DRAFT 13 April 2016

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

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Abstract

This paper presents a model-based assessment of the United Nations-led round of international climate change negotiations in Paris in December 2015 (COP21). We combine a technology-rich bottom-up energy system model with a top-down economic model that captures economy-wide interactions. We analyse the impact of the Intended Nationally Determined Contributions (INDCs) by the individual countries put forward in the run-up to COP21 on greenhouse gas emissions, energy demand and supply, and the wider economic effects, including the implications for trade flows and employment levels. We also illustrate how the gap between the Paris pledges and a pathway that is likely to restrict global warming to 2°C can be bridged, taking into account both equity and efficiency considerations. 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 global action to cut emissions is consistent with robust economic growth. Emerging and lowest-income economies will maintain high rates of economic growth. The analysis also provides evidence that the use of smart fiscal policies tailored to each region, i.e. increasing emission auctions and taxes, reducing indirect taxes to consumption and investment, and/or lowering labour taxes, can further increase GDP growth.

Keywords: international climate negotiations, global stock taking, Paris Agreement, INDC, modelling
JEL codes: C60, Q40, Q50

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. 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. The Paris Agreement is an important step forward in international climate change negotiations. First, the Agreement includes a legally binding 2°C target and mentions the ambition of restricting climate change to 1.5°C. Second, the Agreement puts forward a transparent and common framework for monitoring, reporting and verifying greenhouse gas (GHG) emissions. Third, the Agreement introduces a five-yearly review process with a first global stocktake scheduled for 2023, building on a facilitative dialogue scheduled for 2018. Furthermore, countries have agreed upon climate financing of at least 100 billion $ annually from 2020 onwards to fund projects on both climate change mitigation and adaptation in developing countries. In addition, the text acknowledges policy tools for capacity building in developing countries and allows for voluntary trade of emission reductions between parties. A number of issues, however, remain open by the Paris Agreement. One 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.

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 2.5 – 3°C by 2100 (Gütschow et al., 2015 and Kitous and Keramidas, 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 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. 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.

Numerous studies assess the climate pledges of the Copenhagen Accord (COP15) using CGE models, often with an enhanced representation of the energy sector and energy-intensive industries, such as Dellink et al. (2011), McKibbin et al. (2011), Peterson et al. (2011), and Tianyu et al. (2016); or integrated assessment models like e.g. den Elzen et al. (2011a, 2011b), and Van Vliet et al. (2012). In more recent year integrated assessments models (including CGE models) have been incorporated in multi-model exercises with a focus of the inter-comparison of model results. Kriegler et al. (2013) argue that the lack of socioeconomic cross-model harmonization enables a sensitive-like type of analysis through the variation of key assumptions as GDP and population. The models in Riahi et al. (2015), however, share common key macroeconomic assumptions, and the relevance of cross-model harmonization is recognized.

This paper is an update of the pre-COP21 analysis by Labat et al. (2015), whereas the methodology builds further on Russ et al. (2009) and Saveyn et al. (2011). The assessment combines a detailed, technology-rich energy system model (POLES) and an economy-wide Computable General Equilibrium (CGE) model (GEM-E3)[1] in two ways that allow for a broad assessment while preserving the details and particular strengths of each. First, the models are harmonized along a common Reference scenario and, second, they are soft-linked[2] 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)[3].

A Reference shared by the two models is developed based on common assumptions for the 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, capturing structural changes in developing countries based on historical data. In addition, emissions by greenhouse gas, economic sector and region are shared between the two models in the Reference. Furthermore, 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

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[1] For more detail see Capros et al. (2013) or http://ec.europa.eu/jrc/en/gem-e3

[2] This approach of linking an energy model with a CGE model with a bottom-up representation of the power sector builds further on 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; Sue Wing, 2008, Boehringer and Rutherford, 2008; Abrell and Rausch, 201x).

[3] On the Integrated Assessment Models included in IPCC (2014) Fifth Assessment Report, Working Group III: "One consequence of this very high degree of aggregation is that most IAMs cannot directly and explicitly model the costs and benefits of improvements in the energy efficiency of end-use technologies within each economic sector."

POLES. In particular, the totals of greenhouse gas emissions derived from the bottom-up analysis determine regional emission constraints for the economic assessment with GEM-E3. In addition, the shares of the different technologies in electricity generation in POLES are used as an input in the GEM-E3 analyses. This soft-link is enabled by the split of electricity generation into 10 technologies in the GEM-E3 model. As a result, the technology mix in electricity supply in the 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 and endogenous technological progress.

The remainder of the paper is organised as follows. In the next section, we describe the scenarios studied: the Reference scenario, the Paris pledges or INDCs and a scenario that is likely to put the world on track to meet the 2°C target. Results are presented in section 3. 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. Scenarios

This section describes the three scenarios analysed in this paper: the Reference, the Paris pledges scenario with the INDC's 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 United Nations (2013) 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 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 very low (EU) or zero (rest of the world) in 2015. Furthermore, carbon values range between 0 and 20 US $ (2005) in the year 2030. Second, growth of Gross Domestic Product (GDP) in the Reference is 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[4] and consequent increasing market power of OPEC drive the oil price upwards over time (endogenous in POLES). This upward evolution of price is also sustained by the progressive substitution of conventional resources for expensive energy-intensive liquid fuels: tar sands, extra heavy oil and oil shale are forecasted to represent together approximately 7% of the total production in 2030. The oil price level is projected to reach around 100 US$2005 in 2030. Fourth, the global average of energy intensity of GDP follows a downward trend slighter faster than the one observed in the previous 25 years (-1.4%/year 1990-2015, -2.0% per year 2015-2030), driven by energy efficiency and the increasing technological maturity of low-carbon technologies and the assumptions mentioned above. Fifth, the main data sources for historic emissions are regional and national energy balances for CO_2 combustion; UNFCCC (2014), Edgar (European Commission 2014) and FAO-Stat (FAO 2014) for non-combustion and LULUCF CO_2, $CH_{4,}$ N_2O and agriculture and land-use emissions. The level of global greenhouse gas emissions (excluding sinks) in the Reference gradually increases over the entire time period considered, as illustrated in Figure 1. For non-CO_2 GHGs, marginal abatement cost curves are based on EMF21 (Weyant et al. 2006), US EPA (2013) and GLOBIOM for LULUCF and agriculture (IIASA, 2015a).

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 high-end pledges made, i.e. including elements that are dependent on other conditions, such as the provision of climate financing. In the case where the 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[5], which are implemented in the model by region-specific economy-wide carbon prices. 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 82 US $ (2005) in 2030, indicate that there is potential for enhancing the cost-efficiency on a world level[6]. The global aggregate of GHG emissions does not display a peaking level before 2030, but continues to increase slightly up to 2030 (Figure 1). GHG intensity of the economy decreases at an accelerated pace: -2.9% per year over the period 2015-2030. Global aggregate GHG emissions in 2030 are more than 9% 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 energy

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[4] Main data sources are German Federal Institute for Geosciences and Natural Resources (2013), Schenk (2012) and US Geological Survey (World Petroleum Assessment 2013)

[5] An Excel sheet with the detailed, country-level information is available as online Appendix.

[6] The Paris Agreement (Article 6) discusses 'cooperative approaches', which could include carbon trading.

intensity (GHG per GDP) implied by the INDCs is continued in the period 2030-2050 (global average reduction rate of 3.3% per year).

The 2°C scenario considers a pathway of global greenhouse gas emissions that is compatible with the range indicated by the latest UNEP Gap Report as in line with staying below a 2°C warming by the end of the century (UNEP 2014). Global emission levels converge with levels of the IPCC (2014) RCP2.6 scenario by 2050, but emission levels up to 2030 are slightly higher. A peak in world aggregate GHG emissions appears around the year 2020 (Figure 1). The specification of the 2°C scenario takes both equity and efficiency considerations into account. For most regions, carbon prices converge to around 75 US $ (2005) in 2030. 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 prices of low-income countries 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 19 US $ (2005) in 2030. 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 25% lower than in the Reference in 2030. Accordingly, GHG intensity of the economy decreases at more than double the rate of the recent past (-4.2% 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. The Rest of Central and South America is a region that aggregates countries of both groups, hence the overall carbon price will lie between the high and the low values.

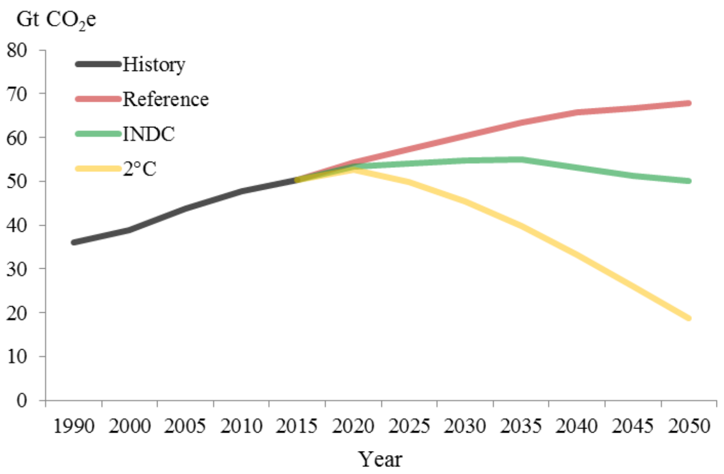

Figure 1: Global greenhouse gas emissions in the three scenarios. Source: POLES model

Table 1: The scenarios

	GHG*	**Yearly GDP growth rate**	**GHG/GDP****	**Change in GHG emissions**		**Carbon value**
	2005	2020-2030	2030	2030 relative to 2005		
		Reference	Reference	Reference	INDC	2°C
World	37.76	2.98	0.41	41.13	23.74	
China	8.16	4.99	0.56	109.53	74.97	High
USA	7.09	2.02	0.27	-20.56	-37.46	High
European Union	5.17	1.97	0.20	-32.38	-36.38	High
Russia	2.23	2.76	0.83	4.77	5.16	High
India	1.98	6.49	0.42	194.01	128.75	Low
Japan	1.35	1.01	0.22	-22.97	-26.54	High
Central Asia and Caucasus	1.13	4.54	0.77	40.07	50.09	High
Brazil	0.92	3.29	0.39	25.68	20.22	High
Rest of Central and S. Am.	0.90	3.71	0.36	59.43	56.12	Intermediate
South-East Asia	0.79	3.40	0.78	43.96	44.72	Low
Sub-Sahara Africa	0.78	6.30	0.39	104.94	105.82	Low
Canada	0.76	2.10	0.40	-5.68	-18.37	High
Rest of Middle East	0.68	3.20	0.61	98.38	82.53	High
Mexico	0.64	3.55	0.32	38.08	18.49	High
Indonesia	0.61	5.10	0.35	55.43	51.22	Low
Iran	0.59	5.23	0.71	83.27	76.54	High
Republic of Korea	0.56	3.19	0.31	32.13	1.10	High
North Africa	0.55	5.41	0.43	80.79	64.75	High
Rest of Asia and Pacific	0.54	6.65	0.43	105.86	94.88	Low
Australia	0.52	2.96	0.40	-0.14	-10.87	High
South Africa	0.49	4.93	0.73	25.90	11.84	High
Saudi Arabia	0.40	3.51	0.59	95.95	96.49	High
Argentina	0.31	2.66	0.43	1.95	2.51	High
Turkey	0.31	3.97	0.33	92.36	96.61	High
Rest of Europe	0.21	2.14	0.21	1.33	-7.55	High
New Zealand	0.08	2.36	0.45	2.11	-16.68	High

* Greenhouse gas emissions are expressed in Gt $CO2_e$ and exclude emissions from LULUCF and bunkers.
** GHG/GDP is expressed in t $CO2_e$/US$(2005) PPP.

3. Results[7]

This section presents the results of the numerical simulations with the POLES and 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

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[7] Since this paper is work in progress, the results presented here should be considered as preliminary.

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 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.

3.1. 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 3.6% (8.1%) and 9.1% (30.7%) 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.

Table 2: Evolution of primary energy demand (total and by fuel type) in the different scenarios, expressed as % of the Reference. Source: POLES model.

INDC Scenario	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Total	0	0	-2	-4	-4	-6	-7	-8
Solids	0	-3	-10	-17	-20	-25	-30	-33
Oil	0	0	-1	-1	-1	-3	-2	-2
Natural gas	0	0	-1	-1	-1	-2	-3	-1
Non-fossil fuel	0	2	7	9	9	11	12	11

2°C Scenario	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Total	0	-1	-4	-9	-15	-20	-25	-31
Solids	0	-4	-18	-37	-54	-65	-72	-78
Oil	0	0	-2	-4	-8	-17	-31	-46
Natural gas	0	0	-2	-4	-12	-18	-22	-30
Non-fossil fuel	0	3	10	17	25	27	30	29

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. Hence, replacing solid fuels by non-fossil fuels is an important element for climate change mitigation policies. Non-fossil fuels include renewables and electricity generated by nuclear power plants.

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 a doubling of the decrease in 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 3.4.

3.2.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 Figure 2 show that both the INDC and the 2°C scenario imply emission reductions of all greenhouse gases (the emissions shown in Figure 2 include LULUCF but exclude sinks). 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.

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 7% lower than the levels in the Reference.

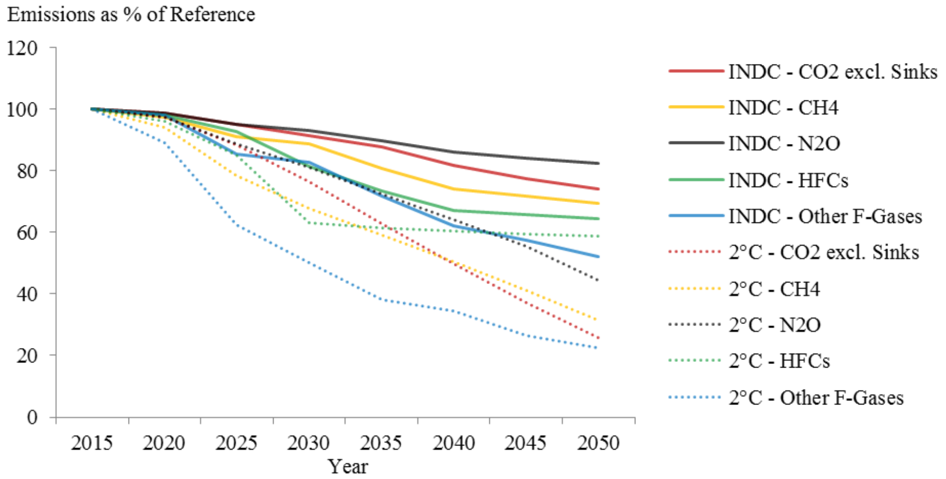

Figure 2: Emission reduction by type of greenhouse gas. Source: POLES model

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 remain stable afterwards. This result indicates that the INDCs exploit nearly the full potential of HFC emission reductions. Furthermore, Figure 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 around 26% lower than the level in the Reference in 2050, while the 2°C pathway studied here suggests a reduction of approximately 74% compared to the Reference in 2050.

3.3. Emission reductions by sector

The previous section decomposed the aggregate GHG reductions into gas-specific abatement profiles over time. As a second way we disentangle the emission reductions on a sector-specific basis. Figure 3 presents emissions reductions in 2030 disaggregated into five categories: CO_2 in the electricity generation sector, other energy-related CO_2 emissions (from combustion), GHG emissions that are not energy related (non-CO_2 gases and process CO_2) in energy sectors and industry (including the waste sector), non-CO_2 emissions in agriculture and emissions from (excluding negative emissions or sinks) land use, land-use change and forestry (LULUCF). A number of insights can be deducted from the 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 half of the emission reductions between the Reference and the INDC in 2030. In addition, the power generation sector bridges around 35% 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.

Second, significant emission cuts appear in energy-related CO_2 emissions from combustion outside the electricity supply sector. 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 away from emission-intensive fossil fuels (in line with the previous section) are the two main options to drive down energy-related CO_2 emissions. In the numerical simulations presented here, a carbon price on a CO_2-equivalent basis provides the incentives to achieve both.

Third, decreasing greenhouse gas emissions other than CO_2 from combustion is a non-negligible possibility. The options to achieve lower emissions in this category include reducing 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).

Fourth, 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 non-CO_2 in energy and industry and 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. Reducing CO_2 emissions from power generation and energy use continues to be the most significant option, particularly in mature economies.

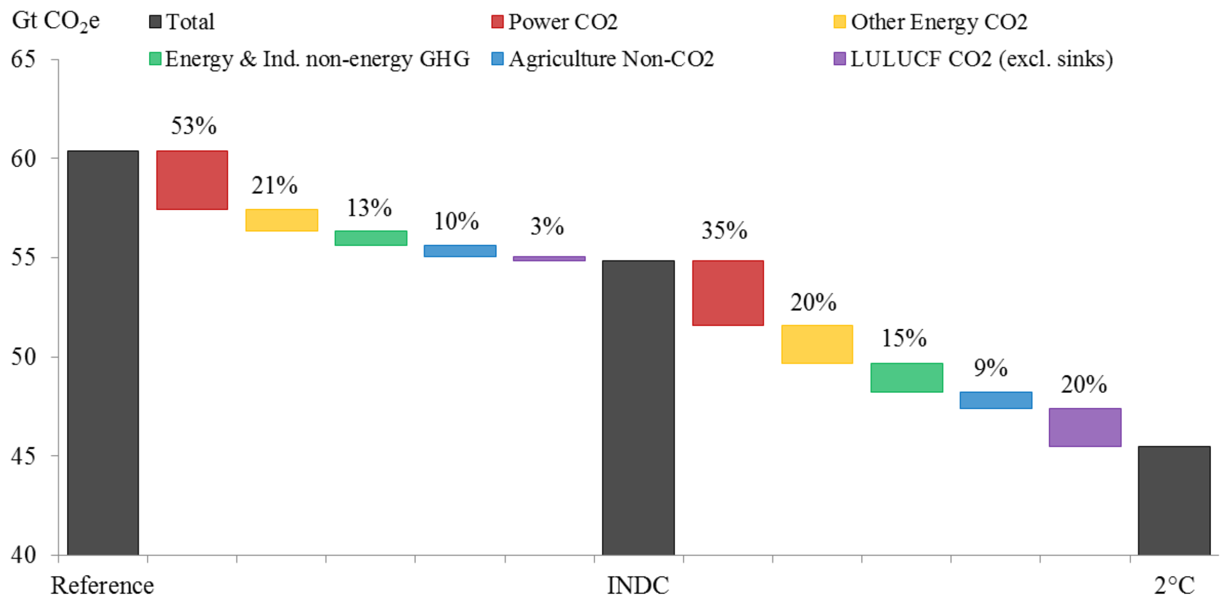

Figure 3: Sector contributions to emission reductions in 2030. The percentage above the bars indicates the share in reductions between scenarios. Source: POLES model

3.4. 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 Figure 4.

Note that, in reality, a broad range of policy instruments exists to achieve a decarbonisation of the power sector, including taxes, subsidies and standards. In this analysis, the transformation of the electricity production sector is driven by carbon prices. Literature indicates that carbon pricing is the policy instrument with the largest welfare-enhancing potential (Paul et al. 2015).

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 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 zero-carbon technologies. In the Reference, fossil fuels account for around 58% of electricity production. This number reduces to 51% and 42% 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.

In the longer run (2050), Carbon Capture and Storage[8] 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 solar capacity, which unlocks (endogenous) technological progress for this technology. As a result, solar power becomes more competitive in the 2°C, and consequently gains market share.

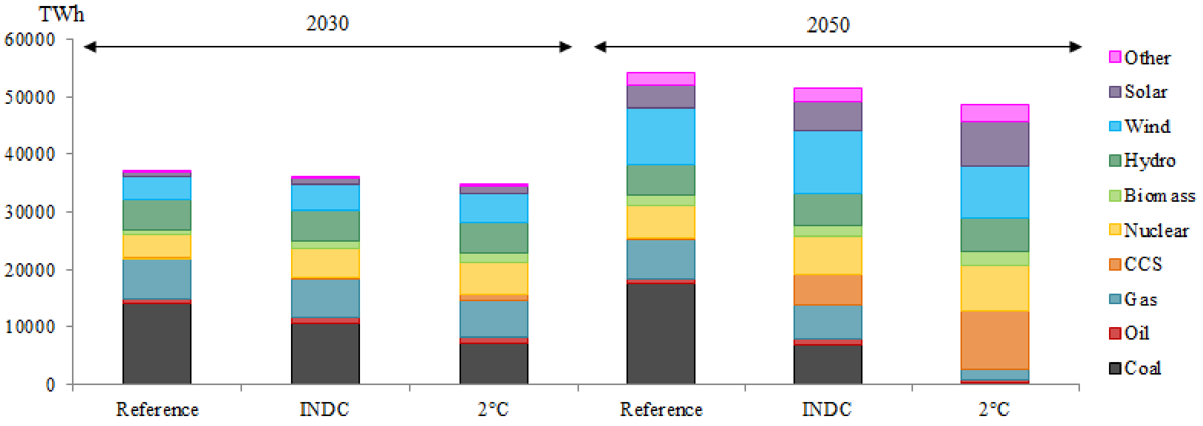

Figure 4: Electricity production by technology. Source: POLES model

Figure 5 sheds more light on the technological progress in electricity production technologies (in the Reference; scenario curves follow 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. POLES models 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). 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 Figure 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.

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[8] CCS is included for coal, gas and biomass power stations.

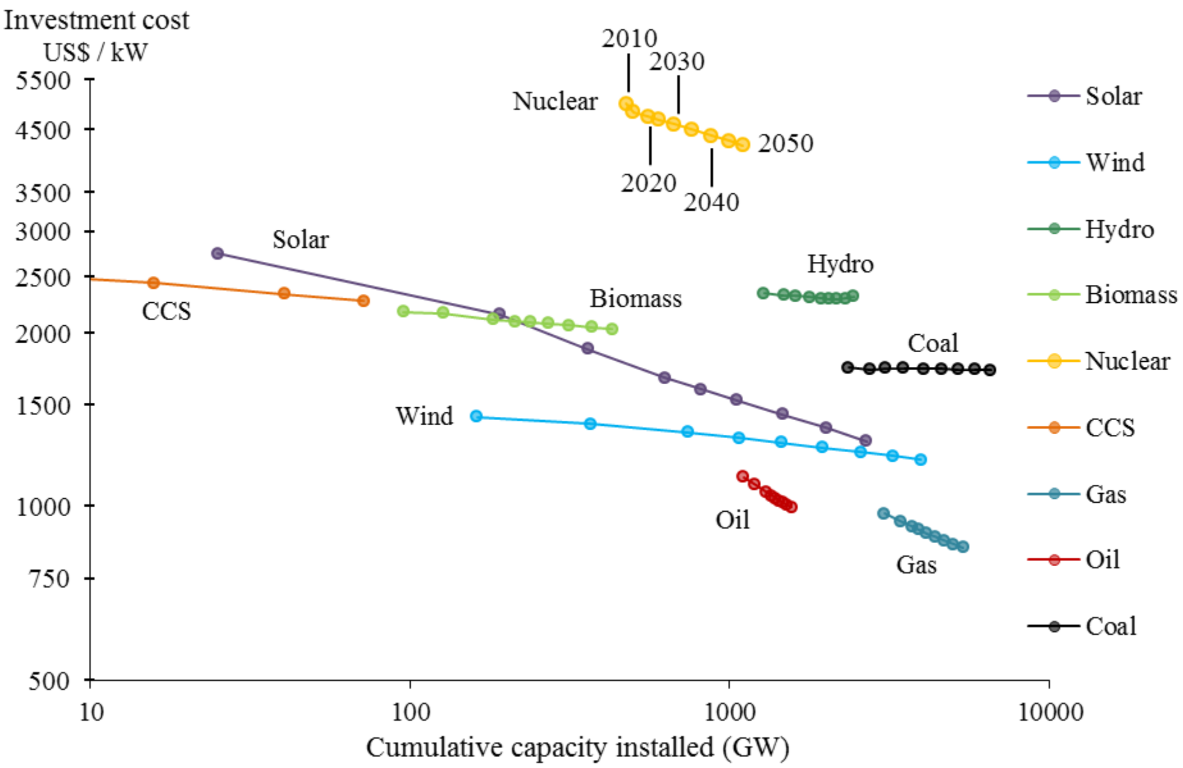


Figure 5: Technological progress in electricity generation technologies (Reference, 2010-2050)

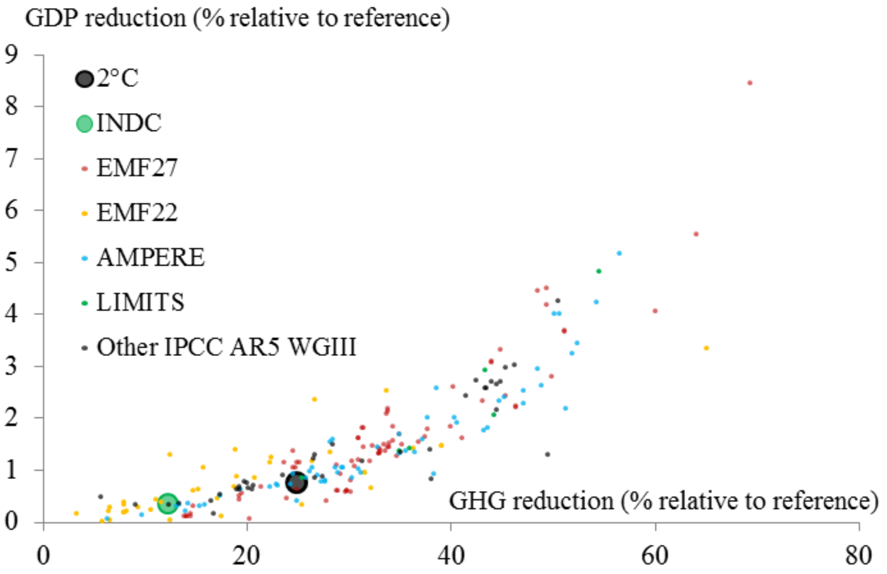
3.5. *Macro-economic costs*

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 3.7 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 -0.35%. 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 -0.79%.

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 2.95% 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 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 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 Figure 6. For each of the models involved with endogenous GDP, Figure 6 plots the change in GDP aggregated at global level against the reduction in greenhouse gases. Note that the changes of both GDP and GHG emissions are expressed here relative to the respective model references. Results from different projects are included: 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). Fourth, by implementing region-specific emission reduction targets based on the results of the 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.

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.



Source: IIASA (2015b) and GEM-E3 model

Figure 6: Impact on global economic output (2030), compared with IPCC AR5 WGIII results.

3.6. 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 GEM-E3 analysis, of which the results are displayed in Figure 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.

Secondly, the INDC scenario shows that a number of regions have relatively unambitious targets, such that their emission levels are 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.

A first look at the results of the 2°C scenario reveals a shift down and to the left compared to the INDC scenario in Figure 7: the 2°C pathway implies stronger emission reductions, leading to more sizeable GDP impacts.

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 19 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 3.3, 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 has more steep reductions than GDP for 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.

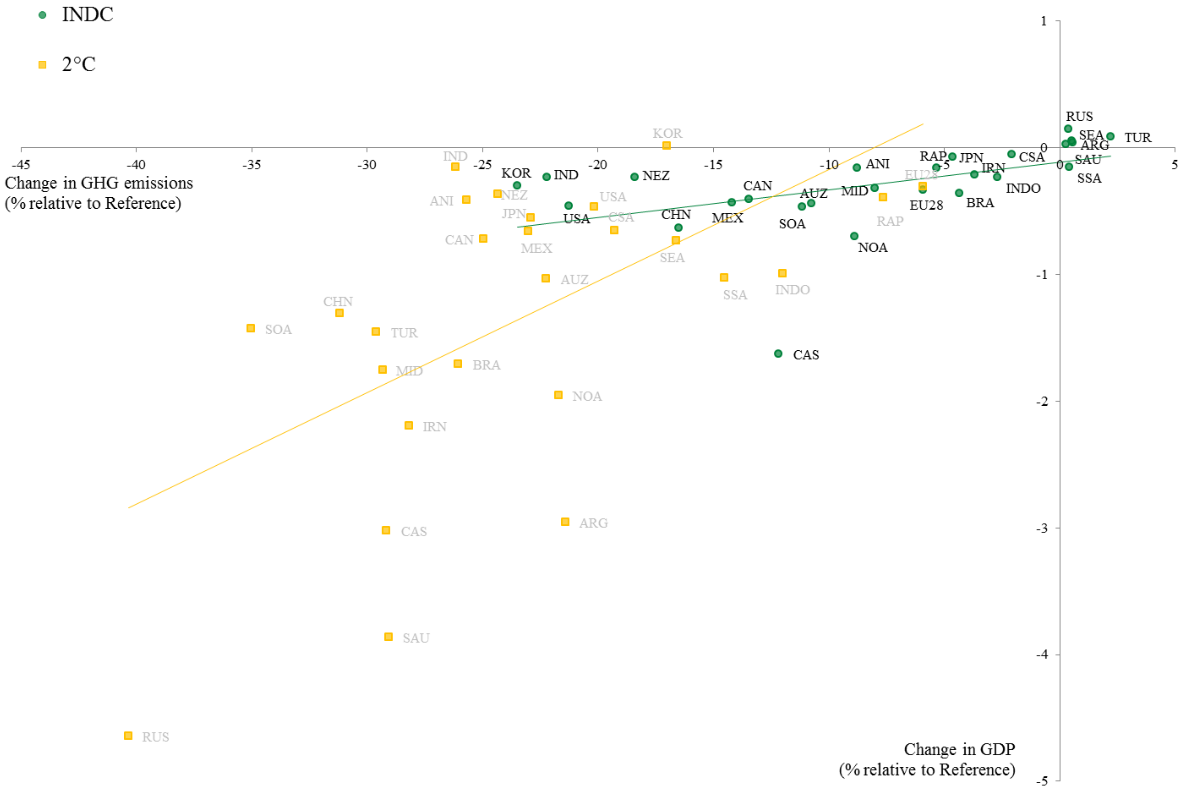


Figure 7: Change in GDP by region in the INDC and 2° scenarios, % difference with Reference in 2030. Source: GEM-E3 model

Table 3: Macro-economic results. Source: GEM-E3 model

% 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	-12.26	-24.73	-0.35	-0.79	-0.46	-1.06					-0.33	-0.63
European Union	-5.91	-5.91	-0.33	-0.30	-0.35	-0.48	-0.78	-1.08	-0.35	-1.46	-0.31	-0.35
USA	-21.28	-20.17	-0.46	-0.46	-0.60	-0.74	-0.69	-0.60	-0.84	-1.34	-0.51	-0.48
Russia	0.38	-40.32	0.15	-4.65	-0.03	-3.73	0.83	-9.07	0.35	-2.73	0.04	-2.13
Canada	-13.45	-24.95	-0.41	-0.72	-0.55	-1.01	-0.60	-0.85	-0.67	-1.02	-0.45	-0.78
Japan	-4.64	-22.91	-0.07	-0.55	-0.18	-0.86	-0.07	-0.72	-0.55	-1.61	-0.13	-0.70
Australia	-10.74	-22.24	-0.44	-1.04	-0.55	-1.30	-0.85	-2.01	-0.68	-1.48	-0.39	-0.82
China	-16.49	-31.19	-0.63	-1.30	-0.75	-1.59	-1.65	-2.90	-1.16	-2.06	-0.43	-0.90
India	-22.20	-26.15	-0.23	-0.15	-0.34	-0.50	-0.27	1.90	-0.84	-0.17	-0.35	-0.27
Indonesia	-2.70	-12.00	-0.23	-0.99	-0.31	-1.15	-0.58	-1.99	-0.59	-1.51	-0.09	-0.45
Brazil	-4.34	-26.06	-0.36	-1.71	-0.51	-2.44	-0.78	-3.57	-0.90	-4.96	-0.17	-1.46
Republic of Korea	-23.49	-17.01	-0.30	0.01	-0.46	-0.39	-0.93	-0.15	-1.17	-1.22	-0.30	-0.13
Turkey	2.21	-29.59	0.09	-1.45	-0.04	-1.72	0.42	-2.28	-0.15	-1.55	0.01	-0.96
Mexico	-14.19	-23.01	-0.43	-0.66	-0.57	-0.92	-0.24	0.03	-0.12	0.05	-0.21	-0.32
Argentina	0.55	-21.40	0.04	-2.96	-0.07	-3.46	0.18	-4.36	-0.33	-3.13	-0.01	-1.98
North Africa	-8.87	-21.70	-0.70	-1.95	-0.83	-2.30	-0.71	-2.39	-0.18	-0.88	-0.32	-0.88
New Zealand	-18.40	-24.34	-0.23	-0.37	-0.32	-0.57	-0.61	-0.98	-0.83	-1.46	-0.42	-0.66
Saudi Arabia	0.28	-29.06	0.03	-3.86	-0.08	-5.16	0.38	-4.50	0.23	-2.54	0.01	-1.66
Iran	-3.67	-28.16	-0.21	-2.19	-0.58	-4.15	0.07	1.12	-0.80	-1.72	-0.32	-2.10
South Africa	-11.17	-35.03	-0.47	-1.43	-0.57	-1.71	-0.90	-2.68	-0.60	-1.74	-0.22	-0.73
Rest of Middle East	-7.99	-29.32	-0.32	-1.75	-0.39	-2.03	-0.42	-2.83	-0.38	-2.24	-0.31	-1.20
Sub-Sahara Africa	0.43	-14.51	-0.15	-1.03	-0.25	-1.49	0.15	-0.70	0.11	-0.83	0.07	-0.31
Rest of Central and S. Am.	-2.08	-19.27	-0.05	-0.65	-0.13	-0.83	0.39	-1.15	0.23	-1.06	0.01	-0.46
Central Asia and Caucasus	-12.18	-29.16	-1.62	-3.02	-1.79	-3.95	-1.76	-4.02	-0.97	-3.53	-0.86	-1.83
South-East Asia	0.53	-16.62	0.05	-0.73	-0.19	-1.21	-0.11	-0.71	-0.51	-1.17	-0.05	-0.87
Rest of Asia and Pacific	-5.33	-7.66	-0.16	-0.39	-0.51	-1.04	0.62	0.44	-0.39	-1.11	-0.22	-0.32
Rest of Europe	-8.76	-25.69	-0.16	-0.41	-0.26	-0.65	-0.12	-0.67	-0.33	-1.16	-0.30	-0.72

3.7. Sector-specific effects

This section disaggregates the global results on a sector-specific basis. Table 4 presents output levels and changes in employment for the 21 sectors of the GEM-E3 model. Since detailed (sectoral) 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 3.1. 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 3.4. 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. Conversely, the impact on output levels of relatively low-carbon service sectors is smaller.

The results on employment include two additional scenarios that explicitly consider the impact of revenue recycling. In these alternative scenarios (labelled INDC – Lab and 2°C – Lab 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 -0.27% to -0.25% in the INDC scenario, and from -0.81% to -0.79% in the 2°C scenario.

Table 4: Sector-specific output and employment results. Source: GEM-E3 model

% change from Reference 2030	**Output level**		**Employment**			
	INDC	2°C	INDC	INDC - Lab	2°C	2°C - Lab
Agriculture	-0.32	-0.83	-0.16	-0.14	-0.95	-0.98
Fossil fuels	-3.75	-7.96	-5.27	-5.28	-10.89	-10.81
Electricity supply	-2.33	-4.50	-2.15	-2.10	-5.96	-6.00
Ferrous metals	-1.10	-2.50	-0.33	-0.29	-2.82	-2.55
Non-ferrous metals	-0.65	-1.31	-0.34	-0.32	-1.65	-1.33
Chemical Products	-0.55	-1.22	-0.18	-0.19	-1.82	-1.66
Paper Products	-0.38	-0.76	-0.25	-0.23	-0.83	-0.73
Non-metallic minerals	-1.03	-1.82	-0.07	-0.03	-1.03	-0.85
Electric Goods	-0.55	-0.79	-0.75	-0.90	-0.84	-0.60
Transport equipment	-0.83	-1.41	-0.75	-0.78	-1.69	-1.42
Other Equipment Goods	-0.61	-1.34	-0.78	-0.80	-1.62	-1.41
Consumer Goods Industries	-0.28	-0.66	-0.32	-0.31	-0.94	-0.89
Construction	-0.29	-0.51	-0.20	-0.16	-0.46	-0.41
Transport (Air)	-0.90	-1.65	0.43	0.46	-0.81	-0.75
Transport (Land)	-0.53	-1.20	-0.38	-0.36	-1.16	-1.12
Transport (Water)	-0.77	-2.18	-0.65	-0.65	-1.74	-1.60
Market Services	-0.27	-0.54	-0.36	-0.31	-0.99	-0.97
Non Market Services	-0.11	-0.22	-0.04	-0.03	-0.14	-0.15

4. Conclusion

This paper provides a model-based assessment of the INDCs, a central element in the global climate change negotiations held in 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 considers both efficiency and equity aspects by introducing carbon prices that converge (efficiency) to different levels for high-income and low-income regions (equity).

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 around three quarters can be bridged by decarbonising the power sector, reducing emissions from land use, land use change and forestry and lowering energy-related CO_2 emissions. 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. Further, 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 analysis also provides evidence that the use of smart fiscal policies tailored to each region, i.e. increasing emission auctions and taxes, reducing indirect taxes to consumption and investment, and/or lowering labour taxes, can improve the economic performance.

The modelling framework has global coverage and exploits the complementarities between a highly detailed energy system model (POLES) and an economy-wide CGE model (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 the countries are expected 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 that will influence the cost of mitigation policies. 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 or any other organization.

References

Abrell, J. and S. Rausch (201x). Cross-Country Electricity Trade, Renewable Energy and European Transmission Infrastructure Policy, *Journal of Environmental Economics and Management*, forthcoming.

Armington, P. S. (1969). A Theory of Demand for Products Distinguished by Place of Production, *IMF Staff Papers*, No. 16.

Blanchflower, D. G. and A. J. Oswald (1995). An introduction to the wage curve, *The journal of economic perspectives*, Vol. 9, No. 3, pp. 153-167

Boehringer, C. and Rutherford, T.F., (2008). Combining bottom-up and top-down. *Energy Economics* 30, 574–596.

Capros, P., D. Van Regemorter, L. Paroussos, P. Karkatsoulis, T. Revesz, C. Fragkiadakis, S. Tsani, I. Charalampidis, authors; M. Perry, J. Abrell, J. C. Ciscar, J. Pycroft, B. Saveyn, editors (2013). GEM-E3 Model Documentation. JRC Scientific and Technical Reports. EUR 26034 EN.

Ciscar Martinez, J.C., Feyen, L., Soria Ramirez, A., Lavalle, C., Raes, F., Perry, M., Nemry, F., Demirel, H., Rózsai, M., Dosio, A., Donatelli, M., Srivastava, A.K., Fumagalli, D., Niemeyer, S., Shrestha, S., Ciaian, P., Himics, M., Van Doorslaer, B., Barrios, S., Ibañez Rivas, N., Forzieri, G., Rojas Mujica, R.F., Bianchi, A., Dowling, P., Camia, A., Liberta', G., San-Miguel-Ayanz, J., De Rigo, D., Caudullo, G., Barredo Cano, J.I., Paci, D., Pycroft, J., Saveyn, B., Van Regemorter, D., Revesz, T., Vandyck, T., Vrontisi, Z., Baranzelli, C., Vandecasteele, I., Batista e Silva, F. and D. Ibarreta Ruiz (2014). Climate Impacts in Europe. The JRC PESETA II Project, *JRC Scientific and Policy Reports*.

Clarke, L. and J. Weyant (2009). Introduction to the EMF 22 special issue on climate change control scenarios, *Energy Economics*, Volume 31, Supplement 2, Pages S63

Dellink, R., Lanzi, E., Chateau, J., Bosello, F., Parrado, R. and K. de Bruin (2014). “Consequences of Climate Change Damages for Economic Growth: A Dynamic Quantitative Assessment”, OECD Economics Department Working Papers, No. 1135, OECD Publishing

Dellink, R., Briner, G. and C. Clapp (2011). The Copenhagen Accord/Cancún Agreements Emission Pledges For 2020: Exploring Economic And Environmental Impacts, *Climate Change Economics*, vol. 2(01), pages 53-78.

den Elzen, M. G. J., Hof, A.F., Mendoza Beltran, A., Grassi, G., Roelfsema, M., van Ruijven, B., van Vliet, J. and D.P. van Vuuren (2011a). The Copenhagen Accord: Abatement costs and carbon prices resulting from the submissions. *Environmental Science and Policy*, 14, 28–39.

den Elzen, M. G. J., Hof, A. F. and M. Roelfsema (2011b). The emissions gap between the Copenhagen pledges and the 2°C climate goal: Options for closing and risks that could widen the gap, *Global Environmental Change*, 21, 733–743

den Elzen, M. G. J., Fekete, H., Admiraal, A., Forsell, N., Höhne, N., Korosuo, A., Roelfsema, M., van Soest, H., Wouters, K., Day, T., Hagemann, M., Hof, A. and A. Mosnier (2015), Enhanced policy scenarios for major emitting countries. Analysis of current and planned climate policies, and selected enhanced mitigation measures, The Hague: PBL Netherlands Environmental Assessment Agency.

European Commission (2012). Review of Regulation (EC) No 842/2006 on certain fluorinated greenhouse gases, Commission Staff Working Document. Impact Assessment (COM(2012) 643 final, SWD(2012) 364)

European Commission (2013). EU Energy, Transport and GHG emissions Trends to 2050, Reference Scenario 2013. DG for Energy, DG for Climate Action and DG for Mobility and Transport.

European Commission JRC (Joint Research Centre) (2014). Emissions Database for Global Atmospheric Research (EDGAR), v4.2 and v4.2 FT2010.

Fankhauser, S. and R.S.J. Tol (2005). On climate change and economic growth, *Resource and Energy Economics*, Volume 27, Issue 1, Pages 1-17.

FAO (Food and Agriculture Organisation of the United Nations) (2014). FAOSTAT Emissions Land Use database. Database.

Gillingham, K., Newell, R.G. and W. A. Pizer (2008). Modeling endogenous technological change for climate policy analysis. *Energy Economics*, 30 (6), 2734–2753.

Houser, T., Kopp, R., Hsiang, S., Muir-Wood, R., Larsen, K., Delgado, M., Jina, A., Wilson, P., Mohan, S., Rasmussen, D.J., Mastrandrea, M. and J. Rising (2014). American Climate Prospectus: Economic Risks in the United States. New York: Rhodium Group.

IEA (International Energy Agency) (2015). Energy and Climate change. World Energy Outlook Special Report. IEA, 2015, Paris.

IIASA (International Institute for Applied Statistical Analysis) (2015a). GLOBIOM model description.

IIASA (2015b). AR5 Scenario Database, http://tntcat.iiasa.ac.at/AR5DB

IPCC (Intergovernmental Panel on Climate Change) (2014). AR5: Assessment Report 5

German Federal Institute for Geosciences and Natural Resources (2013). Energy Study 2013. Reserves, resources and availability of energy resources (17), Hannover.

Gollier, C., and J. Tirole (2015). "Negotiating Effective Institutions Against Climate Change." Discussion Paper 2015-72. Cambridge, Mass.: Harvard Project on Climate Agreements.

Gütschow, J., Jeffery, L., Alexander, R., Hare, B., Schaeffer, M., Rocha, M., Höhne, N., Fekete, H., van Breevoort, P. and K. Blok (2015). INDCs lower projected warming to 2.7°C: significant progress but still above 2°C, *Climateactiontracker.org*

Kitous, A. and K. Keramidas (2015). Analysis of scenarios integrating the INDCs, *JRC Policy Brief*

Kriegler, E., Riahi, K., Bosetti, V., Capros, P., Petermann, N., van Vuuren, D.P., Weyant J.P. and O. Edenhofer (2015). Introduction to the AMPERE model intercomparison studies on the economics of climate stabilization. *Technological Forecasting and Social Change* 90, Part A:1–7

Kriegler, E., Tavoni, M., Riahi, K. And D.P. van Vuuren (2013). Introducing the special issue, *Climate Change Economics*, Vol. 04, No. 04, Special Issue on Implementing Climate Policies in the Major Economies: An Assessment of Durban Platform Architectures — Results from the LIMITS Project

Labat, A., Kitous, A., Perry, M., Saveyn, B., Vandyck, T., and Z. Vrontisi (2015). Global Energy and Climate Outlook: Road to Paris. Assessment of Low Emission Levels under World Action Integrating National Contributions, *JRC Science and Policy Report*.

Löschel, A. (2002). Technological change in economic models of environmental policy: a survey, *Ecological Economics*, 43, 105-126.

Matsumoto, K. and K. Andriosopoulos (2016). Energy security in East Asia under climate mitigation scenarios in the 21st century. *Omega*, Volume 59, Part A, March 2016, Pages 60–71

McFarland, J. R., Reilly, J. M., and Herzog, H.J.: 2004, 'Representing energy technologies in top-down economic models using bottom-up information', *Energy Economics* 26, 685–707.

McKibbin,W. J., Morris, A. C., and Wilcoxen, P. J. (2011). Comparing climate commitments: A model-based analysis of the Copenhagen Accord. *Climate Change Economics*, 2(2), 79–103.

OECD (Organisation for Economic Co-operation and Development) (2013). Economic Outlook No 93, Long term Baseline Projections, June 2013.

OECD (Organisation for Economic Co-operation and Development) (2015), The Economic Consequences of Climate Change, OECD Publishing, Paris.

Paul, A., Palmer, K. and M. Woerman (2015). Incentives, margins, and cost effectiveness in comprehensive climate policy for the power sector, *Climate Change Economics*, 06:04

Peterson, E.B., Schleich, J. and V. Duscha (2011). Environmental and economic effects of the Copenhagen pledges and more ambitious emission reduction targets, *Energy Policy*, Volume 39, Issue 6, Pages 3697-3708

Riahi, K., Kriegler, E., Johnson, N., Bertram, C., den Elzen, M., Eom, J., Schaeffer, M., Edmonds, J., Isaac, M., Krey, V., Longden, T., Luderer, G., Méjean, A., L. McCollum, D., Mima, S., Turton, H., van Vuuren, D.P., Wada, K., Bosetti, V., Capros, P., Criqui, P., Hamdi-Cherif, M., Kainuma, M. and O. Edenhofer (2015). Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technological Forecasting and Social Change*, Volume 90, Part A, Pages 8-23

Rosen, R.A. (2016). Is the IPCC's 5th Assessment Report a denier of possible macroeconomic benefits from mitigating climate change?, *Climate Change Economics*, Vol. 7, No. 1

Russ, P., Ciscar, J-C, Saveyn, B., Soria, A., Szabo, L. (2009). Economic Assessment of Post-2012 Global Climate Policies - Analysis of Gas Greenhouse Gas Emission Reduction Scenarios with the POLES and GEM-E3 models. JRC Scientific and Technical Reports. EUR 23768 EN

Saveyn, B., Van Regemorter, D. and J.C. Ciscar (2011). Economic analysis of the climate pledges of the Copenhagen Accord for the EU and other major countries, *Energy Economics*, Volume 33, Supplement 1, Pages S34-S40

Schenk, C.J., (2012). An estimate of undiscovered conventional oil and gas resources of the world, 2012. U.S. Geological Survey Fact Sheet 2012–3042.

Spencer, T., Pierfederici, R., Waisman, H., Colombier, M. (2015). Beyond the numbers: understanding the transformation induced by INDCs, Study N°05/15, *IDDRI - MILES Project Consortium*, Paris, France, 80 p.

Sue Wing, I., (2008). The synthesis of bottom-up and top-down approaches to climate policy modeling: electric power technology detail in a social accounting framework. *Energy Economics* 30 (2), 547–573.

Tavoni, M., Kriegler, E., Riahi, K., van Vuuren, D. P., Aboumahboub, T., Bowen, A., Calvin, K., Campiglio, E., Kober, T., Jewell, J., Luderer, G., Marangoni, G., McCollum, D., van Sluisveld, M., Zimmer, A. and B. van der Zwaan (2014). Post-2020 climate agreements in the major economies assessed in the light of global models, *Nature Climate Change*, 5, 119–126.

Tianyu, Q., Winchester, N., Karplus, V.J., Zhanga, D., and X. Zhang (2016). An analysis of China's climate policy using the China-in-Global Energy Model, *Economic Modelling*, 52, 650–660.

UNEP (United Nations Environment Programme) (2014). The emissions gap report 2014. A UNEP Synthesis Report.

UNFCCC (United Nations Framework Convention on Climate Change) (2014). Greenhouse Gas Inventory Data, Flexible Queries.

UNFCCC (United Nations Framework Convention on Climate Change) (2016). Intended Nationally Determined Contributions, http://unfccc.int/focus/indc_portal/items/8766.php

United Nations (2013). Department of Economic and Social Affairs, Population Division. World Population Prospects: The 2012 Revision.

US EPA (United States Environmental Protection Agency) (2013). Global Mitigation of Non-CO2 Greenhouse Gases: 2010-2030

van der Zwaan, B. C. C., Rösler, H., Kober, T., Aboumahboub, T., Calvin, K. V., Gernaat, D. E. H. J., Marangoni, G. and D. McCollum (2013). A cross-model comparison of global long-term technology diffusion under a 2°C climate change control target, *Climate Change Economics*, Vol. 04, No. 04

van der Zwaan, B.C.C, Gerlagh, R., Klaassen, G. and L. Schrattenholzer (2002). Endogenous technological change in climate change modelling, *Energy Economics*, Volume 24, Issue 1, Pages 1–19

van Sluisveld, M.A.E., Harmsen, J.H.M., Bauer, N., McCollum, D.L., Riahi, K., Tavoni, M., van Vuuren, D.P., Wilson, C. and B. van der Zwaan (2015). Comparing future patterns of energy system change in 2 °C scenarios with historically observed rates of change, *Global Environmental Change*, Volume 35, Pages 436–449

van Vliet, J. , van den Berg, M., Schaeffer, M. , van Vuuren, D., den Elzen, M., Hof, A., Beltran, A. and M. Meinshausen (2012). Copenhagen Accord Pledges imply higher costs for staying below 2°C warming. *Climatic Change*, Volume 113, Issue 2, pp 551-561

Weyant, J. P., de la Chesnaye, C. and G.J. Blanford (2006). Multi-greenhouse gas mitigation and climate policy, *The Energy Journal* 27.

Weyant, J. P., Kriegler, E., Blanford, B., Krey, V., Edmonds, J., Riahi, K., Richels, R. and M. Tavoni (2014). Special Issue: The EMF27 Study on Global Technology and Climate Policy Strategies, *Climatic Change*, Volume 123, Issue 3-4

World Bank (2014). Global Economic Prospects, World Bank Group publishing.

Appendix

Appendix A: POLES description and categories

The 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 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). POLES 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 3.4).

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 have short term impacts (adjustment of overall energy demand) and long term impacts (energy efficiency, technological substitution).

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 5: 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 gen.
5	Biomass liquefaction 2nd gen.
6	Hydrogen production

Appendix B: GEM-E3 description and nesting structures

The 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. Figure 8, Figure 9 and Figure 10 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 distribution. The resulting cost structure is presented in Table 6. This electricity sector disaggregation is an important step in the integration of POLES and 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 6. The values of the elasticities of substitution are listed in Table 7. 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.

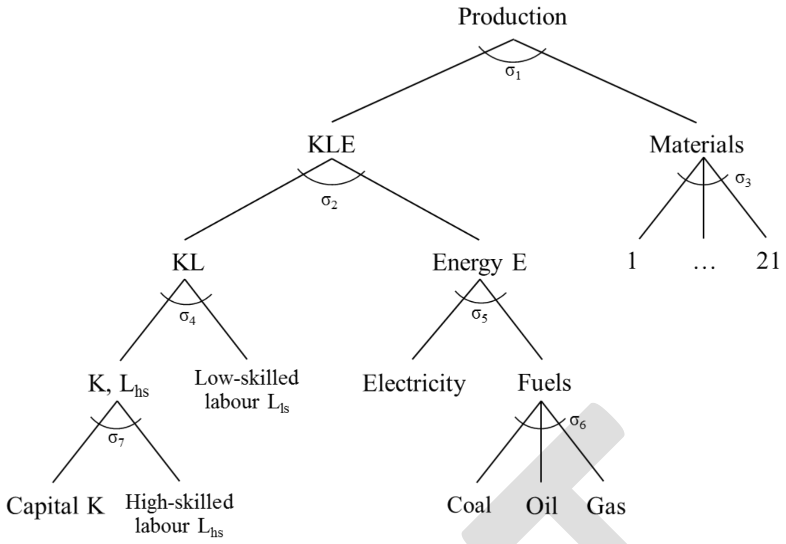


Figure 8: Nested CES production structure for non-energy sectors

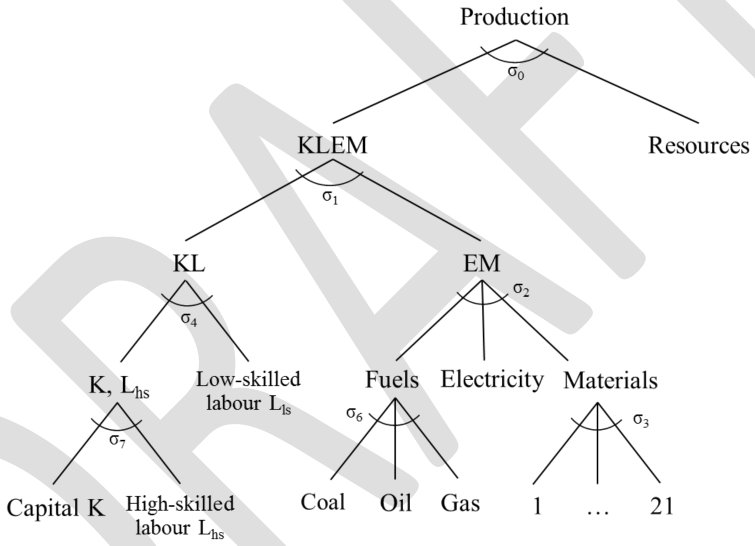


Figure 9: Nested CES production structure for the crude oil sector

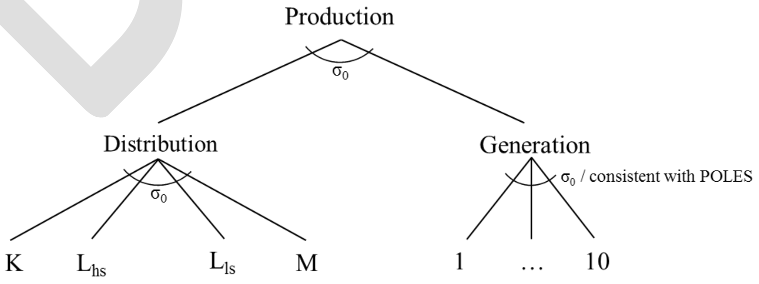


Figure 10: Nested CES production structure for the electricity sector

Table 6: 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

Table 7: 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