ton at least in 2020 and exceeding $400 per ton by mid-century”. Implicit carbon values of the DD2C scenario in this group of developed countries are thus more aligned with these values.

Mexico, the only emerging country in this group, is a special case, since it is the only country among the DDPP countries for which the implicit carbon value of the conditional NDC target is higher than the implicit carbon value of scenario 2C. However, the implicit carbon value of the DD2C scenario for Mexico is relatively close to that of its conditional NDC.

In the other group of countries, composed solely of emerging countries, on the contrary, the carbon value is lower than that of scenario 2C. For China and Brazil, it is just slightly lower, and for the other countries almost twice lower (India, Indonesia, South Africa). Nevertheless, in all emerging countries, the implicit carbon value is at least equal to 50 $/tCO2.

The implicit carbon value in the rest of the world in 2030 for the DD2C scenario is also significantly lower than that of the 2C scenario ($65/tCO2 versus $107/tCO2), thanks to the higher mitigation in 2030 among DDPP countries in the DD2C scenario compared to the 2C scenario.

This same typology of country groupings is also found in the mitigation cost gaps between the DD2C scenario and the 2C scenario. The mitigation cost of the DD2C scenario is more than 5 times higher than that of the 2C scenario for Japan, Canada and South Korea. It is between 1 and 5 times higher for the USA, the EU, Russia, Australia and Mexico. For 6 other DDPP countries, the mitigation cost is lower in the DD2C scenario than the mitigation cost in the 2C scenario (from 0.3 times for South Africa to 0.8 times for China and Brazil). In non DDPP-countries, the mitigation cost is also lower in the DD2C scenario than in the 2C scenario with marginal cost equalization (0.3% of GDP against 0.2%). At the global level, however, the aggregate mitigation cost at the global level is significantly higher in the DD2C scenario than in the 2C scenario with international trading (0.7 % of GDP compared to 0.5 % of GDP in scenario 2C). The cost differences between scenarios 2C and DD2C are related to the higher reduction levels in developed economies and Mexico in the DD2C scenario (Figure 7). This is particularly true for Canada, Russia, Japan and South Korea. Nevertheless, mitigation costs computed with the POLES model do not integrate economy-wide feedback mechanisms including international trade, intermediate input links between industries, and recycling of taxation revenue that would be modelled in a CGE model, nor climate benefits and co-benefits induced by deep decarbonisation pathways in each country.

Figure 5: Implicit carbon values in mitigation scenarios in 2030

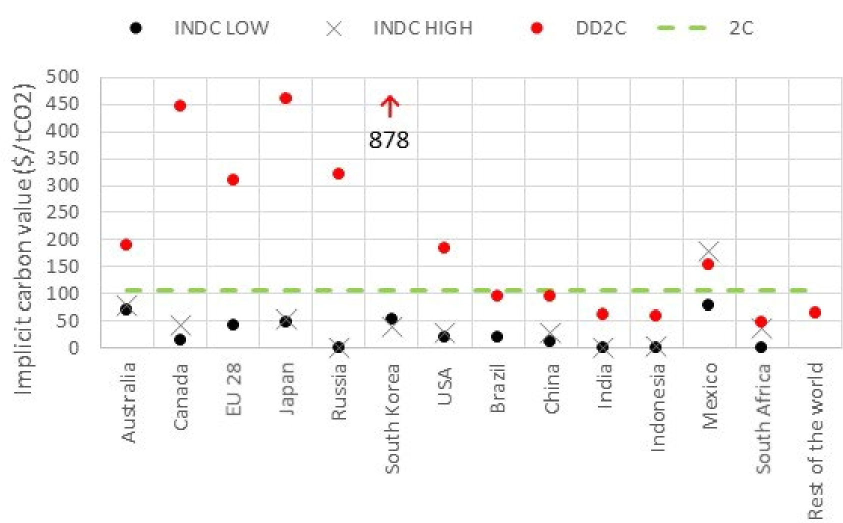


Figure 6: National mitigation cost (/GDP) in mitigation scenarios

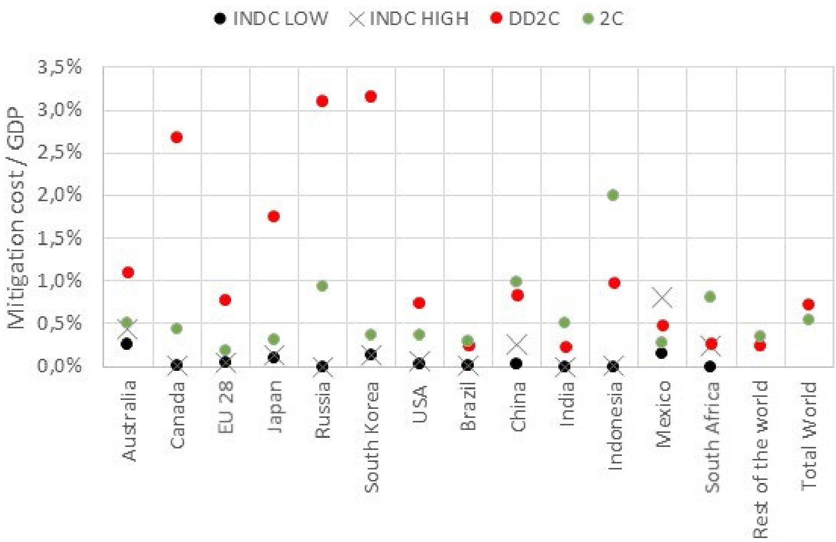
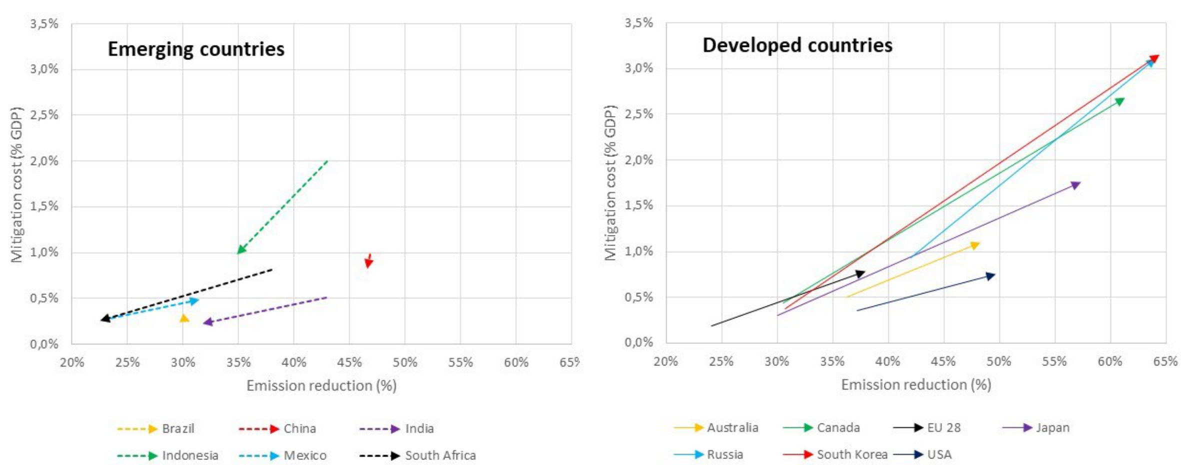


Figure 7: Gap between 2C scenario and DD2C scenario for national mitigation cost (/GDP) and CO2 emissions reduction compared to the reference scenario in 2030



NB: an upward arrow means that the cost is higher in the DD2C scenario than in the 2C scenario. A right arrow means that emission reductions relative to the reference scenario are greater in the DD2C scenario than in the 2C scenario.

4.4. Alignment of NDC with DD2C national long-term emissions

Lastly, we measure the gap in 2030 between NDC LOW and the DD2C objectives, considering the differences in national mitigation cost relative to GDP that are required to reach both objectives.

The three smallest gaps refer to three developing countries: South Africa, Mexico, and Brazil. The gap for India is also small, but this case is particular, as the cost required to reach the DD2C objective is low compared to other countries and consequently, the gap appears small in spite of considering India's NDC with low ambition.

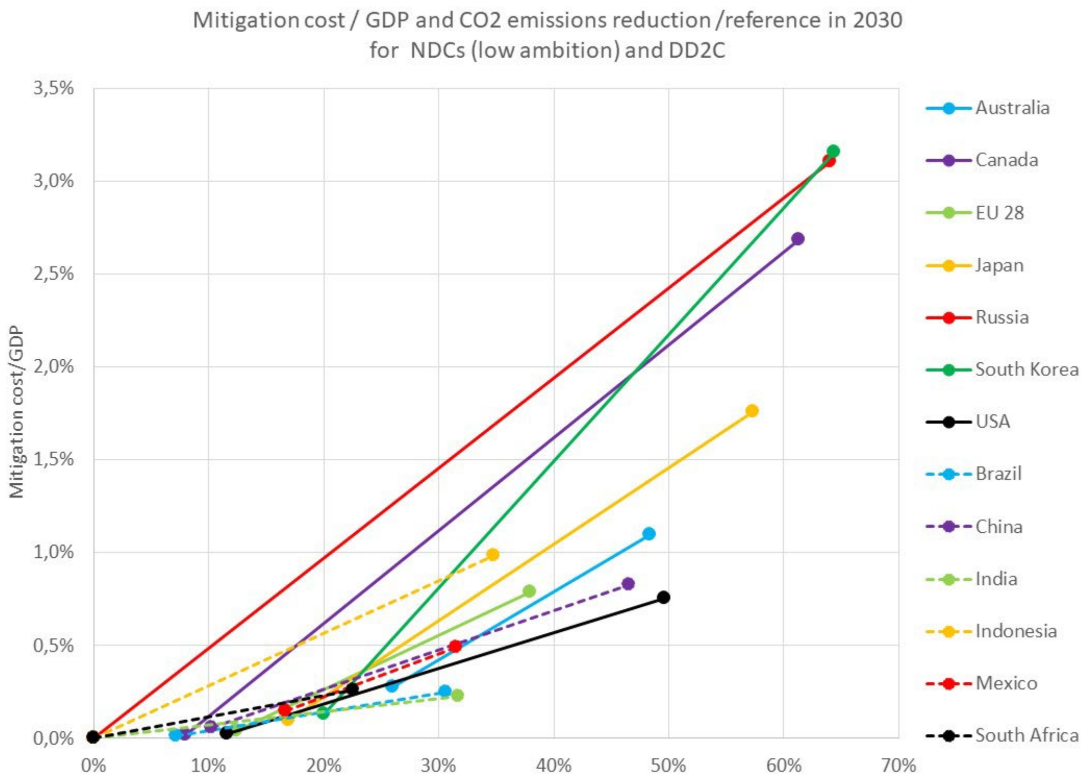
Russia, South Korea and Canada are the three countries with the largest gaps. Figure 8 sheds light on these results as DD2C emission reductions compared to the reference scenario are also the highest (superior to 60% compared to the reference scenario in 2030) for these three countries. The gap for Japan is also high, compared to other countries, as emission reductions in the DD2C amount to 57% in 2030 compared to the reference scenario. In industrialized countries, the smallest gap refers to EU, USA and Australia. The reason for Australia is the ambition level of the NDC, while for EU and USA, the reason is the relatively low DD2C cost corresponding to the NDC CO2 emission reductions.

Only Mexico conditional NDC and South Africa high ambition NDC appear consistent with the long-term decarbonization objectives of DD2C. For other countries, the gap between NDC and DDC2 is high, but for most countries, the difference in total cost is smaller than 1% of GDP, except for Japan, Canada, South Korea, and Russia.

For almost all countries considered here, this assessment highlights the significant increase in NDC effort – as measured by the total cost relative to GDP – that is needed to meet the DD2C. However, under the DD2C case the total mitigation cost remains under 1% of GDP, except for Canada, Russia, Japan, and South Korea.

The results presented in this section are of course dependent on the socio-economic assumptions considered. Hof et al. (2017) show the high sensitivity of regional abatement costs to socio-economic assumptions. We focus on an analysis of the sensitivity of these results to assumptions about technological progress and the cost of low-carbon technologies. The results and assumptions are detailed in the Appendix F. Although the implicit carbon values and total costs show a sensitivity to these assumptions, they only marginally modify the orders of magnitude and the gaps between the NDCs and the DD2C objectives.

Figure 8: National mitigation cost (/GDP) and energy-related CO2 emissions abatement compared to the reference scenario in 2030 for NDC LOW and DD2C



5. Discussion

5.1 The design of Deep Decarbonization Pathways and the Paris Agreement

IAMs allow us to analyze efficient emission reduction scenarios for different countries or regions,and builtin principles of economic efficiency: the equalization of marginal abatement costs, either at international levelthrough the introduction of a world carbon price, or at national level through nationally differentiated prices.

The article is based on a totally different approach of elaboration of national mitigation scenarios. The Deep Decarbonization Pathways approach (Waisman et al., 2019) focuses on strategic energy transition scenarios at the national level. They rely on a careful identification of national development priorities, while taking into account their peculiar constraints and opportunities. Deep Decarbonization Pathways are the result of a shared process for strategy and scenario design among diverse groups of stakeholders in order to inform policy decisions, which are eventually the responsibility of governments. The latter approach can be used by national, regional and city governments working with indigenous peoples, sector associations,

firms, energy utilities, unions, experts, household associations,non-governmental organizations, and by global institutions working with nations, industry institutions and global NGOs.
At the national level, the decarbonization pathways design framework provides organizing principles for the definition of the national long-term strategies specified in the Paris Agreement, and a structure to conduct stakeholder consultations and identify mitigation measures and implementation policy packages. It also can help reveal key enabling conditions, such as technology development and transfer and institutional support, and thus more ambitious national NDCs.

Of course, this approach will have to be adapted to the climate objective of the Paris Agreement. DDPP reflects the state of the art of national commitments and decarbonization scenarios before the COP21 in Paris. These were meant to respond to a 2 °C temperature increase target. The publication of the *Special Report: Global Warming of 1.5 °C* (IPCC, 2018) in advance of COP24 clearly contributes to a change of perspective for climate targets and decarbonization scenarios. A 1.5 °C objective implies reaching carbon neutrality at the global level around 2050 or in the immediately following decades. Carbon neutrality now turns out to be the new frontier of climate policies, whether atglobal or national levels. The question is raised of the methods to be used in order to explore this new frontier.

5.2. A modelling framework to inform the negotiation process

One of the contributions of this work is to propose a methodological approach to evaluate, with a single assessment tool, low-carbon trajectories produced by modelling tools of a highly heterogeneous nature and with various levels of complexity. These national trajectories can also be based on different transnational assumptions related to energy markets, or on different evolutions of the cost of technologies depending on learning factors at the global scale.

The modelling framework developed in this article makes it possible to calculate and compare a number of indicators, as proposed by Aldy and Pizer (2015) (national per capita emissions, emission reduction compared to a reference scenario and to a base-year, carbon prices, and mitigation costs) for informing the discussion on the comparability of efforts, fairness and ambition of each of the national strategies, and the medium and long-term aggregate impact at the global level. The modelling exercise has limitations (some of which are specific to the POLES model used) that would justify modelling exercises based on several models.

Nevertheless, the modelling approach developed in this article can be useful as part of the global stocktake that is scheduled in 2023 for the preparation of revised and more ambitious national determined contributions based on the definition of long-term low GHG emission development strategies.

5.2 Why such differences in the marginal and total abatement costs?

The implicit carbon values resulting from the modelling work raise two comments: first, these values for all DDPP countries in the DD2C scenario are very heterogeneous and second, in developed economies, they are much higher than the uniform carbon value of the 2C scenario. Even if results from the scenarios produced in the DDPP are only illustrative of the methodological approach implemented in the article, it is interesting to analyze the reasons for such a diversity of implicit carbon values in the different national scenarios, and for such high values in some countries. As already mentioned in previous sections, the implicit carbon value is not necessarily a pure price instrument, but should be considered as a proxy of the different instruments.

These differences partly result from the diversity in models and methods used in each country, and also from the diversity in pure energy sector variables, such as the initial energy and carbon intensity of GDP, or the physical potential for low carbon technologies in each country.
Beyond that, the design used for elaborating DDPP scenarios is also important. The differences in abatement costs may reveal different perspectives between stakeholders in the different countries on how important climate change mitigation is, and how much each country should and can contribute to a reduction in global GHG emissions (Layton and Brown, 2000; Nemet and Johnson, 2010).

Moreover, the participatory process also sought to identify synergies between CO2 emission reductions and other national priorities that can be as diverse as air pollution reduction, energy security, employment or energy poverty. All these dimensions must then be considered as potential co-benefits of CO2 emission reductions. Taking into account the co-benefits of climate policies may lead to a significant increase in the willingness to pay to fight climate change (Longo et al., 2012) and to an enhanced ambition in the definition of revised NDCs.

Thus, even if the global model used to aggregate national strategies does not integrate co-benefits of climate policies, this *ex-post* treatment of national trajectories reveals a country-specific willingness to pay to reduce GHG emissions and generate the co-benefits expected from these emission reductions.

5.3 Different carbon values in an international climate regime?

Most model-based approaches to climate policies hypothesize an international carbon price, or at least a long-term convergence toward a unique carbon price. In reality,carbon prices are today varying significantly in the different countries or regions of the world (Bataille et al., 2018). Our analysis of the implicit carbon value of the decarbonization pathways indicates that these differences may persist in the future, due to different national circumstances and priorities.

This clearly raises the question of the type of instrumental architecturethat may be compatible with this operational reality. In the “Kyoto to Copenhagen” period (1997-2009), the dominant paradigm was clearly relying on the existence of flexibility mechanisms or, later, of international emission trading systems. The failure in establishing such a system at a comprehensive scale opened way to less ambitious but hopefully more feasible climate architectures. The Deep Decarbonization Pathways Project has precisely been developed in this context, which doesnot imply a common carbon price at international level.

Does this mean the unfeasibility of any international emission trading system? Surely not, as these types of systems already exist at regional levels, whether in Europe or in North America. They may well persist in the future, and research on regional linking of conversion rates between carbon markets is going on. However, given the differences in carbon value revealed in our study, it seems more and more probable that there will not exist a single and simple carbon market in the foreseeable future.

6. Conclusion and policy implications

This article proposes an original approach for assessing,at the national level, the adequacy of NDCs in relation to the global 2°C target.Most often, the assessment of NDCs against long-term objectives is based on a burden-sharing or cost-minimisation approach relying on IAMs. Such a modelling approach does not take into account national priorities in terms of socio-economic development, in which decarbonization strategies must be integrated and which are central to the definition of the NDC and to the strengthening of their ambition. Weconsider Deep Decarbonization Pathways to 2050 as a benchmark for assessing the 2°C compatibility of NDCs. Such national scenarios were developed by experienced country teams composed of national research centres and experts, which were familiar with the social, technical,and economic preferences and development priorities of the respective societies,and relying on specific modelling tools and methodologies.

Beyond the modelling results showing the need for greater ambition in the next stages of future climate negotiations, the article highlights implicit carbon values for national scenarios compatible with the global 2°C target, that differ between countries. This is the result of the integration of country-specific socio-economic development objectives into decarbonisation strategies (pollution reduction, poverty alleviation, unemployment cuts…).

In addition, the article develops a useful approach to inform the negotiation process on the basis of national trajectories assessed together in a global model. The process resulting from the Paris Agreement aims precisely to ensure, on the one hand, the dynamic nature of NDCs in order to gradually reduce the gap between what is proposed and what is desirable and, on the other hand, transparency in the implementation of the policies and measures necessary to achieve these contributions. This process is structured first by a facilitative dialogue that took place during the COP24 in 2018, and then by a global stocktake scheduled for 2023. This overall review will be carried out on the basis of available scientific information that could contribute to an appropriate monitoring of progress in each country, or strengtheningof the ambition of the policies undertaken. This is precisely to what this paper intends to contribute.

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