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A global stocktake of the Paris pledges: Implications for energy systems and economy

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ABSTRACT

The United Nations-led international climate change negotiations in Paris in December 2015 (COP21) trigger and enhance climate action across the globe. This paper presents a model-based assessment of the Paris Agreement. In particular, we assess the mitigation policies implied by the Intended Nationally Determined Contributions (INDCs) put forward in the run-up to COP21 by individual member states and a policy that is likely to limit global warming to 2 °C above pre-industrial levels. We combine a technology-rich bottom-up energy system model with an economy-wide top-down CGE model to analyse the impact on greenhouse gas emissions, energy demand and supply, and the wider economic effects, including the implications for trade flows and employment levels. In addition, we illustrate how the gap between the Paris mitigation pledges and a pathway that is likely to restrict global warming to 2 °C can be bridged. Results indicate that energy demand reduction and a decarbonisation of the power sector are important contributors to overall emission reductions up to 2050. Further, the analysis shows that the Paris pledges lead to relatively small losses in GDP, indicating that global action to cut emissions is consistent with robust economic growth. The results for employment indicate a potential transition of jobs from energy-intensive to low-carbon, service oriented sectors.

1. Introduction

The twenty-first edition of the annual United Nations-led conference on climate change (Conference of the Parties, COP21) was held in Paris in December 2015. The Paris Agreement is an important step forward in international climate change negotiations. Its main merits include a legally binding 2 °C target, the introduction of a five-yearly review process from 2018 onwards with a first global stocktake scheduled for 2023 and an agreement on international climate financing. Compared to previous editions such as COP3 in Kyoto and COP15 in Copenhagen, the bottom-up approach to climate change mitigation (introduced in Durban, COP17 in 2011) was a fundamental shift in the nature of the policy process. In the run-up to COP21, most countries submitted climate action pledges labelled 'Intended Nationally Determined Contributions' (INDCs). The greenhouse gas emissions of the countries that have communicated INDCs represent over 95% of global emissions in 2010 (UNFCCC, 2016). Hence, in contrast to the Kyoto protocol, the Paris pledges have a broad coverage in terms of emissions. Although unprecedented, this is by no means a sufficient condition to avoid global warming of more than 2 °C above pre-industrial levels by the end of the century, a target included in the Copenhagen Accord (COP15) in 2009 and in the Cancun Agreement (COP16) in 2010. Pre-COP analyses indicate that the INDCs imply an increase in global temperatures in the range of 2.6–3.1 °C by 2100 (Fawcett et al., 2015; Gütschow et al., 2015; Rogelj et al., 2016). Another outstanding challenge is the voluntary nature of individual countries' emission reductions. Once ratified, the Paris Agreement will be legally binding, but the INDCs of individual countries will not. Moreover, whereas the Paris Agreement mentions the economy-wide scope of the emission reduction, it does not include any explicit reference to the aviation and shipping sector.

The outcomes of previous rounds of international climate change negotiations have been assessed by various studies. For instance, Weyant and Hill (1999) summarize that the Kyoto Protocol does not imply a cost-effective climate change mitigation policy and highlight the cost-reducing potential of emission trading, while Böhringer and Vogt (2003) point out that the combination of permit trade and the presence of 'hot air' (due to emission targets well above the projected business as usual) may

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strongly reduce the environmental effectiveness of the Kyoto Protocol. The analyses of the pledges of the Copenhagen Accord based on integrated assessment models (den Elzen et al., 2011a,b; van Vliet et al., 2012; Riahi et al., 2015) and computable general equilibrium (CGE) models (Dellink et al., 2011; McKibbin et al., 2011; Peterson et al., 2011; Saveyn et al., 2011; Tianyu et al., 2016) typically find a policy cost between 0 and 3% of GDP compared to a baseline in 2020 for different cost metrics (abatement cost, GDP, welfare). Pre-COP21 assessments of the INDCs can be found in Fawcett et al. (2015) and IEA (2015).

This paper assesses the energy-related and economic implications of the climate mitigation policies embedded in the INDCs. The main contribution to the literature is twofold. First, we present a timely, policy-relevant, global stocktake of the Paris mitigation pledges that translates the outcome of the latest international climate negotiations into quantifiable changes in a range of variables including energy demand, the composition of energy and electricity production, economic activity, trade and employment. The second contribution lies in the methodological framework, presented in the following section. The combination of a bottom-up, detailed energy system model and a top-down global economic model exploits the complementarities between both and enables an extensive study of climate change mitigation policies.

The remainder of the paper is organised as follows. After presenting the methodology, we describe the scenarios studied: the Reference scenario, the INDC scenario covering the mitigation component of the Paris pledges and a scenario that is likely to put the world on track to meet the 2 °C target. Results are presented in Section 4. We highlight the impact on energy production, demand and investments and the economic effects. Furthermore, we present how the gap between the INDCs and the 2 °C pathway can be bridged. The final section concludes.

2. Methodology

The assessment of climate change mitigation policies presented in this paper builds on the combined modelling effort of a detailed, technology-rich energy system model (JRC-POLES, https://ec.europa.eu/jrc/en/poles) and an economy-wide Computable General Equilibrium (CGE) model (JRC-GEM-E3, https://ec.europa.eu/jrc/en/gem-e3/). The models are harmonized along a common Reference scenario and are soft-linked to exploit complementarities of a detailed representation of energy production, demand and markets on the one hand, and economy-wide feedback mechanisms including international trade, intermediate input links between industries, and recycling of taxation revenue on the other hand. As such, this paper addresses part of the critique on standard modelling practices put forward by Rosen (2016) and Rosen and Guenther (2016), particularly on the high degree of aggregation in most integrated assessment models. In contrast to exercises using numerous models in order to provide a range of results for a common set of output variables (Kriegler et al., 2013, 2015; Riahi et al., 2015), this paper emphasizes that different model types can contribute complementary parts to a complex puzzle. The scenarios analysed here build on the analyses by Labat et al. (2015), Kitous and Keramidas (2015) and Kitous et al. (2016), whereas the methodology further develops the framework adopted by Russ et al. (2009) and Saveyn et al. (2011). The approach of linking an energy model with a CGE model with a bottom-up representation of the power sector contributes to but is distinct from the literature reconciling top-down and bottom-up information while building a high degree of energy system detail into a CGE model (e.g. McFarland et al., 2004; Hourcade et al., 2006; Sue Wing, 2008; Böhringer and Rutherford, 2008; Abrell and Rausch, 2016; Li and Zhang, 2016).The following paragraphs briefly describe the JRC-POLES model, the JRC-GEM-E3 model and the way in which the two models are combined. For more detailed model descriptions we refer to Appendices A and B, the above-mentioned model websites and the mathematical description of JRC-GEM-E3 in Capros et al. (2013).

The JRC-POLES model is a global partial equilibrium simulation model of the energy sector, covering 38 regions world-wide plus the EU. The model covers 15 fuel supply branches, 30 technologies in power production, 6 in transformation, 15 final demand sectors and corresponding greenhouse gas emissions. GDP is an exogenous input into the model, while endogenous resource prices, endogenous global technological progress in electricity generation technologies and price-induced lagged adjustments of energy supply and demand are important features of the model. The mitigation policies discussed in the next section and listed in Appendix C are implemented by introducing carbon prices up to the level where emission reduction targets are met. 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).

The JRC-GEM-E3 model is a global recursive-dynamic CGE model. The model describes the economic behaviour of welfare-maximizing households and cost-minimising firms, includes (exogenous) government policies, different types of energy use and greenhouse gas emissions and endogenously determines changes in international trade flows, unemployment and GDP. Inter-industry connections are explicitly represented via intermediate consumption. Climate policies are introduced in the model via emission constraints. The JRC-GEM-E3 model then endogenously derives the shadow prices to meet these constraints, raising the cost of emission-intensive inputs for firms and consumption of emission-intensive goods for households. Emission reductions occur via three mechanisms: a reduction in output and consumption, substitution towards low-carbon inputs and goods and end-of-pipe abatement technologies.

The analyses presented in this paper benefit from the combination of the two models in a way that allows for a broad assessment while preserving the details and particular strengths of each. First, a Reference shared by the two models is developed based on common assumptions for the (exogenous) evolution of two important factors with regards to climate change: region-specific economic (GDP) and population growth. The evolution of the sector composition of economic activity follows the same projection in both models, projecting structural changes in developing countries based on historical data. In addition, the emissions by greenhouse gas, economic sector and region are identical between the two models in the Reference. Second, scenario results of the disaggregated energy model feed into the economy-wide CGE model to make use of the in-depth treatment of the energy system in JRC-POLES. In particular, the totals of greenhouse gas emissions derived from the bottom-up analysis determine regional emission constraints for the economic assessment with JRC-GEM-E3. In addition, the shares of the different technologies in electricity generation in JRC-POLES are used as an input in the JRC-GEM-E3 analyses. This soft-link is enabled by the split of electricity generation into 10 technologies in the JRC-GEM-E3 model. As a result, the technology mix in electricity supply in the JRC-GEM-E3 model is consistent with an enhanced representation of the specific features that characterize real-world electricity markets, such as price-setting by the marginal technology, capacity investment decisions, intermittency, region-specific potentials of renewable energy sources (per technology) and endogenous technological progress. Changes in electricity trade between regions and the location of production of technologies (e.g. solar panels) are not considered explicitly in this paper. The link between both models is unidirectional – from the JRC-POLES model to the JRC-GEM-E3 model – and does not include changes in coal, oil, gas and electricity volumes and prices (which are endogenous in both models). Future work can further explore these options for the integration of models.

3. Scenarios

This section describes the three scenarios analysed in this paper: the Reference, the INDC scenario representing the mitigation component of the Paris pledges and the 2 °C scenario. All scenarios have identical assumptions on population growth. For the EU, population forecasts are taken from European Commission (2013). For all other regions, population projections of UN (2015) are included. The following three paragraphs focus on the Reference, the INDC scenario and the 2 °C scenario, respectively, and highlight the main assumptions and the resulting global greenhouse gas emissions and emission intensities of GDP. The trajectory of total greenhouse gas emissions in each of the three scenarios is depicted in Fig. 1. A detailed description of the policies included in the Reference, the INDC scenario and the 2 °C scenario can be found in Appendix C and in the online Appendix.

The Reference serves as a benchmark for comparison and builds on various data sources and assumptions. First, the Reference includes the climate policies that are currently implemented or announced, particularly for 2020, without adding new additional policies (taking into account the information provided in den Elzen et al., 2015). In modelling terms, the existing or announced carbon policies are represented by a corresponding carbon price. Carbon values in the Reference are low (EU) or zero (rest of the world) in 2015. Furthermore, carbon values range between 0 and 39 US $ (2015) per tonne of CO_2e in the year 2030. Second, growth of Gross Domestic Product (GDP) in the Reference is exogenous and based on forecasts by the OECD Economic Outlook (2013) and the World Bank (2014). Sector-specific growth paths in the Reference are based on observed historical trends. The projections do not consider the impacts of changing climatic conditions on economic growth, as described in Fankhauser and Tol (2005). Third, the growing scarcity of conventional oil resources and consequent increasing market power of OPEC drive the oil price upwards over time (endogenous in JRC-POLES). The oil prices in the model reflect the low levels observed recently and are projected to reach around 100 US$2005 in 2030. Fourth, as a result of the above-mentioned assumptions and policies, the global average energy intensity of GDP follows a downward trend, at a rate observed in the period 1995–2008, but slightly faster than the average rate observed over the past 25 years (−1.4% per year 1990–2015, −1.7% per year 2015–2030). In addition to the implemented policies, this decoupling is driven by the potential for energy efficiency (especially in fast-growing low-income countries) and the increasing technological maturity of low-carbon technologies. Fifth, the main data sources for historic emissions include regional and national energy balances, UNFCCC (2014), Edgar (European Commission JRC, 2014) and FAO-Stat (FAO, 2014). A more detailed description of data sources used in the JRC-POLES model is included in Appendix A. The level of global greenhouse gas emissions in the Reference gradually increases over the entire time period considered, as illustrated in Fig. 1. For non-CO_2 GHGs, marginal abatement cost curves are based on EMF21 (Weyant et al., 2006), US EPA (2013) and GLOBIOM for land use, land-use change and forestry (LULUCF) and agriculture (IIASA, 2015a).

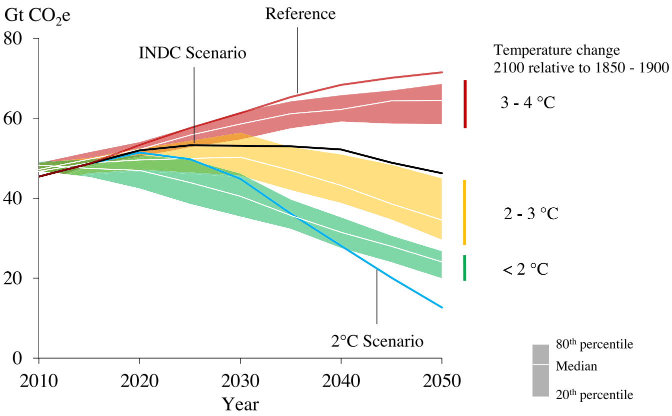

Fig. 1. Global greenhouse gas emissions in the Reference, the INDC and the 2 °C scenario. Shaded areas represent the (median, 80th and 20th percentile per temperature range of) scenarios included in the IPCC AR5 WGIII Scenario Database (IIASA, 2015b). Temperature ranges are based on IPCC (2014) with at least 60% probability for the scenarios below 2 °C, and 55% probability for staying between the ranges 2–3 °C and 3–4 °C.

The INDC scenario represents the climate change mitigation pledges made by individual countries in the run-up to the COP21 in Paris. We consider a complete realisation of the mitigation ambitions in the conditional INDCs, i.e. including mitigation targets that are dependent on other conditions, such as the provision of climate financing. The financial transfers resulting from the Green Climate Fund (the financing mechanism under the UNFCCC) are not part of the analysis here, as little is known about the allocation of the fund at this point. In the case where the mitigation pledges were already reached in the Reference scenario (as a result of market forces and technological deployment), no additional effort was required. The available information in the INDCs is translated into emission targets, which are implemented in the model by region-specific economy-wide carbon prices. More detail on the included policies is given in Appendix C and in the online Appendix. Implicitly and due to lack of more detailed information this assumes that policies are efficient within a region's borders. Widely differing carbon prices, ranging from 0 to 119 US $ (2015) in 2030, indicate that there is potential for enhancing the cost-efficiency on a world level. The global aggregate of GHG emissions stabilises around the level in the year 2025 (Fig. 1). GHG intensity of the economy decreases at an accelerated pace: −2.8% per year over the period 2015–2030 compared to −1.9% in the Reference. Global aggregate GHG emissions in 2030 are more than 13% lower than in the Reference in 2030. The main focus of the results presented in this paper lies on the year 2030, as most of the INDCs do not extend beyond this time frame, Some of the results, however, consider a time horizon up to the year 2050. For these results, we assume a continued climate change mitigation efforts in all regions after 2030. In particular, we assume that policies are introduced such that the yearly rate of reduction of GHG intensity (GHG excluding sinks per GDP; Sinks are defined as negative CO_2 emissions from land-use related activities in a region. Sinks from afforestation and forest management could represent 3 $GtCO_2$ in 2010 and about 2 $GtCO_2$ in 2050 in the Reference. However, due to significant uncertainty on the historical estimates of sinks, they are generally not considered in the result section.) implied by the INDCs in the 2020–2030 period is continued in the period 2030–2050 (global average reduction rate of 3.2% per year).

The 2 °C scenario considers a pathway of global greenhouse gas emissions that is likely to be consistent with limiting global temperature increase to 2 °C by the end of the century compared to levels in the period 1850–1900. With a total carbon budget of 1160 Gt CO_2 over 2011–2050 and a reduction of Kyoto gases of 72% in 2050 relative to 2010, this scenario compares best with the scenario 430–480 ppm with overshoot > 0.4 W/m2 in IPCC (2014, AR5 WGIII Table 6.3) with a 22–37% probability of exceeding the 2 °C warming target. As illustrated in Fig. 1, GHG emissions up to

2040 stay within the 20th to 80th percentile range of the scenarios in the IPCC Scenario Database with a probability of staying below 2 °C of at least 60%, and fall below the 20th percentile in the 2040–2050 period. A peak in world aggregate GHG emissions appears around the year 2020 (Fig. 1). The specification of the 2 °C scenario considers convergence of carbon prices, hence implicitly assumes enhanced economic efficiency for mitigation efforts and enhanced technology diffusion due to international collaboration over time. For middle- and high-income regions, carbon prices converge to around 53 US $ (2015) in 2030, which corresponds with the highest level of carbon values in the INDC scenario (excluding Republic of Korea and New Zealand). Uniform carbon pricing implies that emissions are reduced in the countries and sectors where it is cheapest to do so. However, the 2 °C scenario studied in this paper allows for a two-track climate policy, acknowledging political realities and in line with the “common but differentiated responsibilities” as included in the United Nations Framework Convention on Climate Change, negotiated at the Rio Earth Summit in 1992. In particular, carbon values of low-income countries (with income per capita in 2030 lower than 10000 US $ PPP, including India, Indonesia and a number of countries in Sub-Sahara African, Central America, South-East Asia and the Pacific) converge to a level of around 26 US $ (2015) in 2030, which is approximately half of the carbon value in high-income regions and brings global GHG emissions on the pathway described above and illustrated in Fig. 1. A more elaborate assessment of potential burden sharing agreements and the underlying ethical principles is outside the scope of this paper (see Babonneau et al., 2016, Marcucci et al., 2016 and Rose et al., 2016, for a discussion on the equity dimension in the context of the Paris Agreement). Importantly, all regions contribute to the reductions in GHG emissions and the intensities of climate actions – and, correspondingly, the carbon prices – gradually increase over time. For all countries, we take the effort in the INDC scenario as a lower bound for the 2 °C scenario. Therefore, the 2 °C scenario assumes a cooperative setting with global participation in which free-riding is not considered. Total GHG emissions are around 27% lower than in the Reference in 2030. Accordingly, GHG intensity of the economy decreases at more than double the rate of the past 25 years (−3.9% per year over the period 2015–2030).

Table 1 summarizes the main assumptions behind the analysis. The last two columns present the inputs for the INDC and 2 °C scenarios. The percentage changes of GHG emissions from 2005 to 2030 in the INDC scenario are based on the INDCs submitted by individual countries. The last column indicates whether a region was included (based on GDP per capita) in the group of countries for which carbon prices are assumed to converge to high or low levels of 53 and 26 US $ (2015) in 2030. The Rest of Central and South America is a region that aggregates countries of both groups (with Chile in the high-income group), hence the overall carbon price will lie between the high and the low values.

4. Results

This section presents the results of the numerical simulations with the JRC-POLES and JRC-GEM-E3 models. The first part discusses the impact of the climate change mitigation scenarios on the composition of energy demand. Next, we zoom in on the greenhouse gas emission paths by gas type and by emitting sector. We pay particular attention to the electricity production sector. The second part presents the economy-wide results, highlighting the differentiation of impacts across regions and sectors.

An important caveat for all results presented here is that the scenarios do not consider the (avoided) damages from (mitigating) climate change (Rosen, 2016). For studies on the impact of climate

Table 1
The main characteristics of the Reference, the INDC scenario and the 2 °C scenario.

	GHG[a]	Yearly GDP growth rate	GHG/GDP[b]	Change in GHG emissions		Carbon Value[c]
	2005	2020–2030	2030	2030 relative to 2005		2030
		Reference	Reference	Reference	INDC	2 °C
World	38.59	2.98	0.43	46	28	
China	8.56	4.99	0.62	117	75	High
USA	7.12	2.03	0.30	−14	−38	High
European Union	5.20	1.96	0.19	−34	−36	High
Russia	2.22	2.71	0.82	1	3	High
India	1.93	6.42	0.38	169	171	Low
Japan	1.27	1.00	0.21	−25	−27	High
Central Asia and Caucasus	1.11	4.45	0.86	54	27	High
Brazil	0.93	3.31	0.45	27	23	High
Rest of Central and S. Am.	0.91	3.71	0.39	66	66	Intermediate
South-East Asia	0.79	3.41	0.82	52	53	Low
Sub-Sahara Africa	0.84	6.31	0.44	112	95	Low
Canada	0.77	2.10	0.45	2	−17	High
Rest of Middle East	0.72	3.20	0.69	115	111	High
Mexico	0.64	3.54	0.33	37	13	High
Indonesia	0.62	5.18	0.42	81	82	Low
Iran	0.61	5.26	0.84	103	103	High
Republic of Korea	0.57	3.14	0.26	6	−6	High
North Africa	0.57	5.47	0.48	94	79	High
Rest of Asia and Pacific	0.54	6.66	0.47	126	126	Low
Australia	0.52	2.93	0.38	−6	−7	High
Rest of Europe	0.52	3.00	0.28	3	51	High
South Africa	0.49	4.90	0.72	20	10	High
Saudi Arabia	0.41	3.54	0.64	92	92	High
Argentina	0.31	2.74	0.37	10	10	High
New Zealand	0.08	2.36	0.48	6	−23	High

[a] Greenhouse gas emissions are expressed in Gt $CO2_e$ and exclude emissions from LULUCF and bunkers.

[b] GHG/GDP is expressed in t $CO2_e$/US$(2005) PPP.

[c] ‘High’, ‘Intermediate’ and ‘Low’ carbon values converge to 53, 45 and 26 US $ (2015) in 2030 respectively. Carbon values of Republic of Korea and New Zealand are higher because reduction targets in the 2 °C scenario are set at least as ambitious as the INDCs.

change, we refer to OECD (2015) for a global assessment and to Ciscar et al. (2014) and Houser et al. (2014) for studies on the level of the European Union and the United States, respectively.

4.1. Energy demand

Fuel combustion is one of the main sources of greenhouse gas emissions. Hence, policies that envisage restricting emissions will have an impact on the aggregate level and composition of energy consumption. Carbon pricing raises the price of energy, which leads to a decrease of total energy demand by 3.8% (9.2%) and 8.6% (33.6%) in the INDC and 2 °C scenarios respectively in 2030 (2050) compared to the Reference. This result indicates the importance of energy efficiency as a contributor to emission reductions. Table 2 decomposes the change in aggregate energy demand by fuel type and illustrates the substitution between primary energy sources. The latter is driven by carbon pricing based on a CO_2 equivalent basis, which affects relative prices of different fuel types and incentivizes substitution towards low-carbon energy sources.

The INDCs have a negligible impact on global oil and natural gas consumption. The demand for solid fuels – coal and lignite – is reduced by more than 15% compared to the Reference in 2030. Hence, replacing solid fuels by non-fossil fuels is an important element for climate change mitigation policies. In contrast to increasing volumes of global coal consumption in the Reference (compared to 2010, a 41% increase in 2030, 73% in 2050), the levels remain roughly constant in the 2020–2030 period in the INDC scenario. These results are consistent with the findings presented by IEA (2015).

Table 2 furthermore indicates that the 2 °C scenario implies substantial reductions in world demand for oil and gas from 2025 onwards. Going from the INDCs to a pathway that is likely to limit global warming to 2 °C implies an increased rate of decrease of solid fuel consumption, despite allowing for the possibility of Carbon Capture and Storage (CCS). The contribution of CCS will be discussed in more detail in Section 4.4. The impacts shown in Table 2 are in line with the results presented by Bauer et al. (2015), who assess GHG emission trajectories compatible with a temperature increase of 2 °C with several models and with a focus on fossil fuel markets.

4.2. Emission reductions by greenhouse gas

Carbon dioxide (CO_2) is the primary anthropogenic greenhouse gas, covering around three quarters of global GHG emissions (in CO_2 equivalent terms, IPCC, 2014). However, the results illustrated in Fig. 2 show that both the INDC and the 2 °C scenario imply emission reductions of all greenhouse gases. Both scenarios implement carbon prices that are uniform (on a CO_2-equivalent basis) across the different types of gases. Hence, cost-minimising producers will determine the relative contributions of different gases to the overall emission reduction in an efficient manner, using least-cost options before more expensive alternatives. In particular, the underlying sector- and region-specific technology options (for CO_2) and marginal abatement cost curves (for non-CO_2 emissions and CO_2 emissions in agriculture) lead to different time profiles of the reductions of the various greenhouse gases considered.

Table 2
Changes in primary energy demand (total and by fuel type) in the INDC and the 2 °C scenarios, expressed as% change from the Reference. Non-fossil fuels include renewables and electricity generated by nuclear power plants.

INDC Scenario	2015	2020	2025	2030	2035	2040	2045	2050
Total	0	0	−2	−4	−5	−7	−8	−9
Solids	0	−3	−10	−18	−26	−30	−34	−40
Oil	0	0	−1	−2	−2	−3	−4	−4
Natural gas	0	1	0	−1	−1	−2	−2	−1
Non-fossil fuel	0	1	6	10	14	16	16	17

2 °C Scenario	2015	2020	2025	2030	2035	2040	2045	2050
Total	0	−1	−3	−9	−16	−23	−28	−34
Solids	0	−3	−15	−32	−54	−67	−73	−78
Oil	0	0	−1	−5	−13	−23	−36	−49
Natural gas	0	1	0	−6	−14	−26	−34	−43
Non-fossil fuel	0	1	8	17	30	36	40	44

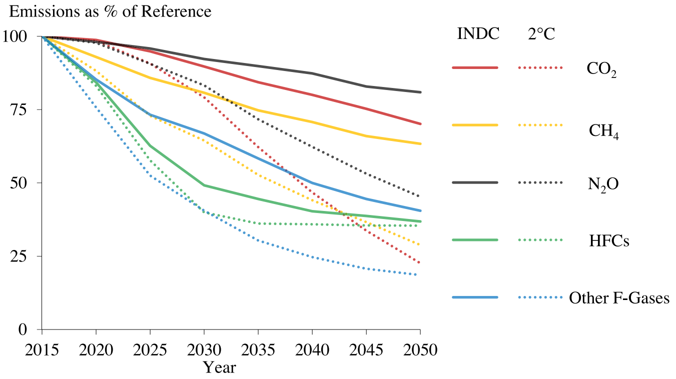

Fig. 2. Emission reduction by type of greenhouse gas in the INDC and the 2 °C scenario. CO_2 emissions included LULUCF but exclude sinks. Greenhouse gases shown are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs) and other fluorinate gases (F-gases).

The INDC scenario leads to strong reductions in hydrofluorocarbons (HFCs) and other fluorinated gases (F-gases), which reveals the fact that the emissions of these gases are relatively inexpensive to abate due to available technological options (European Commission, 2012). The reduction of nitrous oxide (N_2O) emissions is one of the more costly options: a cost-effective implementation of the INDCs leads to N_2O levels that are approximately 8% lower than the levels in the Reference in 2030.

The emission reduction profiles in the 2 °C scenario show stronger reductions for all gases. Interestingly, the emissions of HFCs are reduced at a faster rate than in the INDC scenario up to 2030, but converge towards 2050. This result indicates that the INDCs exploit nearly the full potential of HFC emission reductions. Furthermore, Fig. 2 illustrates a wide gap between the reductions of CO_2 in both scenarios: the INDCs lead to a level of CO_2 emissions that is approximately 30% lower than the level in the Reference in 2050, while the 2 °C pathway studied here suggests a level of CO_2 emissions around one third of the level in the INDC scenario in 2050.

4.3. Emission reductions by sector

The previous section decomposed the aggregate GHG reductions into gas-specific abatement profiles over time. A second way to disentangle the emission reductions is on a sector-specific basis. Fig. 3 presents emissions reductions in 2030 disaggregated into six categories: electricity generation, the energy sectors, industry, land use, land-use change and forestry (LULUCF), agriculture and an aggregate category for buildings, transport and waste. A number of insights can be deducted from the JRC-POLES model simulations.

First, the power sector emerges as the main contributor to emission reductions in both INDC and 2 °C scenarios. A transformation of the electricity production sector covers more than a third of the emission reductions between the Reference and the INDC in 2030. In addition, the power generation sector bridges around 31% of the gap between the INDCs and the 2 °C scenario. The next section reveals in greater detail how the abatement in the electricity sector is achieved.

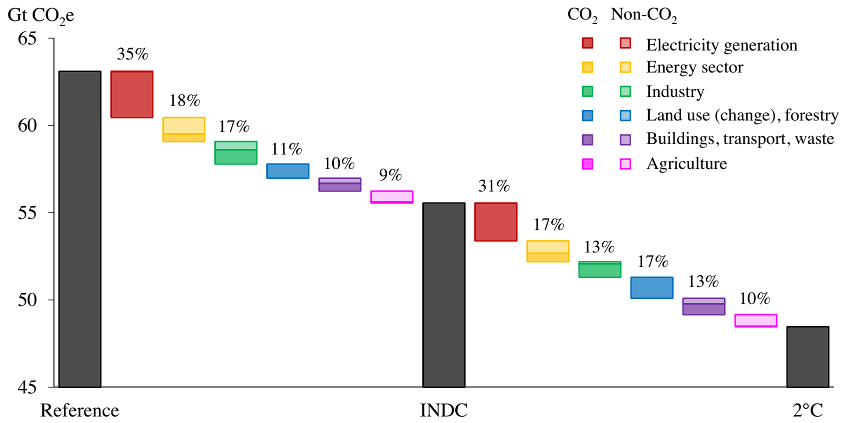

Fig. 3. Sector contributions to greenhouse gas emission reductions in 2030. The percentage above the bars indicates the share in reductions between scenarios. CO_2 emissions exclude sinks. The darker, lower end of the bar represents CO_2 reductions, while the upper part in a lighter colour shows the reductions in non-CO_2 greenhouse gases. Non-CO_2 emission reductions in electricity generation and CO_2 emissions in agriculture are hardly visible, while emission reductions from land use, land use change and forestry (LULUCF) only cover CO_2 emissions. Energy sector emissions include greenhouse gases emitted during extraction, production, transformation (e.g. refining) and transport of energy fuels and associated fugitive emissions.

Second, significant emission cuts appear in the energy sector. A shift away from emission-intensive fossil fuels (in line with the previous section) is the main driver of emission reductions in the energy sector. In the numerical simulations presented here, a carbon price on a CO_2-equivalent basis provides the incentives for this change. Greenhouse gases other than CO_2 represent more than half of the emission reductions in this category, which is to a large extent due to reduction in methane emission from the production of fossil fuels.

Third, decreasing greenhouse gas emissions in the industrial sector is a non-negligible possibility, representing 17% of the GHG abatement between the INDC scenario and the Reference. The options to achieve lower emissions in this category include reducing CO_2 emissions from combustion, non-combustion process CO_2 emissions in the steel, non-metallic minerals and chemical sectors, and other greenhouse gas emissions (N_2O, HFCs, PFCs and SF_6) in industrial sectors such as the aluminium sector. In line with the previous section, the abatement potential of non-CO2 greenhouse gases is to a large extent used in the INDC scenario, while further emission reductions to reach the 2 °C pathway mainly rely on decreasing CO_2 emissions. As a consequence, the contribution of industrial sectors to bridge the gap between the INDC and the 2 °C scenario falls to 13%.

Fourth, reductions in CO_2 emissions from LULUCF (excluding sinks) cover around 11% in the INDC scenario. When sinks are included, CO_2 emissions fall by 1.4 Gt in the INDC scenario compared to the Reference, a result that is comparable with the number of 1.6 Gt obtained by Grassi and Dentener (2015). Moving towards a 2 °C pathway implies a more substantial contribution of CO_2 reduction in LULUCF. Some regions with a significant share of emissions from LULUCF have relatively unambitious INDCs. For these regions, reducing CO_2 emissions from LULUCF are cost-effective options. In addition, due to a relatively flat marginal abatement cost curve, avoided deforestation becomes an important source of emission reductions in reaching the 2 °C target.

Fifth, a reduction in energy demand (e.g. by means of improvements in energy efficiency beyond what is realized in the Reference) and a fuel shift in the building and transport sector and a reduction of methane emissions in waste and agriculture sectors (see IPCC, 2014, Chapters 10 and 11, respectively, for a more in-depth discussion of the technological options) together cover around one fifth of the total decrease of GHG.

4.4. Electricity generation

The previous section highlighted the importance of the contribution of the power sector to the global emission reductions. This section zooms in on the technology composition of electricity production in the different scenarios in 2030 and 2050, presented in Fig. 4.

A first result is that higher carbon prices lower the total level of electricity consumption. Both in 2030 and in 2050, the INDC and 2 °C scenarios slightly reduce global electricity consumption compared to the Reference. This result illustrates that energy

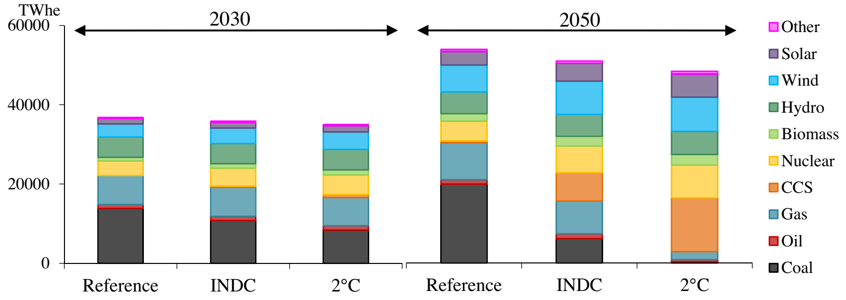

Fig. 4. Electricity generation by technology in the Reference, the INDC scenario and the 2 °C scenario in 2030 and 2050 at global level. Carbon Capture and Storage (CCS) covers coal-, gas- and biomass-fired electricity generation with CCS. Other technologies include geothermal electricity, wave and tidal energy, and (stationary) hydrogen fuel cells. Units are expressed in terawatt hour of electricity (TWhe).

efficiency improvements outweigh a rising share of electricity in total energy demand, mainly in the building and transport sector after 2030, leading to lower electricity consumption levels overall.

By 2030, the INDCs lead to a transformation of the power sector through a substitution from fossil fuels to low-carbon technologies. In the Reference, fossil fuels account for around 60% of electricity production. This number reduces to 53% and 47% in the INDC and 2 °C scenario, respectively. The decrease in the share of fossil fuel-based power production is compensated by an increasing share of low-carbon technologies, mainly nuclear and wind energy, but also biomass, hydro and solar. Gas-fired power covers around 20% of electricity generation in 2030 in the Reference as well as in both scenarios.

In the longer run (2050), Carbon Capture and Storage becomes an important technology for climate change mitigation policy. In the 2 °C scenario, electricity generation from coal without CCS is close to zero. In addition, carbon prices lead to more electricity being generated from nuclear, solar, wind, biomass and other (geothermal, tidal, hydrogen) energy compared to the Reference. The 2 °C scenario implies substantial investments in wind and solar capacity, which unlocks (endogenous) technological progress for these technologies. As a result, wind and especially solar power becomes more competitive in the 2 °C, and consequently gains market share.

Fig. 5 sheds more light on the technological progress in electricity production technologies (in the 2 °C scenario; the Reference and the INDC curves follow a similar trend in investment costs). Incorporating technological change can have important implications for the optimal emission trajectory. As pointed out by van der Zwaan et al. (2002), including technological improvement in climate change modelling may lead to faster deployment of renewables. The JRC-POLES model includes technological progress in electricity generation technologies endogenously using a learning-by-doing approach: investments costs change in response to the cumulative installed capacities on a global level. For a broader discussion on the approaches used in the literature, we refer to Löschel (2002) and Gillingham et al. (2008). A two-factor approach, including both learning-by-doing and learning-by-research in the POLES model is described in Criqui et al. (2015). The capacity expansions are roughly consistent with those presented in van der Zwaan et al. (2013) and van Sluisveld et al. (2015). The technological progress in electricity generation from solar stands out from Fig. 5. Furthermore, the investment costs of oil and gas power plant installation decrease, but represent a smaller fraction of total costs due to higher variable costs of fuel input.

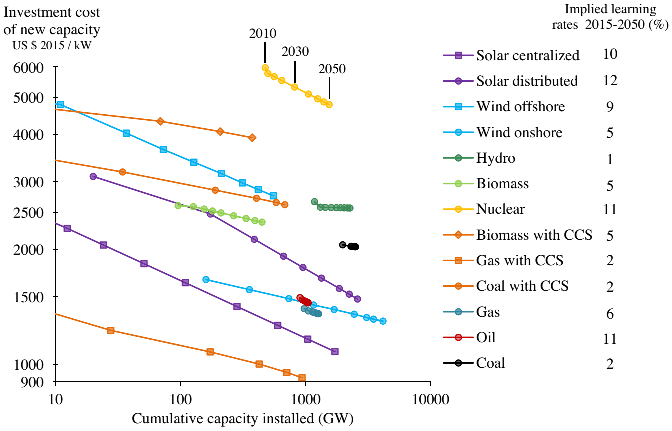

Fig. 5. Technological progress in electricity generation technologies in the 2 °C scenario from 2010 to 2050. The learning curves depicted here are based on a learning-by-doing approach and show the relation in capacity investment cost and installed capacity on the global level. The representative technologies shown here are conventional thermal turbines for coal, oil, gas and biomass; pressurized water reactor generation III/III+ for nuclear; and large hydro installations. Progress in technologies with Carbon Capture and Storage (CCS) aggregates the learning in CCS technology with the learning in the relevant coal-, gas- and biomass-fired electricity generation technologies. The learning rate is defined as the percentage cost decrease corresponding with a doubling of installed capacity.

4.5. Macro-economic costs

This section and the two sections that follow concentrate on the economic impact of climate change mitigation policies. Note that the scenarios here implement a domestic emission trading scheme with grandfathered permits between the economy-wide sectors but without international trade of permits. Section 4.7 considers carbon taxes and studies alternative revenue recycling mechanisms.

The results of the INDC scenario suggest that the Paris pledges have only a limited impact on world aggregate GDP of −0.42%. The 2 °C scenario imposes stronger constraints on emissions, leading to more substantial transformations economy-wide. This is reflected in a reduction of global economic output levels of −0.72%.

Four comments to frame these results are in order. First, yearly growth rates remain high: the 2.98% yearly growth of global output level in the Reference for the period 2020–2030 is only slightly reduced to 2.93% and 2.90% in the INDC and 2 °C, respectively. Hence, climate mitigation policies are compatible with robust economic growth. Second, as mentioned earlier, we emphasize that we only assess the cost side of mitigation policy and do not incorporate the avoided damages of climate change. The JRC-GEM-E3 model is based on optimising behaviour of firms and households under myopic expectations. In absence of the modelling of damages of climate change, imposing GHG emission restrictions in the model implies that agents have fewer options to maximise profits or welfare. Therefore, the results should be seen as an assessment of the abatement cost and should not be confused with the result of a cost-benefit analysis. Third, these results are in line with IPCC (2014), as shown in Fig. 6 below. For each of the models involved with endogenous GDP, Fig. 6 (panel a, left-hand side) plots the model- and scenario-specific change in GDP aggregated at global level against the corresponding reduction in greenhouse gases in 2030. Note that the changes of both GDP and GHG emissions are expressed here relative to the respective model references or baselines. Results from different projects are included, including EMF27 (Weyant et al., 2014), EMF22 (Clarke and Weyant, 2009), AMPERE (Kriegler et al., 2015) and LIMITS (Kriegler et al., 2013; Tavoni et al., 2014). The Figure shows a clear relation between abatement effort and cost, but with substantial heterogeneity due to differing assumptions e.g. on availability of technologies. The right-hand side of Fig. 6 (panel b) illustrates that higher emission levels in the Reference require stronger emission reductions relative to this Reference in order to meet the same target for temperature increase (indicated by the colours in Fig. 6). Some of the references or baselines do not include the policies that are currently in place, which explains why the emission levels in the Reference of the analysis presented in this paper are relatively low. Fourth, by implementing region-specific emission reduction targets based on the results of the JRC-POLES model optimization exercise in the 2 °C scenario, we get different carbon prices in various regions. An efficient scenario with a uniform global carbon price is likely to lead to a lower cost estimate on a global average. On the other hand, the results presented here may underestimate the cost of climate policies in reality. Lobby groups, overlapping or partial (e.g. sector-specific instead of economy-wide) policies, institutional barriers, myopic policy-makers and the absence of international cooperation (preventing convergence of carbon

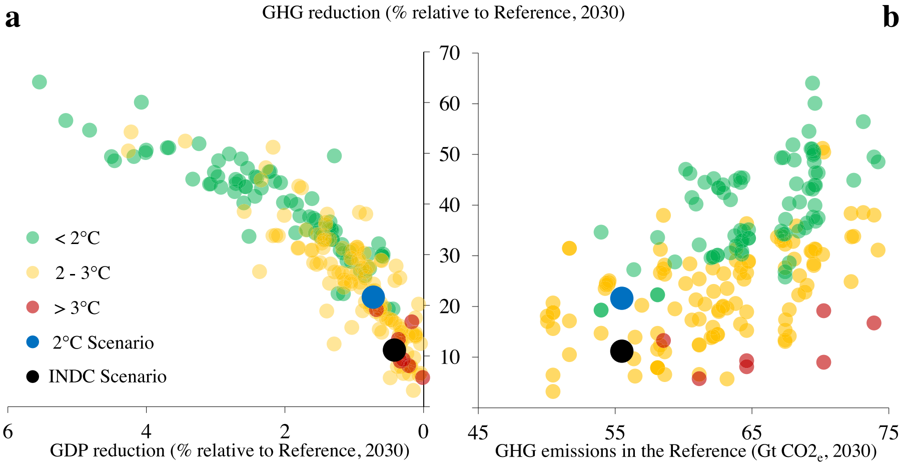

Fig. 6. Impact on global aggregate GDP of the INDC and 2 °C scenario in 2030 (JRC-GEM-E3 results) compared with results (of models with endogenous GDP) included in the IPCC AR5 WGIII Scenario Database (IIASA, 2015b). Each dot represents a model- and scenario-specific result, relative to the respective baselines. Temperature ranges are based on IPCC (2014) with at least 60% probability for the scenarios below 2 °C, and 55% probability for staying between the ranges 2–3 °C and above 3 °C. GHG reduction of the 2 °C scenario and the INDC scenario cover emissions from energy, industry and agriculture, excluding LULUCF. a) More stringent temperature targets require stronger emissions reductions leading to higher abatement costs. b) Higher emission levels in the Reference or baseline imply stronger reductions relative to the Reference to meet a similar target for the rise in global temperature.

prices) could lead to suboptimal policies from an economic efficiency point of view.

Global average results discussed above hide substantial differentiation across regions and sectors. The following two sections therefore disaggregate these results to provide a better understanding of the economic impact and the distributional effects of the INDC and 2 °C scenarios.

4.6. Regional economic impact

One of the main novelties of the Paris COP21 is the bottom-up policy framework: countries put forward INDCs and consequently reveal the level of ambition of their climate change mitigation policies. The broad range of ambition levels is likely to translate into economic impacts that differ substantially across regions. Differences in historical emission reduction efforts, energy intensity, sector composition, natural resource endowments, the production of fossil fuels, the relative importance of trade-exposed sectors, trade links and consumption patterns are among the additional factors that may give rise to impact variation between regions. All the above-mentioned aspects are captured by the JRC-GEM-E3 analysis, of which the results are displayed in Fig. 7 and Table 3.

A first point illustrated by the INDC scenario results is that a substantial number of regions undertake significant climate action that leads to relatively small reductions in GDP (less than 1% reduction from the Reference in 2030) compared to the Reference. However, the INDC scenario shows that a number of regions have relatively unambitious targets, such that their emission levels are close to or even slightly higher than in the Reference in 2030. Some of these regions gain in competitiveness compared to regions with more ambitious climate change mitigation policies and consequently have marginally higher GDP levels than in the Reference. In the majority of these regions, exports increase or imported goods are replaced with domestically produced goods (Table 3). Hence, carbon leakage leads to a geographical shift of emission-intensive production.

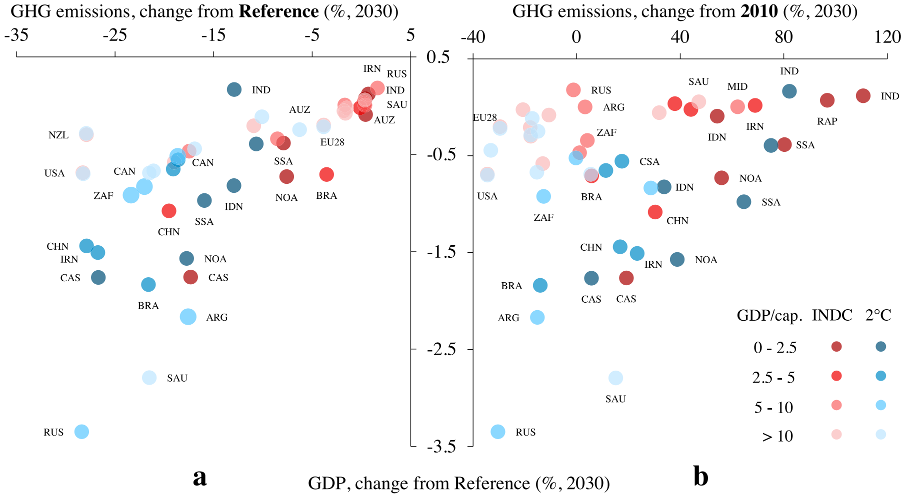

Fig. 7. GDP impact by region in the INDC and 2 °C scenario (% change from Reference in 2030). Colours reflect income groups as expressed by GDP per capita in 2010 (market prices, constant 2004 thousand US $). Some of the labels are omitted to improve the clarity of the figure; numerical results provided in Table 3. GHG emissions cover emissions from energy, industry and agriculture, excluding LULUCF. a) Emission levels that deviate stronger from the Reference imply larger GDP impacts, although there is substantial regional differentiation. b) Higher levels of greenhouse gas emissions in 2030 compared to 2010 in low-income regions can be consistent with a 2 °C scenario.

Table 3
Macro-economic results of climate change mitigation; GHG changes exclude LULUCF.

% change from Reference, 2030	GHG		GDP		Private consumption		Export		Import		Investment	
	INDC	2 °C	INDC	2 °C	INDC	2 °C	INDC	2 °C	INDC	2 °C	INDC	2 °C
World	−11.17	−21.59	−0.42	−0.72	−0.54	−0.96					−0.40	−0.64
China (CHN)	−19.53	−27.89	−1.08	−1.44	−1.22	−1.68	−2.64	−3.35	−1.68	−2.26	−0.78	−1.05
USA	−28.28	−28.25	−0.69	−0.70	−0.85	−0.95	−0.92	−0.98	−1.06	−1.48	−0.85	−0.83
European Union (EU)	−3.85	−3.85	−0.20	−0.22	−0.22	−0.33	−0.67	−0.98	−0.43	−1.23	−0.19	−0.27
Russia (RUS)	1.62	−28.39	0.18	−3.35	0.00	−2.72	0.75	−6.17	0.18	−1.67	0.02	−1.61
India (IND)	0.69	−12.91	0.12	0.17	−0.06	−0.16	2.02	3.32	0.56	0.70	0.03	0.00
Japan (JAP)	−1.50	−16.93	−0.02	−0.44	−0.13	−0.70	−0.05	−0.63	−0.60	−1.42	−0.08	−0.58
Central Asia and Caucasus (CAS)	−17.33	−26.70	−1.76	−1.76	−1.79	−2.22	−1.91	−2.32	−0.86	−1.90	−0.95	−1.05
Brazil (BRA)	−3.54	−21.63	−0.71	−1.84	−0.87	−2.41	−1.39	−4.03	−0.73	−4.04	−0.26	−1.30
Rest of Central and S. Am. (CSA)	−0.14	−18.61	−0.02	−0.56	−0.10	−0.69	0.75	−1.04	0.62	−0.88	0.10	−0.38
South-East Asia (SEA)	0.28	−19.10	0.04	−0.65	−0.20	−1.04	−0.21	−0.78	−0.60	−1.16	−0.04	−0.75
Sub-Sahara Africa (SSA)	−7.92	−15.94	−0.38	−0.97	−0.56	−1.38	0.25	−0.56	0.25	−0.60	−0.06	−0.29
Canada (CAN)	−19.00	−21.11	−0.58	−0.67	−0.75	−0.92	−0.90	−1.02	−0.96	−1.18	−0.70	−0.77
Rest of Middle East (MID)	−1.70	−22.02	0.01	−0.83	−0.19	−1.12	0.14	−1.60	−0.11	−1.55	0.08	−0.56
Mexico (MEX)	−17.49	−18.64	−0.47	−0.52	−0.66	−0.77	0.18	0.19	0.09	−0.04	−0.31	−0.35
Indonesia (IDN)	0.41	−12.94	−0.09	−0.82	−0.15	−0.92	−0.37	−1.91	−0.39	−1.51	0.04	−0.45
Iran (IRN)	0.29	−26.76	0.02	−1.51	−0.16	−3.22	−0.59	2.47	−1.09	−0.95	−0.03	−1.86
Republic of Korea (KOR)	−10.94	−10.11	−0.21	−0.11	−0.40	−0.46	−0.50	−0.35	−0.82	−1.15	−0.19	−0.18
North Africa (NOA)	−7.60	−17.74	−0.73	−1.57	−0.83	−1.83	−0.72	−1.80	0.07	−0.48	−0.18	−0.67
Rest of Asia and Pacific (RAP)	0.38	−10.69	0.07	−0.39	−0.30	−1.05	−0.49	0.46	−1.72	−1.07	−0.14	−0.31
Australia (AUS)	−1.64	−6.28	−0.08	−0.25	−0.17	−0.42	0.08	−0.26	−0.05	−0.52	−0.01	−0.19
Rest of Europe (ANI)	−1.79	−21.52	−0.05	−0.69	−0.18	−0.94	0.04	−0.86	−0.26	−1.00	−0.07	−0.62
South Africa (ZAF)	−8.53	−23.38	−0.34	−0.92	−0.43	−1.14	−0.73	−1.73	−0.61	−1.27	−0.21	−0.52
Saudi Arabia (SAU)	0.33	−21.54	0.06	−2.79	0.01	−3.80	0.47	−3.01	0.42	−1.71	0.03	−1.23
Argentina (ARG)	0.35	−17.59	0.01	−2.17	−0.12	−2.54	0.11	−3.23	−0.40	−2.41	−0.04	−1.49
New Zealand (NZL)	−27.91	−27.93	−0.30	−0.28	−0.36	−0.44	−0.88	−0.85	−1.10	−1.33	−0.60	−0.63

A first look at the results of the 2 °C scenario in Fig. 7 (blue dots in panel a, left-hand side) reveals a shift down and to the left compared to the INDC scenario (red dots): the 2 °C pathway implies stronger emission reductions, leading to more sizeable GDP impacts compared to the Reference in 2030. Panel b of Fig. 7 displays the greenhouse gas emission reductions relative to the levels in the year 2010. This visualization shows that the INDCs of high-income regions imply substantial emission reductions compared to historical levels. In addition, the right-hand side of Fig. 7 illustrates clearly that the 2 °C target can be met while allowing low-income regions to increase emissions relative to the levels observed in 2010.

A more detailed analysis of the results of the 2 °C scenario yields a number of findings. First, fossil fuel-producing regions, such as Saudi Arabia and Russia, experience a relatively strong drop in GDP compared to the Reference in 2030. The Reference does not assume a trend-breaking transformation towards a diversified economy, such that economic activity in some countries remains to rely heavily on fossil fuel exports. As indicated in Table 2, the 2 °C pathway leads to demand reductions for oil, gas and solid fuels. Since these goods typically represent a substantial share of economic activity and exports in some of the fossil-fuel producing regions, strong global climate action appears to lower the GDP levels in these countries. Second, the climate ambitions influence the relative competitive positions between countries. India is a particular case in this respect. The GDP per capita-based assumption to include India among the group of low-income countries for which carbon prices converge to relatively low levels (around 26 US $ (2005) in 2030) leads to competitive gains: an increase in the exports of energy-intensive industries drive GDP to higher levels than in the INDC scenario in 2030. More generally, the contribution of changes in trade balance to the change in GDP differs by regions and is positive for some, but negative for others. Third, for some Latin American countries, such as Argentina and Brazil, the agriculture and consumer goods industry (including food production and processing) represent a significant share of economic activity and are strongly affected by emission reductions policies. As shown in Section 4.3, agriculture is one of the sectors with substantial (non-CO_2) emission reduction potential. The result is that the drop in GDP compared to the Reference in 2030 is strong relative to the reduction levels for Argentina and Brazil. Hence, sector-specific considerations are an important driver behind the results. Therefore, the next section disaggregates the global economic impact by sector.

Investments on average are reduced less than the other GDP components as, despite the reduction of economic activity due to the reallocation of resources, the mitigation action is closely related to low-carbon investments in the power, industrial and residential sectors. On the contrary, private consumption decreases more than GDP for nearly all regions as most domestic and international prices increase due to the carbon price and the reallocation of resources away from the optimal allocation of the Reference scenario.

Note that for the European Union (EU28), the Reference contains substantial climate action, as indicated in Table 1. The results presented here thus only look at the impact of additional climate policies. Since ambitious legislation is already in place, the Reference is close to the INDC scenario for the EU. In particular, the Reference includes the 2020 Climate and Energy Package, which implies a 20% cut in greenhouse gas emissions compared to 1990, a share of 20% renewables in energy consumption and a 20% improvement in energy efficiency by 2020. The INDC scenario considers the 2030 Climate and Energy Framework: 40% reduction of GHG emissions compared to 1990 (43% compared to 2005 in the sectors included in the Emission Trading System, and 30% compared to 2005 in non-ETS sectors), 27% renewables in energy consumption and an indicative target 27% for improvements in energy efficiency compared to projections by 2030.

4.7. Sector-specific effects

This section disaggregates the global results on a sector-specific basis. Table 4 presents output levels and changes in employment for disaggregated for 16 sectors. Since detailed (sectoral)

Table 4
Sector-specific output and employment results in 2030.

% change from Reference	Output level		Employment							
Scenario:	INDC	2 °C	INDC				2 °C			
Labour tax recycling:	no	no	no	no	yes	yes	no	no	yes	yes
Regional employment:	endogenous	endog.	endog.	fixed	endog.	fixed	endog.	fixed	endog.	fixed
Agriculture	−0.5	−0.8	−0.4	0.2	−0.2	0.3	−0.8	0.3	−0.6	0.4
Fossil fuels	−4.0	−7.3	−1.3	−0.8	−1.4	−0.9	−9.9	−9.0	−9.9	−9.0
Electricity supply	−2.6	−4.7	−3.1	−2.9	−3.1	−3.0	−6.0	−5.6	−6.1	−5.8
Ferrous metals	−1.3	−2.4	−0.8	−0.4	−0.9	−0.5	−2.9	−1.8	−2.9	−1.7
Non-ferrous metals	−0.8	−1.3	−0.9	−0.4	−1.1	−0.7	−1.9	−0.8	−2.0	−0.9
Chemical Products	−0.6	−1.1	−0.5	0.0	−0.6	−0.2	−1.6	−0.4	−1.5	−0.3
Paper Products	−0.4	−0.7	−0.4	0.1	−0.4	0.0	−0.7	0.3	−0.7	0.3
Non-metallic minerals	−1.1	−1.7	−0.4	0.1	−0.5	0.0	−1.1	−0.2	−1.1	−0.1
Electric Goods	−0.6	−0.8	−0.8	−0.3	−1.0	−0.4	−0.9	0.3	−0.8	0.5
Transport equipment	−0.9	−1.3	−0.9	−0.4	−0.9	−0.5	−1.5	−0.4	−1.4	−0.2
Other Equipment Goods	−0.9	−1.4	−1.2	−0.8	−1.4	−1.1	−1.7	−0.7	−1.9	−0.9
Consumer Goods Industries	−0.4	−0.6	−0.5	0.0	−0.5	−0.1	−0.8	0.4	−0.8	0.3
Construction	−0.4	−0.5	−0.2	0.1	−0.1	0.1	−0.4	0.2	−0.3	0.2
Transport	−0.7	−1.3	−0.4	0.1	−0.1	0.3	−0.9	0.2	−0.7	0.3
Market Services	−0.3	−0.5	−0.5	0.0	−0.3	0.0	−0.9	0.2	−0.8	0.2
Non Market Services	−0.1	−0.2	−0.1	0.1	0.0	0.1	−0.1	0.2	−0.1	0.2

implementation plans of the INDCs up to 2030 are not available, we assume a common carbon price across all sectors within a region. The notable exception is the EU, where we implement different targets between ETS and non-ETS sectors, as discussed in the previous section.

A first observation is that relatively strong reductions in output and, correspondingly, employment levels occur in the fossil fuel sectors: coal, (crude) oil and gas. These results are consistent with Section 4.1. The underlying explanation is that stronger climate policies lead to more efficient use of energy and to a shift in the composition of fuel consumption. Energy efficiency also leads to a lower demand for electricity, which results in lower output and employment levels in the power sector, in line with Section 4.4. Table 4 shows the electricity supply sector as an aggregate of generation, transmission and distribution, and illustrates that global job creation in renewable energy technologies is not sufficient to compensate for the employment reduction due to lower electricity demand and for the jobs lost in coal-based electricity generation. The results here consider economy-wide feedback mechanisms and inter-industry interactions via intermediate inputs. Therefore they should be seen as complementary with the results in previous sections.

Second, energy intensive sectors, such as ferrous metals and non-metallic minerals are among the sectors that are most affected by stronger climate policies due to more greenhouse gas-intensive production input structures. In addition, some of these sectors emit substantial levels of non-combustion CO_2 and other greenhouse gases, as discussed in Section 4.3. Conversely, the impact on output levels of relatively low-carbon service sectors is smaller.

The results on employment include additional scenarios that explicitly consider the impact of revenue recycling and alternative representations for the modelling of unemployment. In the scenarios with tax recycling (indicated by '*Labour tax recycling: yes*' in Table 4), the revenue raised by carbon taxes is used to lower existing distortionary labour taxes. As a consequence, labour becomes a more attractive input in the production process, leading to more jobs economy-wide: the job decrease is mitigated from −0.34% to −0.26% in the INDC scenario, and from −0.74% to −0.66% in the 2 °C scenario (under the assumption of endogenous unemployment rates). Concerning the modelling of unemployment, two options are considered: endogenous regional unemployment rates according to a wage curve mechanism (indicated by '*Regional employment: endogenous*' in Table 4) and fixed unemployment rates per region. The former is in line with empirical evidence (Blanchflower and Oswald, 1995), while the latter represents the view that climate policy will not affect the fundamental determinants of unemployment in the long run, such that unemployment rates would return to natural rates (see Blanchard and Katz, 1997, for a broader discussion). The outcome of the simulations with fixed unemployment rates highlights a transition of jobs from emission-intensive sectors to low-carbon, service oriented sectors, in line with the findings of Hafstead and Williams (2016). The job transition is clearly illustrated by Fig. 8 (fixed unemployment rate, with labour tax recycling). In addition, Fig. 8 shows that the sectors that experience the strongest negative impact in terms of employment are not necessarily the sectors that provide the largest numbers of jobs (indicated by the height of the bars in Fig. 8).

5. Conclusions

This paper provides a model-based assessment of the INDCs, a central element in the global climate change negotiations held in

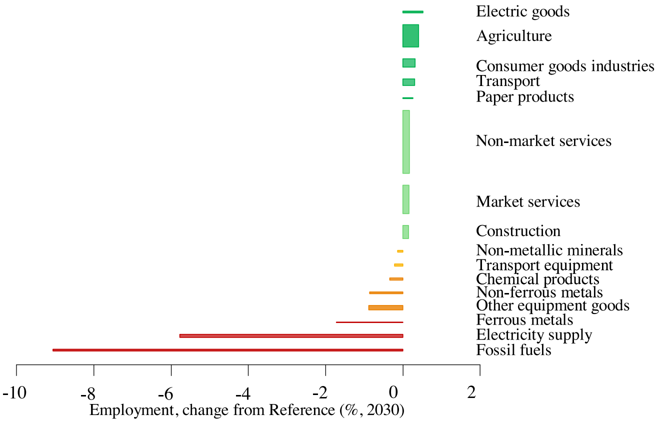

Fig. 8. Transition of jobs from energy-intensive sectors to more service-oriented sectors. The employment impact per sector is shown for the 2 °C scenario with carbon tax revenue recycling via lower labour taxes and fixed unemployment rates per region. The length of the bars shows the percentage change relative to the Reference in 2030, while the height of the bars is scaled to reflect the employment levels in the Reference in 2030. As a result, the surface of the bars reflects the change in absolute number of jobs compared to the Reference in 2030.

Paris in December 2015 (COP21). In addition, we compare the current policy proposals embedded in the INDCs with a pathway that is likely to limit global warming to 2 °C above pre-industrial levels by the end of the century. This 2 °C scenario is designed to respect the carbon budget by 2050 indicated by the IPCC (2014), takes efficiency into consideration through convergence of carbon prices across regions and allows low-income countries to cut greenhouse gas emissions at an adjusted pace, in line with the "common but differentiated responsibilities" specified in the United Nations Framework Convention on Climate Change.

The results of numerical simulations indicate that the INDCs have little impact on global oil and gas demand. Notable, considerable demand reductions of energy in general (efficiency) and solid fuels in particular, lead to lower greenhouse gas emissions. A substantial gap remains between the global GHG emissions in the INDCs and the 2 °C scenario in 2030, of which nearly one third can be bridged by decarbonising the power sector. Economic impacts differ widely between regions and sectors. The INDCs imply modest reductions in GDP for most regions (less than 1% compared to the Reference in 2030), whereas some regions increase GDP due to gains in competitiveness driven by relatively unambitious climate policy proposals. Global economic growth rates are only marginally below levels of the Reference. Hence, the analysis shows that global action to cut emissions is consistent with robust economic growth. Emerging and lowest-income economies will maintain high rates of economic growth, while fossil-fuel exporting countries face larger impacts.

The modelling framework has global coverage and exploits the complementarities between a highly detailed energy system model (JRC-POLES) and an economy-wide CGE model (JRC-GEM-E3). As a result, the analysis contains a rich degree of technological information and incorporates intermediate input links between different economic sectors and trade relations between multiple regions, addressing part of the critique of Rosen (2016).

Future work can improve the analysis in various ways. In the coming years countries are expected to develop detailed implementation plans on how the country targets will be distributed across their economic sectors and which policy instruments are going to be used. This may include mechanisms for the pricing of emissions (tax, market, linkages), as well as fuel-, sector- or greenhouse gas-specific measures and command-and-control policies that will influence the cost of mitigation policy. In terms of methodology, the models used in this exercise can be further harmonized and integrated. Including feedback mechanisms from the aggregate economic model to the partial equilibrium energy system model is one example. Furthermore, the analysis focuses on the cost side of climate change mitigation policy and therefore neglects the (avoided) impact of climate change-induced damages or the benefits that climate policy may have on the energy security of a country (see e.g. Matsumoto and Andriosopoulos, 2016). Finally, this paper does not address the uncertainty that is inherent in the demographic and economic forecasts underlying the scenarios.

Disclaimer

The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

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Appendix A. JRC-POLES description and categories

The JRC-POLES (Prospective Outlook on Long-term Energy Systems) model is a global partial equilibrium simulation model of the energy sector, with complete modelling from upstream production through to final user demand. The JRC-POLES model follows a year-by-year recursive modelling, with endogenous international energy prices and lagged adjustments of supply and demand by world region, combining price-induced mechanisms with a detailed technological description and technological change in electricity generation. The model covers 66 countries or regions worldwide (88 for oil and gas production), 15 fuel supply branches, 30 technologies in power production, 6 in transformation and 15 final demand sectors (Table 5). The JRC-POLES model was specifically designed for the energy sector but also includes other GHG emitting activities. Non-CO_2 emissions in energy, industry and agriculture and CO_2 emissions from land use follow a cost curves approach.

Energy supply is reactive to prices of reserves and resources (technological improvement, increased discoveries). Energy inputs into energy production account into production costs. The role of OPEC as a swing producer, the production cost of the marginal producer, the transport cost and the correlation between regional markets and between commodities' prices are factors influencing each commodity's price. Prices are set once producers have supplied global demand.

In energy transformation, the power sector in particular is detailed. Electricity demand levels and sectoral hourly load curves from representative days serve to form a monotonous load curve, used as a basis for competition in expected needs for new capacities among all technologies using their levelised costs and incorporating limits on potentials. For production, after the contribution of must-run technologies, for each hourly block a merit order competition takes place based on the basis of variable costs. Technology substitution takes place via evolving technology costs, fuel costs, and specific policies (e.g. carbon price, feed-in tariff). Global cumulative installed capacity drives endogenous learning curves that result in decreasing investment costs (based on data from IEA and TECHPOL; discussed in more detail in Section 4.4).

In final demand, the energy services related to sectoral activity variables are supplied with energy-consuming equipment that depreciates over time; substitution can occur in the new equipment to be installed each year, with various levels of detail (from explicit techno-economic description of engine types in private cars to fixed cost and efficiency of fuel use in industrial branches). Energy prices, which can be modified (e.g. carbon price, technology subsidy) in order to reach a policy objective, have short term impacts (adjustment of overall energy demand) and long term impacts (energy efficiency, technological substitution).

The LULUCF and agriculture sectors interact with the energy sector via the supply and demand of biomass-for-energy; emissions levels are determined by climate policies (marginal abatement cost curve, from GLOBIOM (IIASA, 2015a)) and biomass-for-energy supply levels (marginal cost curve, also from GLOBIOM). More stringent climate policies result in increased competitiveness of biomass due to its low carbon content, and in a higher demand for biomass; increased biomass supply (generally) leads to higher emissions from LULUCF and agriculture and higher biomass prices. The biomass price and emissions are a result of these interactions. A large part of the GHG mitigation potential in LULUCF and agriculture is accessible at low cost, and with relatively minor feedback due to an increased demand for biomass. Historical LULUCF emissions of 1 Gt CO_2 fit within the uncertainty range between −0.5 Gt and 1.25 Gt provided by Grassi and Dentener

Table 5
JRC-POLES categories.

	Fuel supply branches		Final demand sectors
1	Oil – conventional	1	Iron and steel industry
2	Oil – shale oil	2	Chemicals
3	Oil – bituminous	3	Non-metallic minerals
4	Oil – extra-heavy	4	Other Industry
5	Gas – conventional	5	Chemical Feedstocks
6	Gas – shale gas	6	Non-energy uses
7	Gas – coal-bed methane	7	Residential
8	Coal – steam	8	Services
9	Coal – coking	9	Agriculture
10	Biomass – forests	10	Road transport
11	Biomass – short rotation crops	11	Rail transport
12	Biomass – other energy crops	12	Air transport
13	Biomass – traditional	13	Other transport
14	Uranium	14	Air bunkers
15	Solar heat	15	Maritime bunkers
Electricity generation technologies			
1	Pressurised Fluidised Coal	16	Nuclear
2	Pressurised Fluidised Coal + CCS	17	New Nuclear Design (Gen.IV)
3	Integrated Coal Gasification (IGCC)	18	Combined Heat & Power
4	Integrated Coal Gasification + CCS	19	Gas Fuel Cells
5	Lignite Conventional Thermal	20	Hydrogen Fuel Cells
6	Coal Conventional Thermal	21	Ocean (wave & tidal)
7	Gas Conventional Thermal	22	Geothermal
8	Gas-fired Gas Turbine	23	Hydroelectricity
9	Gas-fired Gas Turbine + CCS	24	Small Hydro
10	Gas-fired Gas turbine Combined Cycle	25	Wind onshore
11	Oil Conventional Thermal	26	Wind offshore
12	Oil-fired Gas turbine	27	Solar Power Plant (CSP)
13	Biomass Gasification	28	Solar Power Plant (CSP + storage)
14	Biomass Gasification + CCS	29	Distributed Photovoltaics
15	Biomass Thermal	30	Centralised Photovoltaics
	Transformation		
1	Power generation		
2	Coal liquefaction		
3	Gas liquefaction		
4	Biomass liquefaction 1st generation		
5	Biomass liquefaction 2nd generation		
6	Hydrogen production		

Table 6
Main data sources for the JRC-POLES model.

Variable		Data source	Projections
Population		United Nations (2013)	UN (2015, medium fertility)
GDP, growth		World Bank (2014)	EC (2015), IMF (2016), OECD (2013)
Value added		World Bank (2014)	JRC-POLES model
Energy resources	Oil, gas, coal	BGR (2013),USGS (2013), WEC (2013a)	
	Uranium	OECD (2015)	
	Biomass	EU: Green-X model Non-EU: GLOBIOM model	
	Hydro	Enerdata (2015)	
	Wind, solar	NREL (2013), Pietzcker et al. (2014)	
Energy balances	Reserves, production	BP (2015), Enerdata (2015), IEA (2015)	
	Demand by sector and fuel	Enerdata (2015), IEA (2015)	
	Transformation (including. power), losses	Enerdata (2015), IEA (2015)	
Energy prices	International and consumer prices	EIA (2016), Enerdata (2015), IEA (2015)	JRC-POLES model
GHG emissions	Energy CO2	Derived from JRC-POLES energy balances	JRC-POLES model
	Other GHG Annex 1	UNFCCC (2016)	JRC-POLES model, GLOBIOM
	Other GHG Non-Annex 1 (excl. LULUCF)	EDGAR (European Commission JRC 2015)	JRC-POLES model, GLOBIOM
	LULUCF Non-Annex 1	FAO (2014)	JRC-POLES model, GLOBIOM
Technology costs	JRC-POLES learning curves	Based on literature, including: European Commission JRC (2014) IEA Technology Roadmaps WEC (2013b) TECHPOL database	

(2015). Projections are derived from information of the GLOBIOM model translated to match historical emissions.

Main inputs are macroeconomic data, fuel resources and energy and climate policies. Historical data on energy demand, supply and prices are provided by Enerdata (derived from IEA, harmonized and enriched by national statistics). Activity levels are based on exogenous data (GDP, population) and own estimates: sectoral value added is based on correlation with income per capita; car ownership and mobility needs per transport mode are based on income per capita and energy prices; surface and building demand are based on the size of dwelling and the number of persons per dwelling, both of which are based on income per capita.

Table 6 lists the main data sources for the JRC-POLES model. A few comments accompany the historical data sources and sectors covered:

- UNFCCC: flexible data queries. Used for Annex I industrial process CO2 and non-CO2 GHGs in energy, industry, waste, LULUCF and agriculture.
- EDGAR: v42 and v4.2 FT2010. Used for: non-Annex I industrial process CO2 and non-CO2 GHGs in energy, industry and waste; non-Annex I CH4 and N2O in LULUCF and agriculture; Indonesia CO2 from peat fires.
- FAO: FAOSTAT. Used for non-Annex I CO2 in LULUCF.
- Complemented by national inventories (Brazil LULUCF emissions decrease, Mexico).
- Peat fires are not covered (except for Indonesia).

The following notes elaborate further on the projections of data:

- Energy CO2 is derived from the projections of energy.
- For non-CO2 GHGs in energy and industry, marginal abatement cost curves are based on EMF21 (Weyant et al., 2006) and US EPA (2013). The MAC curves were extended to 2050, by considering the same abatement potential (as a share of emissions for that gas and sector) as in 2030.
- For LULUCF and agriculture, marginal abatement cost curves are based on GLOBIOM, with data corresponding to GLOBIOM's 2015 scenarios. The behaviour of emissions from the GLOBIOM emissions from the MACCs is applied to the JRC-POLES model emissions, from the historical starting level (from UNFCCC or FAO).

Appendix B. JRC-GEM-E3 description and nesting structures

The JRC-GEM-E3 (General Equilibrium Model for Economy, Energy and the Environment) model is a recursive-dynamic CGE model. The model describes the economic behaviour of households and firms, includes (exogenous) government policies, international trade flows (in the style of Armington, 1969), different types of energy use and greenhouse gas emissions. The main data source is GTAP8, complemented with other data sources such as employment data from the International Labour Organization and energy statistics from IEA.

In each region, a representative household maximizes utility, represented by a nested Stone-Geary utility function (Linear Expenditure System), subject to a budget constraint. The nesting structure, distinguishes between durables (residential and mobility equipment) and non-durables (11 categories). Importantly, the use of durables requires the consumption of fuels and leads to emissions. The stock of durables depreciates over time, and the investment decision is based on both the price of the durable and of the fuels. Labour supply is represented by a wage curve mechanism which relates wages to unemployment rates in accordance with the empirically validated elasticity of −0.1 (Blanchflower and Oswald 1995).

Firms, disaggregated into 31 sectors, maximise profits subject to a nested Constant Elasticity of Substitution (CES) production technology constraint. Fig. 9, Fig. 10 and Fig. 11 illustrate the nesting structure for the non-energy sectors, the crude oil sector and the electricity sector, respectively. Firms are myopic in their investment choices, which implies that sectors invest to attain a desired level of capital stock in the next period given current prices and exogenous depreciation rates. Based on data from PRIMES, TECHPOL and IEA, the electricity sector is disaggregated into 10 generation sectors and a sector covering transmission and

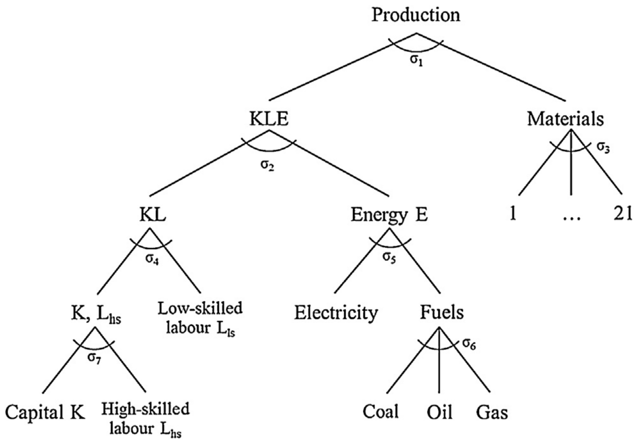

Fig. 9. Nested CES production structure for non-energy sectors.

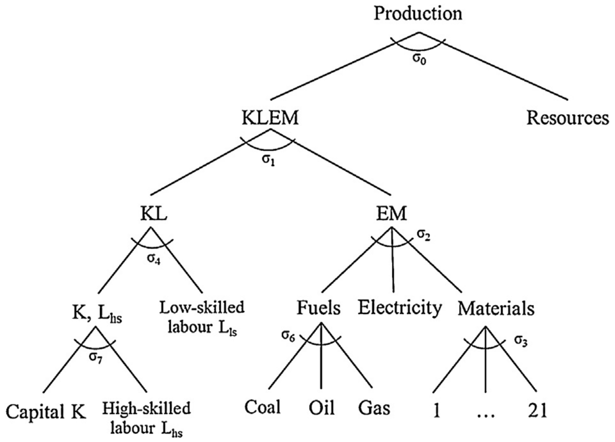

Fig. 10. Nested CES production structure for the crude oil sector.

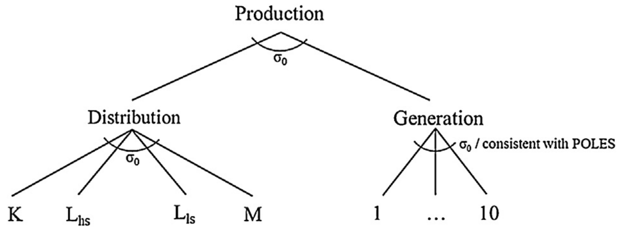

Fig. 11. Nested CES production structure for the electricity sector.

Table 7
Input cost shares (%, global average, 2004) for electricity generation technologies.

	Electricity generation technology									
	Coal fired	*Oil fired*	*Gas fired*	*Nuclear*	*Biomass*	*Hydro*	*Wind*	*Solar*	*CCS coal*	*CCS Gas*
Inputs										
Agriculture					31.9					
Coal	32.8								31.9	
Oil		78.7								
Gas			80.3							81.1
Chemical Products				8.8						
Other Equipment Goods	4.9	0.4	0.4	0.5	1.9	1.1	10.5	1.0	6.1	0.3
Construction	2.7	1.2	3.2	1.1	1.6	2.3	6.8	8.2	2.3	2.9
Labour	9.7	3.4	1.7	4.1	4.2	15.8	4.3	9.1	9.0	1.6
Capital	49.8	16.4	14.4	85.5	60.5	80.8	78.4	81.7	50.8	14.0

distribution. The resulting cost structure is presented in Table 7. This electricity sector disaggregation is an important step in the integration of JRC-POLES and JRC-GEM-E3, as detailed below.

The figures below present the nested CES production technologies for different sectors. Furthermore, the nesting structure of the oil refinery sector follows the structure of the non-energy sectors with the addition of a Leontief top-level substitution between a capital-labour-energy-materials bundle and the input of crude oil. The electricity generation technologies follow a Leontief input structure of which the cost shares are presented in Table 7. The values of the elasticities of substitution are listed in Table 8. It is useful to remark here that σ_0 represents a Leontief structure ($\sigma_0 = 0$) and that σ_4 is sector-specific, with higher values in service-oriented sectors and lower values in agriculture and resource sectors.

Appendix C. Policies

This Appendix provides details on which policies were considered in the scenarios discussed in this paper. Further information on the policies considered, how they were modelled and on other countries can be found in the Excel sheet included as online appendix.

Policies were modelled in the JRC-POLES model with the following instruments: carbon prices for GHG emissions targets; imposed fuel standards for vehicles; feed-in tariffs for renewable technologies in the power sector. Climate-related policies were modelled using carbon prices that impacted all sectors of the economy. Table 9 summarizes the carbon values in the Reference, the INDC scenario and the 2 °C scenario. The above-mentioned instruments are modified iteratively until the modelled outputs reach the desired objective. In energy prices, the components of energy taxation are held constant by default (VAT is held constant as a percentage; excise duties are held constant in volume, excluding the impact of carbon prices); energy subsidies are kept constant as ratios of international prices.

Emissions reductions are obtained by comparing the emissions and energy system obtained in the Reference scenario with those in a scenario with additional policies, for each sector and country or region. They are achieved depending on the economic attractiveness of mitigation options within each sector and across sectors. Energy prices, including carbon price or technology subsidies, have short term impacts (adjustment of overall energy demand) and long term impacts: overall energy efficiency of the sector, energy efficiency of specific technologies, technological substitution towards less costly technologies in the competition for new equipment (e.g. fossil fuel switch when gas is more competitive than more carbonated fuels, or gain in market shares of renewable technologies).

Table 8
Calibrated values of the constant elasticities of substitution.

Elasticity of substitution	Value
σ_0	0
σ_1	0.2
σ_2	0.25
σ_3	0.25
σ_4	0.20–1.68
σ_5	0.5
σ_6	0.9
σ_7	0.35

Table 9
Carbon values in the Reference and the scenarios.

Carbon values, 2030 US $ 2015	Reference	INDC	2 °C
China (CHN)	0	29	53
USA[a]	0	53	53
European Union (EU)[b]	29	53	53
Russia (RUS)	0	0	53
India (IND)	0	0	26
Japan (JAP)	0	6	53
Central Asia and Caucasus (CAS)	0	49	53
Brazil (BRA)[c]	0	5	53
Rest of Central and S. Am. (CSA)	0	2	45
South-East Asia (SEA)	0	0	26
Sub-Sahara Africa (SSA)	0	7	26
Canada (CAN)	1	42	53
Rest of Middle East (MID)	0	4	53
Mexico (MEX)	0	46	53
Indonesia (IDN)	0	0	26
Iran (IRN)	0	0	53
Republic of Korea (KOR)	39	119	119
North Africa (NOA)	0	20	53
Rest of Asia and Pacific (RAP)	0	0	26
Australia (AUS)	20	32	53
Rest of Europe (ANI)	25	46	53
South Africa (ZAF)	0	10	53
Saudi Arabia (SAU)	0	0	53
Argentina (ARG)	0	0	53
New Zealand (NZL)	0	114	114

[a] USA: INDC carbon value reached already in 2025 (target year in the INDC).
[b] EU: average value over all sectors (ETS and non-ETS).
[c] Brazil: INDC carbon value is 3 US $ 2015 in 2025 (target year in the INDC).

C.1. The Reference: 2020 policies

A number of energy and climate policies announced for the 2020 time horizon in energy and climate are taken into account in the Reference scenario. Policies are sourced from previous rounds of UNFCCC negotiations ("Copenhagen Pledges") or from objectives either submitted to UNFCCC (National Communications) or, more recently, announced as national policies. Table 10 and Table 11 give

Table 10
Climate policies for selected countries in the Reference.

Climate policies					
UN Party	GHG coverage	Sectoral coverage	Target type	Target year	Objective
EU	All GHGs	All excl LULUCF	% reduction	2020 vs 1990	−20%
		ETS sectors	% reduction	2020 vs 2005	−21%
Canada	All GHGs	All excl LULUCF	Absolute	2020	727 MtCO2e
USA	All GHGs	All	Intensity of GDP	2020 vs 2005	−17%
Brazil	All GHGs	All	% relative to BAU	2020	−36.1% to −38.9% BAU: 2704 MtCO2e
Australia	All GHGs	All	% reduction	2020 vs 2000	−5%
Japan	All GHGs	All	% reduction	2020 vs 2005	−3.8%
South Korea	All GHGs	All excl LULUCF	% relative to BAU	2020	−30% BAU: 776 MtCO2e
China	CO$_2$	All excl LULUCF	Intensity of GDP	2020 vs 2005	−40% to −45%
India	GHG	All excl agriculture	Intensity of GDP	2020 vs 2005	−20% to −25%
Indonesia	All GHGs	All	% relative to BAU	2020	−26% BAU: 2200 MtCO2e
Russia	All GHGs	All	% reduction	2020 vs 1990	−15% to −25%
South Africa	All GHGs	All	% relative to BAU	2020	−34% BAU: 800 MtCO$_2$e

Table 11
Energy policies for selected countries in the Reference.

Energy policies				
UN Party	Technology	Metric	Target year	Objective
EU	Renewables	Share of gross final demand	2020	20%
	Renewable fuels	Share in transport demand	2020	10%
	Private vehicles emissions	Emissions, in g/km	2021	95
	Primary energy demand	% reduction vs. BAU (2007)	2020	−20%
Canada	Private vehicles emissions	Emissions, in g/km	2025	88
Mexico	Non-fossil + cogeneration	Share in power capacities	2018	34.60%
		Capacity targets	2018	Nuclear: 1.4 GW Renewables: 23.3 GW
	Non-fossil	Share in power generation	2024	35%
USA	Wind, Solar, Geothermal	Power production	2020	Double of 2012 level
	Private vehicles emissions	Consumption, miles/gal	2020	54.5
Argentina	Renewables	Share in power generation	2017	8%
Brazil		Capacity targets	2024	Biomass: 18 GW Large hydro: 117 GW Small hydro 8 GW Nuclear: 3 GW Solar: 7 GW Wind: 24 GW
Australia	Renewables	Share in power generation	2020	23.50%
Japan		Capacity targets	2020	Biomass: 5.5 GW Solar: 28 GW Wind: 6 GW
South Korea	Renewables	Share in primary demand	2020	5%
China	Non-fossil	Share in primary demand	2020	15%
		Capacity targets	2020	Hydro: 350 GW Nuclear: 58 GW Solar: 100 GW Wind: 200 GW
India		Capacity targets Additional vs. 2010	2022	Biomass: +10 GW Solar: +100 GW Wind: +60 GW
Indonesia	Renewables	Share in power generation	2019	19%
Turkey	Renewables	Share in gross final energy consumption	2023	20.50%
		Capacity targets	2023	Hydro: 34 GW Solar: 5 GW Wind: 20 GW
	Renewables	Share in power generation	2023	30%
South Africa		Capacity targets	2030	Solar: 9.4 GW Wind: 8.5 GW

an overview of included climate and energy policies respectively for a selection of countries.

Policy targets in terms of technological deployment or GHG emissions are reached via the combination of various instruments. Some energy and GHG targets are reached, or even over-achieved, following the evolution of economic activity, energy prices, technology costs and substitution effects without specific policy intervention being necessary. After 2020, fuel standards are relaxed, feed-in tariff policies are phased out, and carbon values are kept constant over time. Energy and emissions are thus then driven by income growth, energy and (2020) carbon values and expected technological evolution with no supplementary incentivizing of low-carbon technologies.

No policies targeting specifically non-CO$_2$ greenhouse gases and emissions from LULUCF and agriculture were included. As a result, emissions from these sectors are the result of the endogenous modelling (using marginal abatement cost curves, see data sources) given the price for biomass (determined by biomass demand) and the carbon price (in the countries where one was included in order to reach the other emissions policies).

The objectives of all the policies listed in the tables below were reached in the Reference scenario. The only policy in addition to these that was considered and implemented was the extension of the EU ETS beyond 2020 (decreasing cap beyond 2020).

C.2. The INDC scenario: 2030 policies

The INDC targets for 2030 (2025 for some countries) were reached using carbon prices and technology-specific instruments (such as feed-in tariffs). All INDCs are implemented, whether expressed as unconditional or conditional contributions. Several objectives were reached without the need of changing modelling parameters compared to the Reference scenario, as a result of energy prices and technological evolution, or as a result of the climate policies feedback on the energy system. Table 12 and Table 13 list the climate and energy policies included.

Emissions targets were set according to the following steps. First, the INDC target was calculated considering the perimeter of the INDC policy in each case (e.g. energy-only emissions, or all sectors excluding LULUCF, etc.). Climate-related policies were then modelled using carbon values that impacted all sectors of the economy, including agriculture and land use. Emissions reductions in each sector were achieved depending on the economic attractiveness of mitigation options across sectors. Emission reductions related to LULUCF are calculated endogenously; hence LULUCF-specific policies were not necessarily met. Second, for countries modelled individually, the emission reduction targets were taken directly from the INDCs. For regions modelled as a grouping of several countries, the individual countries' INDCs were summed into a single target for the region. If the summed countries represented only a share of the region (e.g. rest of Gulf, rest of sub-Saharan Africa), the summed INDC target expressed as a percentage growth compared to the summed historical emissions of 2010 was taken as the target for the whole region. Third, several countries (notably non-OECD countries) have expressed their INDCs as reductions compared to a Business-As-Usual (BAU) scenario. In certain cases, the Reference scenario was found to have lower emissions compared to the country's (or region's) announced BAU scenario or to its INDC target (this can be due to, for example, differences in the assumptions in economic growth, in the modelling frameworks, in energy prices, in energy consumption growth); in these cases no additional policies were implemented.

Beyond the time horizon of the INDCs (usually 2030), the level of policy ambition continues at a similar pace at the global level. Regional carbon values increase, including for countries that previously had no climate policies, progressively converging at a speed that depends on per capita income. The carbon price level of convergence was determined such that the global decrease of GHG intensity of GDP over 2030–2040 and 2040–2050 matches the rate of 2020–2030. Carbon prices converge in 2040 in high income countries (>30 k$2005 PPP per capita in 2030) and in 2050 in the middle and low (<20 k$2005 PPP per capita in 2030) income countries (at levels of 50% and 25% respectively of the carbon price in the high income regions).

C.3. The 2 °C scenario

In the 2 °C scenario, additional climate policies are implemented via higher carbon values. Energy policies of the INDC scenario are maintained. The climate policies increase in ambition from 2016 in all regions of the world, including countries with low income or whose INDC target was already reached without any policies in the INDC scenarios or that did not submit an INDC.

To account for the different financial capacity across regions, the scenario also differentiates the intensity of mitigation between

Table 12
Climate policies in the INDC scenario.

Climate policies					
UN Party	GHG coverage	Sectoral coverage	Base year	Target year	INDC
EU	All GHGs	All sectors	1990	2030	−40%
Canada	All GHGs	All sectors (LULUCF net-net)	2005	2030	−30%
Mexico	All GHGs	All sectors	2030 (BAU) BAU: 973 Mt CO2e	2030	−36%
USA	All GHGs	All sectors (LULUCF net-net)	2005	2025	−28%
Argentina	All GHGs	All sectors	2030 (BAU) BAU: 670 Mt CO2e	2030	−30%
Brazil	All GHGs	All sectors	2005	2025	−37%
Australia	All GHGs	All sectors	2005	2030	−28%
Japan	All GHGs	All sectors excl sinks	2013 2013: 1408 Mt CO2e	2030	−26%
Korea (Republic)	All GHGs	All sectors excl LULUCF	2030 (BAU) BAU: 850.6 Mt CO2e	2030	−37%
China	CO2 CO2 intensity of GDP	Energy	2005	2030	−65%
India	All GHGs GHG intensity of GDP	All sectors	2005	2030	−35%
Indonesia	All GHGs	All sectors	2030 (BAU) BAU: 2881 Mt CO2e	2030	−41%
Russian Federation	All GHGs	All sectors	1990	2030	−30%
Saudi Arabia	All GHGs	All sectors	2030 (BAU)	2030	−130 MtCO2e
Turkey	All GHGs	All sectors	2030 (BAU) BAU: 1175 Mt CO2e	2030	−21%
South Africa	All GHGs	All sectors		2030	2020–2035: plateau at 398–614 MtCO2e

Table 13
Energy policies in the INDC scenario.

Energy policies		
UN Party	Target year	Policy
EU	2030	At least 27% of renewable energy consumption (binding target)
	2030	At least 27% energy savings compared with BAU (binding target)
Brazil	2030	18% sustainable biofuels in energy mix
	2030	45% of renewables in energy mix
	2030	28–33% of renewables (other than hydro) in the total energy mix
	2030	23% renewables (other than hydro) in power supply
Japan	2030	20–22% nuclear
	2030	2–24% renewables
China	2030	20% non-fossil fuels in primary energy consumption
India	2030	40% of installed electricity generation capacity from non-fossil fuel based energy sources
Indonesia	2025	Minimum 23% energy from renewable sources (binding target)
Turkey	2030	Increasing capacity of production of electricity from solar power to 10 GW
	2030	Increasing capacity of production of electricity from wind power to 16 GW
	2030	Tapping the full hydroelectric potential
	2030	Commissioning of a nuclear power plant
	2030	Reducing electricity transmission and distribution losses to 15%
South Africa	2050	Decarbonised electricity by 2050 (US$349bn 2010–2050)
	2050	CCS: 23 Mt CO2 from coal-to-liquids plant (US$0.45bn)
	2050	Investment in electric vehicles (US$513bn 2010–2050)
	2030	Hybrid electric vehicles: 20% by 2030 (US$488bn)

regional groups. Carbon prices in the high, middle and low income countries converge in 2030 to the level of 53 US $ (2015). Regions with very low income per capita (<10 k$2005 PPP per capita in 2030) are allowed a longer transition period, with carbon prices of 26 US $ (2015) in 2030 and no full convergence to the level of countries with higher income per capita before 2050. Table 9 displays the carbon values for all regions and scenarios.

Appendix D. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2016.08.006.

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