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Global Energy and Climate Outlook 2017: How climate policies improve air quality

Global energy trends and ancillary benefits of the Paris Agreement

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Global Energy and Climate Outlook 2017: How climate policies improve air quality - Global energy trends and ancillary benefits of the Paris Agreement

This study shows that achieving the climate change mitigation target of staying below 2°C temperature rise is possible technically – thanks to an acceleration of decarbonisation trends, an increased electrification of final demand and large changes in the primary energy mix that include a phase out of coal and a reduction of oil and gas – and is consistent with economic growth. It yields co-benefits via improved air quality – including avoided deaths, reduction of respiratory diseases and agricultural productivity improvement – that largely offset the cost of climate change mitigation. These co-benefits arise without extra investment costs and are additional to the benefits of avoiding global warming and its impact on the economy.

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Executive summary

This report reveals the value of climate policy in lowering air pollution impacts. We show that ambitious climate action will decouple economic growth from fossil fuel combustion transforming the way energy is produced, reducing not only greenhouse gases but also leading to significantly fewer emissions of local air pollutants and consequently saving lives, avoiding sickness and increasing agricultural yields.

Policy context

The Paris Agreement puts forward the goal to limit global warming to well below 2°C above pre-industrial levels. In addition to being a major driver of climate change, energy combustion contributes significantly to air pollution, with severe impacts on human health, especially in fast-growing countries such as India and China.

This report studies the implications of global climate policies for energy systems, the economy and the co-benefits in terms of air quality. Based on extensive datasets and a cutting-edge modelling toolbox, this interdisciplinary study aims at informing international climate change negotiations, is relevant for air quality policies and tackles multiple Sustainable Development Goals simultaneously (climate action – clean energy – good health).

Key conclusions

The study shows that mitigating climate change is possible technically, consistent with economic growth, and yields co-benefits via improved air quality that largely offset the cost of climate change mitigation. Co-benefits include avoided deaths, reduction of respiratory diseases and agricultural productivity improvement.

These co-benefits arise without extra investment costs and are additional to the benefits of avoiding global warming and its impact on the economy. They take place in all regions, varying with the ambition level of climate policies and the initial energy mix, and are strongly linked to the reduction of fossil fuel use; they occur locally and in a shorter time frame, providing strong complementary incentives for policymakers to move ahead on ambitious climate action.

The reduction of greenhouse gas (GHG) emissions is indeed driven by a shift of the energy system towards carbon-free energy sources, a large diffusion of renewables, especially in the power sector, and increased energy efficiency in buildings and transport. The total investment needs in energy supply would remain similar across scenarios, but the distribution reflects a new equilibrium: higher in the power sector to finance capital-intensive technologies and lower for fossil fuels production. The new energy system emits less NO_x, SO_2 and particulate matter due to reduced fossil fuel combustion, of coal in particular.

Although climate policy does not replace direct air pollution controls, exploiting the synergies between both clearly provides opportunities towards a more sustainable future for all. By considering such an approach, the report strengthens previous findings that limiting global warming is consistent with long-term robust healthy economic growth.

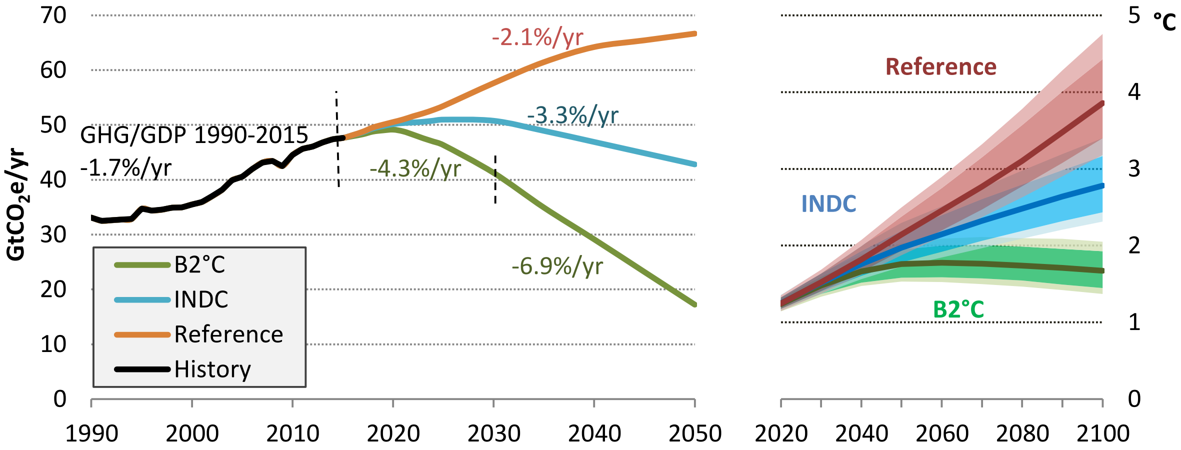
Main findings

Although the countries' pledges under the Paris Agreement (INDCs) initiate a break with historical GHG trends, reaching the below 2°C target demands a decorrelation of emissions from economic growth by an acceleration of decarbonisation trends from 2020 onwards (energy intensity decrease 5.8% per year on average over 2015-2050 vs. -1.7% per year in 1900-2010), an increased electrification of final demand (35% in 2050 vs. 18% in 2015) and large changes in the primary energy mix (phase out of coal, reduction of oil and gas after 2030; fossil fuels 46% and low carbon including CCS 59% in 2050, vs. 81% and 19% in 2015, respectively).

The Paris Agreement is estimated to avoid approximately 100,000 air pollution-related deaths annually by 2030 on a global level, of which more than half in China alone.

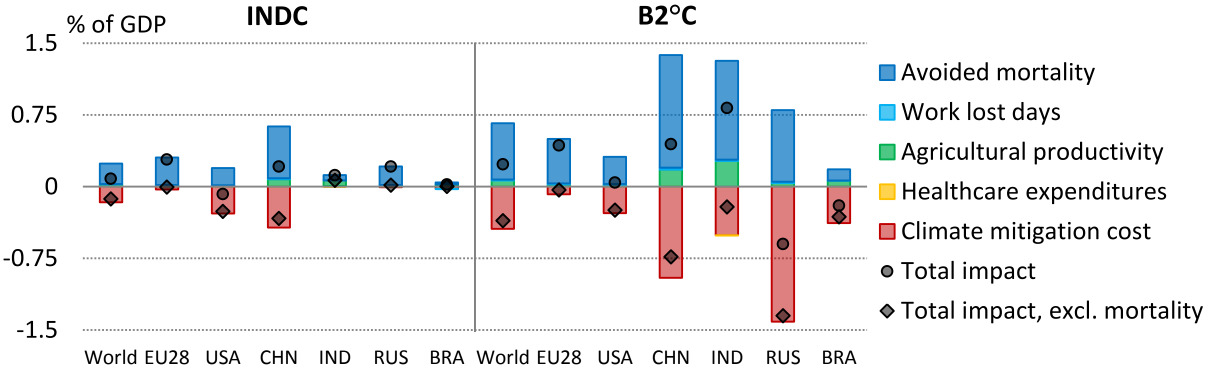
Reaching a GHG trajectory compatible with temperature increases well below 2°C could save roughly 1.5 million lives annually by 2050. In addition to avoided deaths, it also reduces the number of air pollution-related cases of illnesses such as asthma and bronchitis by 15-40% annually by 2050 and raises crop yields by 2.5-6.6%.

Figure 1 ES1: GHG emissions, World, and average annual growth rates for GHG emissions intensity of the economy (left); global average temperature change (right)



By 2030, global air quality co-benefits more than compensate the cost of climate change mitigation policies. This finding is particularly strong for highly polluted fast-growing low income countries relying on coal, and less so for regions with a strong economic dependence on fossil fuel exports (higher mitigation costs) or for countries whose mitigation policy relies heavily on land use measures (lower co-benefits).

Figure 2 ES2: Comparison of mitigation cost and air quality co-benefits in 2030



Related and future JRC work

This report is the third issue of the GECO series, initiated by the JRC in collaboration with DG CLIMA in the run-up to the 2015 Paris climate conference. It participates to the JRC work in the context of the UNFCCC policy process and the IPCC assessment reports.

Quick guide

The report builds on climate policy scenario analysis of the Paris Agreement: *Reference*: serves as a benchmark and includes current climate and energy policies; *INDCs*: covers countries' pledges or *Intended Nationally Determined Contributions Below 2°C*: ambitious pathway with more than 75% probability of limiting global warming to 2°C. The evolution of the related energy mix leads to changes in local air pollution. The last section of the report provides the economic analysis of the climate policies and of their associated co-benefits in terms of air quality improvement.

1 Introduction

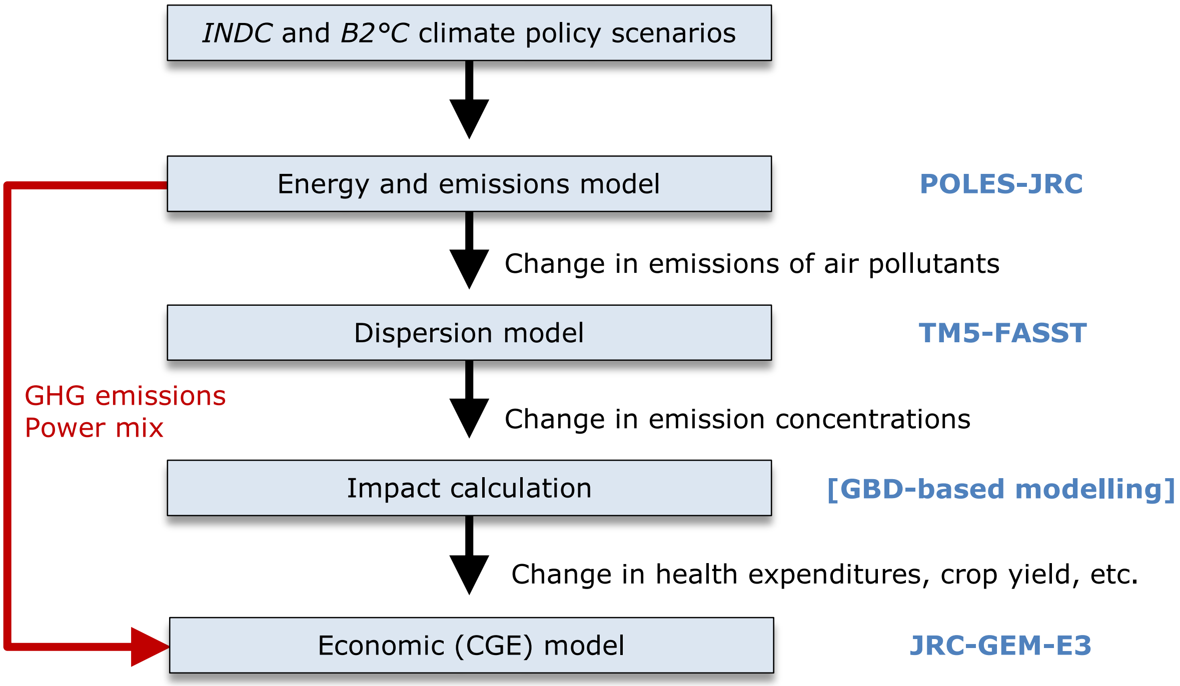
This report has been prepared as a JRC contribution to the upcoming milestones of the international process coordinated by the United Nations Framework convention on Climate Change (UNFCCC), following the 2015 Paris Agreement (1); in particular the facilitative dialogue to take stock of the global mitigation effort in 2018 (1), and the update of the commitments (INDCs and NDCs) to be put forward by countries in 2020.

This report addresses a possible path towards a global low carbon economy while widening the scope of the greenhouse gas (GHG) mitigation policy analysis towards associated co-benefits on air pollution. In addition to being a major driver of climate change, energy combustion significantly contributes to air pollution, with severe impacts on human health, especially in fast-growing countries such as India and China. The latter is crucial at a time where the scientific community is calling for rapid and robust action on the climate change policy area that is sometimes perceived as displaying few short-term political dividends.

This report provides quantitative analyses of the impacts of global and regional climate and energy policy developments and assesses the economics of the mitigation policies taking into account the avoided costs thanks to associated air quality improvements. As such, this report illustrates the knock-on effects of the Paris Agreement on the levels of air pollution and analyses the interaction between two Sustainable Development Goals (2) – 'Climate Change' and 'Good Health and Well-being'.

This analysis relies on a multidisciplinary modelling toolbox that combines engineering, atmospheric chemistry, economics and health research. An overview of the different steps in the analysis is presented in Figure 3.

Figure 3: Overview of the modelling toolbox



Note: For more information on the models used, see Annexes 1-4.

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(1) http://unfccc.int/paris_agreement/items/9485.php
(2) http://www.un.org/sustainabledevelopment/sustainable-development-goals/

The black arrows represent the steps to quantify the co-benefits on air quality, while the red arrow indicates the models involved in the estimation of the climate change mitigation policy cost. Model names are highlighted in blue on the right-hand side.

The report is organised as follows:

- a description of the energy and climate scenarios (Section 2);
- an analysis of the evolution of the global energy system under various policy conditions, with some sectoral and regional focus (Section 3);
- the resulting GHG emissions and global temperature rise (Section 4);
- the impact of the climate and energy policies on emissions of air pollutants (Section 5);
- the economic analysis, covering energy system costs, GHG mitigation policy costs as well as co-benefits from air pollution reduction, including health (Section 6).

This report is complemented by detailed regional energy and GHG balances (see companion document, Keramidas and Kitous (2017a)).

Caveats and evolution since GECO2016

An important caveat of this analysis is that it does not consider the potential impacts of a changing climate (stronger when the climate mitigation policies are lower), either on the energy system or on the economic activity in general (agriculture, health, labour productivity, coastal infrastructures, migration).

Another caveat is that GDP impact of energy and climate mitigation policies considered here are not fed back into the scenarios, neglecting potential second order effects.

Various impacts of air pollution are considered, but the study is not exhaustive. In particular, the impacts of air pollution on buildings, acidification, eutrophication and ecosystems are not included.

The present analytical framework includes some differences with GECO 2016:

- The current analysis includes more recent historical data, as well as an update of climate and energy-related policies;

- Energy subsidies are kept constant as ratios of international prices (versus kept constant in volume at the last historically observed subsidy level in the GECO2016 scenarios).

- In addition, the scenario compatible with a temperature rise below 2°C by 2100 assumes earlier action (2018) than in GECO2016 (2020);

- All countries participate fully by 2050 to the mitigation effort to go below 2°C (this is translated into the convergence of all countries' carbon values to a common value by 2050);

- Results and graphics displayed in this report on greenhouse gases now include emissions from land use, land use change and forestry, including emissions sinks (whilst certain GECO2016 results/graphics were net of LULUCF and/or sinks).

2 Scenarios definition

This report explores three scenarios:

- **Reference scenario**: It includes adopted energy and climate policies worldwide for 2020; thereafter, CO_2 and other GHG emissions are driven by income growth, energy prices and expected technological development with no supplementary incentivizing for low-carbon technologies.

  Although the GECO2017 Reference scenario integrates national climate and energy policies, it is not a replication of official national scenarios. This also applies to the particular case of the EU28 (3).

- **INDC scenario**: All the Intended Nationally Determined Contributions (INDCs) put forward by countries are implemented in this scenario, including all conditional contributions. Countries where the Reference already leads to GHG emissions at or below their INDC pledge are assumed to stick to the Reference level. Nearly all INDC objectives are formulated for 2030; beyond 2030 it is assumed that the global GHG intensity of GDP decreases at the same rate as for 2020-2030. This is achieved through an increase of regional carbon values (including for countries that previously had no climate policies) and progressive convergence of carbon values at a speed that depends on the countries' per capita income.
- **Below 2°C scenario (B2°C)**: This scenario assumes a global GHG trajectory over 2010-2100 compatible with a likely chance (above 66%) of temperature rise staying below 2°C above pre-industrial levels. It assumes in particular further intensification of energy and climate policies already from 2018, captured in the modelling through increasing carbon value and other regulatory instruments, and a progressive convergence of the countries' carbon values after 2030 depending on their per capita income.

The scenarios are produced with the same socio-economic assumptions and energy resources availability. Energy prices are the result of the interplay of energy supply and demand, and are thus scenario-dependent. Country- or region-level energy supply, trade, transformation and demand, as well as GHG emissions, are driven by income growth, energy prices and expected technological evolution, within the constraints defined by energy and climate policies. In sum, scenarios differ on the climate and energy policies that are included, with repercussions on the projections of the energy supply and demand system and GHG emissions.

The scenarios are further described below, with additional detail provided in Annex 5. Annexes 1 to 4 describe the modelling framework.

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(3) Although calibrated on the EU "Trends to 2050 – Reference scenario 2016" (EC, 2016), the GECO2017 Reference results for EU28 should not be considered or used as an official European Commission projection of energy and GHG emissions for the European Union.

2.1 Socio-economic assumptions

The three global scenarios considered share a common set of socio-economic assumptions: country-level population, GDP growth and economic activity at sectoral level represented by its value added. Key assumptions are summarized in Table 1.

According to these assumptions, economic growth is sustained in all regions and the global average GDP per capita triples in the period 2010-2050. The strong growth in countries with low-income levels in 2010 would enable them to join middle-income levels by 2050.

The macro-economic impacts of climate change mitigation are tackled in section 6.2. However, these impacts on economic activity are not fed back in the scenario assumptions. This approach eases the comparability of scenarios, while neglecting potential second-order effects.

These projections do not consider the impacts of climate change on economic growth and energy system.

Population

Population estimates used in this study are from UN (2015) for all world countries and regions (medium fertility scenario), except for the EU which are taken from the 2015 Ageing Report (EC, 2015).

The world will see important changes in population distribution in the forthcoming decades: while population growth in the OECD countries slows down (decreasing to 15% of world population by 2050), the population in Africa has the highest growth rate by far, with its population more than doubling in 40 years. The population of Asia is expected to stabilize by 2050 at around 4.5 billion inhabitants, with India becoming the single most populated country.

Economic activity (4)

Non-OECD regions are expected to benefit from a higher economic growth rate than OECD regions over the forthcoming years up to 2050, in line with the 1990-2010 developments and a foreseeable further shift of their economy towards services. The yearly growth rate in the OECD remains 1 percentage below the one of the world average throughout 2050.

The structure of the economy evolves slowly over time in all regions, with the share of services gaining 5 percentage points to reach around 69% by 2050 (+4% to 78% in the OECD, but +13% to 65% in non-OECD countries), at the expense of industry (from 30% to 25%), while the share of agriculture remains roughly stable in the OECD and decreasing in non-OECD countries to 7%.

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(4) GDP figures in this report are given in constant USD of 2005, in purchasing power parity (PPP), unless indicated otherwise.

Table 1: Regional population, GDP and income per capita

	Population (M)				GDP (PPP, CAGR)			Income (k$ PPP /cap)				Income (CAGR)		
	1990	**2010**	**2030**	**2050**	**'90-'10**	**'10-'30**	**'30-'50**	**1990**	**2010**	**2030**	**2050**	**'90-'10**	**'10-30**	**'30-50**
EU28	476	503	519	525	1.8	1.2	1.5	20	28	34	45	1.5%	1.1%	1.4%
Australia	17	22	28	33	3.2	2.8	2.2	24	34	46	61	1.9%	1.5%	1.4%
Canada	28	34	40	44	2.4	1.9	1.9	27	35	43	58	1.3%	1.0%	1.5%
Japan	122	127	120	107	0.9	0.7	0.9	27	31	38	51	0.7%	1.0%	1.5%
Korea (Rep.)	43	49	53	51	5.1	2.8	1.1	11	27	44	57	4.4%	2.5%	1.3%
Mexico	86	119	148	164	2.7	3.0	3.0	10	12	18	29	1.0%	1.8%	2.4%
USA	253	310	356	389	2.5	2.0	1.6	33	44	56	71	1.5%	1.3%	1.2%
Rest of OECD	82	107	129	141	3.2	3.0	2.1	12	17	25	35	1.8%	2.0%	1.6%
OECD	**1062**	**1233**	**1359**	**1423**	**2.2**	**1.7**	**1.6**	**23**	**30**	**39**	**51**	**1.4%**	**1.2%**	**1.4%**
Russia	148	143	139	129	0.4	1.6	0.7	13	14	20	25	0.5%	1.8%	1.1%
Rest of CIS	128	134	146	149	0.4	4.5	3.2	6	6	14	26	0.2%	4.0%	3.1%
China	1155	1342	1416	1349	10.1	6.0	2.7	1	7	21	38	9.2%	5.7%	3.0%
India	871	1231	1528	1705	6.6	6.9	4.5	1	3	9	20	4.7%	5.7%	4.0%
Indonesia	181	242	295	322	4.7	5.5	3.8	2	4	9	18	3.2%	4.4%	3.4%
Rest of Asia	581	820	1035	1173	5.1	4.8	4.3	2	3	7	13	3.3%	3.6%	3.6%
Argentina	33	41	49	55	4.2	2.8	2.4	7	13	19	28	3.0%	1.8%	1.8%
Brazil	150	199	229	238	3.1	1.5	2.4	7	10	12	18	1.7%	0.8%	2.2%
Rest of Latin America	165	224	275	305	3.6	4.0	3.7	5	7	13	24	2.0%	3.0%	3.2%
North Africa	120	168	226	274	3.9	4.7	4.1	4	6	10	19	2.2%	3.2%	3.1%
Sub-Saharan Afr. (excl. ZAF)	475	825	1393	2138	4.5	6.2	6.2	1	1	3	6	1.6%	3.4%	4.0%
South Africa (ZAF)	37	52	60	66	2.7	2.6	2.8	8	9	13	21	0.9%	1.8%	2.4%
Iran	56	74	89	92	4.5	3.1	3.4	6	11	17	32	3.0%	2.2%	3.2%
Saudi Arabia	16	28	39	46	4.0	3.0	2.2	19	24	31	41	1.3%	1.3%	1.4%
Rest of Middle-East	61	115	176	235	6.5	3.2	2.8	6	10	13	16	3.2%	1.0%	1.3%
Non-OECD	**4246**	**5697**	**7151**	**8328**	**5.0**	**5.0**	**3.5**	**3**	**5**	**11**	**19**	**3.4%**	**3.8%**	**2.7%**
World	**5308**	**6930**	**8509**	**9750**	**3.2**	**3.4**	**2.8**	**7**	**10**	**15**	**24**	**1.9%**	**2.4%**	**2.1%**

The differences in growth rates across OECD and non-OECD regions comes short of bringing GDP per capita of non-OECD regions to OECD levels, even when expressed in PPP. In addition, by 2050 a clear distinction is projected in GDP per capita between the Least Developed Countries (LDCs ([5])) and other non-OECD countries.

The countries' level of income is differentiated as follows ([6]):

- **High income**: North America remains the wealthiest region, followed by other high-income regions (Pacific OECD and EU).
- **Middle income**: emerging economies which are already upper-middle income countries, like China (which reaches one of the highest non-OECD per capita level in 2050: 38 k$ PPP), Latin America (Brazil, Mexico) or Middle-East further increase their income levels.
- **Low income**: for countries with currently lower-middle income or low-income levels, in which half the world population is located, GDP per capita remains comparatively lower than in other regions: i.e. developing Asia (13 k$ PPP per capita) and Sub-Saharan Africa (6 k$ PPP).

Based on these differences, the INDC and B2°C scenarios distinguish the mitigation effort undertaken by countries according to their income per capita (see scenario definitions in section 2.2 below).

([5]) LDCs, as defined by the UN, gather countries mostly from Sub-Saharan Africa and South Asia

([6]) GDP and GDP per capita levels in the entire report are expressed in real US dollars of 2005 in purchasing power parity (PPP) terms, unless indicated otherwise.

2.2 Policies considered

The full list of the policies considered for the GECO2017 Reference scenario, and their implementation are provided in Annex 5.

These can also be downloaded from the GECO website: http://ec.europa.eu/jrc/geco.

2.2.1 Reference scenario

A number of energy and climate policies announced for the 2020 time horizon are taken into account in the Reference scenario. Policies are sourced from previous rounds of UNFCCC negotiations and submissions to the UNFCCC (notably the "Copenhagen Pledges" and periodic National Communications) or by more recent national policies that supersede them.

Some of these policies include objectives for years beyond 2020 that were also considered in this scenario. Objectives announced in the INDCs but that do not yet have corresponding national policies (for 2025 and beyond) were considered only in the INDC scenario.

For the EU, the GECO2017 Reference has been derived from the EU "Trends to 2050 – Reference scenario 2016" (EC, 2016), from which it follows the energy trajectory (and resulting CO_2 emissions) at sector level up to 2050.

2.2.2 INDC scenario

The INDC scenario is built upon the Reference scenario. It is assumed that all INDCs announced are achieved, both unconditional and conditional contributions, regardless of the current status of national implementation measures.

Countries where the Reference already leads to GHG emissions at or below their INDC are assumed to stick to Reference level emissions.

For countries individually represented in the modelling, the INDC targets were taken directly. For regions modelled as a group of countries, the individual countries' INDCs have been aggregated.

Some countries (notably non-OECD countries) have expressed their INDCs as percentage reductions compared to a Business-As-Usual (BAU) scenario. In certain cases, the GECO2016 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 a number of factors (among which differences in the assumptions in economic growth, in the modelling frameworks, in energy prices, in energy consumption growth); however, the detailed explanation of these differences is beyond the scope of this report. In the cases where the INDC targets were reached or exceeded with the policies that were already present in the Reference scenario, no additional policies were implemented.

The objectives are reached respecting the INDC perimeter: e.g. energy-only emissions, or all sectors excluding LULUCF ([7]), etc. Climate-related policies have been translated into single country-wide emissions reduction objectives and were modelled using carbon values that impacted all sectors of the economy, including agriculture and land use. Emissions reductions in each sector are achieved depending on the economic attractiveness of mitigation options across sectors and reductions at a sectoral level were calculated by the modelling. For LULUCF this has been done via marginal abatement cost curves for each country/region; as a result, while a country's total reduction objective might have been met, a LULUCF-specific GHG reduction objective might have been exceeded or might not have been met ([8]).

([7]) LULUCF: land use, land use change and forestry (deforestation, reforestation and afforestation, forest management, cropland management, grazing land management and revegetation)

([8]) Non-GHG LULUCF policies were not considered (e.g. forest area coverage).

Most countries' INDCs have been formulated for 2030, with some countries having targets for 2025 or 2035. Beyond the time horizon of the INDCs, the scenario was designed so as to represent a world where the level of policy ambition continues at a similar pace at the global level, with the world GHG intensity of GDP decreasing over 2030-2050 at the same rate as for 2020-2030. This goes through an increase of regional carbon values (including for countries that previously had no climate policies) and progressive convergence at a speed that depends on the countries' per capita income.

2.2.3 Below 2°C (B2°C) scenario

The "below two degrees" (B2°C) scenario is built upon the Reference and the INDC scenarios.

It is a global mitigation pathway in which immediate strengthening of climate action from 2017 reduces emissions to levels consistent with a likely chance to meet the long-term goal of a temperature increase over pre-industrial levels below 2°C (section 4.1), while reflecting the need for a global transition towards a low-emission economic development pattern.

Under this scenario, total, cumulative carbon emissions over 2011-2100 cumulate to 1100 $GtCO_2$. This budget is reached through a progressively increasing carbon value starting from 2017 and rising over time, acting on top of the policies considered in the Reference and INDC scenarios, and considering differentiation between regions to account for their different financial capacity and response flexibility (see Figure 60).

2.2.4 Modelling of policies

Energy taxation and subsidies

In all scenarios, the components of energy taxation are held constant by default: VAT is held constant in percentage terms, and excise duties are held constant in volume (excluding the impact of the carbon value). Domestic prices thus evolve with the prices in the international markets and with climate-specific policies.

Similarly, nationally implemented energy subsidies are kept constant as ratios of international prices. Subsidy is defined as the difference between the domestic fuel price and the level of the related reference price (when the latter is higher than the former). The reference price corresponds to the import price (9) (for importers) or the international market price at the closest market (for exporters).

Reference scenario

In the Reference scenario, policy targets, in terms of capacity deployment or GHG emissions, can be reached with or without policy intervention. First of all, the evolution of economic activity, energy prices, technology costs and substitution effects entail changes in the energy sector. For constraining objectives the following instruments can be introduced: fuel or emission standards for vehicles, capacity for nuclear, feed-in tariffs for renewable technologies in the power sector, or carbon values for GHG emissions targets among others.

After 2020, feed-in tariff policies are phased out, and carbon values are kept constant over time and fuel efficiency is driven by price once fuel standards are reached. Energy market and GHG emissions are thus then driven by income growth with no supplementary incentivizing for low-carbon technologies.

INDC scenario

The INDC scenario goes beyond the Reference scenario, implementing more ambitious policies where relevant. In particular the support to technologies (extended to 2020 and

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(9) This corresponds to the international market price to which are added import taxes, transport and distribution duties and value-added taxes (differs with end-user price only on energy taxes or subsidies).

then progressively phased out by 2030) and the carbon values in the INDC scenario were set to be at least as high as in the Reference scenario. This was done in order to maintain the definition of a higher-ambition scenario for the INDC scenario, despite potential spill-over effects and/or carbon leakage (through lower international energy prices).

The world GHG intensity of GDP is assumed to decrease over 2030-2040 and 2040-2050 at the same rate as for 2020-2030 (-3.3%/year). To respect this global constraint the countries' carbon values progressively converge towards a common worldwide carbon value at a speed that depends on their per capita income in 2030: three groups of countries are distinguished (10), with the first group converging in 2040 to the lead carbon value, the second group reaching 50% of this value in 2050 and the third group reaching 25% of this value in 2050.

B2°C scenario

In addition to INDC energy and climate policies, in this scenario countries are assumed to collectively engage into a higher policy ambition regarding climate protection. This is represented in modelling terms by assuming a set of carbon values starting in 2018 in all regions including countries with low incomes, and those with non-constraining GHG objectives or no GHG objective in the INDCs. The carbon values are prescribed at least as high as in the INDC scenario.

To account for the different financial capacity across regions, the scenario also distinguishes the intensity of mitigation between regional groups based on their per capita income in 2030 (11). Middle- and low-income countries are assumed to converge to the common carbon value of high-income countries in 2030. Regions with very low income per capita are allowed a longer transition period and converge fully in 2050.

Policy synergies (12)

While most INDCs formulate GHG emission objectives, some of them mention policy instruments or programmes to reach these objectives. When explicitly put forward by the countries, these instruments and programmes (e.g. renewable energy support schemes or vehicle emissions standards) are represented in the modelling, and are completed where necessary by a carbon value applying to the economy to reach the country's GHG objective (13).

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(10) Distinguished based on their income per capita in 2030 (expressed in $2005 PPP): >30 k$/cap, 20-30 k$/cap, <20 k$/cap; see also section 2.1.

(11) Country groupings based on income per capita in 2030; similar country groupings to the INDC scenarios (footnote 10), with an additional fourth group for very low-income countries (<10 k$/cap).

(12) An analysis of policies that jeopardize the low carbon objectives (e.g. favouring local fossil fuels) are beyond the scope of this report.

(13) It is worth noting that applying sector-specific regulation can lower the required carbon value on the rest of the economy compared to a situation where only a carbon value would be applied, but also result in higher economic cost - see Jaccard (2016) for a discussion on the relative merits of economy-wide carbon value versus sectoral regulation.

3 Global energy trends

This section gives an overview of the main characteristics of the energy sector for the various scenarios. The companion document of this report (Kitous and Keramidas, 2017) provides detailed energy and emissions balances.

3.1 Energy sector

3.1.1 Primary Energy

Total primary energy demand is the sum of final energy demand and losses in energy transformation (including power generation). These are discussed in detail in 3.1.2 and 3.1.3.

3.1.1.1 Regional trends

A growing world population alongside better living standards coming with increasing income per capita are expected to result in an increase of global demand for energy services in the coming decades. This trend will be partially moderated by a declining energy intensity of the economy due to the progressive shift towards (less energy-intensive) services and the deployment of energy efficient technologies. In the Reference scenario, global primary energy demand (14) by 2050 would still more than double compared to the year 2000, exceeding 21 Gtoe (Figure 5).

The INDC scenario would help to limit the growth of global primary energy demand, reducing it by some 10% compared to the Reference scenario. The evolution of the energy intensity is expected to decrease to a rate averaging -2.1%/year over 2015-2050, a pace slightly higher than the one experienced over the decade 1990-2000 (-1.6%/year) and more than twice the one observed during 2000-2010 (-0.9%/year). As a consequence, by 2030, the world energy demand would merely grow by 24%, whereas its economy would grow by nearly 70% (both figures compared to the 2015 levels). Despite these improvements however, the primary energy demand would still increase globally from circa 14 Gtoe in 2015 to 17 Gtoe in 2030 (nearly twice the energy demand of 1990), and further to 19 Gtoe by 2050.

It is only with the B2°C scenario, which triggers deeper and earlier changes in the energy system through accelerated fuel substitution and strengthened energy efficiency, that total energy demand would peak at around 16 Gtoe in 2030 and then stabilise over 2030-2050 at a level about 15% higher than that of 2015.

Figure 4 presents primary energy demand per world region. Asian countries in particular are projected to increase their share in the world energy demand, getting close to 50% by 2030 compared to 35% in 2015, fuelled by a growing population and a quickly expanding economy. Nevertheless, OECD countries would still account for 31% in 2030, compared to 38% in 2015, with their demand per capita significantly higher than in non-OECD countries (see Table 2).

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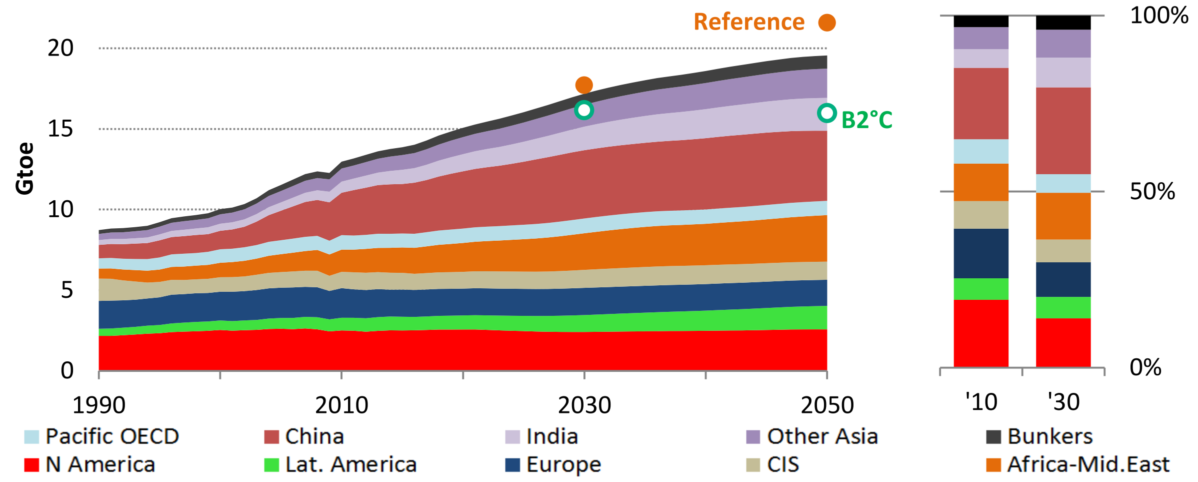
(14) Primary energy demand is calculated using heat-equivalence for electricity from nuclear (efficiency of 33%) and geothermal (efficiency of 10%).

Figure 4: Primary energy demand per world region, INDC scenario



On average, energy demand per capita increases over time in the Reference scenario, with differences in countries' energy demand per capita persisting by 2050. The implementation of climate policies decelerates the growth of energy demand per capita which even decreases in the long term in the B2°C scenario, while there is a progressive convergence between countries (Table 2): energy demand per capita in OECD countries keeps decreasing over time, while in non-OECD countries, by contrast, it would increase up to 2030 on average, before stabilising afterwards. Crucially, Brazil and India would show an increase in energy demand per capita up to 2050. However, non-OECD regions with currently low or subsidised domestic energy prices (mostly oil and gas exporters: e.g. CIS, Middle East) are expected to undergo a decrease in their energy per capita consumption compared to recent historical years, due to the high reduction potential of the economy's energy intensity.

Table 2: Primary energy demand per capita and average annual growth

ktoe per capita		1990	2010	2030	2050	'90-'10	'10-'30	'30-'50
Reference	World	1.60	1.81	1.99	2.12	0.6%	0.5%	0.3%
INDC	World			1.94	1.92		0.3%	0.0%
B2°C	World			1.82	1.58		0.0%	-0.7%
	OECD	4.28	4.41	3.90	3.49	0.2%	-0.6%	-0.6%
	Non-OECD (excl. LDCs)	1.46	2.12	2.55	2.40	1.9%	0.9%	-0.3%
	LDCs	0.41	0.56	0.71	0.66	1.6%	1.2%	-0.4%

Note: LDCs (Least Developed Countries) refer here to regions where income is inferior to 5 k$/cap in 2030, i.e.: Rest of Central America, Egypt, Rest of Sub-Saharan Africa, India, Rest of South Asia, Indonesia, Vietnam, Rest of South-East Asia, Pacific Islands (see Annex 1 for regions' definition).

3.1.1.2 Energy mix

The structure of primary energy demand by fuel is expected to evolve according to each fuel's relative competitiveness, taking into account that resource scarcity differs from region to region (Figure 5 and Figure 6), whereas policies adopted within each scenario and the growing role of new technologies also crucially determine the fuel mix evolution.

Figure 5: World primary energy demand, INDC scenario

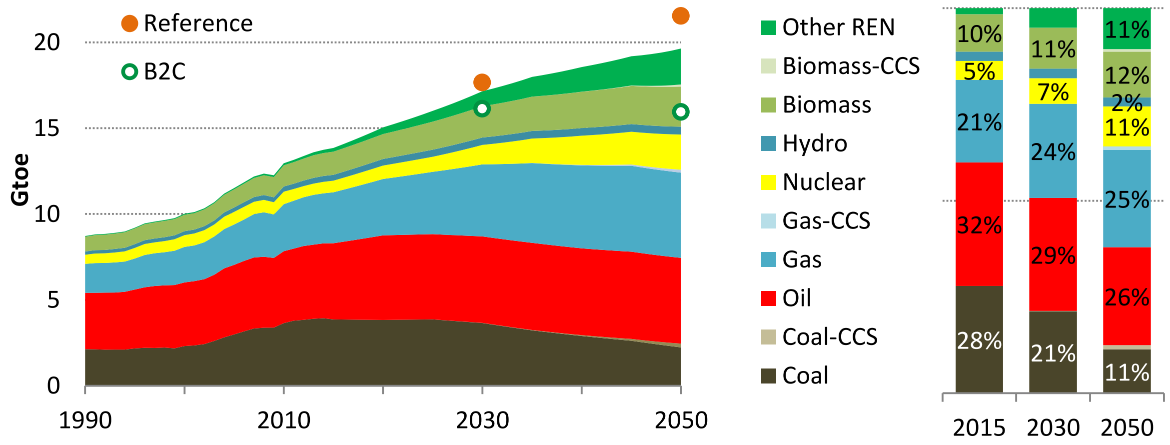
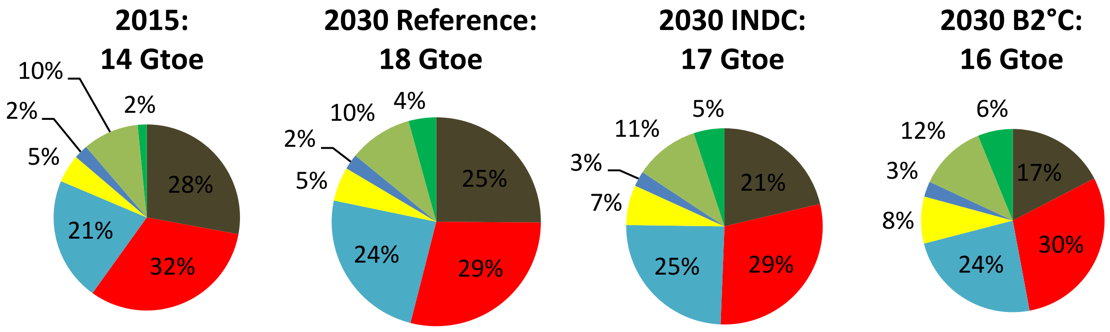


Figure 6: World primary energy demand and energy mix in 2015-2030


2015: 14 Gtoe

2030 Reference: 18 Gtoe

2030 INDC: 17 Gtoe

2030 B2°C: 16 Gtoe

Renewables and nuclear are the only primary energy sources with an increasing contribution throughout 2050 in all scenarios, in particular in the B2°C scenario (Figure 7). Depending on the climate policies, these carbon-free energy sources become –combined- larger than any of the three fossil fuels as early as 2030 (B2°C scenario) or by 2050 (Reference).

- **Renewables** expand in all three scenarios. For example, in the INDC scenario, they represent 26% of the total mix in 2050 vs. 14% in 2015, mainly through the increased contribution of two key primary renewable electricity technologies (wind and solar: "Other REN" in Figure 5) due to costs reduction and increased competitiveness. More ambitious climate policies reinforce this expansion, mainly at the expense of coal.
- **Nuclear** energy supply is expected to increase in all scenarios leading to a marginally increasing share in the energy mix. In the B2°C scenario nuclear, doubles its growth rate to 4.2%/year and the share of nuclear in the energy mix triples to 17% in 2050 vs. 5% in 2015.

Fossil fuels overall would peak in the early 2030s with in the INDC scenario and earlier (2020) in the B2°C scenario.

- The share of **coal** declines in all scenarios for reasons that can already be observed in the Reference scenario: phase-out of coal as a cooking fuel in the residential sector, increasing electrification of final energy demand, which displaces fossil fuels, and increasing cost competitiveness of renewables in the power sector. In addition, the extent of the reduction of coal demand strongly depends on the stringency of the climate policies: in the INDC scenario, by 2050 it drops to 21% of primary energy consumption, the lowest share it has had over the past forty years. In the INDC scenario, coal demand would be reduced significantly compared to the Reference scenario; it would enter a plateau and peak in the early 2020s. With stronger climate policies, coal demand would never recover from the peak observed in 2014 and would fall back to 1990 levels by 2040, despite the deployment of CCS technologies. The INDC and B2°C scenarios differ in the rate of decrease of coal demand, averaging respectively -1.6%/yr and -5.1%/yr over 2020-2050.
- Throughout all scenarios, the share of **oil** progressively declines, in line with a longer trend observed since the 1970s. In the INDC scenario, oil demand enters a plateau at 100 Mbl/d throughout the middle of the century. In the B2°C scenario, demand starts decreasing progressively from the late 2020s; by 2050 it would reach its 1990 levels.
- The share of **gas** is expected to rise progressively in the Reference scenario. In the INDC scenario, gas demand would observe an increase, although at a decelerated rate compared to the 2000-2015 period. With stronger climate policies, the share of gas and its demand level would decrease after 2030, reaching about the same level as 2015 in 2050.

Figure 7: World primary energy demand by fuel

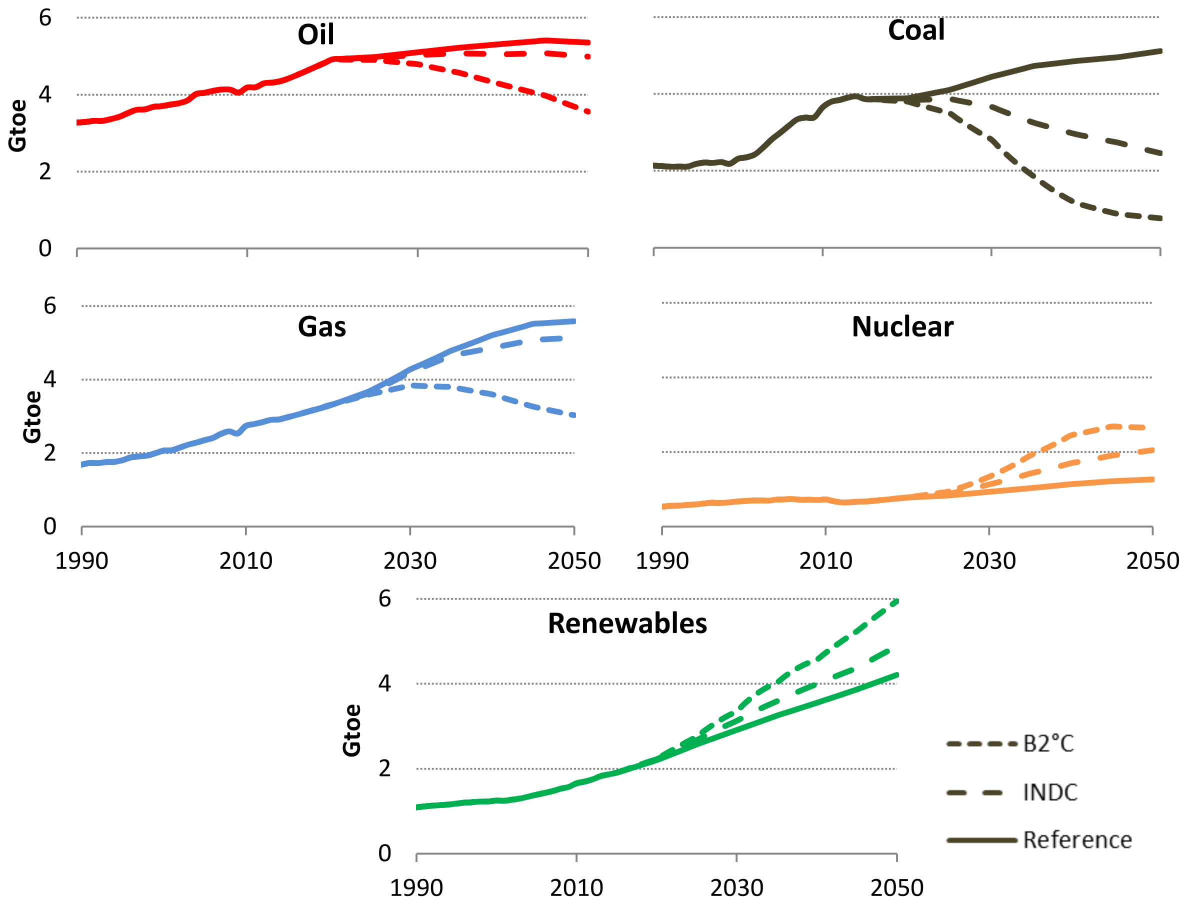
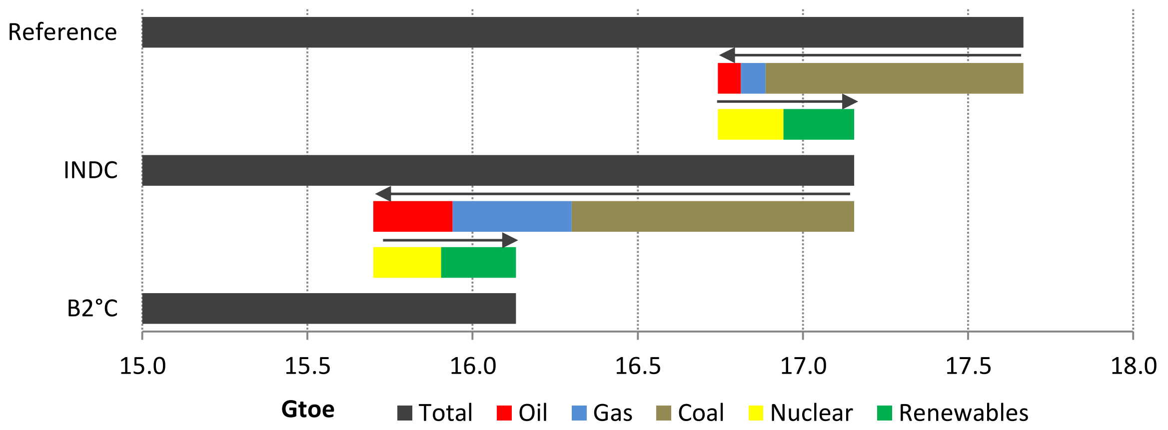


Figure 8 shows the impact of climate policies on the different fuels in 2030. The largest impact of INDC policies, compared to the Reference scenario, is the expected significant reduction in coal consumption (with the coal decrease in 2030 being larger than the total primary energy decrease), followed by higher contribution of renewables (see sections 3.2.5, 3.2.7 and 3.2.8) and, to a lesser extent, nuclear (section 3.2.6). Noticeably, the oil and gas markets would be only marginally affected by the policies in the INDC scenario.

Figure 8: World primary energy demand changes by fuel across scenarios, 2030



The share of low-carbon energy in total primary energy consumed expands very fast in the B2°C scenario (Table 3). In the OECD countries it would exceed 50% as early as 2040 and then would keep increasing to 65% by 2050, while in the non-OECD countries would follow laying just a few percentage points below over the 2030-2050 period.

Including international air and maritime bunkers, the world average would reach a 59% share of low carbon primary energy by 2050, as opposed to 19% in 2015. Large fossil fuel exporters have a slower uptake of these technologies, but they also see a fast increase beyond 2030.

The B2°C scenario allows accelerating this pace, which would take place anyway albeit at slower pace in the INDC scenario (15 years delay) or even the Reference scenario (25 years delay).

Table 3: Low-carbon energy in primary energy, B2°C scenario, share

	1990	2000	2010	2020	2030	2040	2050
EU28	*18%*	*21%*	*25%*	*33%*	*39%*	*50%*	*69%*
Australia	6%	6%	5%	10%	17%	34%	54%
Canada	25%	23%	27%	30%	48%	66%	78%
Japan	16%	20%	19%	21%	31%	46%	61%
Korea (Rep.)	18%	17%	19%	23%	37%	50%	61%
Mexico	14%	13%	11%	11%	22%	44%	61%
USA	14%	14%	17%	20%	37%	53%	64%
Rest of OECD	19%	22%	25%	33%	39%	49%	67%
OECD	**17%**	**18%**	**20%**	**24%**	**36%**	**51%**	**65%**
Russia	6%	9%	9%	12%	27%	51%	65%
Rest of CIS	5%	10%	11%	11%	17%	38%	57%
China	25%	20%	12%	16%	28%	49%	64%
India	46%	36%	28%	22%	26%	46%	65%
Indonesia	45%	36%	31%	30%	30%	41%	57%
Rest of Asia	54%	50%	46%	41%	45%	54%	65%
Argentina	11%	11%	13%	17%	27%	53%	67%
Brazil	46%	41%	46%	47%	55%	64%	74%
Rest of Latin America	29%	24%	21%	23%	33%	49%	65%
North Africa	5%	5%	4%	4%	6%	21%	41%
Sub-Saharan Afr. (excl. SoA)	82%	81%	78%	69%	64%	61%	65%
South Africa	12%	13%	10%	12%	22%	46%	63%
Iran	1%	0%	1%	1%	5%	24%	46%
Saudi Arabia	0%	0%	0%	1%	2%	14%	31%
Rest of Middle-East	1%	1%	1%	1%	4%	20%	39%
Non-OECD	**22%**	**23%**	**18%**	**19%**	**27%**	**45%**	**60%**
World - B2°C	**19%**	**19%**	**18%**	**20%**	**29%**	**45%**	**59%**
World - Reference	**19%**	**19%**	**18%**	**20%**	**22%**	**23%**	**26%**
World - INDC	**19%**	**19%**	**18%**	**20%**	**25%**	**31%**	**37%**

Notes: Low-carbon energy includes renewables (hydro, biomass, wind, solar, geothermal, ocean), nuclear, fossil fuels with carbon capture and sequestration. Biomass includes traditional biomass, which is high in certain regions (e.g. Asia, sub-Saharan Africa). EU28 includes both OECD and non-OECD member states. World includes international bunkers.

3.1.2 Final energy demand

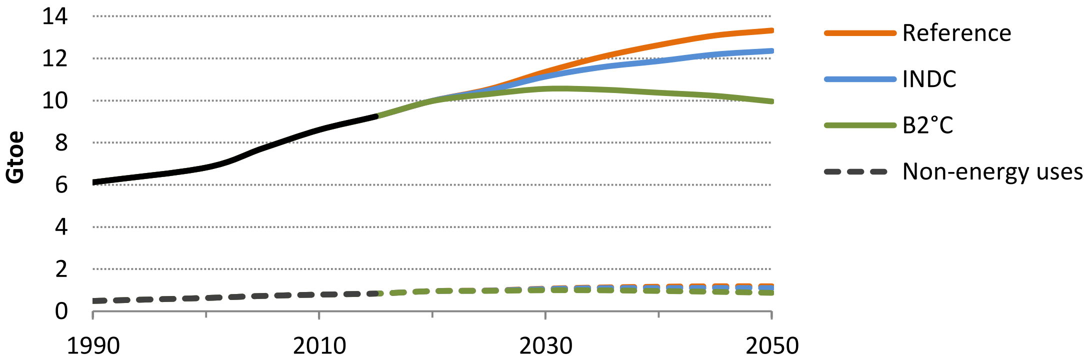
3.1.2.1 Total

With increasing population and rising living standards, final energy demand is expected to continue to grow up to 2050. However, ambitious climate policies triggering an enhanced energy efficiency effort would reverse this trend, resulting in a decrease beyond 2030.

After a decade with a high annual growth (2000-2010, 2.4%/year) and a notable deceleration in recent years due to the global economic slowdown (2010-2015, 1.4%/year), future energy efficiency improvements and a lower economic growth on average result in a decelerating growth of final energy demand in the future: 1.5-1.6%/year in the second half of the current decade for all scenarios, decreasing progressively by 2050, to 0.5% and 0.4%/year respectively in the Reference and INDC scenarios.

Total final energy demand ([15]) is projected to increase from 10 Gtoe to around 12 Gtoe in 2050 in the INDC scenario, against about 13 Gtoe in the Reference scenario. In the B2°C scenario, it peaks in 2025 and then stabilizes around 10 Gtoe (Figure 9).

Figure 9: Final energy demand, World

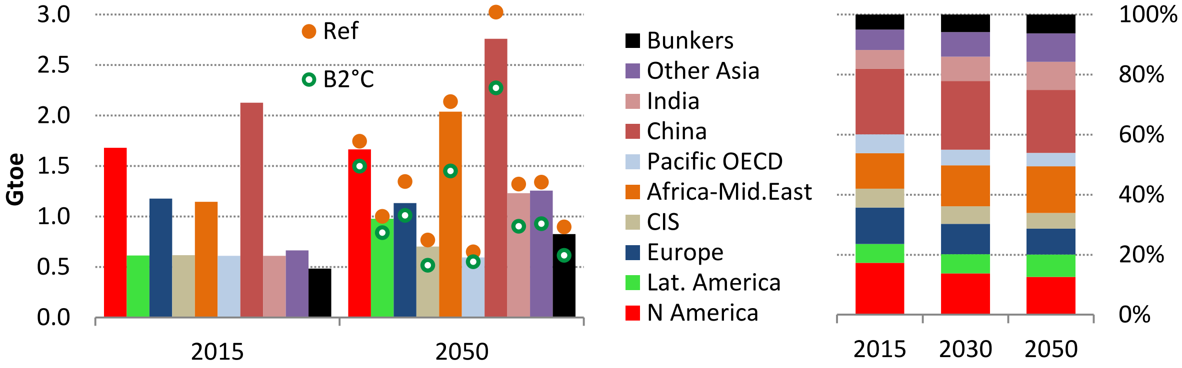


Note: Total, includes non-energy uses of energy fuels.

In terms of the regional distribution of this final energy demand (Figure 10), the largest structural changes take place over the period 2010-2030, with a decrease of the shares of OECD countries and an increase for non-OECD countries, particularly China. Beyond 2030 these shares are expected to stabilize, with a notable redistribution between non-OECD countries: further demand increase is expected in Africa-Middle East whereas the shares of China and India decrease while Other Asia (Indonesia and Rest of Asia) increases. These trends are observed across all scenarios.

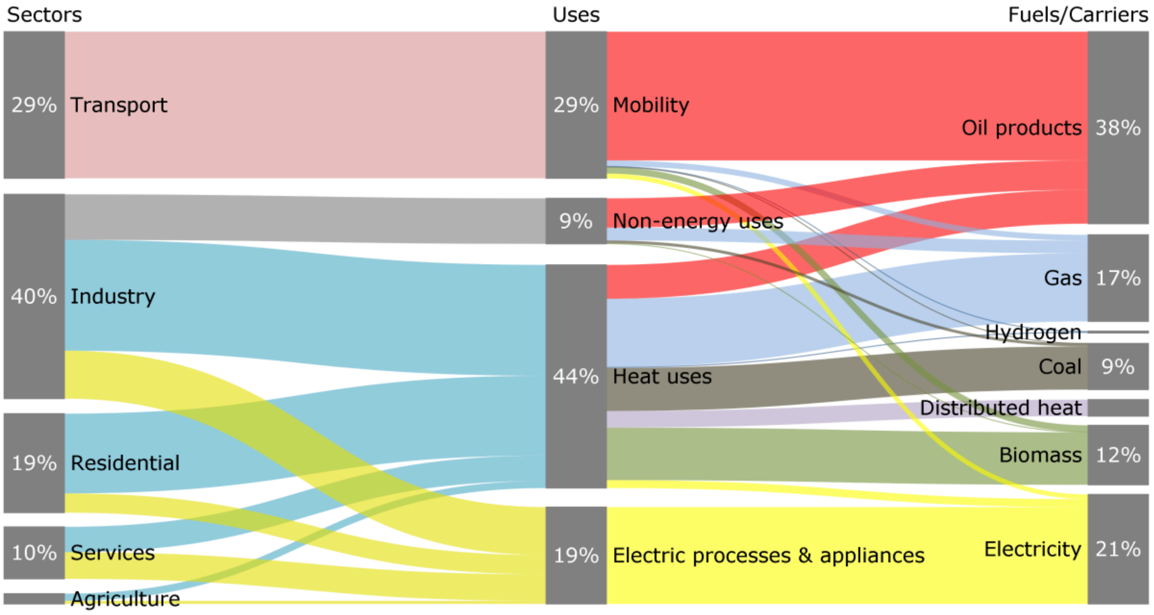
([15]) Excludes international aviation and maritime bunkers; includes non-energy uses.

Figure 10: Final energy demand by world region, INDC scenario



Final energy demand can be decomposed in demand by end-use, by economic activity sector and by fuel or energy carrier (Figure 11) ([16]). By 2030 heat uses represent the bulk of fuel consumption in the INDC scenario, distributed between industry, residential and services, and fuelled by fossil fuels and biomass. A large share of oil products still goes to mobility needs, where electricity remains a minor contributor.

Figure 11: Diagram of global final energy flows of sectors-uses-fuels/carriers, INDC scenario, 2030 (Total: 11.8 Mtoe)

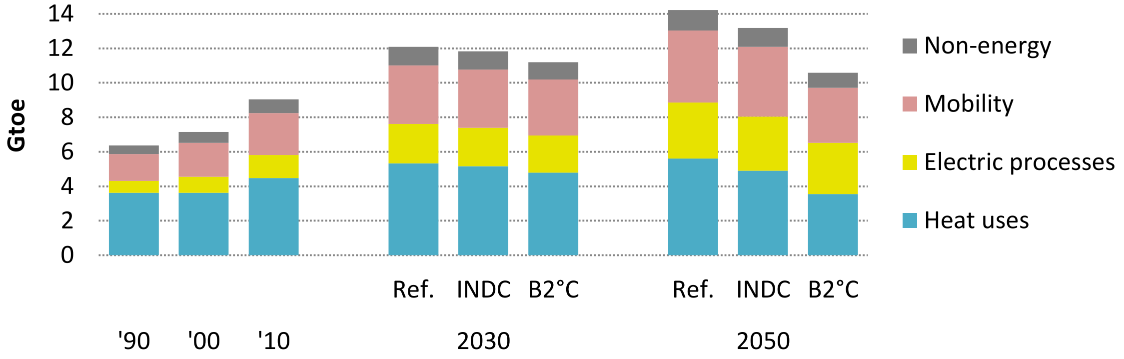


The decomposition of final energy demand by *end-use* is provided in Figure 12. Climate policies would reduce much heat uses in industry and buildings through increased energy efficiency via technology and fuel substitution and buildings insulation. They are followed by lower energy use in transport due to a decrease in mobility and substitution towards electricity-fuelled vehicles (which display much lower energy losses than the current oil-fuelled internal combustion engine vehicles). While consumption for electric processes and appliances keeps increasing over time, the impact of climate policies on the electricity consumption remains limited (see section 3.1.2.4 for more detail).

In addition, non-energy use of energy fuels (mainly oil and gas, for plastics, chemical feedstock materials and fertilizers) would increase slowly to 1.1 Gtoe in 2050 in the INDC scenario, compared to 0.8 Gtoe in 2015.

([16]) See the Glossary section for the definitions of sectors and end-uses.

Figure 12: World final energy demand by end-use

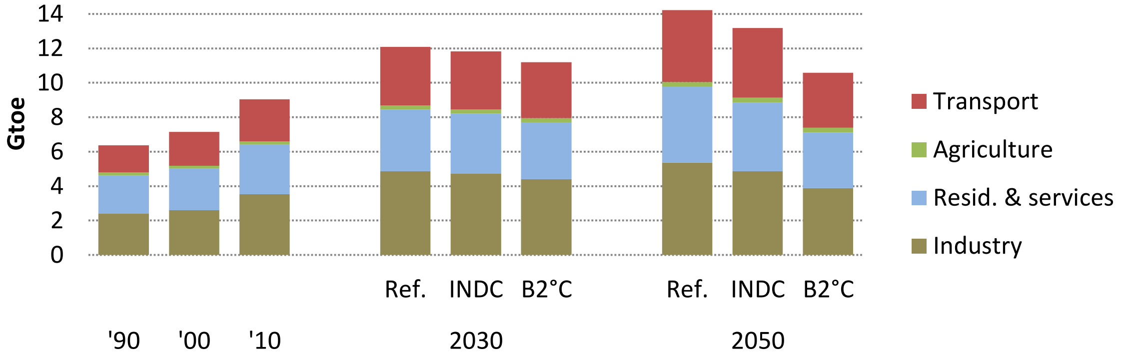


Notes: Electricity demand is found in "Mobility", "Electrical processes" and "Heat uses". "Electrical processes" include electrical appliances.

The sectoral distribution of energy demand (Figure 13) would remain fairly stable in the future and across all scenarios – at roughly 40% for industry (slightly increasing by 2030) and 30% each for residential & services (slightly decreasing by 2030) and transport (slightly increasing over the whole period).

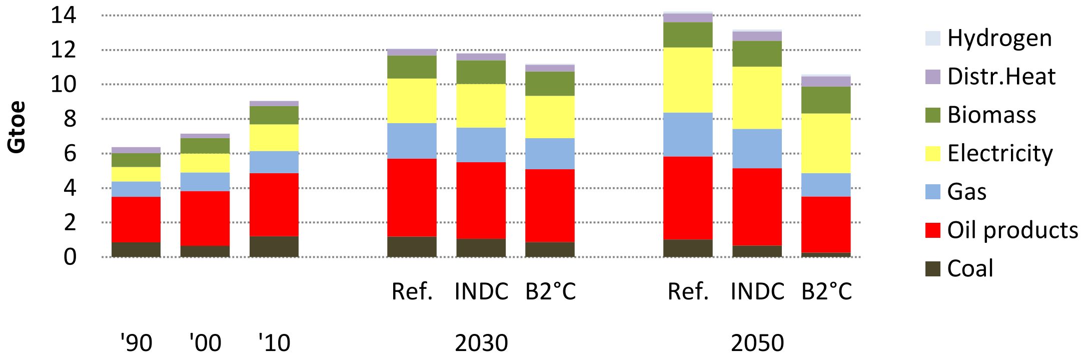
However, different regions would follow a somewhat different pattern. In OECD countries the share of transport in total final energy would decrease, due to stabilizing mobility and improved efficiency of vehicles, while that of residential & services would increase, especially with the increasing role of electrical appliances. In non-OECD countries the industry share is decreasing from 2030 onwards, while the transport share increases steadily to almost a fourth of total demand by mid-century.

Figure 13: World final energy demand by activity sector



In terms of consumption per fuel/carrier (Figure 14), all scenarios show an acceleration of final energy demand electrification observed historically (electricity share in total final demand up to 30%-40% depending on the scenario, vs. 18% in 2015, see also Figure 18 for detail by sector) and an increase of biomass consumption (around 10-15% of total across 2015-2050 and all scenarios). Coal reduces in volume as soon as climate policies are introduced, while on the contrary oil and gas demand tend to maintain their shares by 2030, even in a context of climate policies. Oil consumption would grow slowly due to its predominant role in transport, a sector characterised by growing demand for mobility, a fairly inelastic response to prices and low substitution possibilities especially for heavy vehicles and air transport (see section 3.1.2.3 on mobility); only in the B2°C context would it decrease after 2030. Natural gas benefits first from its relatively lower carbon content compared to coal in the power sector (and compared to oil in the industry sector) and thus acts as a transition energy vector; however, like oil, its consumption decreases with more stringent climate policies after 2030.

Figure 14: World final energy demand by fuel/carrier

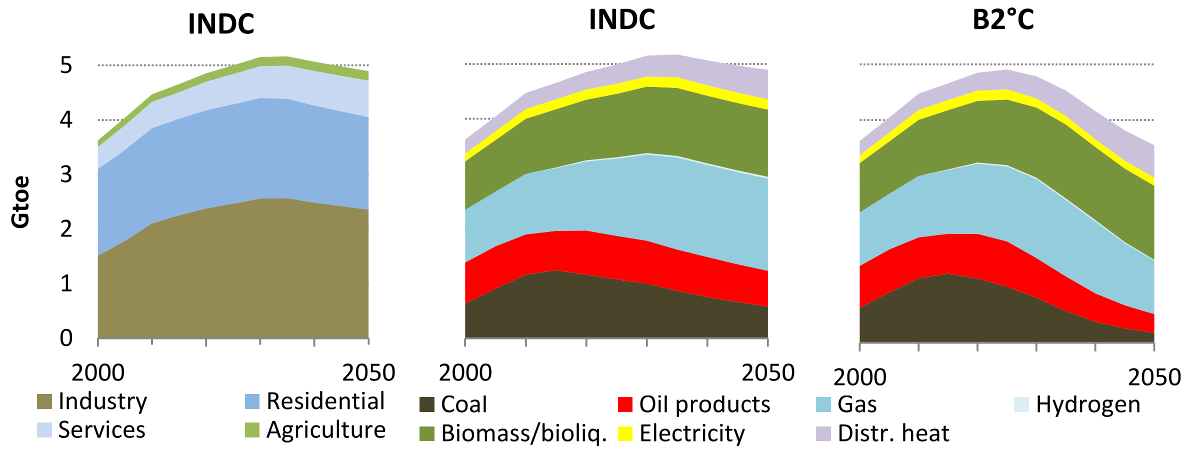


The following sections focus on energy demand for the end-uses for heat and for mobility, on electricity as a whole, and on the total share of renewables.

3.1.2.2 Heat uses

In the recent past, energy in the form of heat use was evenly shared between needs for space heating, water heating and cooking in residential, services and agriculture on one side, and process heat in industry on the other side. This distribution remains fairly unchanged in the three scenarios considered (Figure 15).

Figure 15: Energy demand for heat uses per sector and per fuel/carrier, World



Note: Distributed heat refers to both urban heat networks and low enthalpy heat traded by pipe in industry.

Energy needs for heat uses are set to increase in the medium term regardless of climate policies (17). Energy efficiency and fuel substitution induced by climate policies would result to energy demand first plateauing and then decreasing in the long term, reaching about the same level as 2015 in 2050 in the INDC scenario. Fossil fuels, especially gas, would still make up about 60% of energy use in 2050; it is only with stronger climate policies that fossil fuels would be progressively phased down, down to about 40% in 2050 in the B2°C scenario.

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(17) Increasing outdoor temperature due to climate change is not considered in this analysis, which is likely to play a role by reduction the need for space heating in buildings – see Ciscar et al. (2014)

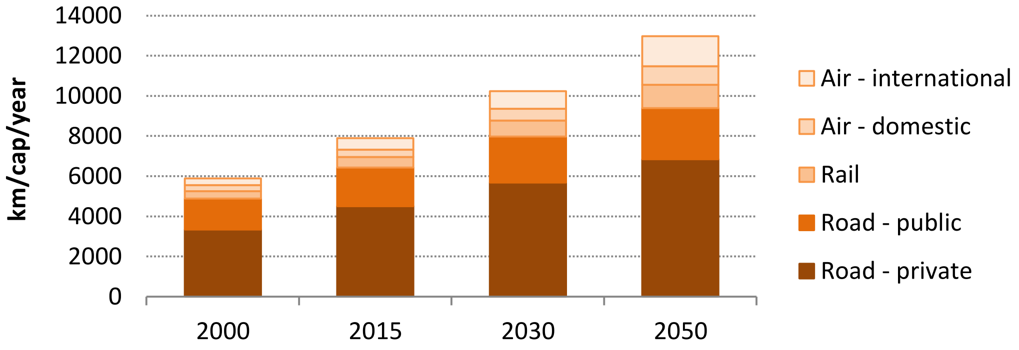
3.1.2.3 Mobility

Passenger mobility and freight transport both drive up the final energy demand of the transport sector.

The demand for passenger mobility is foreseen to increase significantly over time, particularly in developing economies. As a world average, it would double over the 2015-2050 period (INDC scenario). Road transport continues to represent the most important mode of transport throughout the projection period, with steady growth in both public modes of transport and in private cars (and represents the bulk energy demand increase). However, air transport is the sector experiencing the highest growth of mobility (+156% increase over 2015-2050 in the INDC scenario).

For all transportation modes, passenger mobility increases over time; total passenger traffic increases at around 2.7%/year over 2015-2050 (INDC scenario, Figure 16). The increase in passenger mobility would slow down only with the implementation of more stringent climate policies, which would raise the cost of energy for transport.

Figure 16: World average passenger mobility by mode of transport, INDC scenario

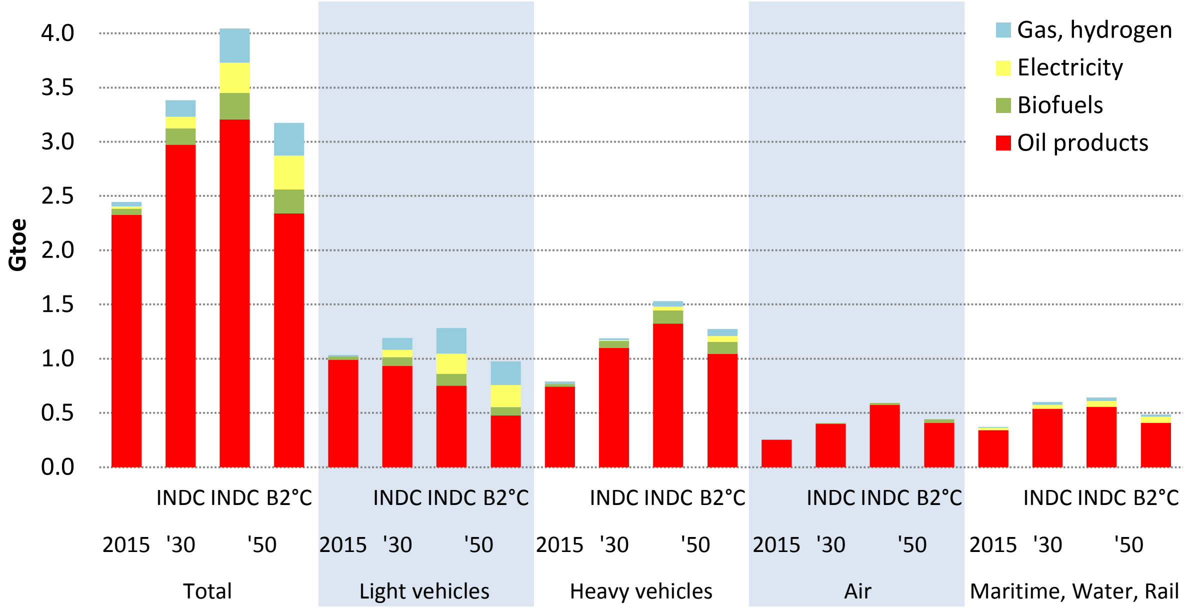


Freight activity is also expected to grow significantly driven by increasing consumption and the corresponding growth in manufactured goods being transported; total goods traffic increases at around 2.1%/year over 2015-2050 (INDC scenario). The highest growth in freight is expected to occur in international maritime bunkers, while energy demand will still be mostly consumed in road freight transport.

The decomposition of energy demand in transport by type can be seen in Figure 17. Although air transport is experiencing significant growth, transport energy demand overall is still dominated by road transport throughout 2050. Energy demand for road freight transport reaches and exceeds the total level of road passenger transport around 2030, depicting a global situation in which trade tends to grow faster than population.

Climate policies compatible with staying below 2°C would entail an important reduction in energy demand in transport, driven by a combination of reduced mobility, better logistics, improved technical efficiency and increased penetration of electricity in road transport (important because of the higher efficiency of electrical engines). Transport energy demand for maritime and light vehicles would fall back to 2015 levels.

Figure 17: Energy demand in transport



Substitution by alternatives to oil in the transport sector has been historically low, with alternative fuels/carriers (usable in ICEs) having entered the market over the last decade to a limited extent, and with novel technologies requiring different drivetrains (e.g. electric vehicles) having started to be deployed more recently. Liquid biofuels, natural gas and electricity represented respectively 3%, 2% and 1% of total energy used in transport in 2015 globally. Despite the emergence of these alternatives, their role in the short-run still is expected to remain small: liquid biofuel production increased by just 2% worldwide over the past two years 2014-2016 (Enerdata, 2017) while oil demand has increased by 4% (IEA, 2017); world electric car sales, although increasing fast over the last years (sales have increased 15-fold over 2011-2016), made up only 0.8% of total car sales in 2016 at world level (EV-Volumes, 2017; OICA, 2017). Additionally, the evolution of mobility tends towards an increasing fuel demand, particularly in the large and inefficient categories[18], which is only partially offset by the fuel efficiency standards implemented in different countries.

It is considered that electric and hydrogen alternatives to liquids combustion are more suited for passenger road mobility than for goods road transport, and would not get any noticeable market share in air and sea transport. Although substitution is possible, it would be limited outside of passenger mobility due to the technical requirements for long range autonomy and to the weight of electric batteries. The techno-economic improvement of electrical batteries and the better coverage of the road network with recharging facilities, however, can help accelerating the penetration of electricity in transport. Hydrogen shows a limited development in all scenarios, hampered by the high cost of fuel cells.

Thus, fuel substitution in the road transport sector is expected to be very gradual rather than disruptive, with alternative fuels/carriers gaining just about 0.5% of market share per year over the next decades in the INDC scenario. Oil still dominates but decreases: it would drop to 60% of total light vehicles energy consumption, substituted by electricity, gaseous fuels and biofuels, and to 85% in heavy vehicles energy consumption (Figure 17).

Moreover, significant advancements in fuel efficiency for oil use are expected (close to 2%/year over 2015-2030 in the Reference scenario) due in particular to a better use of

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(18) Highest sale increase was in the following categories: SUV, Pickup, CUV - see: http://www.autoalliance.org/auto-marketplace/popular-vehicles

energy in vehicles with internal combustion engines (e.g. "hybrid" engines allowing a recovery of braking energy, automatic start/shutoff, …).

Finally, energy demand for international bunkers ([19]) is expected to be an increasing contributor to future energy demand in transport, in all scenarios. Energy demand in bunkers reached 11% of total oil demand in 2015; it has grown faster than demand in road transport. It is expected to keep growing at a fast pace due to increasing international traffic of freight and passengers (both being strongly correlated to economic activity): a 42% increase in bunkers' energy consumption by 2030 compared to 2015 in the INDC scenario, and another 20% increase over 2030-2050, on the same trend as the historical doubling over 1990-2015). Oil would still dominate both air and maritime bunkers throughout 2050 in all scenarios. More in detail:

- **Maritime bunkers:** Maritime freight traffic is expected to increase by 50% over the 2015-2030 period, with half of this due to traffic of containers and various industrial products, which are growing as per capita income increases and the world economy becomes more inter-connected over time. The rest of the increase in maritime freight traffic is due to the international trade of energy goods, which would be impacted by climate policies as the demand for fossil fuels decreases: traffic over 2015-2030 could grow by as much as 59% (Reference) or by as little as 30% (B2°C). Combined with fuel efficiency measures that could be adopted in existing and new ships, the total energy demand growth for bunkers in the B2°C scenario over 2015-2030 could be limited to 27% (vs. +48% in Reference). In the B2°C scenario, maritime bunkers energy demand peaks in the mid-2020s and decreases thereafter.
- **International air:** Air traffic, both domestic and international, is expected to grow significantly in all scenarios; over 2015-2030 it grows by +81% (Reference), with climate policies limiting it to +63% (B2°C). With fuel efficiency measures, this brings the energy demand growth for international air to +44% for the Reference and +29% with the. By 2030 the contribution of alternative fuels in air transport is small (a few %). Traffic and energy demand are expected to significantly grow beyond 2030 in the Reference and the INDC scenarios, and stabilize progressively around 2050 in the B2°C scenario.

3.1.2.4 Electricity

Electricity demand is expected to increase in all scenarios along with economic activity and rising standards of living around the world. In addition, electricity offers also the widest set of technical opportunities to decarbonize and implement climate mitigation options.

Electricity represented just 18% of global final energy demand in 2015, and would reach a share of 35% of final demand in 2050 in the B2°C scenario vs. less than 30% in both the Reference scenario and the INDC scenario (Figure 18).

Roughly speaking, electricity demand would increase by about 6,000 TWh every ten years, starting from about 20,000 TWh in 2015 and more than doubling by 2050 in all scenarios. The sector experiencing the largest increase in electricity consumption in relative terms is the transport sector due to the emergence of electro-mobility starting from very low levels today; the other demand sectors would also double their demand by 2050 with respect to 2015. In absolute terms, the rise in electricity demand is most pronounced in industry, followed by captive uses in residential & services (appliances, lighting, cooling).

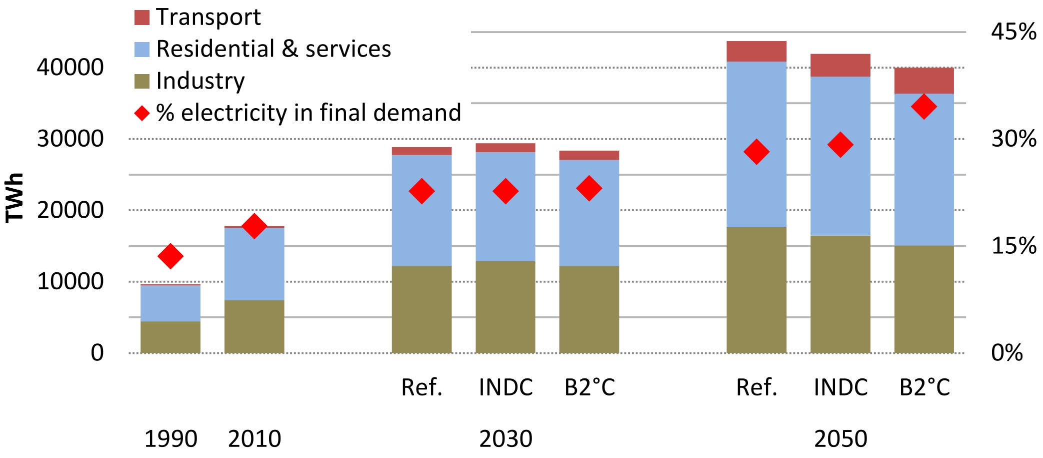
Total electricity demand is lower in the INDC and B2°C scenarios compared to the Reference scenario (4% lower for the INDC scenario in 2050, 9% for the B2°C scenario).

([19]) International bunkers include both international air transport and international maritime transport

This is due to higher electricity prices in all final demand sectors combined with higher energy efficiency in residential & services.

This is partially compensated by an increase in electricity demand in the (road) transport sector where electrical vehicles (both plug-in and fully electrical) develop faster with stronger climate policies (Figure 17).

Figure 18: Electricity demand by sector (bars, left axis) and share in final demand (diamonds, right axis)



3.1.2.5 Renewables

Renewables are used in final energy demand either directly (solar thermal; geothermal heat pumps; direct biomass combustion) or as indirect inputs to energy carriers (wind, solar, hydro, biomass combustion in power generation; biomass inputs into liquid biofuels production).

As a general trend, the share of renewable energy in gross final demand ([20]) is projected to increase over time in all scenarios (Figure 19, Table 4). This rising share materialises primarily through their rapid deployment in power generation: indeed, while renewables in power generation represented about a third of total renewable energy in 2015, this share would rise to above 50% by 2040 in all scenarios, and would be further pushed with more ambitious climate policies (63% in 2050 in the B2°C scenario).

This happens in most of the world except where traditional biomass ([21]), a historically important energy source, is phased out in favour of more efficient and cleaner fuels, such as in India, South-East Asia or Sub-Saharan Africa.

([20]) Defined as the energy consumption of renewable origin as a share of gross final energy demand, including auto-consumption and transmission and distribution losses of the energy sector, and excluding non-energy uses of fuels.

([21]) Refers to direct burning of wood or manure for cooking and heating purposes in the residential sector.

Table 4: Share of renewables in gross final demand, 2030, INDC scenario

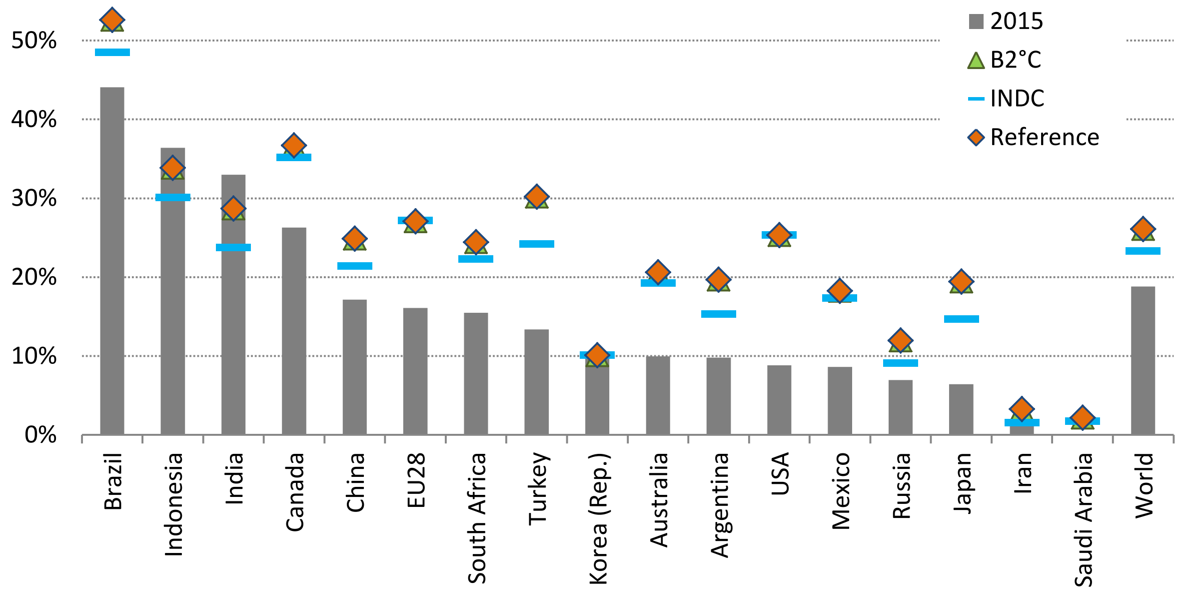
	2015	Total	Biomass	Hydro	Wind +Solar	Other
EU28	*16%*	*27%*	*15%*	*3%*	*8%*	*1%*
Australia	10%	19%	9%	2%	8%	0%
Canada	26%	35%	12%	18%	9%	0%
Japan	6%	15%	6%	3%	5%	0%
Korea (Rep.)	10%	10%	6%	0%	5%	0%
Mexico	9%	17%	9%	2%	4%	1%
USA	9%	25%	13%	2%	6%	0%
Rest of OECD	17%	28%	14%	5%	4%	3%
OECD	12%	24%	12%	4%	6%	0%
Russia	7%	9%	5%	4%	8%	0%
Rest of CIS	6%	9%	4%	3%	0%	0%
China	17%	21%	10%	6%	2%	0%
India	33%	24%	17%	2%	6%	0%
Indonesia	36%	30%	26%	1%	5%	1%
Rest of Asia	27%	19%	15%	2%	3%	0%
Argentina	10%	15%	7%	5%	1%	0%
Brazil	44%	48%	26%	16%	3%	0%
Rest of Latin America	29%	31%	16%	11%	7%	0%
North Africa	5%	6%	2%	1%	4%	0%
Sub-Saharan Africa (excl. ZAF)	79%	66%	62%	2%	3%	0%
South Africa (ZAF)	15%	22%	15%	1%	1%	0%
Iran	1%	2%	1%	1%	6%	0%
Saudi Arabia	0%	1.77%	0%	0%	0%	0%
Rest of Middle-East	1%	3%	1%	0%	1%	0%
Non-OECD	23%	27%	17%	5%	3%	2%
World	19%	23%	14%	4%	4%	0%

Notes: EU28 includes both OECD and non-OECD member states. The share in EU28 follows the definition of the Directive 2009/28/EC (EC, 2009). Includes traditional biomass. Gross final energy demand includes auto-consumption and transmission and distribution losses of the energy sector and excludes non-energy uses of fuels.

Globally, in the INDC scenario the share of renewables grows at about 3-3.5 percentage points per decade, reaching 23% in 2030 and 31% in 2050 (vs. 19% in 2015); with stronger climate policies, the growth rate would be twice as high throughout the 2015-2050 period, and the share of renewables would reach 26% in 2030 and 43% in 2050.

Wind and solar contribute to the renewables share increase over time in all scenarios. The comparative advantage of these "pure" electrical renewables is reflected by the fact that it is only in the B2°C scenario that biomass becomes a significant contributor to that share increase over time.

Figure 19: Share of renewables in gross final demand, 2030



Note: Includes traditional biomass.

Many countries and regions are expected to experience a strong increase in the share of renewables between 2015 and 2030; this would be particularly pronounced in North America, EU-28, Australia or Turkey.

In some countries with a very strongly growing total energy demand (India, Indonesia), renewables may expand at a slower pace than that of total energy demand, resulting in a share of renewables that may even decrease over time; a stabilisation of the share would occur only with ambitious climate policies and more energy efficiency.

Strengthening climate policies towards the B2°C scenario result in an increase of the share of renewables in all regions (22).

3.1.3 Power and other energy transformation

3.1.3.1 Power generation

Power generation increases in all three scenarios, as a result of increasing overall energy demand and the increase of electrification of demand (section 3.1.2.4); transport and distribution losses remain at around 8% of total power produced.

It would rise at a global level from about 24,000 TWh in 2015 to about 50,000 TWh in 2050 in the INDC scenario (5% higher and lower in the Reference and B2°C scenarios, respectively).

In the Reference scenario, power production from all technologies is foreseen to increase over time; the same is true in the INDC scenario except for coal. In the B2°C scenario, the contribution of fossil fuels technologies decreases. Renewables are expected to expand in both volume and share across all scenarios.

In 2030 the level of electricity production is still fairly similar across scenarios (Figure 20). However, the fuel shares do differ with the intensity of climate policies: power from coal contracts substantially while carbon-free power from nuclear, wind and solar expands, leaving the share of gas roughly unchanged. B2°C policies imply a further reduction of

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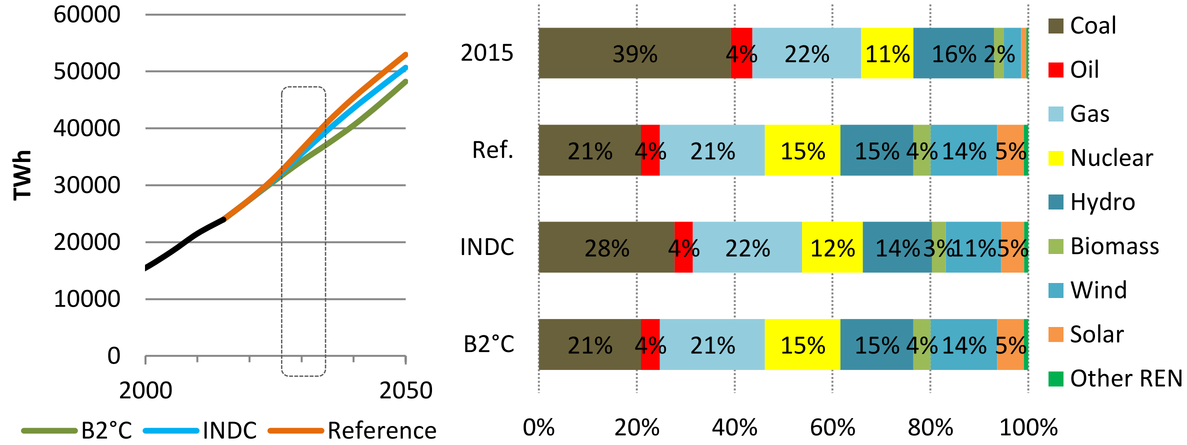
(22) For certain countries and regions, the share remains the same from INDC to B2°C scenarios, as the INDC policies are stringent and coherent with a pathway towards a below 2°C temperature increase. This is the case for EU28 and USA (see Figure 60 for carbon values used in the scenarios).

fossil fuels, to less than half of power production (44%) and a further expansion of wind (which reaches 14% of total production).

Beyond 2030, with climate policies, fossil fuels decrease in both share and volume despite the expansion of CCS technologies (Figure 21).

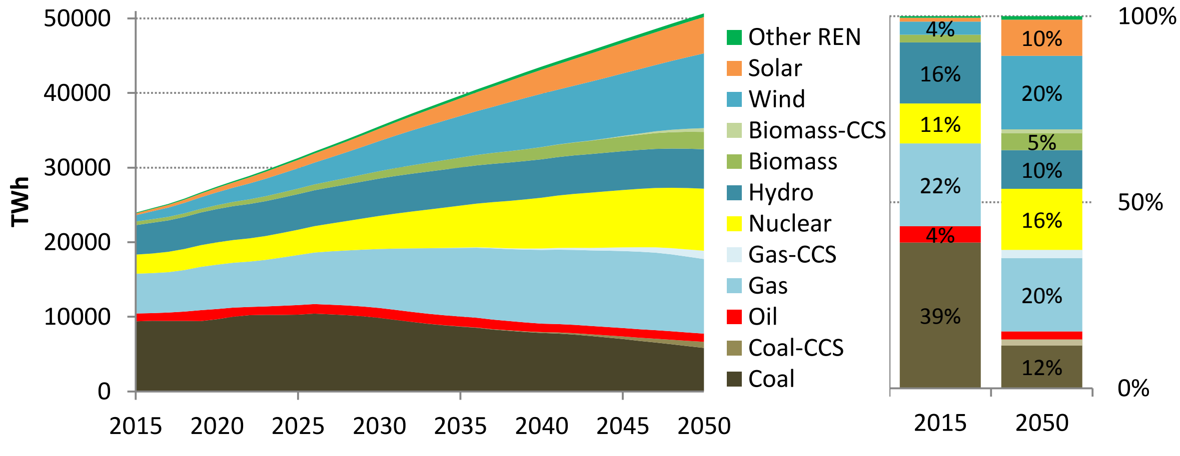
Figure 20: World power production and production mix in 2030



Note: no CCS capacities have been installed by 2030 in any of the scenarios.

Since the power sector is the one offering the widest and cheapest decarbonisation opportunities, the power production mix varies substantially across scenarios. Renewables and nuclear would rise to cover most of power production in 2050 with INDC policies (46% and 16%, respectively); conversely, the fossil fuels contribution to the power mix would drop from 66% in 2015 to 37% in 2050. In the B2°C scenario the renewables share would grow to 59% (8% of which being bioenergy with CCS - BECCS) and the fossil fuels share would contract to 19%, most of it associated with CCS (12%).

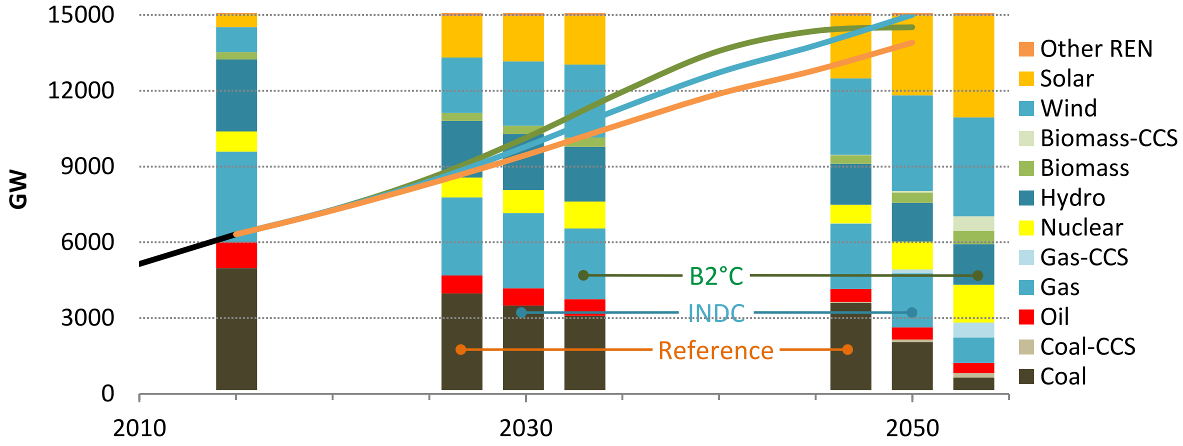
Figure 21: World power production and production mix in the INDC scenario



3.1.3.2 Power generation capacities

Total installed power generation capacity is projected to increase at the pace observed since 2000, by around +2 – 2.5 TW every decade, from 6.3 TW globally in 2015 to about 10 TW in 2030 and 15 TW in 2050 (a more than twofold increase vs. current capacity) in all three scenarios. Slightly different dynamics of electricity demand (see Figure 18) is compensated by contrasted average load factor stemming from differentiated penetrations of wind and solar technologies (23). Renewables exceed 60% of the total installed capacity by 2050 in the INDC scenario and 70% in the B2°C scenario (vs. 26% in 2010 and 31% in 2015) (Figure 22).

Figure 22: World installed power capacity (left axis) and technology mix (right axis)



New installations would need to be deployed quickly, to cover for the new demand and to substitute for decommissioned power plants. While total new installations averaged below 200 GW/year over 1990-2010, this would rise to above 300 GW/year over 2010-2030 and to 500 GW/year over 2030-2050 at global level in the INDC scenario, with a very different investment pattern across world regions (see Figure 24).

In the Reference scenario, there would still be a non-negligible expansion of coal-based power in the future, gas and hydro would remain at their 1990-2010 paces and nuclear would undergo an increase to around 20 GW/year. Installation rates for wind and solar would each exceed 100 GW/year in 2030-2050 while coal and gas would follow with around 80 GW/year each.

In the B2°C scenario, the dynamics would be very different: coal technologies without CCS would essentially stop being installed from 2025 and the market size of coal-fired facilities being reduced to barely 10 GW/year of coal with CCS. Wind and solar would each exceed 150 GW/year in 2030-2050, while total CCS technologies (combined across coal, gas and biomass) would exceed 60 GW/year.

Overall, in terms of distribution of annual power capacity installations as a world average (Figure 23), there would be a shift from fossil-based capacities towards renewables. Renewables would exceed half the annual new installed capacities in all scenarios and future decades, starting from the current decade in the Reference (50%; it was 43% over the 2010-2015 period) and reaching a share of about three quarters in the 2030-2050 decades in the B2°C scenario (77%).

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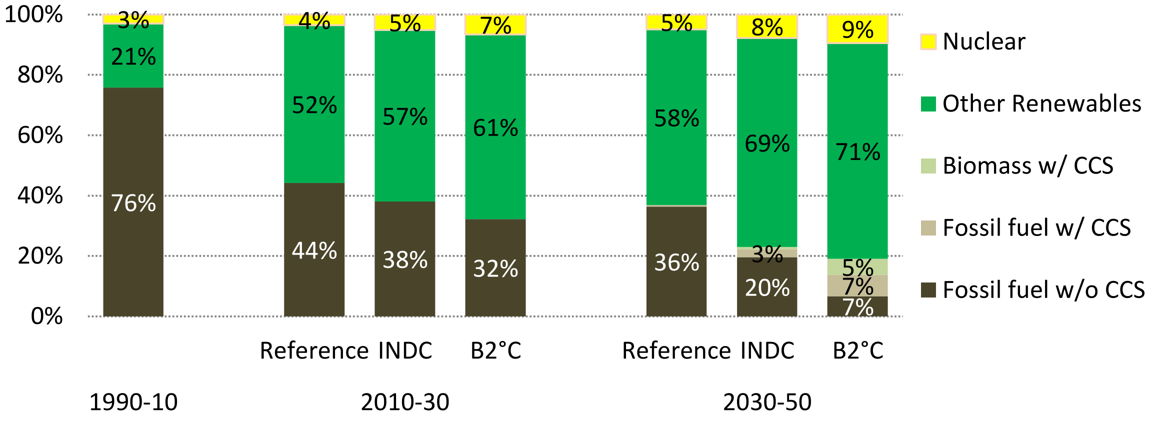
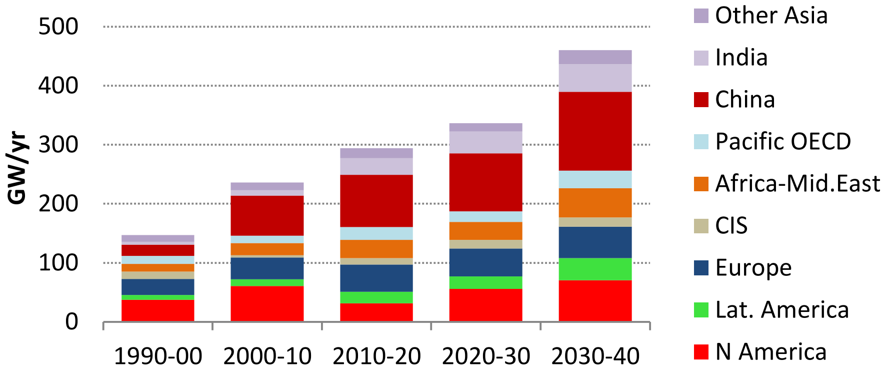
(23) Additionally, in the B2°C scenario the power mix quickly adapts to the needs for low-carbon electricity in 2025-2040 and thus the load factor of non-CCS technologies is decreasing quickly; these are eventually decommissioned in the 2040-2060 decades at the end of their lifetime.

Figure 23: Technology shares of average new annual power capacity installations, World



New installations grow following the increase of electricity demand and to substitute decommissioned plants, resulting in different profiles for regions across the world (Figure 24). Over 80% of power capacity installations from 2010 to 2050 take place in non-OECD regions (Asia, part of Latin America, Africa, CIS), driven by the fast increase of electricity demand. The regional distribution changes little across scenarios.

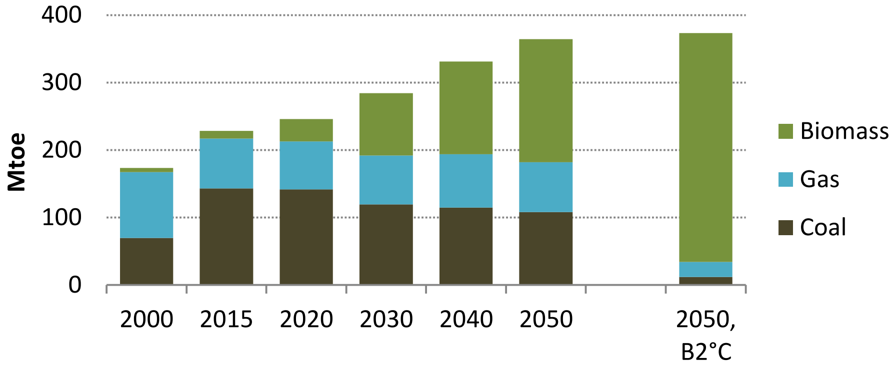
Figure 24: Distribution by region of average new annual installations, INDC scenario



3.1.3.3 Other energy transformation

Centralized heat production, supplying heat to industry, residential and services, is expected to increase in all scenarios. Input to heat plants would continue representing around 2% of total energy demand throughout 2050. Depending on the stringency of climate policies, coal input is phased out more or less quickly, substituted by biomass input (Figure 25).

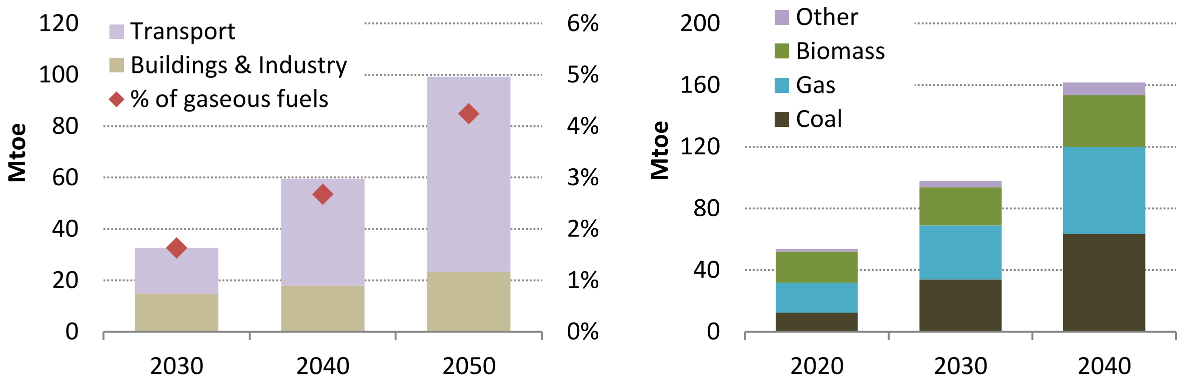
Figure 25: Inputs in heat plants, World, INDC scenario



Hydrogen production for energy uses is expected to remain limited, although it should increase to respond to demand from road vehicles and from stationary uses. By 2050, the contribution of hydrogen in total gaseous fuels consumption is relatively limited: less than 5% in the INDC scenario, up to 8% in the B2°C scenario.

Hydrogen production would be dominated by processes using coal (coal gasification), gas (mostly gas steam reforming) and biomass (mostly biomass pyrolysis) in all scenarios, despite the relative loss of competitiveness of fossil fuel-based production technologies with climate policies (Figure 26).

Figure 26: Hydrogen demand (left) and production inputs (right), World, INDC scenario



3.2 Energy markets

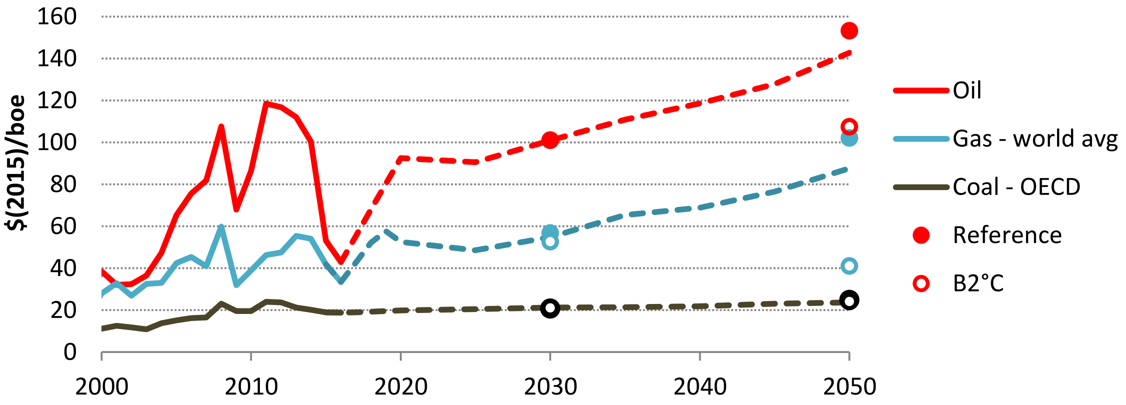
3.2.1 International energy prices

Overall, prices for internationally traded energy commodities follow an evolution reflecting the balance between demand and supply. Demand is determined by energy needs, technology costs and inter-fuel substitution, and supply is determined by production costs (capital and technology), transport costs and the evolution of reserves – with many of these factors being inter-dependent.

In the short- to medium-term, oil and gas prices experience changes (Figure 27) due to an under-investment in supply in recent years (IEA, 2016a; also see section 3.2.2.2).

In the long term, in the Reference and INDC scenarios, fossil fuel prices are on a broadly increasing trend, due to a growing demand and/or investment needs in supply. In the B2°C scenario, the decrease in demand of all fossil fuels results in stable or decreasing prices.

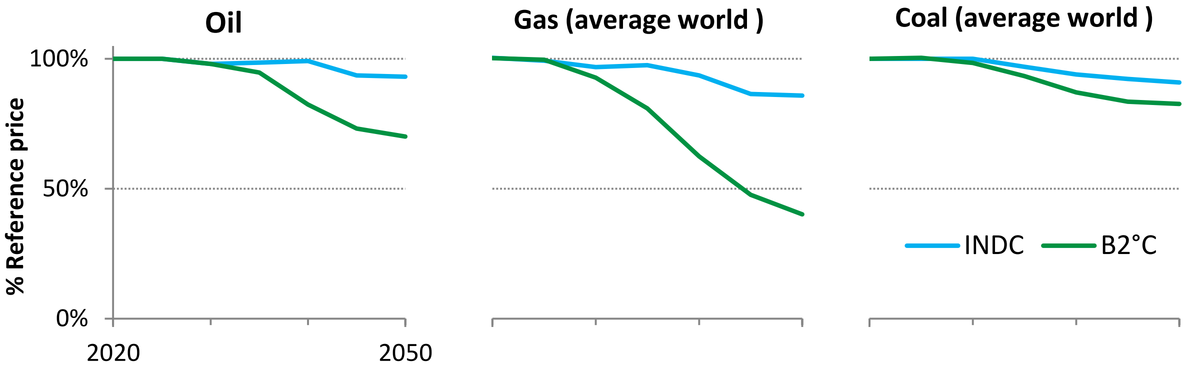
Figure 27: International fossil fuel prices in the INDC scenario



The world gas and oil markets are expected to be progressively decoupled, although possibly at a slower rate than what was experienced in the late 2000s to early 2010s due to high oil price levels reached during that period.

The oil market dynamics do not differ much between the Reference and the INDC scenarios, but going to below 2°C would entail more structural changes in the transportation sector and a lower demand, leading to a relatively lower price in the long run (Figure 28). It must be kept in mind that an increasing part of oil production is expected to be energy-intensive and emits CO_2. As a consequence a share of the production base will become more expensive with the pricing of CO_2 emissions, shifting upwards the supply curve and thus limiting the downward impact on price of the new supply-demand equilibrium.

Figure 28: Impact of climate policies on the international fossil fuel prices



Climate-protecting policies could also reduce the gas market price, even further than the oil price.

Under moderate climate policies gas could be favoured with respect to other fossil fuels and its demand could comparatively increase (or decrease less); its prices would therefore be sustained. However, with more climate ambition, the substantial penetration of renewables in the power sector as well as the accelerated insulation in buildings, power generation and heating in buildings being the main sectors where gas is consumed, would further decrease gas demand and deflate gas prices.

Additionally, the pricing of carbon emissions should affect less the structure of the production cost of gas compared to that of oil production. Indeed, gas production is and will remain less energy- and carbon-intensive than oil production; as a consequence, the cost of energy inputs, carbon value included, should increase less. In the B2°C scenario, gas prices by 2050 could be up to 60% lower than in a world without any climate policy.

Coal demand is deeply impacted by climate policies, however coal prices less so. Prices follow production cost, which increase with investment needs in new production capacities, and higher transport costs.

3.2.2 Oil and liquids

Demand for liquid fuels is met by crude oil supply, in conventional forms (including shale oil and tight oil, deep offshore fields, Arctic oil) or from new non-conventional (tar sands, extra-heavy oil, kerogen), as well as by synthetic liquid fuels converted from coal, gas, or biomass.

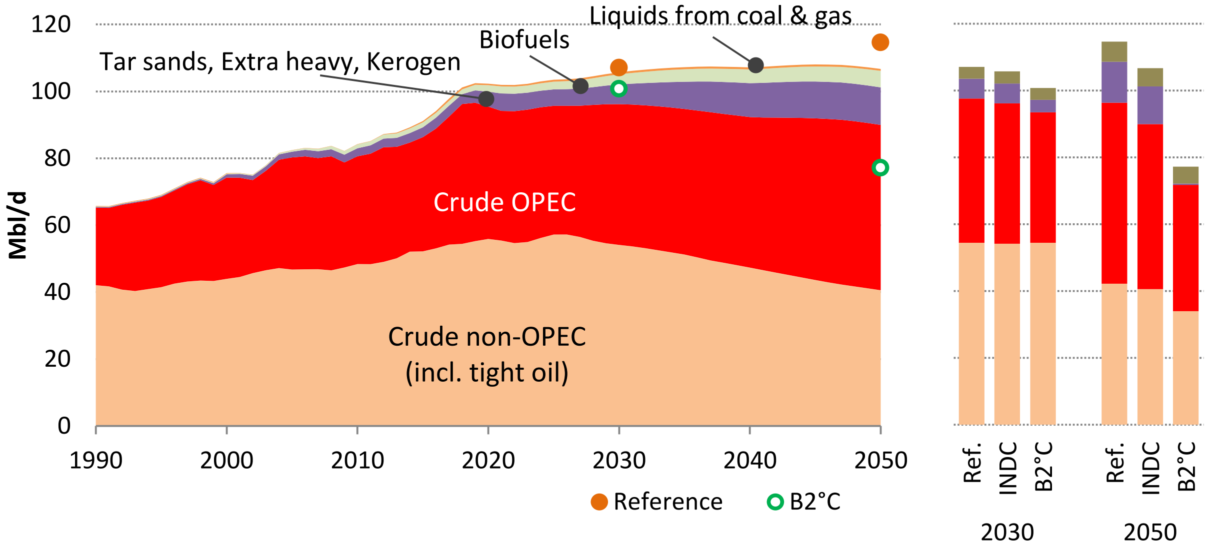
3.2.2.1 Supply

The main feature of future crude oil supply is the growing scarcity of conventional oil resources (crude, including tight oil) ([24]) in non-OPEC producers and the consequent long-term increasing market power of OPEC despite the increase of non-conventional oil production (Figure 29).

An increase in oil demand is expected for the medium term (2020), spurred by the recent low oil price and a reinvigorated economic growth (section 3.2.2.2). The expected required increase in production is expected to take place in the Middle East (Saudi Arabia, Iraq, UAE), followed by the USA and Central Asian countries (Kazakhstan, Turkmenistan).

In the longer term, oil supply is expected to remain at an undulating plateau at around 100 Mbl/d; total liquids demand is only slightly increasing after 2020 throughout 2050, at around 105 Mbl/d (INDC scenario). In that period, most non-OPEC producers would see their conventional output decline, with only two regions, Middle East and Africa, increasing their production. The Reference scenario would be little different, with crude oil production only increasing to 110 Mbl/d over the three decades to 2050.

Figure 29: Crude oil and liquids supply by source, World, INDC scenario



The market undergoes a progressive substitution of conventional resources by expensive energy-intensive oil, representing together 11% of the total liquids supply in 2050 (vs. 3% in 2015); the bulk of this non-conventional production is concentrated in Canadian tar sands and Venezuelan extra-heavy oil throughout the projection period. The large resources of US kerogen ([25]) are not expected to kick-in within the projected period.

([24]) Estimates from fossil fuel resources used in this report come from BGR (2015) and USGS (USGS 2013 and Schenk 2012).

([25]) Kerogen (shale oil) is contained in oil shale formations; not to be confused with (light) tight oil and oil shale, which is oil in low-permeability shales.

Production of expensive conventional oil from deep-water reservoirs is foreseen to expand in the medium term (Brazil, USA, Nigeria and Angola). Liquids from transformed fuels (biomass, coal, gas) would reach 5% of total liquids supply (vs. 2% in 2015).

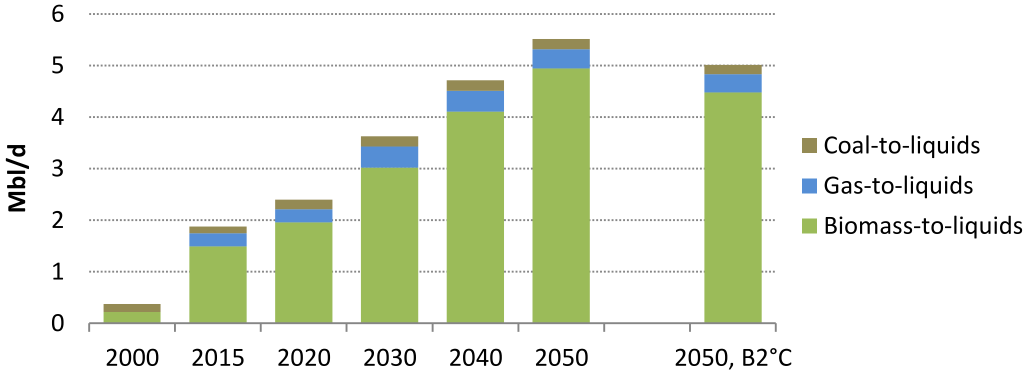
Within conventional crude oil, the ease with which OPEC countries can tap into their significant and relatively cheap resources counter-balances the decrease in production from non-OPEC countries. This results in a growing market share for OPEC over time (from 37% to 46-49% depending on the scenario), along with a growing role for Asia in terms of imports, which might lead to significant consequences in terms of trade rules and international relations.

Cumulated production of crude oil rises from about 1.4 Tbl in 2015 to about twice that in 2050, i.e. from 23% to 45% of total technically recoverable oil resources ([26]); for conventional oil these figures are 32% and 61%, respectively. These figures reflect increasing oil scarcity that takes into account demand-side adjustments such as fuel efficiency measures and fuel substitution in transport and industry.

A more stringent climate policy (B2°C scenario) would affect negatively first the most CO_2-intensive productions (extra heavy, tar and kerogen) and reduce the call on OPEC compared to the Reference scenario. In the longer term, the decrease in demand and in oil price also affects the more expensive non-OPEC and deep-offshore production. Cumulated production by 2050 would still reach 2.5 Tbl in this case (1.1 Tbl over 2015-2050), or 43% of total resources.

The market for all types of synthetic liquids – conversion of biomass, coal, or gas – grows over time in all scenarios (Figure 30). However, synthetic liquids would remain marginal contributors to total liquids supply even in the B2°C scenario. From 2.1% of world liquids demand in 2015 (essentially from biofuels), they contribute 5.2% in 2050 in the INDC scenario (6.5% in the B2°C scenario), still essentially from biofuels. See section 3.2.5 on biomass for more details.

Figure 30: Biofuels and synthetic liquids production, World, INDC scenario

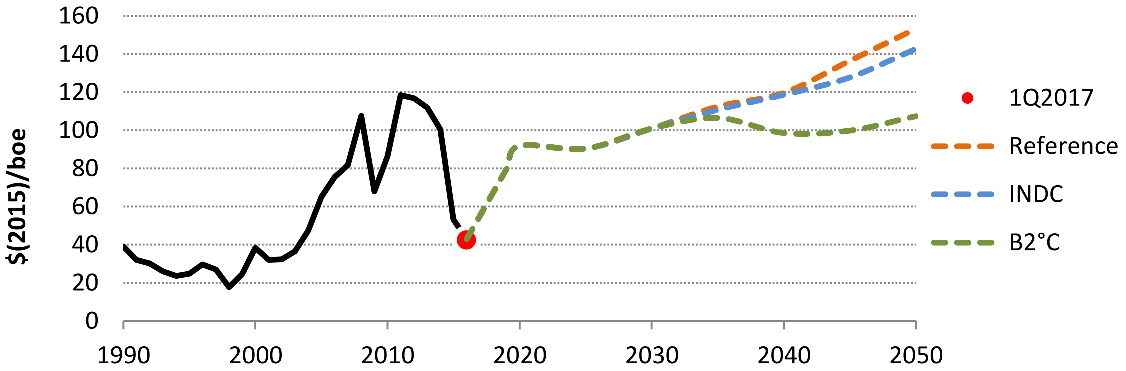


3.2.2.2 Price and trade

After a period of volatility in the coming decade due to short-term supply-demand dynamics observed in all scenarios (see box on short-term oil price), the oil price would resume a long-term rising trend, albeit at a much slower pace than the one experienced in the 2000s decade (Figure 31).

([26]) Technically recoverable oil resources (including already produced resources): 3.7 Tbl for conventional and environmentally-sensitive oil; 2.8 Tbl for non-conventional oil (see BGR 2015).

Figure 31: Oil prices in the GECO2017 scenarios, 1990-2050



In the medium term, the demand increase induced from the present low oil prices would mean that significant investments will need to be made in production for it to grow. Growing extraction costs and additional investments needs would suggest a long-term oil price increasing trend. Conversely, in a world with ambitious climate policies, the decrease in oil demand (at about -1%/year after 2020 throughout 2050) would offset the effect of these cost-increasing tensions, resulting in a stable price

Short-term oil price

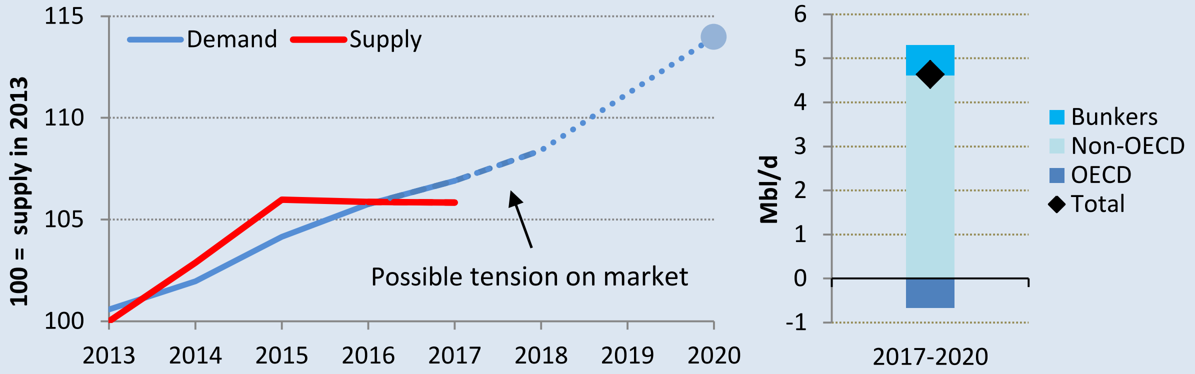
Oil price projections presented in this report take into consideration the recent (2014-early 2017) drop in prices and corresponding stock movements.

In the short term, the fall of oil prices since late 2014 would trigger a resurgent oil demand growth worldwide that soon would encounter supply constraints. Oil demand is expected to increase over 2016-2020 by almost 5 Mbl/d, most of which taking place in non-OECD countries and bunkers, while OECD countries would have a stable or slightly decreasing demand over that period (Figure 32).

The recent fall in oil prices have resulted in a reduction of the most expensive oil production; IEA (2017) expect total non-OPEC production to stabilize, except for the USA which should recover the 2015 production level after a decrease in 2016 (EIA, 2017). In addition, investment in exploration and production has decreased substantially since the peak year of 2014 (it was 42% lower in 2016; IEA, 2016a) while discoveries of new oil reserves over 2015-2016 reached their lowest level since the mid-50s ([27]). That being said, the extent of the drop in supply has been less than first expected by analysts due to decreasing costs of production, efficiency gains and restructuring, especially in US tight oil production ([28]).

These two opposite trends would result in a need for additional oil production, from OPEC countries in particular, which might need to increase their production by 17% by 2020 compared to 2015 (+8% for non-OPEC). Stock changes in 2016 were already significantly lower than in 2015 (+0.9 Mb/d versus +1.8 Mb/d) and are moving towards negative values (-0.5 Mb/d in 2Q2017 according to IEA, 2017) similar to those experienced during the 2010-2013 period. As a consequence the oil market should shift form a situation of abundant supply towards a tighter configuration, leading to possibly rising oil prices by 2020. In anticipation, investment in exploration and production is expected to rise again in 2017, although only by 3% ([29]) (and still 35% below the 2014 level by 2019).

Figure 32: Historic and projected oil demand vs. supply (left), projected new demand 2017-2020 (right)



Note: 2013-2017 data and 2018 estimates come from IEA (2017) and OPEC (2017); demand in 2020 from this report's analysis.

This supply bottleneck is likely to occur regardless the pace of implementation of climate policies, which are expected to have an effect on the international oil market only from 2020-2025 onwards (Figure 29).

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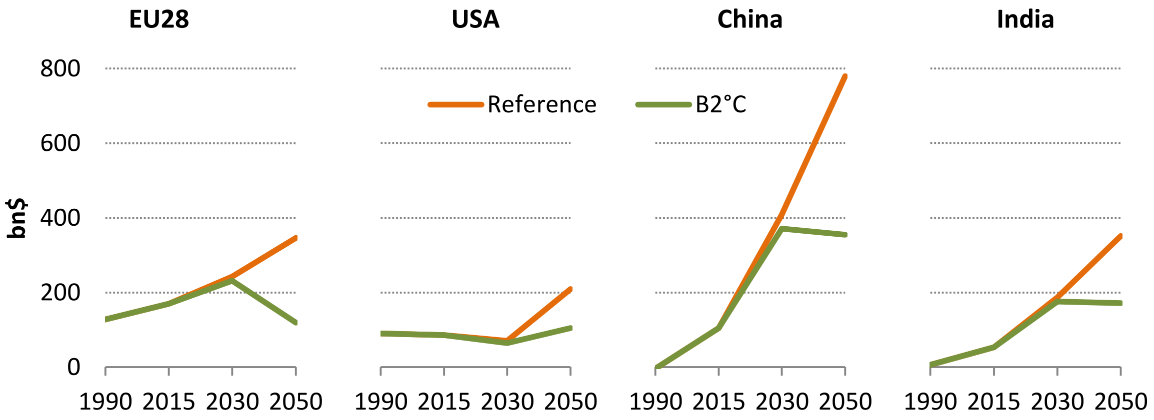
(27) According to a survey by IHS quoted in the Financial Times (8th May 2016): http://www.ft.com/intl/cms/s/0/1a6c6032-1521-11e6-9d98-00386a18e39d.html#axzz4BZJuRsWY

(28) According to the IEA (2016a), "lower costs accounted for just less than two-thirds of the total fall in upstream investment between 2014 and 2016, with reduced activity levels covering the remainder".

(29) According to a WoodMackenzie report (8th December 2016): http://www.woodmac.com/theedge/index.php/2016/12/08/global-upstream-investment-set-to-rise-in-2017/

International oil trade (Figure 33) is set to increase in the future with growing (or plateauing) demand for oil: traded oil would increase by 5% and 20% compared to 2015 in 2030 and 2050, respectively (INDC scenario), corresponding approximately to half of global oil production in all scenarios. Over time, China and India overtake EU28, US and Japan as the largest oil importers; by 2030 China and India combined would absorb nearly half of the oil traded globally (versus just a quarter in 2015). The largest exporters would continue to be the Persian Gulf region, Russia and Canada.

Figure 33: Net oil trade in volume for EU-28, USA, China and India, Reference and B2°C scenarios (30)



3.2.2.3 Demand

Oil and liquids demand can be foreseen to increase in the future, possibly at a slower pace compared to the past two decades; in 2050 it is 18% higher than 2015 in the INDC scenario (Figure 34). This is the result of opposite trends in OECD and non-OECD countries with respect to transportation needs, efficiency in end-uses and fuel substitution opportunities.

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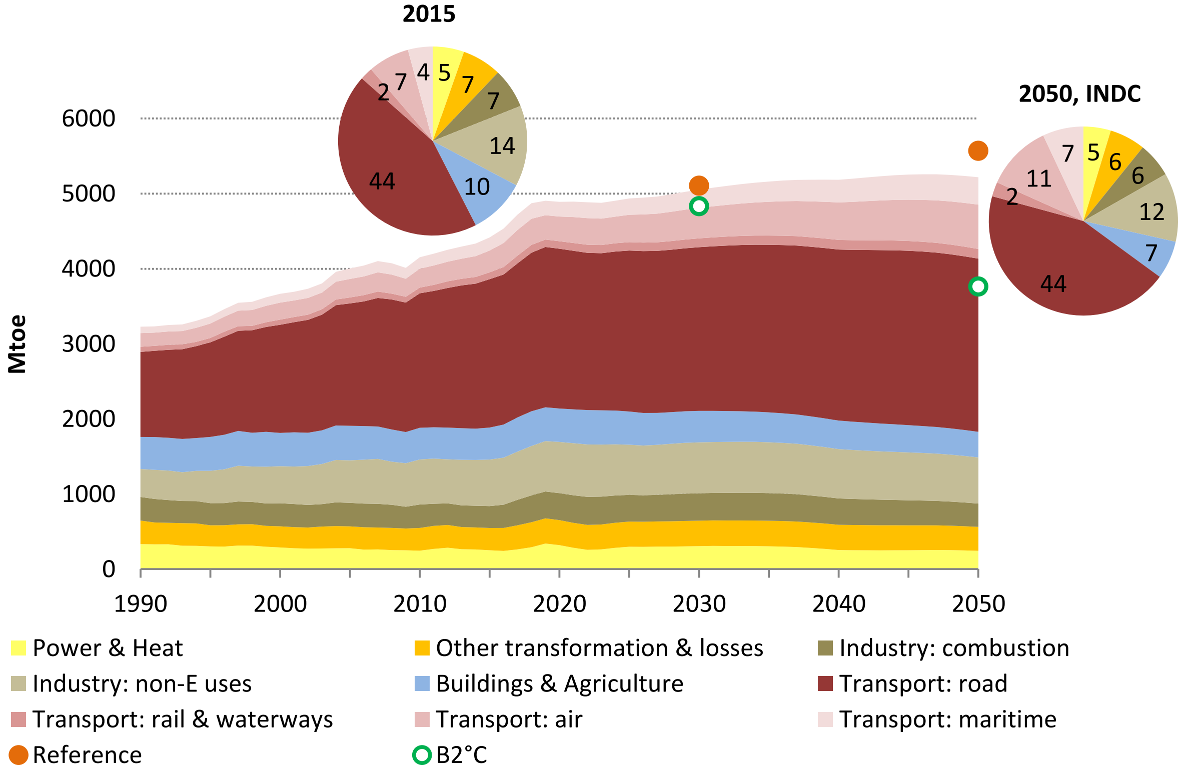
(30) Trade volumes in this report are given in real USD of 2015.

Figure 34: Oil and liquids demand by activity sector, World, INDC scenario



Note: Contains both oil products and synthetic liquids (liquids from gas, coal and biomass). Other transformation & losses refer to auto-consumption in oil and gas production, oil and gas refineries, and losses in pipelines.

The global transport sector is the main consumer of oil globally (57% in 2015, against 45% in the early 90s), ahead of industry, residential & services and the power sector. It remains so in the future, and in all scenarios (63-66% in 2050 depending on the scenario). Road transport in particular represented 45% of global oil demand in 2015; it is expected to remain at about the same market share throughout 2050 in all scenarios, with demand in air transport and maritime bunkers covering most of the growth (see section 3.1.2.3 on mobility for more details).

In terms of regional distribution of oil demand, significant shifts are expected in all scenarios. In 2012, oil demand (excluding international bunkers) was equally shared between OECD and non-OECD countries. This ratio may progressively change until by 2050 non-OECD would cover three quarters of total demand. OECD demand, after reaching a peak in 2005, has decreased due to efficiency gains in transport and/or displacement by other fuels/carriers in industry and residential & services. This trend continues, with demand in the OECD dropping by 33% over 2015-2050. Non-OECD demand, on the contrary, would increase by 41% over the same period. Most of that increase in non-OECD countries is expected come from the transport sector (+73% over 2015-2050), mainly driven by mobility demand in fast-growing Asian countries. Indeed, the number of private cars in non-OECD countries could experience a five-fold increase over the same period.

3.2.3 Gas

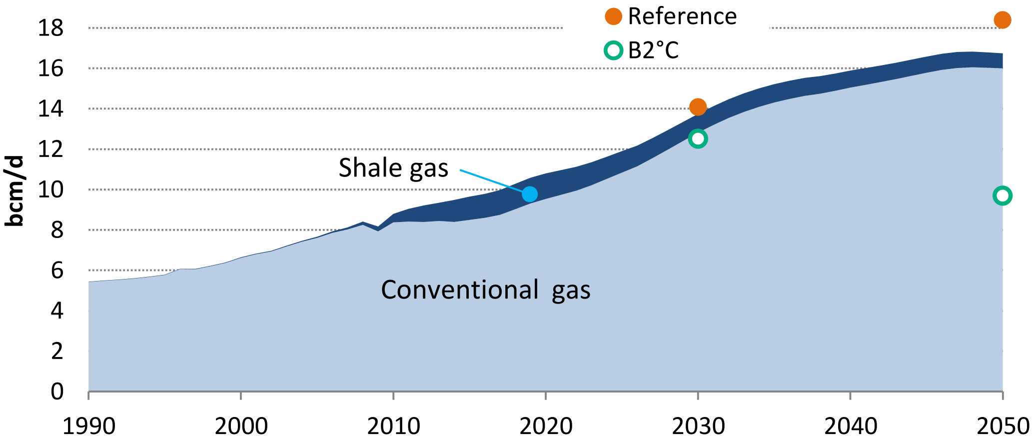
3.2.3.1 Supply

Gas supply grows at a sustained rate throughout 2035, and with a slower growth rate thereafter (Figure 35). The world market increases by 74% compared to 2015 in the INDC scenario (+91% for Reference); in the B2°C scenario, it peaks in the early 2030s and is at the same level as 2015 in 2050.

In all scenarios and throughout 2050, gas production is still dominated by conventional gas. While Russia and the Caspian region are foreseen to continue to be major producers in the future and expand their supply while European and US output declines (despite the development of shale gas), it is the Middle East that could experience the most important increase in production and market share. This will also call for a substantial change in the transportation pattern of gas in the global market, relying more on liquefied natural gas (LNG) in the future.

Conventional gas remains relatively abundant, with about 37% of accessible resources having been exploited by 2050 compared to 13% in 2015 ([31]) (INDC scenario).

Figure 35: Gas supply by source, World, INDC scenario



In all the scenarios addressed and throughout 2050, the contribution of shale gas to total world gas supply does not exceed the share observed in 2015 (12%); with expanding conventional production, this share even decreases over time. Due to production costs differing across regions and competition with other gas sources, the "shale gas revolution" would take off with difficulty in countries outside the USA, which still represents three quarters of world shale gas production by 2050 regardless of the climate policy in place.

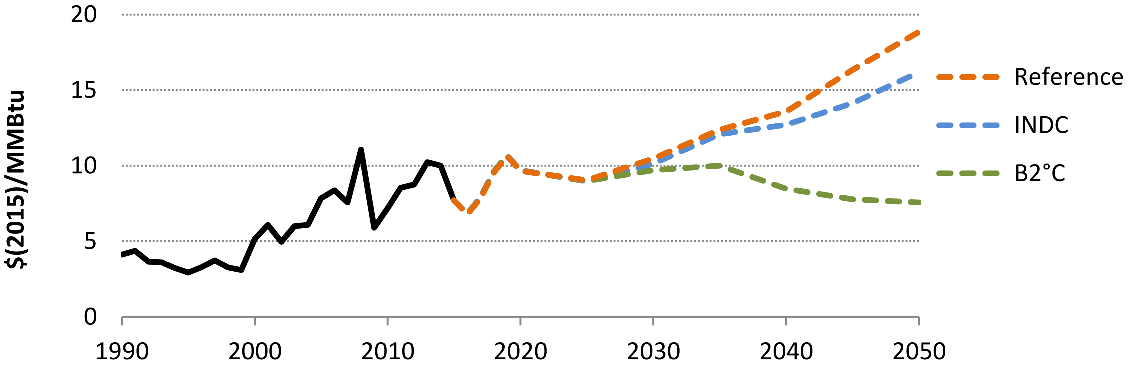
Gas produced in environmentally sensitive regions (deep-water and the Arctic) is foreseen to remain a marginal source, with Russia (Arctic), USA, Nigeria and to a smaller extent Brazil (deep-water) making up most of this kind of production.

3.2.3.2 Price and trade

Average world gas prices are expected to keep increasing unless strong climate policies are adopted (Figure 36), while retaining significant regional differences reflecting supply patterns and transport costs (Figure 37). With the development of international liquefied natural gas (LNG) trade, convergence across regional price signals gradually takes place.

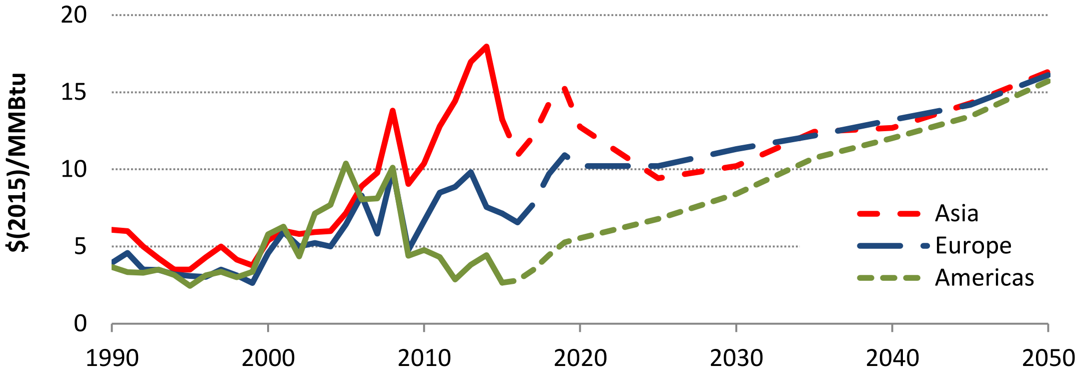
([31]) Technically recoverable gas resources: 950 Tm^3 for all types, including 650 Tm^3 for conventional gas alone (see BGR, 2015).

Figure 36: Average world gas prices, all scenarios



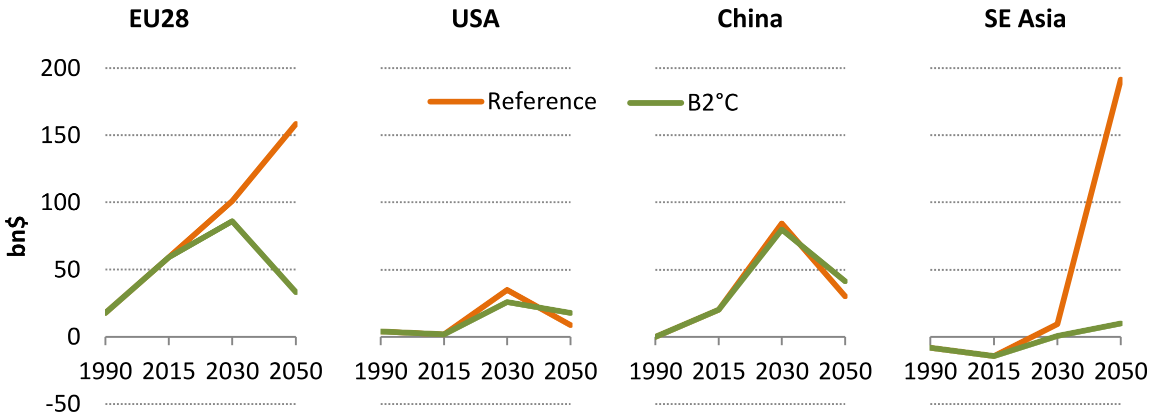
Indeed, LNG trade already covered about a third of international gas trade in 2015; this share is expected to exceed 50% by 2030 and would further grow to 60% by 2050. The LNG market is foreseen to reach 3,100 mcm/d in 2030, i.e. three times the volume compared to 2015, regardless of the scenario considered. Current LNG trade is dominated by exports towards Japan and Europe; in the future, China and other Asian economies would become significant destinations. Qatar in the medium term and Russia, Australia and Iran in the longer term could develop to be the largest exporters.

Figure 37: International gas price, INDC scenario



In particular, the convergence of prices results in a decreasing price for Asian market and an increasing price for the American market in the medium term. With oil price levels in the medium term similar to those observed in the 2007-2015 period, the indexation of gas prices to the oil price would decrease but still persist and would contribute in the gas prices rise.

Figure 38: Net gas trade in volume for EU-28, USA, China and Southeast Asia, Reference and B2°C scenarios (32)



The Asian market would increasingly be defined by imports from the rest of the world: by the 2030s the emerging Asian economies could absorb more than half the world's internationally traded gas (compared to 22% in 2015) and all Asian regions would become net importers (Figure 38). While Europe remains the main destination for Russian gas throughout 2050, Russia expands its exports to China and, as Russia's LNG export capacity progressively develops, to South-East Asia and South Asia.

3.2.3.3 Demand

Demand of gas is expected to keep growing in future decades, albeit at a decelerated growth rate in the INDC scenario (Figure 39). This is particularly motivated by additional demand in industry and the power sector, two sectors that would continue being responsible for about two thirds of total gas demand throughout 2050.

Gas demand maintains an important role in the power sector in the B2°C scenario, due to its comparative advantage with coal and its role as a key technology to buffer intermittent renewable technologies, whose share is expected to grow substantially. However, demand in other sectors is projected to shrink, due to both energy efficiency and substitutions by carbon-neutral energy vectors. As a result, in the B2°C scenario total gas demand peaks in 2030 and then decreases to 2015 levels by 2050.

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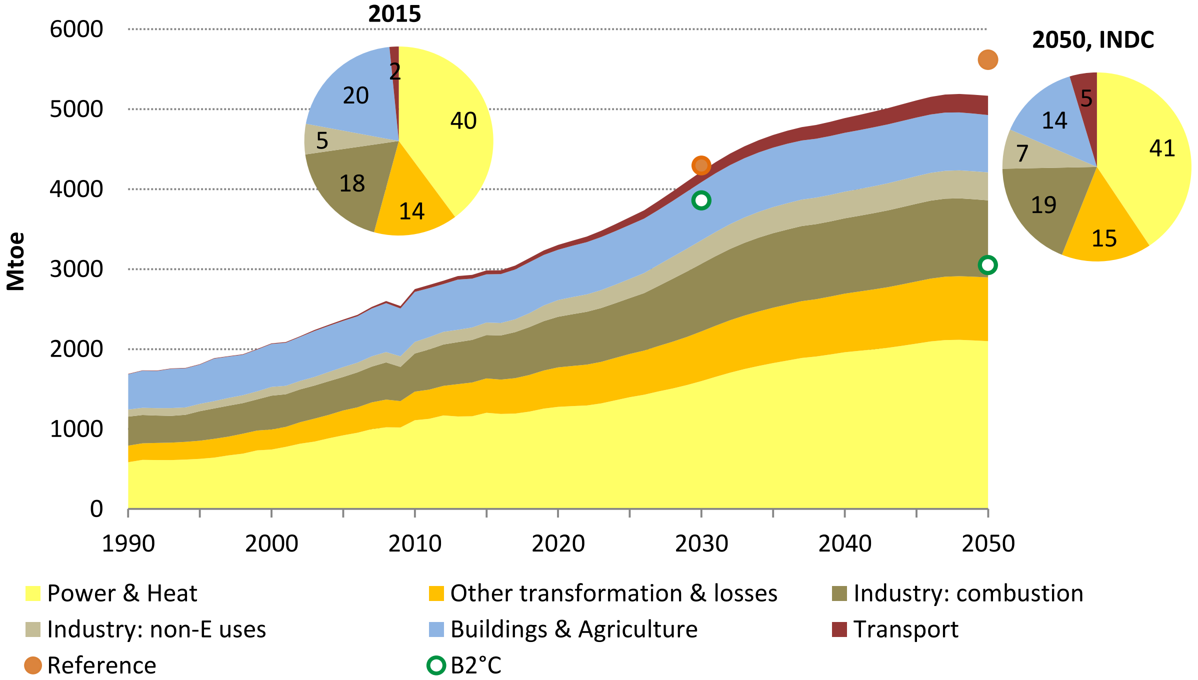
(32) Trade volumes in this report are given in real USD of 2015.

Figure 39: Gas demand by activity sector, World, INDC scenario



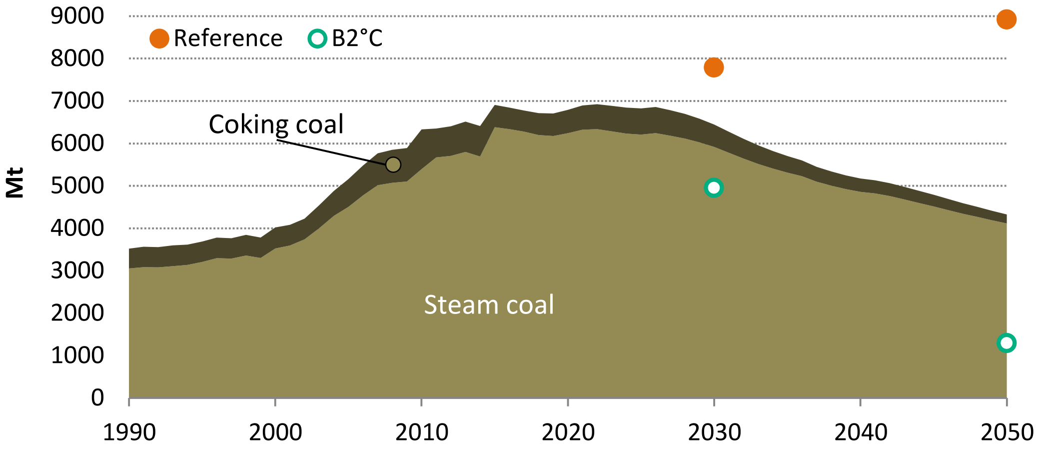
Note: Other transformation & losses refer to auto-consumption in oil and gas production, oil and gas refineries, and losses in pipelines.

3.2.4 Coal

3.2.4.1 Supply

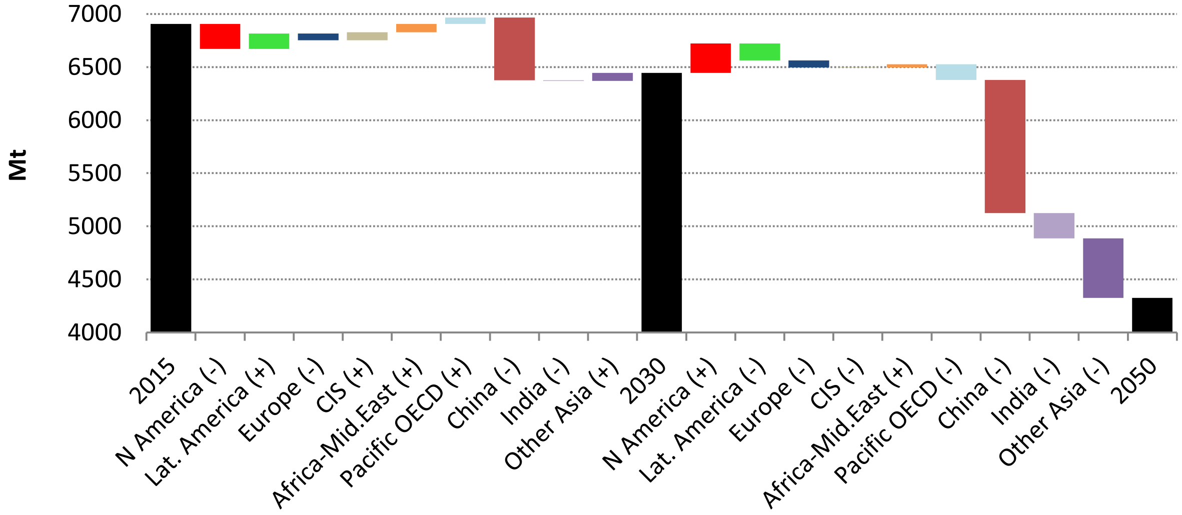
World demand for solid fossil fuels stabilizes at the 2015 level (6.9 Gt) throughout the mid-2020s in the INDC scenario. Coal is the primary energy carrier that is most heavily impacted by climate policies: only in the Reference scenario coal production grows beyond 2020, reaching 8.9 Gt in 2050. Coal production in the INDC and B2°C scenarios peaks in or around 2020, then decreases at different rates (-2 to -5%/year), reaching 4.3 Gt and barely 1.3 Gt in 2050, respectively (Figure 40).

Figure 40: Coal supply by source, World, INDC scenario



The regional distribution of coal production changes significantly over time (Figure 41). In the INDC scenario, USA, Europe and most importantly China production decreases over the 2015-2030 period. Beyond 2030, coal production decreases in essentially all regions of the world.

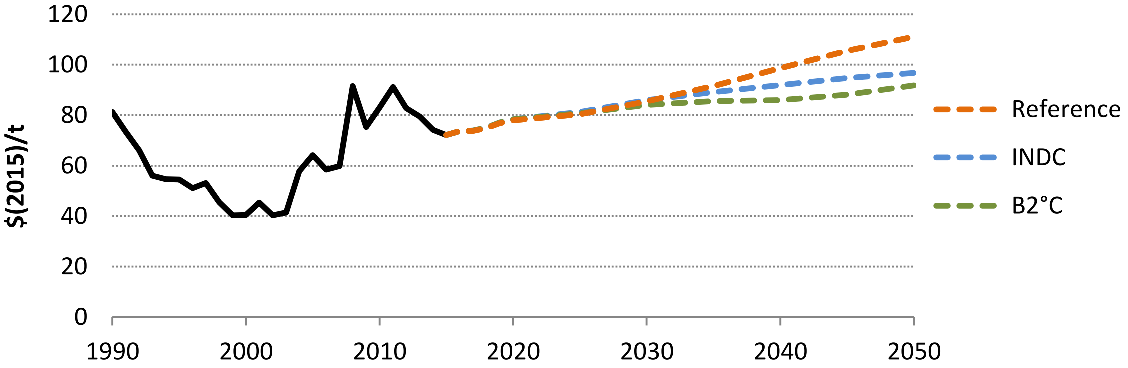
Figure 41: Coal production by region, INDC scenario



Out of total production, only a minor part is traded across borders – although the share of trade is increasing in all scenarios considered. It rises to 29% in 2030 and 41% in 2050 (INDC scenario). Imports for emerging economies in Asia, especially India, are the driving force behind this growing importance of trade.

Coal prices, which by 2015 were back to the level they were at before the price spikes of the late 2000s, should follow a moderate rising trend in all scenarios, driven by growing freight costs and, in the long term, by increasing mining costs (Figure 42).

Figure 42: Coal prices, 1990-2050



3.2.4.2 Demand

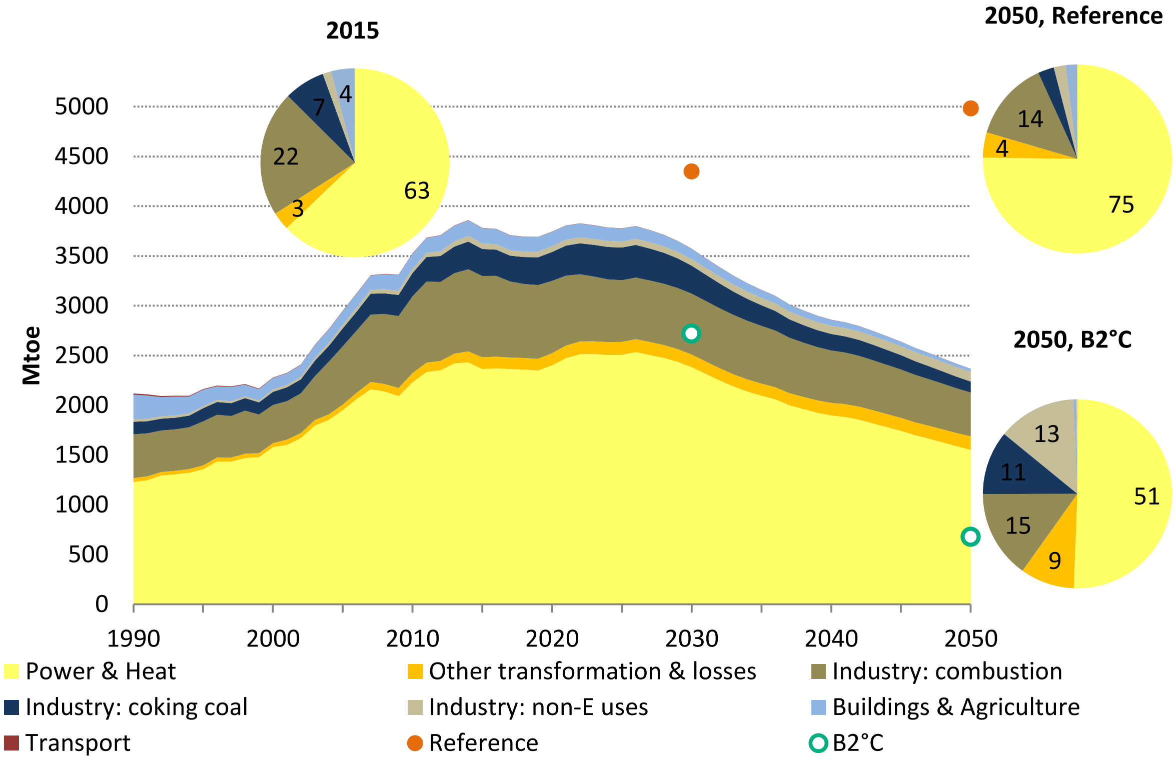
Coal demand is strongly related to the implementation of climate policies. With the INDC policies, coal demand first stabilises in the mid-2020s and then decreases so that, by 2050, it is reduced by 37% compared to its 2015 level (vs. a 32% increase in the Reference scenario and an 82% decrease in the B2°C scenario) (Figure 43).

The coal market remains mainly driven by demand from the power sector, followed by industry, despite air pollution concerns which would force the adoption of pollution mitigation technologies and the move of power generation and industrial activities far from urban centres (section 5.1).

Most of the coal consumption remains steam coal: the demand for coking coal decreases as the demand for primary steel also decreases over time due to the increasing role of steel recycling (secondary steel), and its share in total coal demand would drop to 5% by 2050 (vs. 8% in 2015).

Demand in the residential sector and services is expected to shrink and would virtually disappear worldwide by 2050.

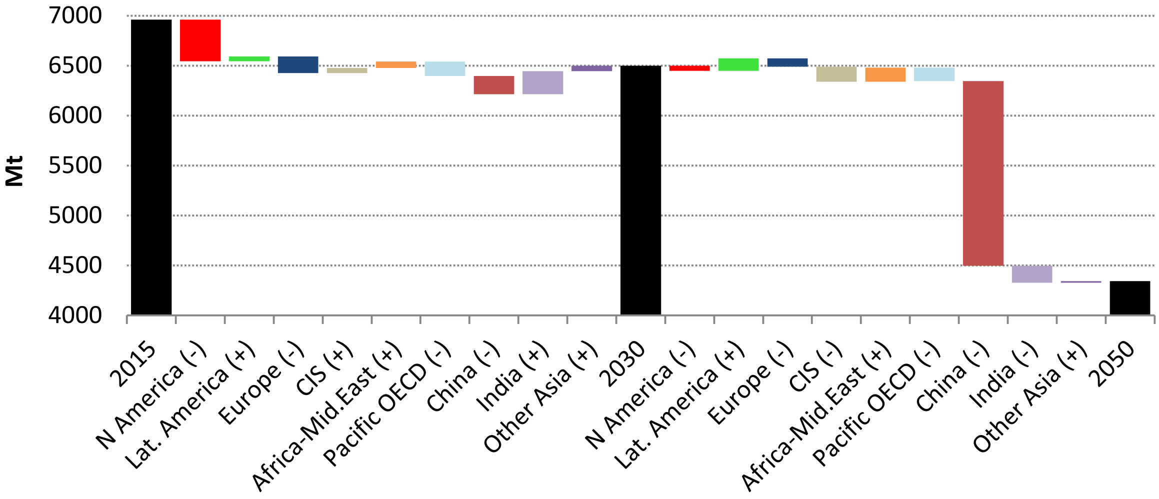
Figure 43: Coal demand by activity sector, World, INDC scenario



Note: Other transformation & losses refer to auto-consumption in oil and gas production, and in coking coal plants.

The coal demand decrease in the INDC scenario is mostly felt in China (Figure 44), where it is displaced by renewables, gas and nuclear. In this scenario, power generation from coal in China decreases from 70% in 2015 (world: 39%) to 46% in 2030 (world: 28%) and 13% in 2050 (world: 13%).

Figure 44: Coal demand by region, INDC scenario



3.2.5 Biomass

3.2.5.1 Supply

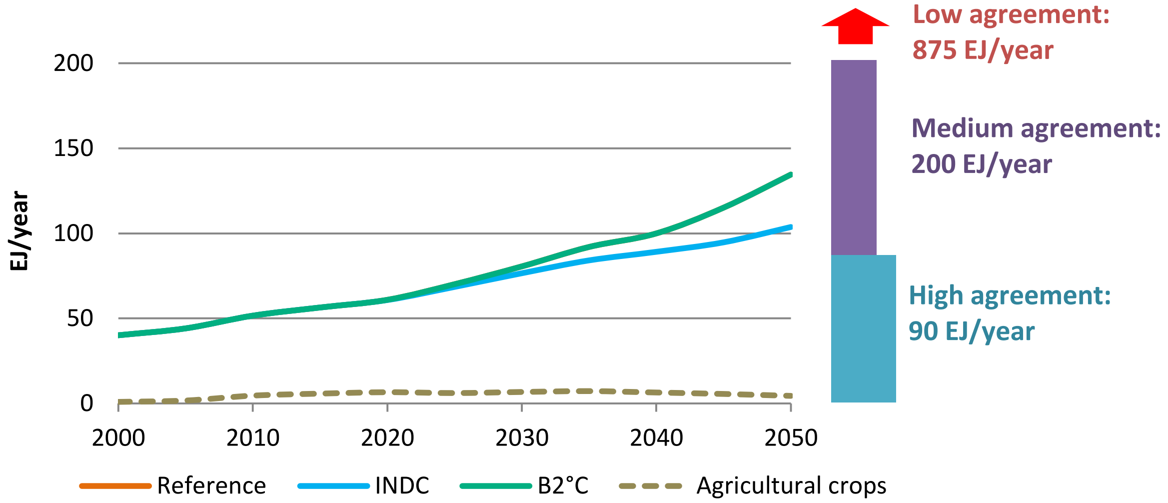
Biomass use for energy is projected to increase in the future; as an alternative to fossil fuels for combustion or for the production of liquid fuels, its use would be further enhanced by climate policies. By 2050 its demand would increase by 65-140% compared to 2015 depending on the scenario.

Most of biomass-for-energy supply would come from lignocellulosic resources (forestry residues and dedicated short rotation coppices for biomass-to-energy conversion); non-lignocellulosic resources (dedicated agricultural crops) made up 10% of total biomass supply in energy terms in 2015, and their share would remain limited and even decrease over time.

Current biomass inputs to the energy system exceed 50 EJ/year ([33]); by 2050 they would increase to as much as 135 EJ/year in the B2°C scenario. This raises a number of questions on the impact on land-related issues, most notably food security, biodiversity conservation or water cycles.

Figure 45 plots long-term biomass-to-energy potentials estimates ([34]) from a comparative study that provides various ranges of bio-energy potentials across biomass source types; estimates vary on a multitude of criteria such as social, political and economic factors but also the stringency of sustainability criteria. According to Creutzig et al. (2015) there is a moderate agreement in the literature for a potential of about 200 EJ/year, which is higher than what is used by 2050 in the GECO scenarios, and a high level of agreement for 90 EJ/year, which is exceeded by 2050 in the case of the B2°C scenario.

Figure 45: Biomass for energy vs. sustainable potential estimates (right)



Note: Production levels of biomass from agricultural crops very similar across scenarios. Source for qualification of agreement of potential estimates in literature: Creutzig et al. (2015).

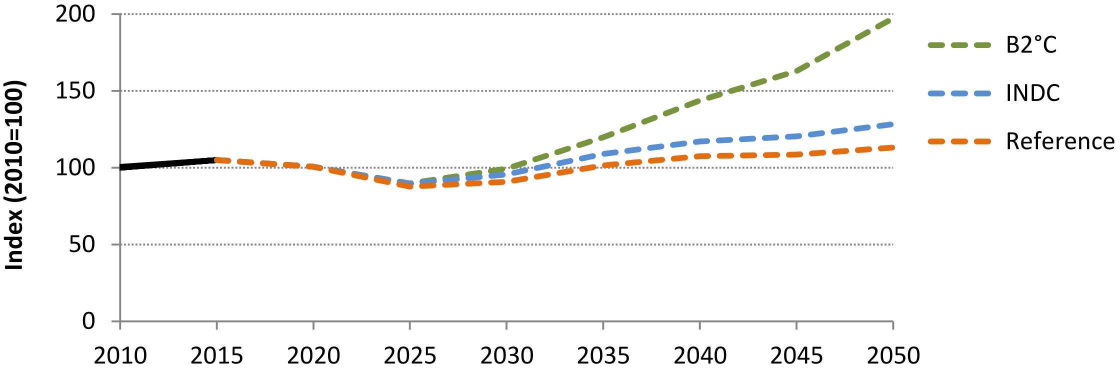
The scenarios presented in this study were produced considering a maximum potential for bio-energy of 250 EJ/year in 2050 (using information from the GLOBIOM model, see IIASA, 2016), taking into account the future development of yields and an increasing cost of production as more of the potential is being used.

([33]) Biomass consumption in the energy sector in 2011 amounted to about 30% of total biomass production (food, industrial uses, energy) – see Morrison and Golden (2015)

([34]) Accessible potentials regardless of time horizon considered

Accordingly, the price for biomass increases over time as more of the resource is being used (Figure 46).

Figure 46: Solid biomass price indicator

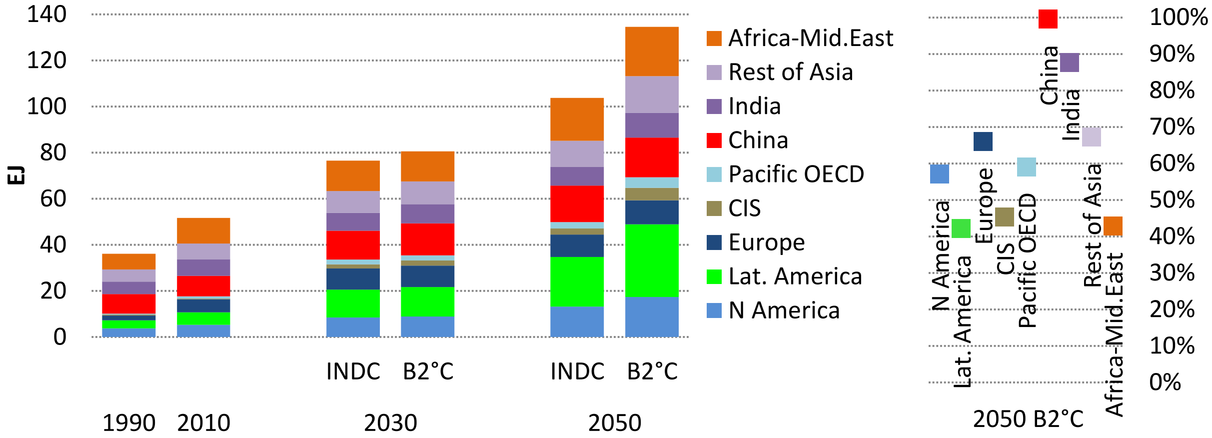


As the use of biomass in the energy system increases it becomes a globally traded commodity. As of 2015, only 1.5% of biomass used on bioenergy was traded across borders; by 2050 this share grows to 16-19% in this analysis ([35]).

In all scenarios, the use of traditional biomass in Africa, China and India is expected to reduce and be progressively replaced by "modern" biomass produced with more efficient exploitation methods and commercialized.

Biomass production would grow in all regions (see Figure 47); the dominant exporters would particularly be in Latin America, followed by Southeast Asia and Sub-Saharan Africa. North America, Europe, Middle East, OECD Pacific and North Africa would be the most salient importing regions in 2050. These broad trends are mostly observed in all scenarios, with stronger climate policies increasing the volumes of trade across regions and with Middle East and India in particular becoming significant importers.

Figure 47: Primary biomass-for-energy production by region (left) and share of the region's biomass-for-energy potential being used in 2050 in the B2°C scenario (right)



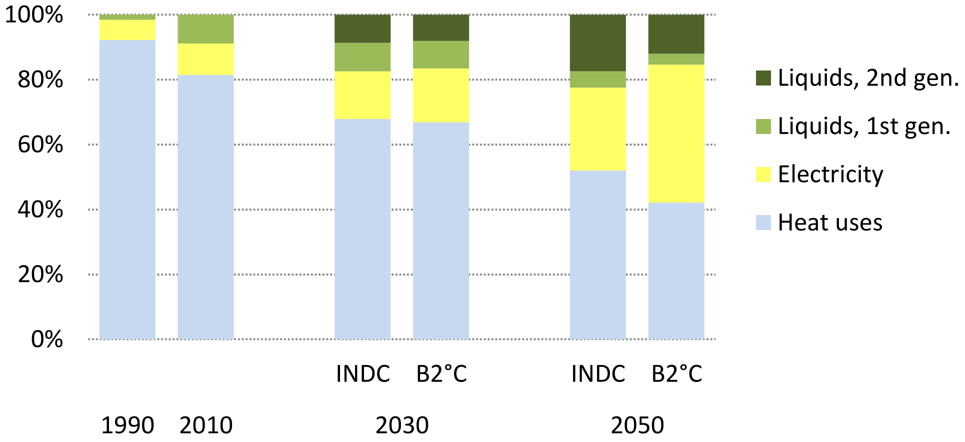
3.2.5.2 Demand

Most of biomass consumption is currently dedicated to combustion for heat uses (about 80% in 2015), with approximately 10% being consumed in the form of liquid biofuels (first generation biofuels).

([35]) Concerns exist that the low energy density of biomass could limit the transport distance from farm gate to biomass power plant that is economical and thus limit global biomass transport (IRENA 2012).

In contrast, future demand growth should be driven by power production and second generation biofuels (Figure 48). In the ambitious climate policy scenario, the development of bioenergy with CCS (BECCS) would draw significant amounts of biomass: accounted for as technology providing negative CO_2 emissions, it is perceived to play an important role in the mitigation effort ([36]). By 2050 biomass in power production reaches the same market share as biomass for heat, slightly above 40% of total biomass use in the energy sector.

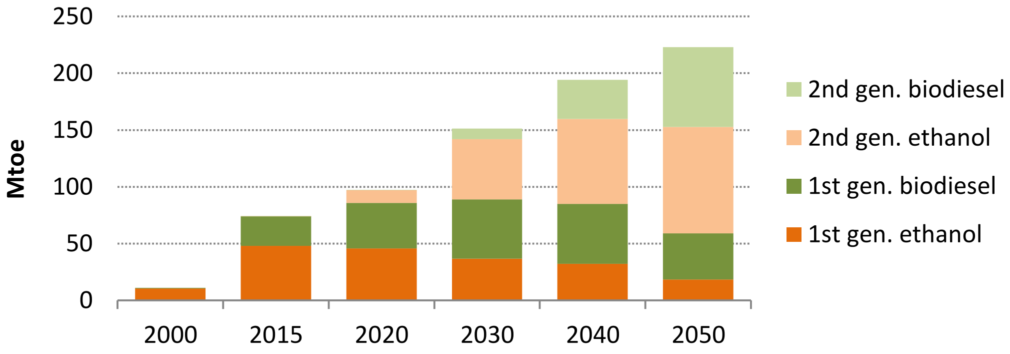
Figure 48: Primary bio-energy demand by use, share



In 2011 the production of liquid fuels consumed 4% of all crops production ([37]) (Morrison and Golden, 2015), while its contribution in the world energy system has been small: in 2015, biofuels were 1.6% of total liquids demand and 3.7% of liquids demand in road transport.

Liquid biofuels demand is expected to grow in all scenarios, with the highest increase (a multiplication by 2.4 over 2015-2050) in the scenario with the highest oil price and the weakest climate policies: the Reference case (Figure 49). Ambitious climate policies do not appear as a key driver of liquid biofuels demand, as higher vehicle engine efficiency and substitution with other technologies (most notably electric vehicles) limit their development. By 2050 and depending on the scenario, biofuels would count for 10-11% of liquids demand in road transport as a world average, and 2-8% in world air transport.

Figure 49: Liquid biofuels production, World, INDC scenario



The share of first generation biofuels, which use primary biomass that is in competition with agriculture over land use, is expected to decrease over time with the development of second generation biofuels.

([36]) Use of biomass-for-energy without CCS is considered carbon-neutral when taking into account the carbon sequestration in the crop or timber grown to obtain that biomass. BECCS is considered carbon-negative.

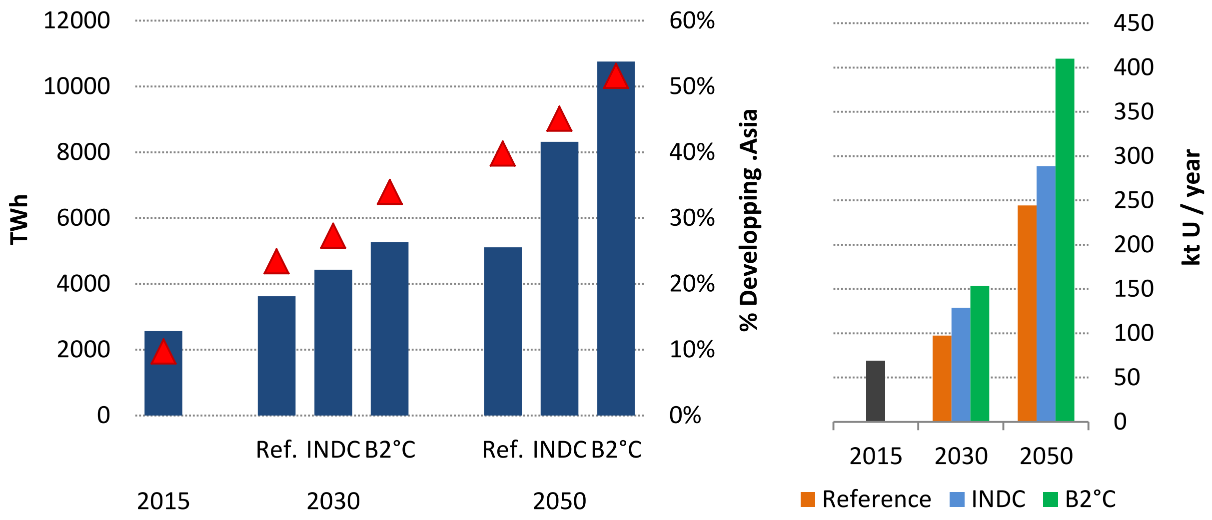
([37]) In tonnage of all cereals, roots, fruits and vegetables; not including roundwood forestry.

3.2.6 Nuclear

World nuclear supply is projected to grow in the coming decades, increasing by over 70% over 2015-2030 in the INDC scenario and continuing at this rate beyond 2030 (Figure 50).

This is mainly due to the expansion of nuclear power in non-OECD countries (mostly concentrated in China, India, South-East Asia, Central Asia and Russia). Non-OECD countries account for over half the nuclear production by 2050 (56% and 64% in the INDC and B2°C scenarios, respectively), compared to 23% in 2015. In OECD countries, the growth would be smaller and new installations mostly replace decommissioned plants.

Figure 50: World nuclear power supply (left) and annual uranium consumption (right)



Note: Developing Asia consists of China, India, Rest of South Asia and South East Asia. Uranium consumption includes natural uranium mining and consumption from other sources (depleted re-use, used fuel recycling).

Annual installations increase significantly in all scenarios throughout 2050. Compared to a period of few installations in the recent past (4 GW/year in 2000-2015), the power plants market grows to 10-30 GW/year in the 2015-2030 period and 20-50 GW/year in the 2030-2050 period (38), with climate policies expanding the market significantly.

The total demand for nuclear uranium fuel correspondingly increases as well.

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(38) Refers to Light Water Reactors (LWR, Gen. III) reactors. Gen. IV reactors (fast breeders) or fusion reactions are considered not to be available on a commercial scale before the end of the period assessed in this report (2050).

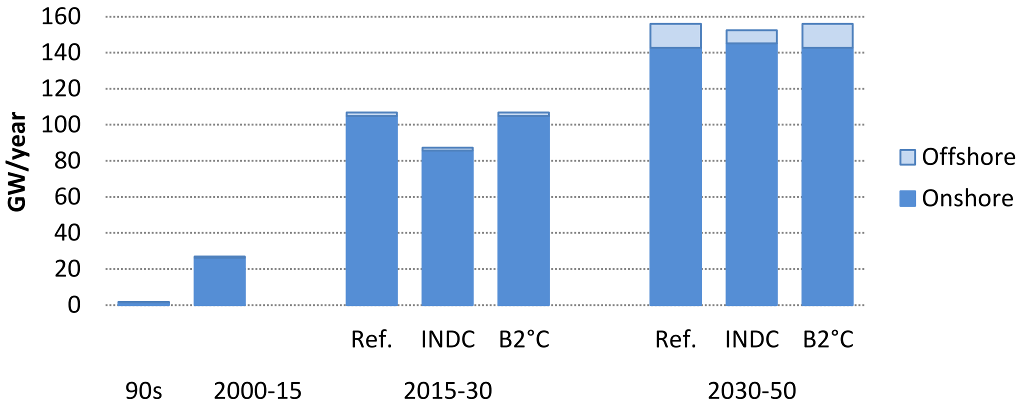
3.2.7 Wind

Wind power would reach 20% of total world power generation in 2050 in the INDC scenario, compared to 4% in 2015. The wind market is expected to grow over time in all cases, and benefits from the implementation of climate policies. Even though the growth rate progressively decreases over time it stays fairly high over the whole period.

Average annual installations would more than double over the 2015-2030 period compared to 2000-2015 even in the Reference scenario (Figure 51). By 2030 climate policies clearly have an effect on the market development, with yearly installations reaching 100 GW in the B2°C scenario. Though comparatively smaller than onshore wind, the market for offshore wind would also more than double compared to its development over 2000-2015, with over 75% of offshore installations concentrated in the EU and China.

After 2030 the effect of the climate policies is partially offset by the need for having flexible capacities in the power mix (hydro pumped storage, thermal backup power plants and/or other forms of electricity storage) to allow for a proper integration of wind.

Figure 51: World average annual installations of wind energy by technology

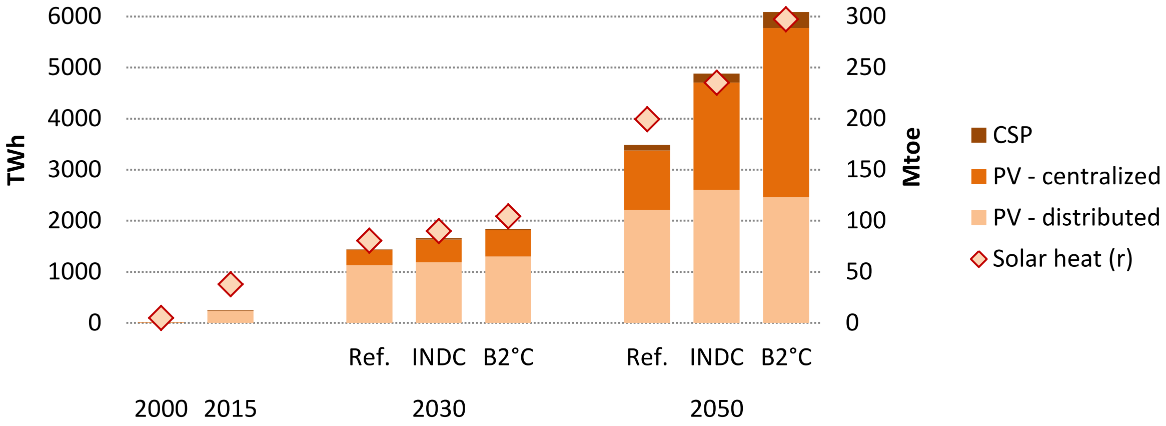


3.2.8 Solar

Solar energy undergoes an even higher growth in annual new installations than wind (Figure 52). Like for wind, its development is positively impacted by climate policies (and constrained by the need of flexibility to accommodate its integration in the grid).

Solar power reaches about 10% of total world power generation in 2050 in the INDC scenario, compared to 1% in 2015. Low-temperature solar thermal, providing heating and water heating to residential & services, grows from providing 1% of their heat uses in 2015 to 11% in 2050 in the INDC scenario.

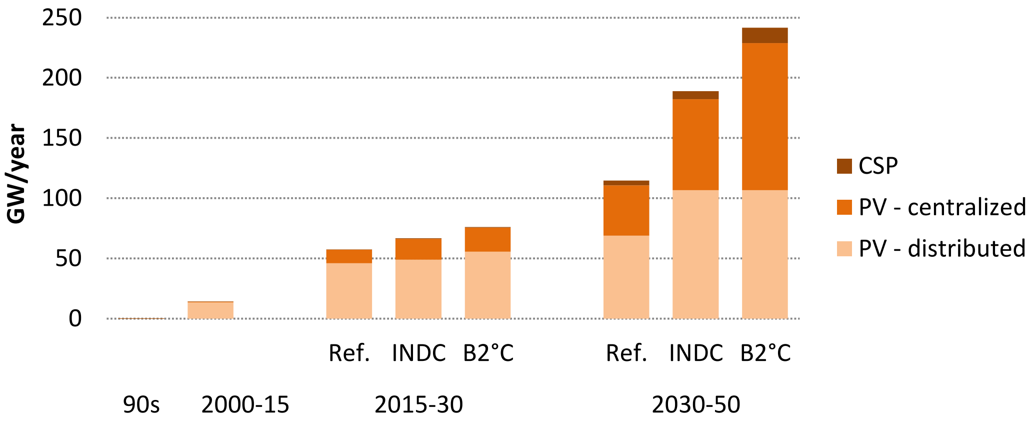
Figure 52: World solar energy: power production (left axis) and thermal (right axis)



The market for solar power technologies grows over time for all scenarios, with growth rates for PV technologies that continue increasing throughout 2030 and decelerate thereafter, while Concentrating Solar Power (CSP) technologies become a significant market only after 2030.

Average annual installations for PV are multiplied five-fold over the 2015-2030 period compared to 2000-2015 even in the Reference scenario, then more than double again over the 2030-2050 period (Figure 53). In the INDC and B2°C scenarios, solar even exceeds wind after 2030 in becoming the largest market of additional installed capacities, i.e. the power technologies with the largest average annual sales worldwide, with nearly or over 200 GW/year, respectively (in the Reference scenario average annual sales of wind and solar technologies are roughly similar).

Figure 53: World average annual installations of solar power technologies



4 Greenhouse gas emissions and climate

Greenhouse gases (GHG) emissions and their impacts on climate for the scenarios analysed are discussed in this section, including emissions from the energy sector and from land use.

GHG emissions from the different gases are aggregated into CO_2-equivalent values, using the 100-year global warming potentials of the IPCC Second Assessment Report (39).

4.1 Global emissions and temperature change

Total GHG emissions (40) continue to increase from their 2015 level of 47.6 $GtCO_2e/yr$ over the coming decade (INDC) or even beyond (Reference) unless ambitious climate policies are implemented urgently and worldwide (B2°C) (Figure 54). The implementation of the policies in the INDC scenario has a worldwide aggregated effect for total GHG emissions to peak in the 2020-2030 decade and start decreasing afterwards, if the effort (expressed in improvement of emission intensity of the GDP) is pursued beyond 2030. Without these policies and with only the policies in the Reference scenario, no peak in emissions would be foreseen by 2050.

INDC policies bring about a global peak in emissions as early as 2025 at 51 $GtCO_2e/yr$, i.e. 7% above 2015 levels. Quick and decisive action to fully close the gap towards a 2°C world would require a significant further emissions reduction: the peak in the B2°C scenario is accelerated to the end of the current decade (2020), at 49 $GtCO_2e/yr$, i.e. just 3% higher than in 2015.

While with current policies (Reference) emissions continue to increase throughout 2050 and beyond, although at a decelerating pace, they decrease in the INDC and B2°C scenarios with -0.5%/year and -3.4%/year on average over 2020-2050, respectively.

By 2030 the gap between scenarios widens significantly, with emissions ranging from 58 $GtCO_2e/yr$ (Reference) to 51 and 41 $GtCO_2e/yr$ (INDC and B2°C, respectively). In 2050 the situation is radically different across scenarios: emissions in the Reference scenario would grow to 67 $GtCO_2e/yr$ (twice the emissions in 1990) while emissions in the B2°C scenario would decrease to 17 $GtCO_2e/yr$ (about half the emissions in 1990), with the INDC scenario in-between at 43 $GtCO_2e/yr$ (29% higher than 1990).

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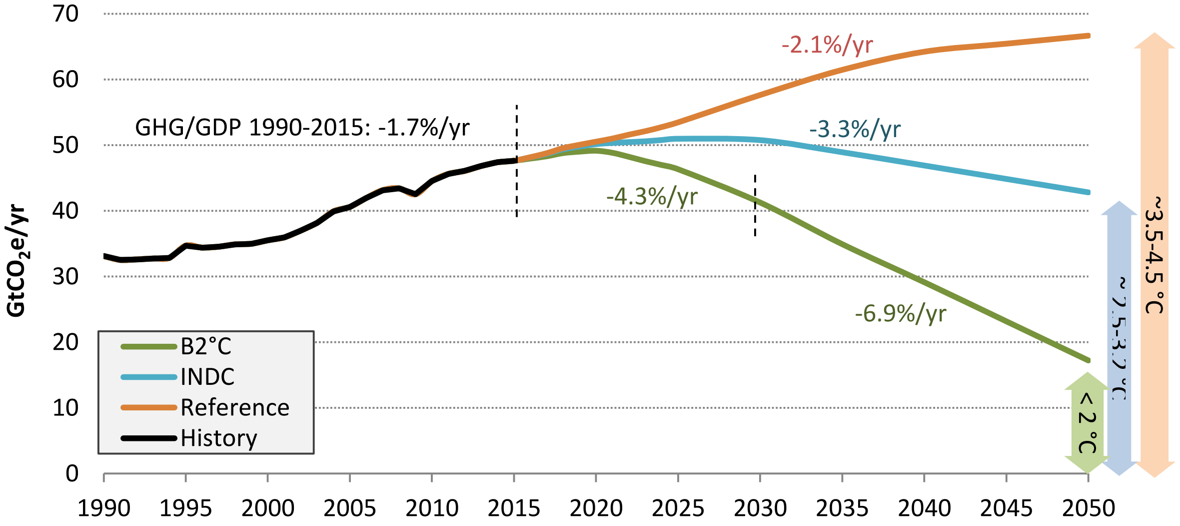
(39) See Table 4 of the Technical Summary of IPCC (1996).

(40) This includes net CO_2 removals from LULUCF activities (sinks). The uncertainty on the historical estimates of sinks is significant (estimated at 3 $GtCO_2/yr$ in 2010). Nevertheless, this report covers emissions projections that include sinks from afforestation and forest management as mitigation options. Projected CH_4 and N_2O agriculture emissions and CO_2 land-use emissions are derived from the GLOBIOM model (Global Biosphere Management Model) which has been linked to the POLES-JRC model and historical GHG data – for more information on the GLOBIOM model see IIASA (2016) and Havlík P. et al. (2014).

Figure 54: Greenhouse gases emissions, World, and average annual growth rates for GHG emissions intensity of the economy



Note: Total GHG emissions, including removals (LULUCF sinks, CCS). Temperature increases refer to 2100 expected temperatures compared to pre-industrial levels.

The profile of the global average temperature change is dependent on annual emissions of all GHG (especially species with short lifetimes but strong warming potential, such as CH_4, N_2O and F-gases) as well as their cumulated volumes over the long term (especially for CO2, which has a long lifetime). In order to build scenarios with a stabilized long-term global temperature, emission trends before as well as after 2050 are important. Thus, the scenarios presented in this report were developed throughout 2100, with emissions reductions continuing to take place in a cost-efficient manner, and they are characterized with regards to the temperature change reached at the end of the century.

In addition, certain non-GHG air pollutants have a cooling effect on the temperature, especially nitrate and sulphate as well as carbonaceous compounds (particulate matter components); some others (black carbon, another particulate matter component) warm the atmosphere ([41]).

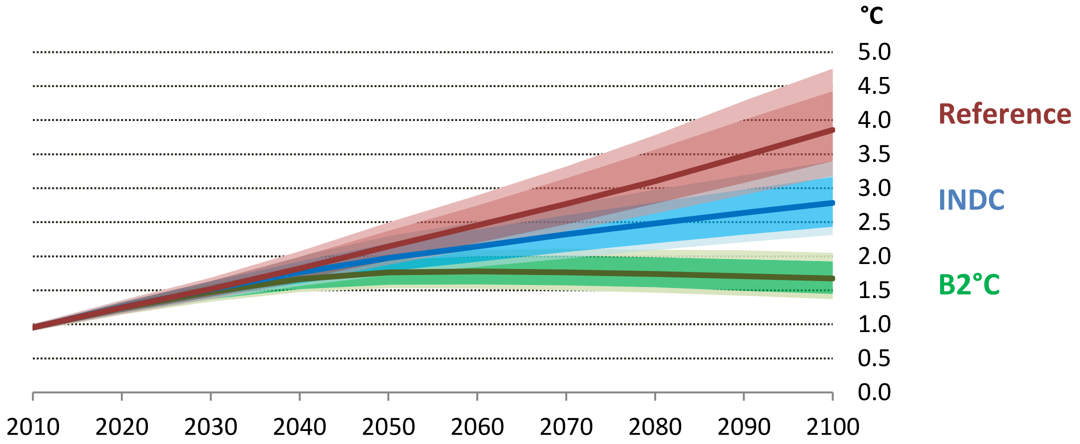
The long-term global temperature increase resulting from the greenhouse gases and air pollutants emissions for each of the scenarios is presented in Figure 55. These scenarios correspond to end-of-century temperature increases compared to pre-industrial levels close to 4°C (Reference, on an upwards trend beyond 2100), 3°C (INDC, on an upwards trend beyond 2100) and below 2°C (B2°C, stabilizing or even slightly decreasing by 2100) with 50% probability.

In the B2°C scenario the temperature stabilizes around 2050 and stays at levels below +2°C compared to pre-industrial levels by 2100 with a probability of 75%; the temperature change would be limited to +1.7°C with a probability of 50%.

In the other two scenarios, temperatures increase throughout the century. The Reference scenario results in a temperature increase by 2100 between 3.5°C and 4.5°C ([25%-75%] confidence interval) while a prolonged INDC scenario would result in a temperature increase between 2.5°C and 3.2°C ([25%-75%] confidence interval).

([41]) Pollutants emissions used in these temperature projections use the "PROG" pollutants emissions profiles presented in section 5.1.

Figure 55: Global average temperature change



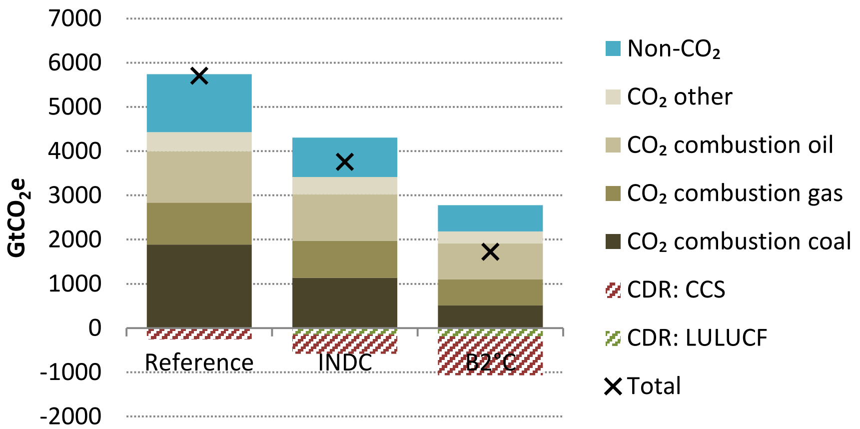
Note: the graph shows the probability of exceeding a temperature increase; dark shading denotes the 25%/75% percentile region and light shading the 17%/83% percentile region, the line in the middle represents the median. Probability distribution is from www.live.magicc.org (Meinshausen et al., 2011) using outputs form GECO: GHGs (all sources), aerosols and air pollutants (see section 5.1).

In order to extend the mitigation effort beyond the "below 2°C" limit to the "1.5°C" limit, global emissions would have to decrease even further and the mitigation options would have to be more massively and more quickly adopted. The scientific literature for scenarios with a high probability of keeping global warming below 1.5°C by 2100 is still scarce, with figures on cumulated CO_2 emissions over 2011-2100 ranging from 200 to 550 $GtCO_2$ ([42]). Taking into account the fact that cumulative emissions over 2011-2015 were already of approximately 180 $GtCO_2$, this leaves very little room for net emissions to take place for the rest of the century.

Cumulated over 2011-2100, total GHG emissions in the Reference the INDC scenarios get close to 6000 $GtCO_2e$ and 4000, respectively, versus less than 2000 $GtCO_2e$ for the B2°C scenario. They are the result of net GHG emissions (fossil fuel combustion, industrial processes, agriculture, waste) and CO_2 removal (CDR: carbon dioxide removal) in the form of LULUCF net sinks and CCS. The contribution of each of these sources is illustrated in Figure 56, showing the important role of coal phase-out, non-CO2 abatement and CCS deployment as important options to achieve the goal of temperature increase of below 2°C. In particular, technologies like Biomass Energy with Carbon Capture and Storage (BECCS) that would allow CO_2 removals through using biomass energy (BE) – assumed to be carbon neutral – combined with carbon capture and storage (CCS) would be key in limiting temperature change to below 2°C or 1.5°C.

([42]) See Rogelj et al 2015, IPCC 2014 (AR5 Synthesis Report Table 2.2)

Figure 56: Cumulated GHG emissions from 2011 and emissions sources



Note: "CO$_2$ other" includes industrial process emissions, waste emissions and fugitive emissions. "CO$_2$ combustion" includes the emissions that are abated by CCS.

4.2 Regional dynamics

As regions will develop their economies, implement INDC policies and adopt low-carbon technologies, the regional distribution of GHG emissions is foreseen to change over time (Figure 57). The growing role of Asia can clearly be seen: this region should represent about 50% of global GHG emissions from 2030 onwards, led in particular by China until 2030 when it sees its emissions peaking. Africa and Middle-East would also experience a continuous increase, representing about 20% of the total by mid-century. North America, Europe and Pacific, which still represent about 30% of the total in 2015, fall to 14%, followed by CIS (6%) and Latin America (4%), both with slightly decreasing shares, by 2050. International air and maritime bunkers rise to 6% by 2050.

With the stronger climate policies of the B2°C scenario, all regions would drastically reduce their emissions over time from early on, depending on the differentiated participation to the global mitigation effort considered in the scenario design, with only India, among the major economies, delaying its peak in emissions to late in the 2020-2030 decade. The regional distribution of emissions would be similar to the INDC scenario, with some interplay across regions due to the cost-efficiency of a concerted global mitigation effort.

Figure 57: Regional GHG emissions, INDC scenario

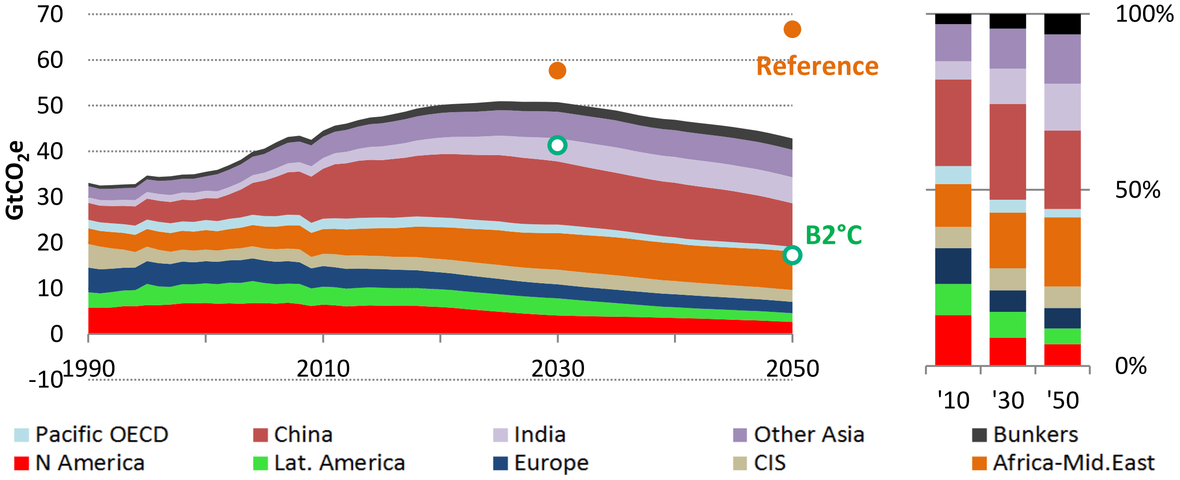


Table 5: GHG emissions peak information per region

Region	INDC			B2°C		
	Peak level ($GtCO_2e$)	**Peak year**	**GDP/cap at peak (k$)**	**Peak level ($GtCO_2e$)**	**Peak year**	**GDP/cap at peak (k$)**
North America	6.9	2007	44	*(same as INDC)*		
Latin America	4.8	2004	8	*(same as INDC*		
Europe	5.1	before 1990	20	*(same as INDC)*		
CIS	4.4	before 1990	8	*(same as INDC)*		
Africa-Middle East	*n/a (beyond 2050)*			6.8	2021	5
Pacific OECD	2.4	2013	31	*(same as INDC)*		
China	14.6	2026	18	13.5	2021	14
India	*n/a (beyond 2050)*			4.0	2029	9
Other Asia	*n/a (beyond 2050)*			5.3	2020	5
World	51	2025	14	49	2020	12

Note: GDP in $2005 PPP. GDP/cap at peak year is independent from mitigation policy cost (see section 2.1 on the economic assumptions and section 6 for the analysis of policy cost and co-benefits).

Information on different regions' emissions peak year is presented in Table 5, displaying how a global effort to limit temperature change to below 2°C can be distributed across regions. Peak years and levels are the result of each region's economic development and climate policies, taking into account a differentiated pace of mitigation effort (as explained in section 2.2).

For a given ambition level, the overall economic effort to curb GHG emissions down crucially depends not only on the economic structure of the different countries, but also on the different policy mixes adopted to maximize the opportunities offered (enhancing technology deployment, removal of distortionary taxes, etc) and minimize the negatives aspects (more expensive provision of energy services, etc). Therefore, while countries and regions undertake mitigation and see their emissions decline, their economy would still continue to grow (e.g. EU). The macro-economic impacts of climate mitigation are explored in sections 6.2-6.4.

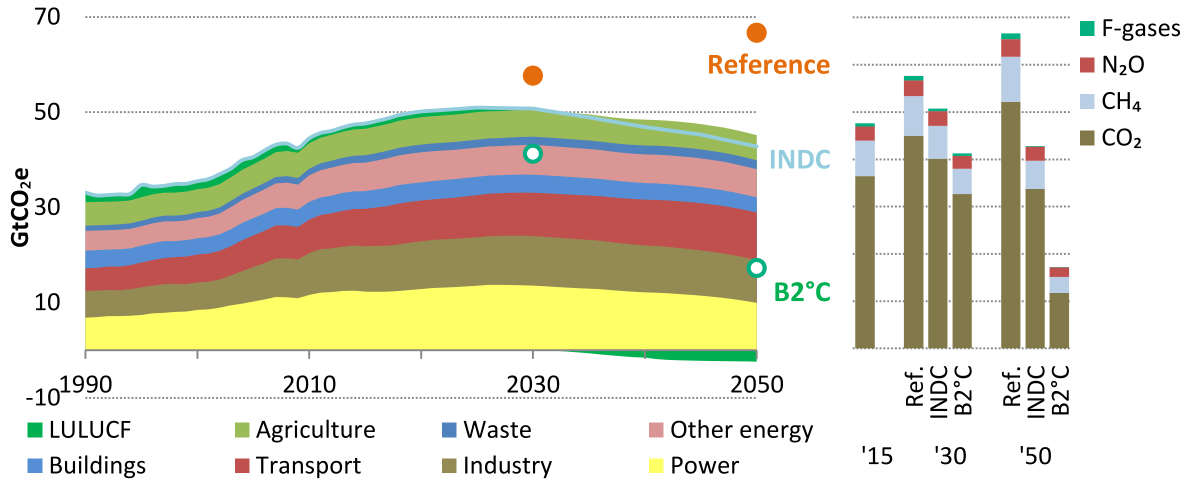
4.3 Sectoral dynamics

In the INDC scenario, sectoral contributions to total emissions change little by 2030, compared to 2015 (Figure 58). Historically the power sector is the largest emitting sector and, at the same time, the one with largest technological flexibility. It would remain the dominant sector in emissions, ahead of industry and transport, followed by other energy supply (primary supply, other transformation), agriculture, residential & services and waste. The Land Use, Land-use Change and Forestry (LULUCF) sector becomes carbon-neutral around 2030 at the world level, with significant differences in how this sector contributes to emissions balances across countries.

With further decarbonisation beyond 2030 particularly in power generation, emissions from transport surpass those from the power sector; they are followed, by order of importance, by industry, other energy supply, agriculture, residential & services and waste. In the Reference scenario the share of power sector emissions would actually increase.

The sectoral distribution in the B2°C scenario would shift significantly after 2030. In terms of early action by 2020, the non-power energy supply sector would be very responsive to the policies put in place, especially given the relatively higher abatement potential in non-CO_2 gases (e.g. reduction of fugitive emissions and flaring in the production of fossil fuels). In addition, the LULUCF sector would become carbon-neutral early in the 2020-2030 decade. Next, the power sector would react also strongly to the policies put in place and could reach full decarbonisation at the world level by 2050, with its emissions starting to decline starting from 2020 and even becoming negative by 2050 (thanks to the combined use of biomass and CCS). This would leave the bulk of the remaining emissions after 2030 to sectors more difficult to decarbonise: transport, industry and agriculture.

Figure 58: World GHG emissions in the INDC scenario by sector and by greenhouse gas



4.4 Drivers of GHG emissions

The GHG intensity of the economy is expected to decrease steadily over time in all scenarios: as the economy grows threefold over 2015-2050 (and GDP/capita more than doubles) and even in the Reference scenario the emissions would increase by 40% at most.

In the INDC scenario the GHG intensity of the economy is reduced by a factor of 3 over 2015-2050, resulting in decreasing emissions per capita as a world average (-28%). GHG intensity thus decreases at around 3.3%/year over the next three decades (Figure 54), an acceleration (near doubling) compared to the recent past (-1.7%/year over 1990-2015) ([43]). Going to the B2°C scenario would lead to a significant further acceleration of emission intensity improvement: -5.8%/year, more than three times the rate observed since 1990.

The decomposition of world GHG emissions into components related to energy intensity of the economy and the carbon content of energy ([44]) is presented in Figure 59.

The energy intensity of the economy, a measure of energy efficiency, decreases over time in all scenarios (cut by half over 2015-2050 in the INDC scenario). The GHG content of the energy mix, a measure of decarbonisation of the economy, also decreases and, more significantly, shows stronger change across scenarios. It decreases only marginally in the Reference scenario: -11% over 2015-2050, showing an increasing competitiveness of renewables even in the absence of ambitious climate policies, but a level far from allowing a decoupling of emissions and economic growth. The decrease is much stronger in the INDC and B2°C scenarios: it is one third and two thirds lower in 2050 compared to

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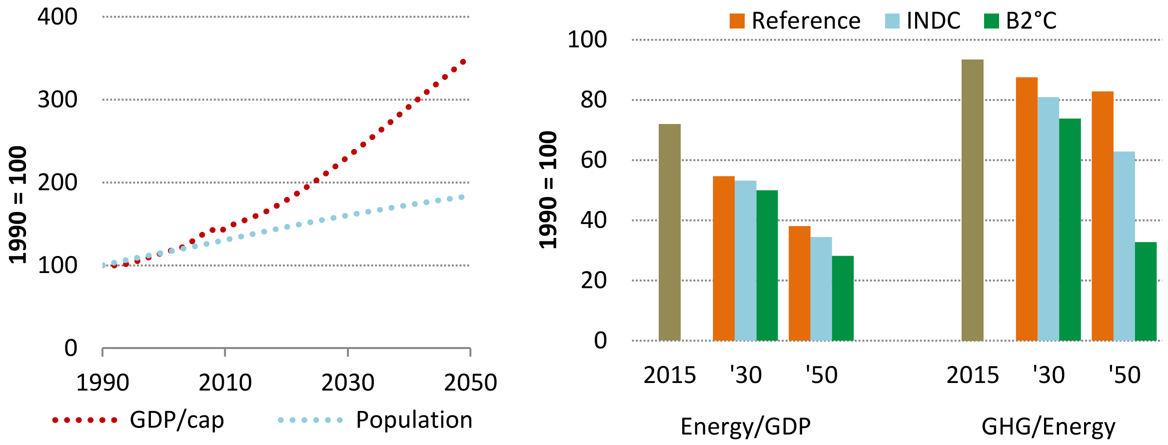
([43]) Emission intensity improvement was relatively lower in 2000-2010 due to the important role of coal in some emerging economies.

([44]) Decomposition of the emissions into the following four explanatory variables: the GHG content of energy use, the energy intensity of GDP (expressed in real US dollars of 2005), the GDP per capita, and the population: GHG = [GHG / Energy] * [Energy / GDP] * [GDP / Pop] * [Pop]

2015, respectively, making decarbonisation of the energy sector the main means for GHG emissions mitigation.

This transformation can only take place with an accelerated fuel and technology shift towards GHG-neutral options. It must be noted that this section does not consider the impact of policies on income and economic activity: an assessment of the macro-economic impacts is carried out in section 6.2.

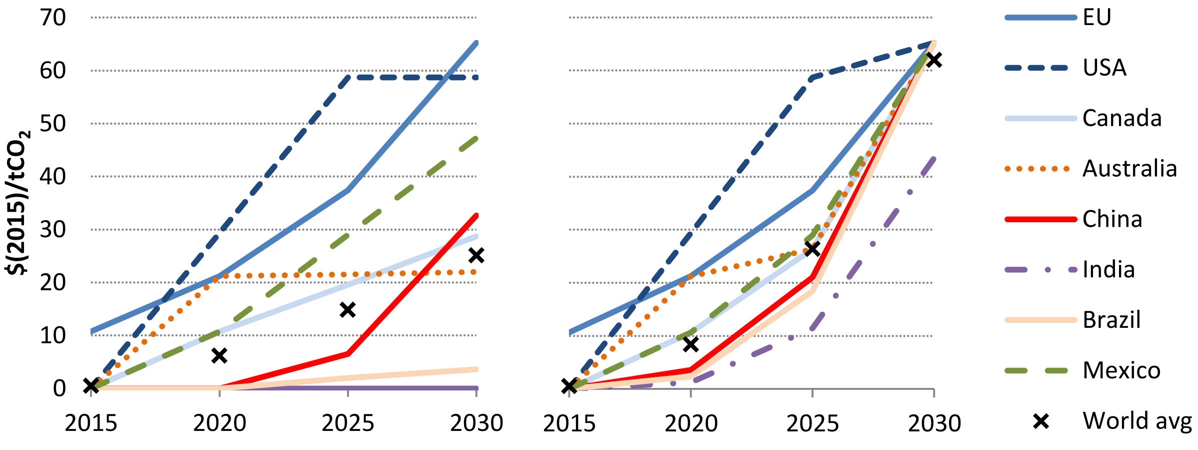
Figure 59: Decomposition of world GHG emissions



The main mechanisms leading to these emissions trajectories are thus GHG mitigation policies, technological change and market dynamics.

The Reference emissions are mainly the result of technological change and market dynamics, with little or no effect attributable to GHG mitigation policies. Several regions of the world implement their 2020 policies without the need of a carbon value, including countries like China and India. While it can reach from 10 $/tCO$_2$ in Canada to 20 $/tCO$_2$ in EU (ETS sectors only) and Australia, the average world carbon value (45) is thus very low, only of 2 $/tCO$_2$ in 2020 and 2030.

Figure 60: Carbon values by 2030 in the INDC (left) and B2°C scenarios (right)



Note: EU price refers to the ETS sector's price until 2020, then to the average price over all sectors (ETS and non-ETS) for 2025 and 2030. World average is all countries' carbon prices averaged over their GHG emissions.

The INDC emissions are a balanced result of both technological change (and resulting market forces) and GHG mitigation policies. While some countries did put forward non-

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(45) Refer to carbon prices of individual countries averaged over countries' GHG emissions (unless stated so). Carbon values expressed in this section are in real US dollars of 2015.

constraining INDC policies (e.g. India, Turkey, most of Middle East, Russia, Argentina, Indonesia), above 70% of emissions around the world (46) would be subject to a constraint, leading to an average "implicit" world carbon value of 25 $\$/tCO_2$ in 2030. Carbon values in 2030 (Figure 60) range from around 5 $\$/tCO_2$ in Brazil to 65 $\$/tCO_2$ in the EU (averaged over the entire economy, ETS and non-ETS sectors).

The B2°C scenario emissions are strongly driven by climate policies, which are implemented very quickly and across all sectors of the economy and with a clear signal that they will be strengthening in the future. The average "implicit" world carbon value would reach 62 $\$/tCO_2$ in 2030, with all countries subject to a carbon value from 2020 and most countries converging to 65 $\$/tCO_2$ in 2030; countries with very low income (47) (e.g. India, South-East Asia, Sub-Saharan Africa) are allowed to converge later and thus reach in 2030 a lower level (43 $\$/tCO_2$).

4.5 Decarbonisation indicators

Depending on the current energy mix and economic structure, the endowment of renewable energy resources, as well as the financing capacity and expected economic growth, world countries develop their own pathway and behave differently in their pattern to reduce GHG emissions. Table 6 reports GHG emissions growth per decade.

While OECD countries have been undergoing a stabilization of GHG emissions over the last years, most non-OECD countries have experienced a fast increase (48). However, the average world emissions growth in 2010-2020 is half that of 2000-2010 or lower: OECD countries stabilize their emissions while non-OECD countries reduce substantially their growth.

In the B2°C scenario, during the 2020-2030 decade most countries have their emissions already declining, except countries with low income, which have a large gap to cover to satisfy their population's energy needs and have a low financing capacity for a transition to a low-carbon economy. From 2030 onwards the yearly decline is steep, with both OECD and non-OECD reaching or exceeding -4%/year over 2040-2050. These emission reduction rates are consistent with scenarios described by the IPCC (AR5 WGIII, IPCC 2014).

Table 6: Annual average GHG emissions growth

	%/year	'90-'00	'00-'10	'10-'20	'20-30	'30-'40	'40-50
Reference	World	0.8%	2.5%	1.3%	1.3%	1.0%	0.4%
INDC	World			1.2%	0.3%	-0.4%	-0.7%
B2°C	World			1.0%	-1.0%	-3.0%	-4.6%
	OECD	0.9%	-0.1%	-1.0%	-2.3%	-3.3%	-5.4%
	Non-OECD (excl. LDCs)	0.0%	5.0%	1.5%	-1.2%	-3.8%	-4.7%
	LDCs	2.7%	3.1%	3.2%	1.0%	-1.8%	-4.8%

Note: EU28 is distributed among OECD and non-OECD regions. LDCs: Least Developed Countries.

While the Reference scenario maintains large regional differences in emissions per capita throughout the entire period, the B2°C scenario assumed to be adopted worldwide leads to more convergence across countries (Table 7). World average emissions reach 2.1 tCO2e per capita in 2050 (median at 2.2 tCO2e per capita), i.e. at around the same level as least developed countries in 2015. For instance, emissions per capita in China and Southeast Asia would be reduced by a factor of 2.5 over 2015-2050.

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(46) Refers to the share of these countries' emissions in the world total in 2015.

(47) Countries with income per capita in 2030 lower than 10 k$ PPP.

(48) The small 1990-2000 emissions increase rate is heavily influenced by the sharp reduction in the countries of the Commonwealth of Independent States following the breakup of the Soviet Union.

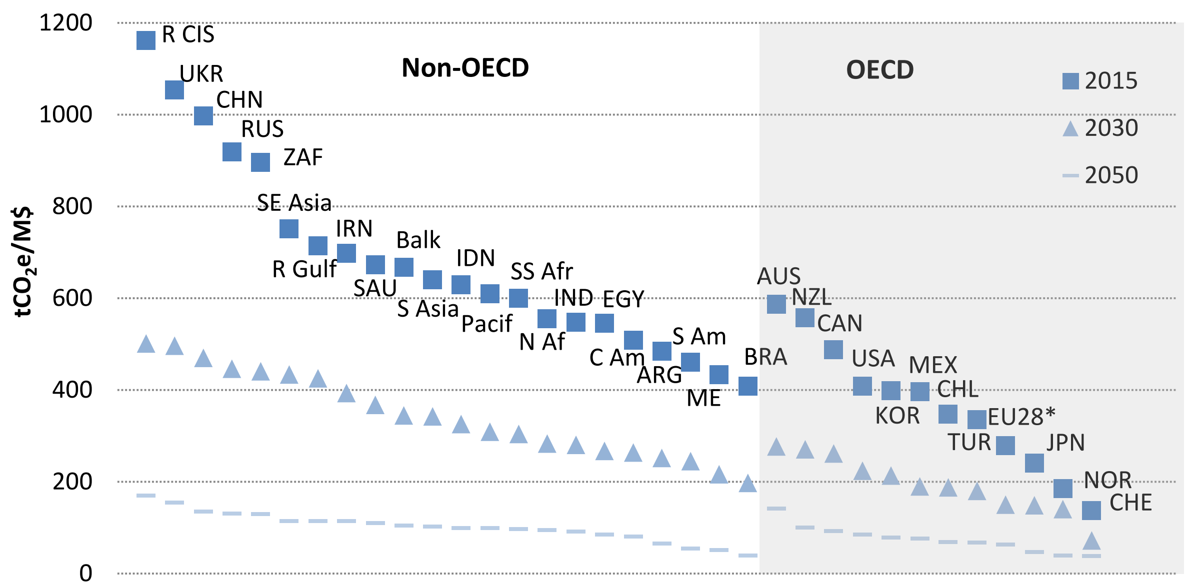
Table 7: GHG emissions per capita

	tCO$_2$e/cap	1990	2000	2010	2020	2030	2040	2050
Reference	World	5.9	5.5	6.3	6.3	6.6	6.8	6.6
INDC	World				6.3	5.9	5.3	4.6
B2°C	World				6.2	5.1	3.5	2.1
	OECD	13.5	13.6	12.5	10.6	8.1	5.6	3.2
	Non-OECD (excl. LDCs)	6.0	5.4	8.2	8.9	7.6	5.1	3.1
	LDCs	1.6	1.7	2.0	2.3	2.2	1.6	0.9

Note: EU28 is distributed among OECD and non-OECD regions. LDCs: Least Developed Countries.

A dynamic, cross-regional plot of the emissions intensity of GDP in the B2°C scenario shows a global convergence of world regions across time (Figure 61). The emissions intensity becomes lower than 200 tCO$_2$e/M$ for all countries in 2050, i.e. at the level of some of the best-performing economies of 2015 (Japan, EU). World average GHG intensity (excluding LULUCF emissions) would be nearly halved between 2015 and 2030 (from around 520 to 260 tCO$_2$e/M$), and more than halved again between 2030 and 2050 to reach around 80 tCO$_2$e/M$.

Figure 61: GHG emissions intensity of GDP, B2°C scenario

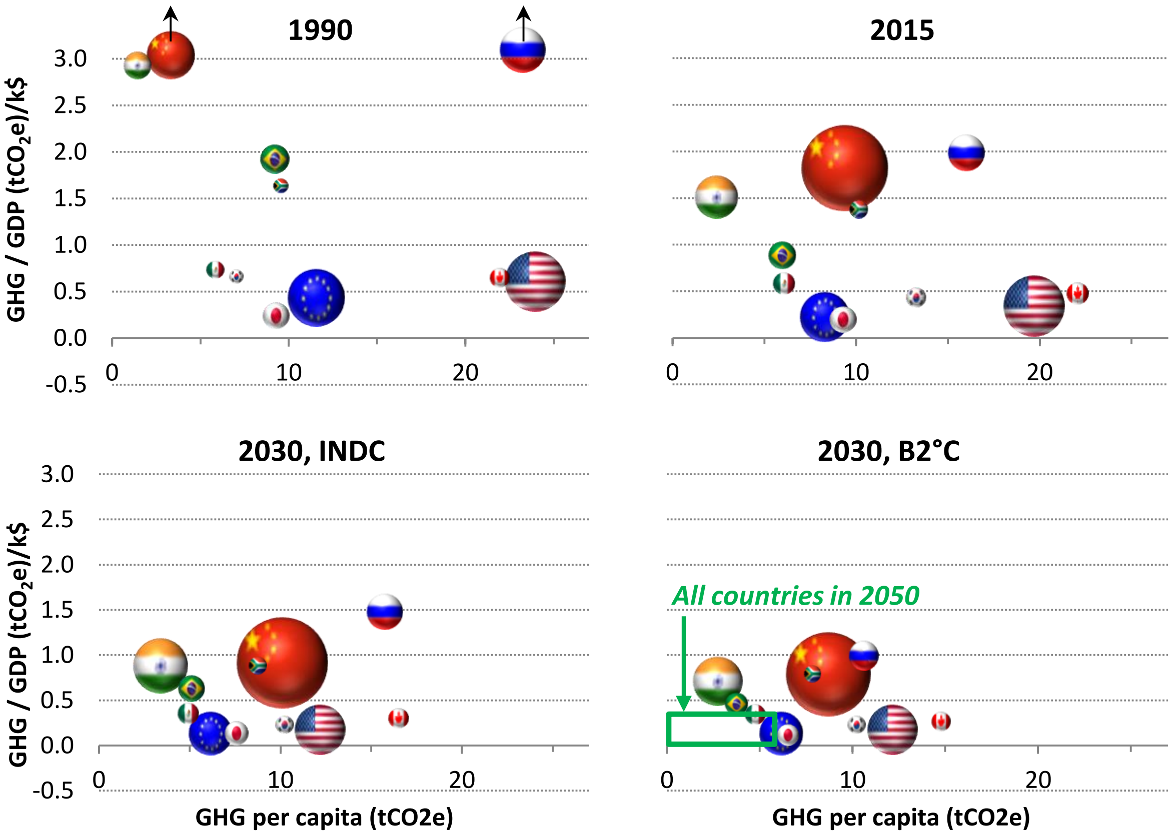


Note: Figures exclude LULUCF emissions; GDP in PPP. Individual countries with ISO3 codes; for regions see section on regional definitions. EU28 includes both OECD and non-OECD member states.

The evolution of the GHG emissions intensity with income is visualized in Figure 62, showing the decarbonisation path depending on the country and its economic and demographic structure.

OECD countries would primarily reduce their emissions per capita (they move to the "left" from INDC to B2°C scenario) while non-OECD countries tend to decrease their emissions intensity of GDP (they first move "downwards"). By 2050, the drastic reductions in the B2°C scenario would find all countries fitting in a box defined by low emissions per capita and emissions intensity (left-down green box in the 2030 B2°C graph).

Figure 62: GHG emissions intensity vs. GDP per capita for major economies



Note: Bubble size gives total emissions. 1990 y-axis: China: 5.1 tCO$_2$e/k$, Russia: 3.4 tCO$_2e/k. GDP in $2005 PPP.

Overall, it can be observed that all countries and regions would have to converge to low levels of emissions, of emissions per capita, and of emissions intensity of their economy. This would necessarily imply a shift of their energy mix towards low-emission sources; across all countries and regions, investments in the energy sector determine the transition from the Reference scenario to the INDC scenario and then to the B2°C scenario. However, there is no uniform pattern: countries would follow very diverse pathways towards that goal with their own set of policies and national circumstances, relying on different mitigation options and experiencing different paces of emissions reductions.

4.6 GHG emissions mitigation options

By comparing the Reference, INDC and B2°C scenarios, it is possible to identify the contribution of individual efficiency and technological options by sector to the total reduction in emissions over time. The following section provides an overview of these contributions by 2030 and 2050.

By 2030 the worldwide reduction in emissions achieved in the B2°C scenario is 16.2 GtCO$_2$e compared to the Reference scenario; announced INDC policies would achieve 40% of this by 2030 (Figure 63, Table 8).

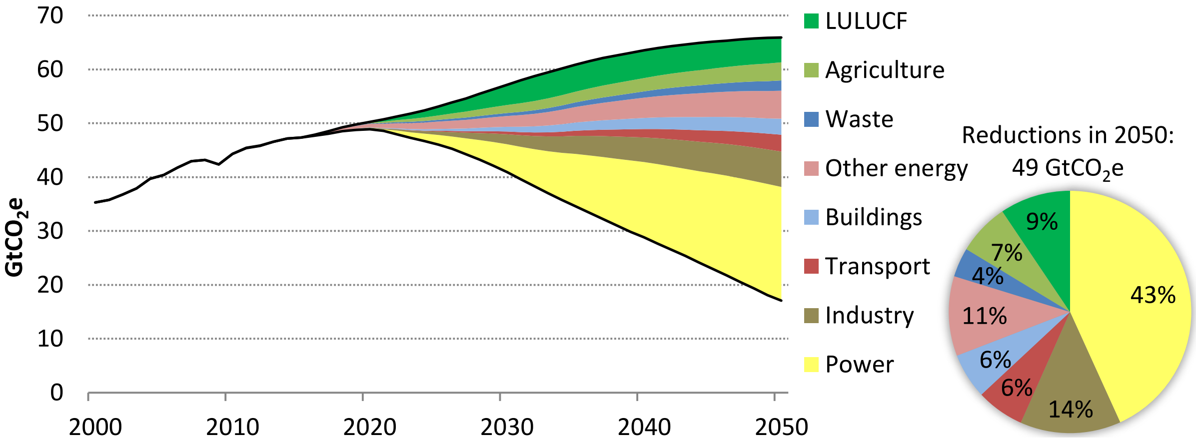
With more ambitious emissions reductions taking place after 2030, these figures are different when comparing the mitigation effort over the entire period of 2015-2050: the B2°C scenario is 49 GtCO$_2$e lower than the Reference scenario in 2050; while the INDC scenario represents 44% of the cumulative mitigation effort required to reach the B2°C trajectory.

4.6.1 GHG emissions reductions by sector of activity

The power sector and LULUCF would be able to carry out 28% and 23% of the cumulated mitigation effort achieved in the B2°C scenario by 2030, respectively. The remaining contributions would come from the other energy sector ([49]) (18%), agriculture and industry (10% each), residential & services (5%), waste (4%) and transport (2%).

Other energy supply proves particularly flexible, with reductions quickly taking place in fugitive CH_4 emissions in coal, oil and gas production and gas transport when the climate policies are put in place. The industry sector also includes reductions from HFCs, which are subject to the Kigali Agreement of the Montreal Protocol (a policy implemented in both the INDC and B2°C scenarios ([50])).

Figure 63: Sectoral emissions mitigation from the Reference to the B2°C scenarios, World



Beyond 2030, the power sector would largely contribute to the mitigation effort as well (39% of the cumulated effort, see Table 8), but the role of LULUCF would be reduced (15%). The other sectors of the economy will also have to do their share: industry (13%; a third of which is due to HFC-related policies), the "other energy" sector[49] (12%), agriculture (8%), residential & services (6%), transport (5%) and waste (4%).

INDC policies would initiate reductions in most sectors, except in transport which appears more difficult to decarbonise due to the growing needs for mobility and its low elasticity to energy price and carbon value.

([49]) The "other energy" sector includes the fuel extraction industry, fuel transport and fuel refining activities.
([50]) F-gas policy is implemented in the Reference for the EU (as it is an adopted policy).

Table 8: Sectoral emissions mitigation from the Reference to B2°C scenarios (annual and cumulated) and share (of cumulated) achieved in the INDC scenario

$GtCO_2e$	2030			2050		
	Ref./B2°C mitigation in 2030	% of cum. mitigation (2015-30)	of which achieved in INDC	Ref./B2°C mitigation in 2050	% of cum. mitigation (2015-50)	of which achieved in INDC
Total	**16.2**	100%	38%	**48.9**	100%	47%
Power	5.2	28%	46%	21.1	39%	46%
Industry	1.8	10%	46%	6.6	13%	45%
Transport	0.5	2%	3%	3.1	5%	18%
Resid. & services	0.9	5%	40%	3.0	6%	40%
Other energy	2.0	18%	33%	5.2	12%	49%
Waste (non-CO_2)	0.5	4%	40%	1.9	4%	43%
Agri. (non-CO_2)	1.5	10%	39%	3.4	8%	47%
LULUCF	3.7	23%	32%	4.6	15%	64%

Regarding the role of technological options to reach the B2°C scenario (Table 9):

- **Renewable energy sources** are the largest contributor (18-24% in 2030 and 2050) thanks to their important role in the power sector (42%) and in residential & services (biomass ensuring around a third of total reductions).
- **Energy demand reduction and efficiency gains** play undoubtedly a key role in all sectors, representing 16-18% of total mitigation both in 2030 and in 2050 compared to the Reference case, respectively; it is the main option in the transport sector (where the additional development of alternative fuel/engines beyond what is taking place in the Reference scenario is mostly limited to light vehicles).
- The contribution of fossil **fuel switch** to less carbon-intensive fuels or carriers like gas or electricity varies across sectors and time, in the range 4%-20% (the latter applying to transport, with hybrid and full electric vehicles notably).
- **Non-CO_2** emissions mitigation across in industry and energy is a relatively low-hanging fruit by 2030; in the longer term non-CO_2 from agriculture is also a significant contributor to mitigation.
- **LULUCF** is a key sector for emissions reductions prior to 2030 (23%), its mitigation potential is more limited beyond (9% of total mitigation in 2050).
- Given the technology assumptions made for **CCS** in this report, it does not develop much by 2030, while it becomes a key option in the longer run, with about a quarter of the emission reductions of the power sector in 2050. Total CCS in power generation and in industry is then about equivalent to the total reductions from residential & services and the transport sector.

Table 9: Emissions mitigation options from the Reference to the B2°C scenarios, World

2030	Total	Power	Industry & Energy	Resid. & Services	Transport	Waste & Agri. & LULUCF
Total ($GtCO_2e$)	**16.2**	**5.2**	**3.9**	**0.9**	**0.5**	**5.8**
of which:	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*
Energy efficiency & reduced demand	16%	15%	27%	43%	87%	
Renewables	18%	42%	11%	33%	4%	
Fuel switch (fossil, elec., H_2)	7%	17%	4%	10%	8%	
CCS	2%	0%	8%			
Nuclear	8%	26%				
Industrial process CO_2	0%		1%			
LULUCF CO_2	23%					65%
Non-CO_2 (all sectors)	25%		49%	14%	1%	35%
2050	**Total**	**Power**	**Industry & Energy**	**Resid. & Services**	**Transport**	**Waste & Agri. & LULUCF**
Total ($GtCO_2e$)	**48.9**	**21.1**	**11.8**	**3.0**	**3.1**	**9.9**
of which:	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*
Energy efficiency & reduced demand	18%	3%	38%	46%	79%	
Renewables	24%	42%	16%	37%	0%	
Fuel switch (fossil, elec., H_2)	7%	8%	6%	9%	20%	
CCS	13%	26%	9%			
Nuclear	9%	21%				
Industrial process CO_2	0%		2%			
LULUCF CO_2	9%					47%
Non-CO_2 (all sectors)	18%		29%	8%	1%	53%

Note: "Fuel switch" refers either to shifts from high-carbon content fossil fuels towards lower-carbon content fossil fuels (generally from coal to gas) or to shifts from fossil fuels to other energy carriers (electricity, hydrogen). "Renewables" refers to either all forms of renewables (in power generation), to liquid biofuels (in transport) or to solid biomass (in other sectors). "Industry & Energy" refers to the manufacturing industry, construction, mining and the energy transformation industry excluding the power sector (fuel extraction, refining, transport).

The mix of mitigation options pursued by each country depends on their local circumstances: mitigation potential, cost, renewable resources (Table 10). In OECD countries on average, more reductions are achieved in energy efficiency in buildings and transport, reflecting these sectors' mitigation potential (more energy needs for space heating in the OECD; large car fleet to be renewed). By contrast, in non-OECD countries, while the power sector is also the largest contributor, buildings and transport have a lower mitigation potential (12% total mitigation in 2050, vs. 20% for OECD regions) and agriculture, waste and LULUCF contribute as much as energy and industry (22-24%). Most of LULUCF reductions are achieved in non-OECD countries (Sub-Saharan Africa, South America).

Table 10: Emissions mitigation by option and by sector from the Reference to the B2°C scenarios

2050	World	OECD	Non-OECD
Total ($GtCO_2e$)	48.9	9.4	39.5
By option:	*100%*	*100%*	*100%*
Energy efficiency & reduced demand	18%	23%	17%
Renewables	24%	26%	24%
Fuel switch (fossil, elec., H_2)	7%	8%	6%
CCS	13%	14%	13%
Nuclear	9%	10%	9%
Industrial process CO_2	0%	0%	0%
LULUCF CO_2	9%	4%	11%
Non-CO_2 (all sectors)	18%	15%	19%
By sector:	*100%*	*100%*	*100%*
Power	43%	46%	43%
Industry & Energy	24%	23%	24%
Buildings	6%	8%	6%
Transport	6%	12%	5%
Waste & Agri. & LULUCF	20%	11%	22%

4.6.2 GHG emissions reductions in the power sector

The power sector is crucial to achieve substantial GHG mitigation (see section 4.6.1 above for an overall view of mitigation options):

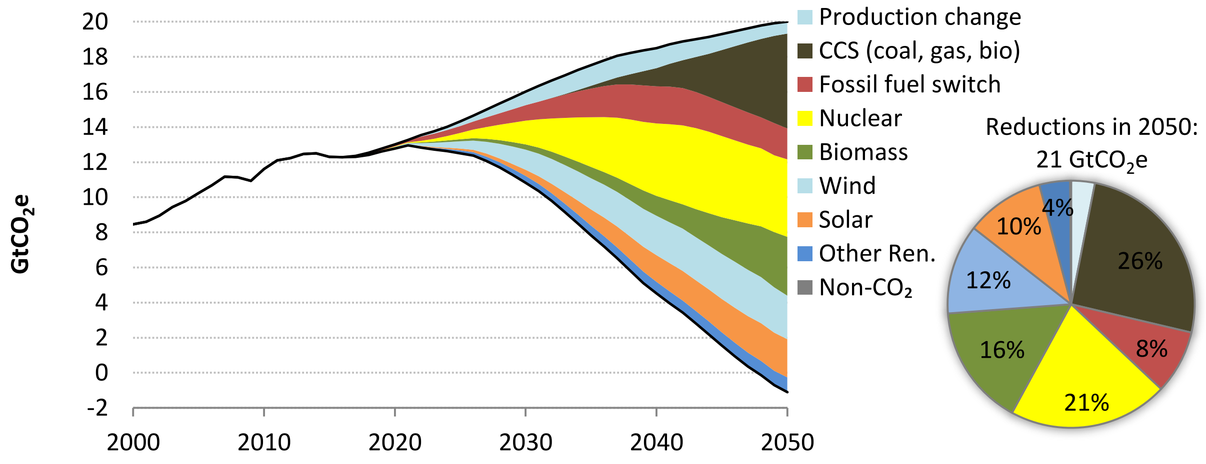
- it offers a very wide technological options portfolio and can accommodate at affordable cost decarbonisation for traditional technologies;
- in particular, it can integrate many renewable energy technologies.

All regions are expected to diversify their power mix towards low-emission sources as a growing diversity of renewable energy sources gets exploited, according to each region's domestic potential and market conditions.

By 2030, the power sector alone would account for about a third of the mitigation entailed by the INDC policies, and also around a third of the reduction needed towards the B2°C scenario (Table 8).

Mitigation options within the power sector are presented in Figure 64 and Table 11.

Figure 64: Contribution of mitigation options in the power sector from the Reference to the B2°C scenario, World



Note: "Other Ren." consists in hydro, geothermal and ocean power.

Whilst renewables undergo a significant expansion in the Reference scenario, they expand even further in the INDC and B2°C scenarios. With INDC policies, renewables contribute to nearly half (46%) of the cumulative reductions from the power sector by 2050, followed by nuclear (25%) and switch from coal and oil to gas (13%), well ahead of CCS (11%, and taking place beyond 2030 only). Further decarbonisation towards the B2°C scenario is particularly achieved by more renewables (especially biomass) and CCS. Energy efficiency, triggered by ambitious climate policies, leads to a slightly lower electricity demand compared to the Reference case thanks to a further electrification of demand.

Table 11: Mitigation options in the power sector from the Reference to B2°C scenarios (annual and cumulated) and share (of cumulated) achieved in the INDC scenario

$GtCO_2e$	2030			2050		
	Ref./B2°C mitigation in 2030	% of cum. mitigation (2015-30)	of which achieved in INDC	Ref./B2°C mitigation in 2050	% of cum. mitigation (2015-50)	of which achieved in INDC
Total	**5.2**	100%	47%	**21.1**	100%	48%
Prod. change	0.8	15%	41%	0.7	3%	68%
CCS	0.0	0%	0%	5.4	26%	20%
Fossil fuel switch	0.9	17%	49%	1.8	8%	72%
Nuclear	1.4	26%	47%	4.4	21%	58%
Biomass	0.3	6%	41%	3.4	16%	35%
Wind	1.1	22%	51%	2.5	12%	76%
Solar	0.4	7%	51%	2.2	10%	55%
Other Ren.	0.4	7%	42%	0.8	4%	45%
Non-CO_2	0.0	0%	37%	0.0	0%	93%

Note: "Other Ren." consists in hydro, geothermal and ocean power.

4.6.3 GHG emissions reductions by gas

The technology options considered determine the relative shares of the different GHGs within each emission reduction scenario.

Implementing the INDC policies in a cost-effective manner across all greenhouse gases, by applying the carbon value on a single comparable metrics (CO_2-equivalent) (51), would result in different emissions reductions profiles across gases (Figure 65). While total emissions in the INDC scenario would roughly reach the same level by 2050 as in 2010, CO_2 from combustion and N_2O from agriculture would still be above 2010 levels, while CH_4 and N_2O from energy and industry would be below (-20%); global LULUCF would switch from being a net CO_2 emitter today to behaving as a net CO_2 sink from 2030.

The B2°C scenario consistently requires emissions reductions in all sectors and sources, including international aviation and shipping, and very significant reductions in the levels of CO_2 emissions. The contributions to total reductions from the various gases would develop according to different dynamic profiles over time: the reductions of CO_2 emissions from energy and industry take place progressively (about the same level as 2010 in 2030 to 56% below in 2050); non-CO_2 gases in energy and industry tend to react faster while emissions in agriculture have less mitigation potential (especially N_2O).

The behaviour of fluorinated gases emissions is noticeable: without additional climate policies, in the Reference scenario they would exhibit a substantial growth in industrial

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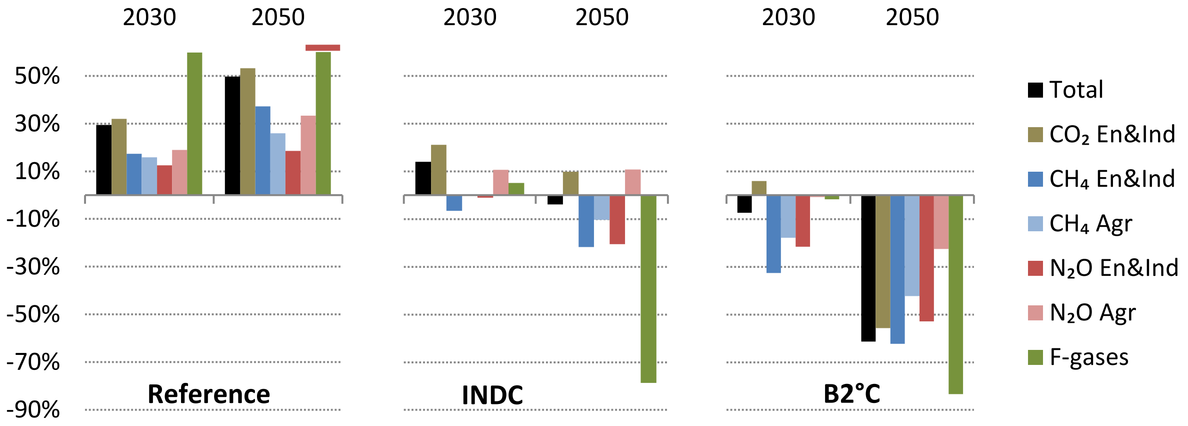
(51) Using the 100 years global warming potential from the IPCC Second Assessment Report (IPCC 1996).

sectors. The Kigali amendment of the Montreal Protocol on HFC emissions is assumed to be implemented in the INDC and B2°C scenarios ([52]); this results in a stabilization of F-gases as a whole by 2030 and then a significant drop (-79% in INDC compared to +120% in Reference in 2050, versus 2010).

CO_2 emissions from LULUCF would also significantly drop, from a net emissions source in recent years (about 1 $GtCO_2$ in 2010), to a net sink beginning from 2030 in the INDC scenario (early 2020s in the B2°C scenario), stabilizing at about -3 $GtCO_2$.

Figure 65: Evolution of GHG emissions by gas compared to 2010



Note: F-gases in Reference in 2050 at +120%. Total includes CO_2 LULUCF; CO_2 LULUCF are not displayed separately.

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[52] As well as in the EU in the Reference scenario.

5 Air pollutants emissions and concentrations

Most emissions of major air pollutants are driven by human activity and actually originate, to a large extent, from the same source as GHG emissions: energy fuel combustion. Actual emissions depend on the type of activity, the fuel type and the technology used, which can evolve with air quality policies and standards.

Pollutant emissions are commonly mitigated by targeted air quality control policies (so-called end-of-pipe or technical measures) but also result of changes in the energy system. By reducing energy fuel consumption, energy and climate policies can bring about significant co-benefits on the emissions of pollutants.

In this section the potential co-benefits of the air quality and climate protecting policies are analysed at a global level.

5.1 Air pollutants emissions

5.1.1 Air pollution control policies and climate protecting policies

The ancillary co-benefit of climate policies on air quality depends on the levels of air pollution or the stringency of controls already in place. They can be significant and bring about pollutant emissions reductions that would be comparable to end-of-pipe measures in the absence of climate policies. Importantly, benefits on air quality follow instantaneously upon mitigation (53) and are mostly felt in the regions close to where measures are being implemented (depending on the pollutant species, the pollutant source and health exposure pathway).

As an additional interaction with climate policies, certain air pollutants have an effect on the temperature; the combined effect of greenhouse gases and air pollutants on temperature change is presented in section 4.1, using the "PROG" pollutants emissions profiles (see below the definition of the air pollution cases investigated).

Emissions coverage

Some pollutants emissions come from fires that may, at least to a large extent, be of anthropogenic origin (agricultural waste burning, forest fires, peat fires) and natural sources (dust, sea salt, volcanoes).

Table 12 shows the contribution of fires and fossil fuels; their contribution can be significant depending on the pollutant.

Table 12: Global pollutants emissions in 2010 and contributions from fires and fossil fuels (Mt)

	Total	of which fires	*% fires*		Total excl. fires	of which fossil fuels	*% fossil fuels*
SO_2	94	3	*3%*		92	74	*81%*
NO_x	132	16	*12%*		116	102	*88%*
$PM_{2.5}$	98	57	*58%*		41	20	*50%*
CO	993	453	*46%*		541	195	*36%*
VOC	140	28	*20%*		113	40	*36%*
NH_3	61	7	*11%*		54	1	*2%*

Note: non-fire natural sources (dust, sea salt, volcanoes) are not included.

In the rest of this section, pollutants emissions from fires and natural sources are not considered as they are not influenced by the mitigation options considered; their effect is taken into account in section 6.

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(53) Health benefits from changes in air quality accrue several years after mitigation (see Section 6.3).

Definition of the air pollution cases investigated

Over time, an increasing number of countries around the world are expected to adopt more stringent air quality standards; for example, China is implementing transport emission standards (54) equivalent to Euro 6/VI currently in place in Europe (55). Thus, emissions of pollutants are expected to grow less than their underlying fuel use or economic activity levels, and might even decrease. Pollutant emissions are also affected by adopted or planned climate policies that target GHG emissions and type of fossil fuel use.

The air quality policies and pollution control cases are characterized in GECO2017 by different evolution of the emission intensity factors (the ratio between the emission levels and the relevant emission driver). The cases are:

- **FROZ**: The frozen case with high pollution levels. It keeps the last available observed emission intensity factors constant over time ("frozen" policies and technological diffusion at 2010 values).
- **PROG**: a progressive "middle-of-the-road" trajectory of emission intensity factors, between FROZ and the maximum technically feasible reduction case (MTFR). In particular, certain specific policies for the medium term were included: the China objectives for 2020 (56) and the EU objectives for 2030 (57). The methodology by country group for this case is represented in Table 13.
- **MTFR**: The maximum technically feasible reductions are achieved through the full use of the best available technologies in a future year (58). This pollution control case has been used to calibrate the PROG case.

Each of these sets of air quality assumptions (which act on air pollutants emissions) can be combined with climate policies (which act on the energy system and greenhouse gas emissions) to obtain complete scenarios.

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(54) China started to introduce the China 6/VI standards in 2017 and with full implementation on new cars in 2020.

(55) Europe applies the Euro 6 for light vehicles (since 2016) and Euro VI for heavy vehicles (since 2015), see: http://ec.europa.eu/environment/air/transport/road.htm

(56) China 13th Five-Year Plan

(57) EU Clean Air Package (Directive 2016/2284/EU), see: http://ec.europa.eu/environment/air/pollutants/ceilings.htm

(58) The evolution of emission intensity factors by country group and across time is similar to the method in Rao et al. (2016).

Table 13: Evolution of pollutant emission intensity factors

Scenario	Region income group	2030	2050
FROZ	All	2010 emission factor	2010 emission factor
PROG	High	Current legislation	75% of 2030 best feasible emission factor
	Medium +	Current legislation	75% of 2030 best feasible emission factor
	Medium -	Current legislation	Convergence to group's best emission factor
	Low	Current legislation	Convergence to group's best emission factor

Note: Current legislation refers to policies adopted in 2015, except EU: 2016 (EU: Directive 2016/2284/EU, China: China 13th Five-Year Plan; Rest of world: see IIASA (2017). Income groups defined following World Bank methodology for 2015 per capita income (59): low (<1 k$/cap); medium- (1-4 k$/cap); medium+ (4-12 k$/cap); high (>12 k$/cap).

For instance, Figure 66 illustrates the potential of co-benefits with different combinations of air quality and climate control policies as defined in Table 13, in this case for SO_2 emissions, for which the co-benefits are most notable. The pollutant emissions profile with climate action and no targeted effort on air quality (B2°C-FROZ) is similar to that of no climate action combined with air quality policies (Reference-PROG) from 2030 onwards. The lowest SO_2 levels are reached when climate action and air quality policies are combined (B2°C-PROG).

Figure 66: World SO_2 emissions under different policy assumptions

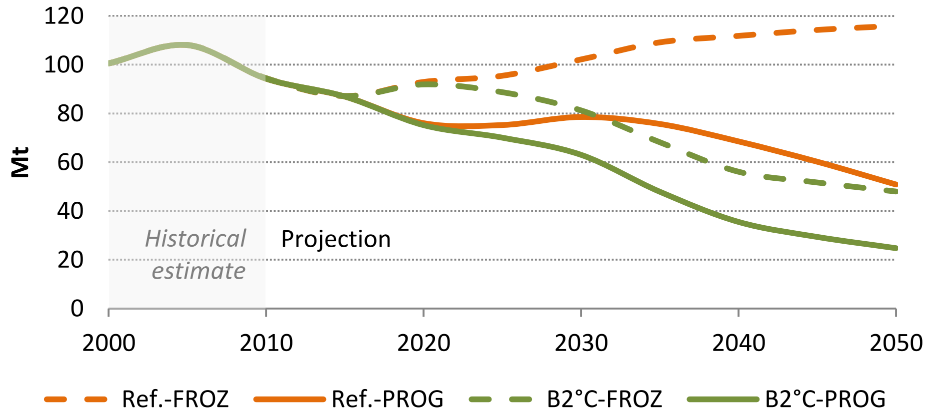

Table 14 presents the contribution of climate policies to air quality for all pollutants considered, comparing the level of pollutant emissions under different air quality control policies and climate policies combinations.

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(59) https://datahelpdesk.worldbank.org/knowledgebase/articles/906519

Table 14: Contribution of climate policies to air pollutants emissions, World (Mt)

a) 2030

	2015	Ref.-FROZ	B2°C-FROZ	B2°C-PROG	% achieved by climate policies
SO_2	85	100	76	58	59%
NO_x	118	149	127	94	39%
$PM_{2.5}$	46	53	47	44	62%
VOC	117	155	150	133	24%
CO	566	634	599	497	26%
NH_3 *	58	68	55	55	100%

b) 2050

	2015	Ref.-FROZ	B2°C-FROZ	B2°C-PROG	% achieved by climate policies
SO_2	85	114	46	24	76%
NO_x	117	172	104	59	60%
$PM_{2.5}$	43	53	42	24	38%
VOC	117	200	177	121	30%
CO	560	633	493	278	39%
NH_3	58	78	45	36	77%

Note: Fires and other natural sources are not included. "Ref." and "B2°C" refer to climate policies; "FROZ" and "PROG" refer to air pollution control policies. "% achieved by climate policies" refer to the distance from Ref.-FROZ to B2°C-FROZ compared to the distance from Ref.-FROZ to B2°C-PROG.

**: No pollution control effort by 2030 for NH_3 in the PROG cases.*

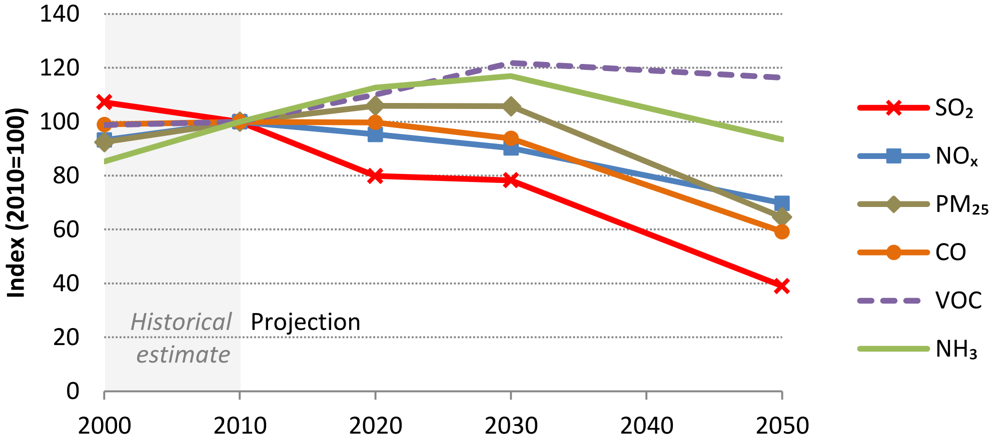
In the remainder of this section, the projected air pollutant emissions are calculated under different climate policies assuming a "progressive" air quality control policy context (PROG). Temperature change projections (section 4.1) used the same assumptions.

The economic assessment in the following chapter (sections 6.3, 6.4 and 0) use a "frozen" air quality control policy context (FROZ), thus focusing on the co-benefits of climate policies on air quality and not on air quality policies' costs.

Emission trends

In the context of INDC climate policies complemented by a moderate diffusion of air quality policies, sulphur dioxide (SO_2) emissions are expected to decrease significantly, nitrogen oxides (NO_x), particulate matter ($PM_{2.5}$) and carbon monoxide (CO) are expected to decrease more moderately, while ammonia (NH_3) emissions would continue growing moderately until 2030 and then decrease and volatile organic compound (VOC) emissions would grow until 2030 and then stabilize (Figure 67).

Figure 67: Evolution of pollutants emissions, World, INDC scenario (PROG air quality)



Note: Excludes emissions from fires and natural PM.

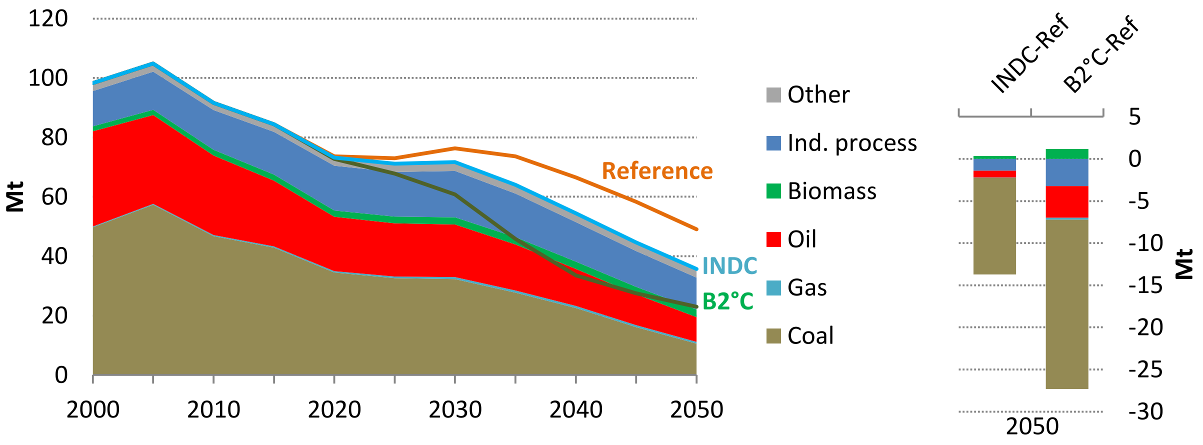
The sectoral decompositions of the pollutant emissions as well as the co-benefits of the climate policies (see section 4) are explored below.

5.1.2 SO_2 emissions

In OECD countries, SO_2 emissions, one of the main causes of acid rain, have been the subject of strict policies since the 1970s and 1980s; as a consequence, emissions have decreased significantly since the 1990s. In non-OECD countries, strong economic growth has led to a sharp rise in SO_2 emissions which has resulted in the development of air quality policies in many countries over the past decade. Strong air quality control policies in Asia have succeeded in decreasing emissions. In China, SO_2 emissions in 2015 were 28% lower than in the peak year of 2006 ([60]). This drop is expected to continue as more stringent air quality policies are implemented and flue gas desulfurization is applied to more and more existing and future coal- and oil-fired power plants, which are the main emission sources, in China and elsewhere ([61]).

In this context, global SO_2 emissions in the INDC scenario are expected to drop by about 20% and 60% compared to 2010 by 2030 and 2050, respectively (Figure 68).

Figure 68: Volumes and sources of SO_2 emissions of progressive air quality policies (PROG), World, for three climate scenarios (left), and contributions to reductions compared to the Reference scenario in 2050 (right)



Note: Other includes solvents, agriculture, waste. Fires are not included.

The co-benefits of climate policies compatible with remaining below a 2°C temperature rise on SO_2 emissions are large: SO_2 emissions halve in 2050 compared to Reference climate policies, essentially thanks to decreased coal use in power generation, industry and households. SO_2 emissions related to an increased use of biomass are relatively small and easily offset by other SO_2 reductions (2 Mt additional for a net total decrease of 25 Mt from the Reference scenario to the B2°C scenario).

([60]) Sources: reports on the State of the Environment in China (MEP 2015) and China Statistical Yearbooks (NBSC 2016).

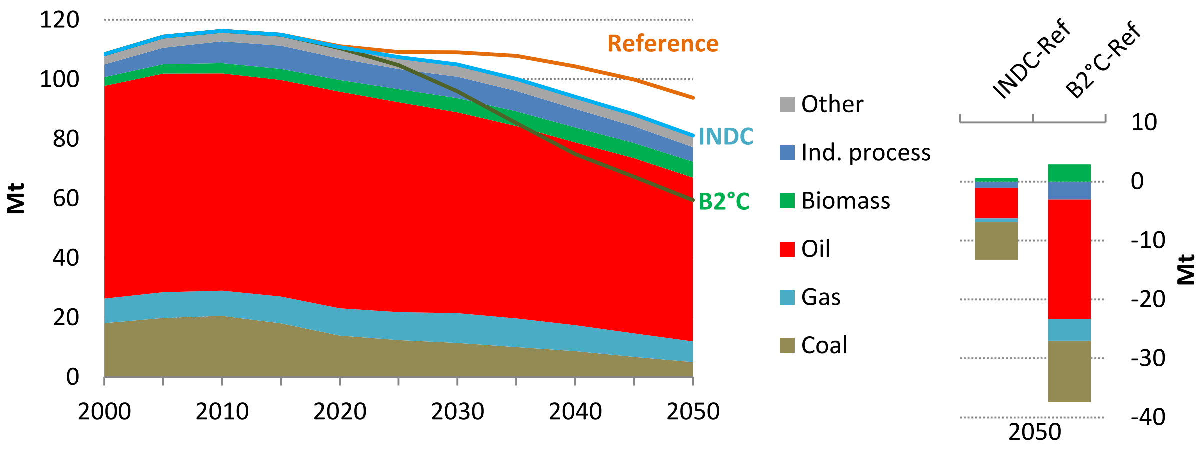
([61]) The removed SO_2 can then be used in the sulphuric acid production industry, e.g. as an input in fertilizer and other chemicals production.

5.1.3 NO_x emissions

NO_x emissions have been subject to numerous regulations due to their direct health effects (particularly with road traffic exposure in dense urban centres), its role in ground-level ozone chemistry, as well as cause of acid rain. The spread of catalytic converters to treat road vehicles exhaust gases since the 1980s, notably, has helped reduce these emissions. Nevertheless, half of current NO_x emissions still come from oil combustion in road transport vehicles and international marine bunkers.

The introduction of stricter vehicle emissions regulations (all scenarios) should result in a decrease of total NO_x emissions worldwide compared to its maximum level of the years around 2010, despite increasing mobility needs particularly in emerging economies. With the announced INDC climate policies, global NO_x emissions would drop by an additional 10% and 30% compared to 2010 by 2030 and 2050, respectively (Figure 69).

Figure 69: Volumes and sources of NO_x emissions of progressive air quality policies (PROG), World, for three climate scenarios (left), and contributions to reductions compared to the Reference scenario in 2050 (right)



Note: Other includes solvents, agriculture, waste. Fires are not included.

NO_x emissions would decrease significantly with ambitious climate policies, due to a further decrease of coal use (power plants) and of oil use especially in road transport (internal combustion engine efficiency, electric vehicles) and maritime (see section 3.1.2.3). A shift towards large-scale biomass power generation in the B2°C scenario would result in a relatively small additional amount of NO_x emissions from biomass, similar to what would happen with SO_2 emissions. NO_x emissions could decrease up to 50% compared to the 2010 level by 2050 with policies aiming at staying below a 2°C temperature increase alone.

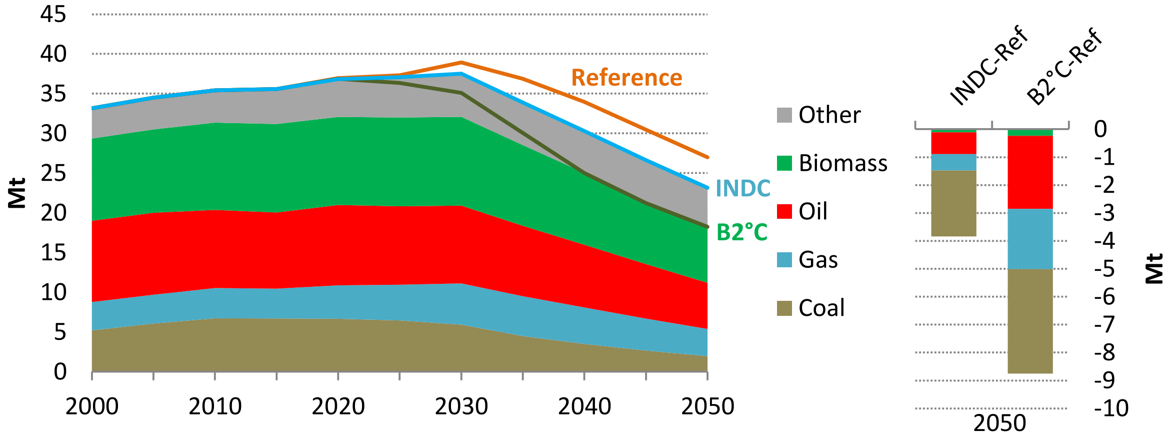
5.1.4 $PM_{2.5}$ emissions

Fine particulate matter (PM) emissions have significant health impacts; as such, they are the subject of increasingly stringent air quality control policies, for example with fuel quality standards for road transport fuels. Certain PMs also have a climate impact (black carbon), even though they are short-lived species. This study focuses on $PM_{2.5}$, for which the long-term health and mortality effects are more significant ([62]).

With certain $PM_{2.5}$ emissions excluded (such as natural sources and fires), combustion of energy fuels (in particular biomass use in households, oil use in road transport and coal use in power generation and industry) as well as industrial processes are then the most important sources for PM emissions.

Given the fuel substitutions taking place in the energy sector with the implementation of INDC climate policies along with the adoption of pollution control technologies and the progressive phasing out of heavily polluting traditional biomass use in households, the emissions of $PM_{2.5}$ would increase at a slow rate until 2030 (slightly higher than the 2010 level) and decrease thereafter, to about 30% lower than the 2010 level in 2050 (Figure 70).

Figure 70: Volumes and sources of $PM_{2.5}$ emissions of progressive air quality policies (PROG), World, for three climate scenarios (left), and contributions to reductions compared to the Reference scenario in 2050 (right)



Note: Other includes solvents, waste, industrial processes. Fires are not included.

Changes in the energy mix induced by more ambitious climate policies bring about large co-benefits on $PM_{2.5}$ emissions reduction, with lower coal, gas and oil consumption. Regarding biomass, its consumption would increase in particular as a power sector input (where PM pollution control technologies are more easily implemented). At the same time, however, biomass use in households would decrease globally (due to the combined effect of reduced use of traditional biomass and increased thermal efficiency), even though it could increase locally. As a consequence of this trade-off, global $PM_{2.5}$ emissions from biomass use do not increase in the B2°C scenario. Across all fuels, staying below 2°C would entail a peaking of $PM_{2.5}$ emissions in 2020 and decrease thereafter to -40% in 2050 vs. 2010.

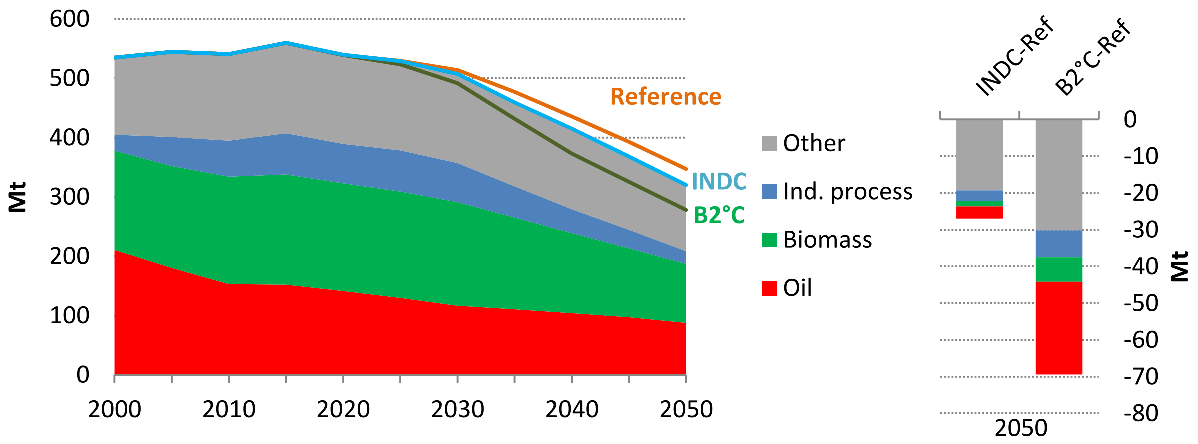
([62]) For instance, the World Health Organization estimates the impacts on mortality up to 20 times higher for PM2.5 as compared to PM10 (WHO, 2013).

5.1.5 CO emissions

Carbon monoxide (CO) is a short-lived chemical that can be a health hazard in indoor pollution and plays a role in road traffic pollution in urban areas. Emissions from fires excluded, combustion of biomass (households) and oil (road transport) as well as industrial processes are the most important CO emissions sources.

CO emissions would plateau and then decrease from current levels, given fuel substitutions in the energy mix induced by the INDC policies, the phase-out of heavily polluting traditional biomass in households and the deployment of pollution control technologies. By 2050, they would be 40% lower than the 2010 level (Figure 71).

Figure 71: Volumes and sources of CO emissions of progressive air quality policies (PROG), World, for three climate scenarios (left), and contributions to reductions compared to the Reference scenario in 2050 (right)



Note: Other includes coal, gas, solvents, agriculture, waste. Fires are not included. Coal makes up most of the "other" reductions.

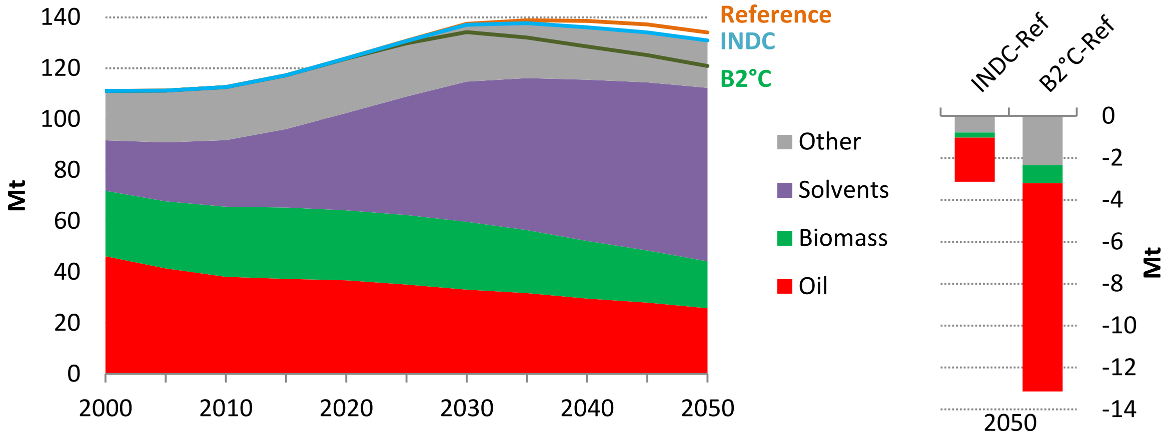
Ambitious climate policies reduce further CO emissions. Total CO emissions from biomass decrease overall as a result of the phase-out of traditional biomass use in households and despite biomass being used more associated to technologies with more controlled combustion (in the power sector, in industry and in households). Engaging in policies compatible with staying below 2°C would lead CO emissions to reduce by 50% between 2010 and 2050.

5.1.6 VOC emissions

Certain species of VOCs (Volatile Organic Compounds) have significant health impacts and are strongly regulated (indoor exposure via paints, cleaning products and other chemicals). The future evolution of VOC emissions is strongly linked to industrial processes and solvents production, as VOC emissions from oil and biomass would decrease over time in all scenarios. Emissions from solvents are assumed this analysis to be driven in by the evolution of chemical industry value added, and would come to represent half of VOC emissions by 2050, compared to about a 20% today.

As a consequence, total VOC emissions would continue growing at a slow rate, reaching a peak in 2030. 2050 emissions would be between 10% and 20% higher than 2010 emissions, depending on climate policies (Figure 72).

Figure 72: Volumes and sources of VOC emissions of progressive air quality policies (PROG), World, for three climate scenarios (left), and contributions to reductions compared to the Reference scenario in 2050 (right)



Note: Other includes coal, gas, agriculture, waste, industrial processes. Fires are not included. Industrial processes make up most of the "other" reductions.

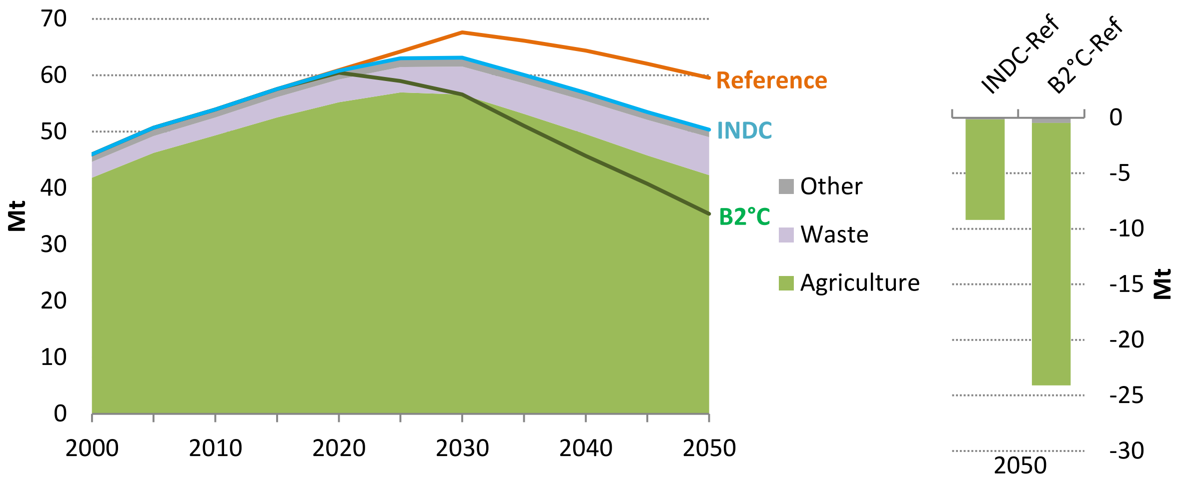
Climate policies would have a certain impact due to the decrease of oil use, but the bulk of VOC emissions (not related to energy use) would remain.

5.1.7 NH_3 emissions

NH_3 emissions are responsible for water eutrophication and soil acidification. They originate almost entirely from the agriculture sector (from animal waste treatment and from the use of nitrogen-based fertilizers) but with some contribution also from road transport (as a result of steam reforming and/or reaction with NO_x at the vehicles' catalysts, especially in gasoline). Their evolution is thus mainly driven by food production and climate mitigation measures in the agriculture sector.

In an INDC context NH_3 emissions would peak in 2030, with an increase by 10% above 2010 levels, before decreasing in 2050, to about 10% below 2010 emissions (Figure 73). Agriculture emissions would still constitute the bulk (about 80%) of NH_3 emissions throughout the time period of the projections.

Figure 73: Volumes and sources of NH_3 emissions of progressive air quality policies (PROG), World, for three climate scenarios (left), and contributions to reductions compared to the Reference scenario in 2050



Note: Other includes coal, gas, oil, biomass, solvents, industrial processes. Fires are not included. Coal and oil make up most of the "other" reductions. Waste refers to solid waste and wastewater; animal waste management and agricultural waste burning are accounted for in agriculture.

With changes in the agriculture sector triggered by ambitious climate policies (63) compatible with staying below 2°C, NH_3 emissions would be further reduced, peaking as early as in 2020 and reaching a level in 2050 that would be about 30% below the 2010 level.

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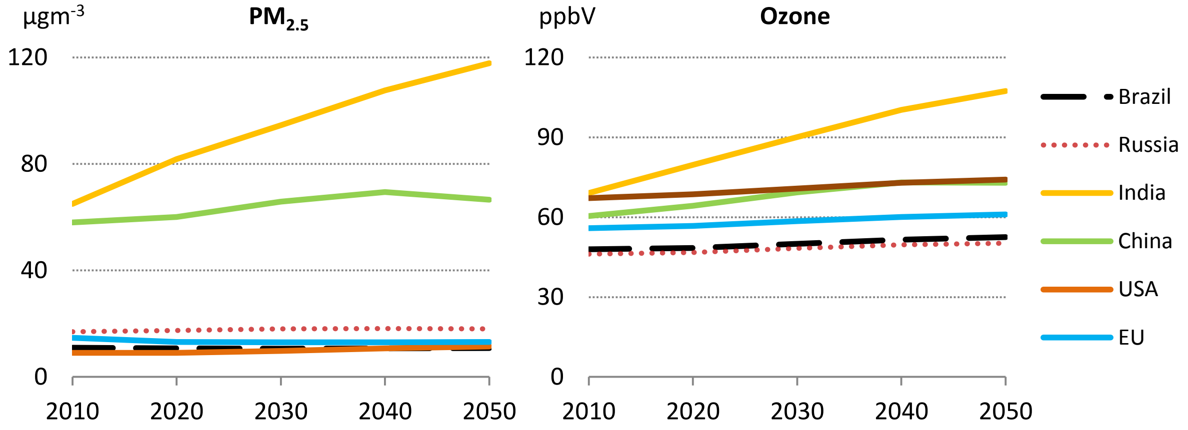
(63) Derived from the GLOBIOM model; see footnote 40 and IIASA (2016) and Havlík P. et al. (2014).

5.2 Air pollutant concentrations

The emissions of air pollutants described in the previous section are transported with atmospheric convection and dispersion and are involved in chemical reactions in the atmosphere, resulting in atmospheric concentrations of particulate matter and ozone. The Reference concentrations ([64]) are shown in Figure 74.

Figure 74: Concentrations of $PM_{2.5}$ (left) and ozone (right) in the Reference climate policy and frozen air pollution controls policy



Primary $PM_{2.5}$ includes emissions of black carbon and organic matter, but also natural sources such as sea salt and dust contribute to particulate matter concentrations. Emissions from these natural sources are kept fixed across scenarios to restrict improvement in air quality to climate policies. In addition, secondary particulate matter forms via chemical reactions of SO_2, NO_x, NH_3, and VOCs, the so-called precursor gases. The composition of particulate matter can differ across time and space, and so can the toxicity and corresponding health impacts. In this report, we assume the same toxicity across all components of PM, and constant toxicity over time and space.

Tropospheric or ground-level ozone forms when VOC, CO, NOx, react in the presence of sunlight. Ground-level ozone forms through photochemical reactions and should not be confused with stratospheric ozone, commonly known as the ozone layer absorbing ultraviolet (UV) radiation from the sun.

Mapping the air pollutant emissions to concentrations of particulate matter with diameter smaller than 2.5 µm ($PM_{2.5}$) and ozone was done taking into account transportation and chemical reactions in the atmosphere ([65]). The resulting reductions in concentration of $PM_{2.5}$ and ozone due to climate policies are shown in Figure 75 for both the INDC scenario and the B2°C scenario.

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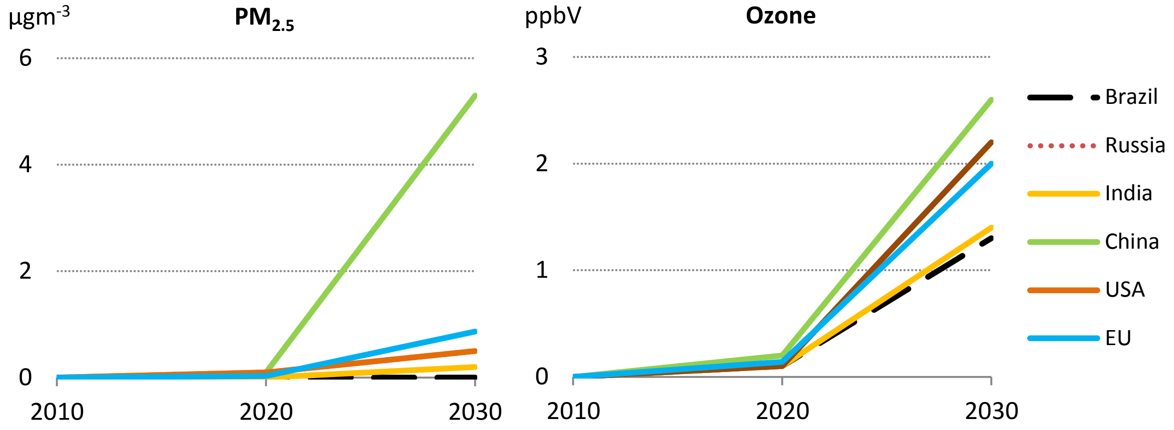
[64] under "FROZ" air pollution controls.

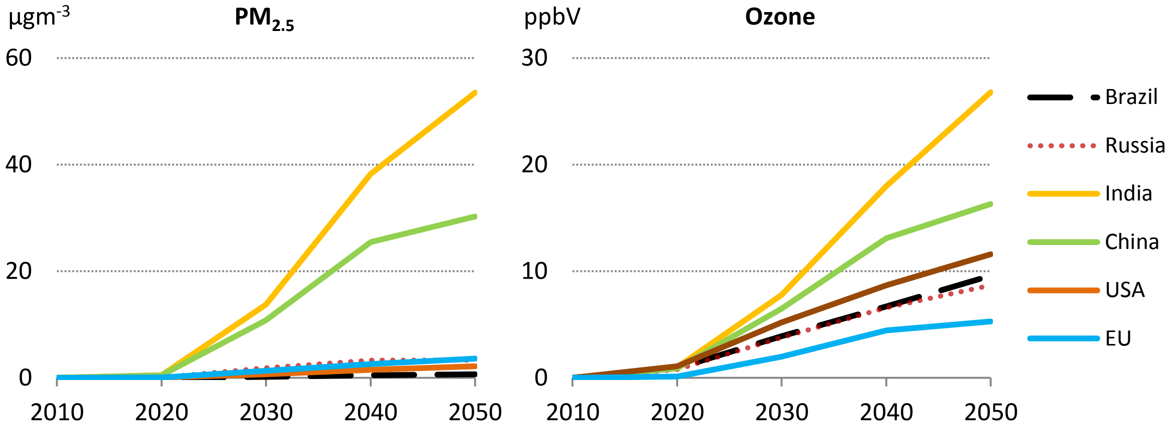
[65] done by using the TM5-FASST model, which is described in more detail in Annex 3.

Figure 75: Reductions in $PM_{2.5}$ (left) and ozone (right) concentrations compared to Reference (under Frozen air quality policy) in key regions as a consequence of climate policies

a) as a consequence of INDC climate policies



b) as a consequence of B2°C climate policies

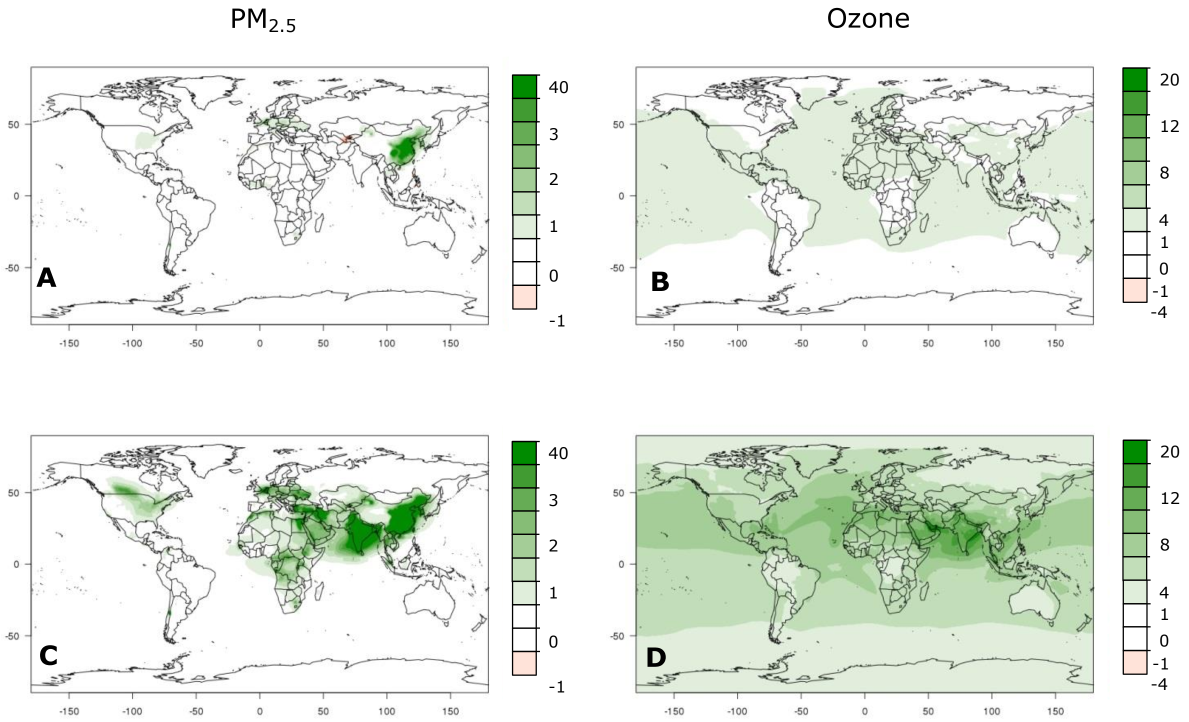


INDC policies result in only a moderate reduction of PM2.5 and ozone concentrations across world countries and only after 2020 (most notably a 8% reduction in PM2.5 concentrations in China in 2030, among others driven by the effect of climate policies on coal use). The small changes in India are due to the lack of ambitious climate action in the INDC scenario.

Co-benefits are larger with ambitious climate policies (B2°C), with a near-three-fold higher effect in concentration reductions in many countries by 2030 and increasing further beyond. In this case, $PM_{2.5}$ concentrations nearly halve and ozone concentrations decrease by nearly a quarter in India and China in 2050 compared to a Reference with no new climate, energy or air pollution policies. In high-income regions such as the EU and the USA, the B2°C climate action brings annual average concentrations of $PM_{2.5}$ in line with the WHO (2005) guideline of 10 μgm^{-3} in 2050.

The improvements in air quality are mapped in Figure 76.

Figure 76: Global improvement in air quality due to climate change policies in the INDC scenario in 2030 (A,B) and B2°C in 2050 (C,D), for $PM_{2.5}$ (μgm^{-3}) and ozone (ppbV)



These improvements in air quality can have substantial benefits for human health, which are assessed in the section 6.3.

6 Economic assessment and climate – air quality policies synergies

This section looks into the economic aspects of climate change mitigation and air quality co-benefits. The first section quantifies the investments related to the transition in the energy system. Next, the macroeconomic costs of climate change mitigation policies are discussed. Section 6.3 addresses the benefits of reduced air pollution in terms of avoided premature deaths, reduced illness and agricultural productivity, while Section 6.4 presents the corresponding macroeconomic view. A direct comparison of climate change mitigation costs with air quality co-benefits is presented in Section 0. Finally, an important complementary line of research on the impacts of changing climatic conditions is discussed.

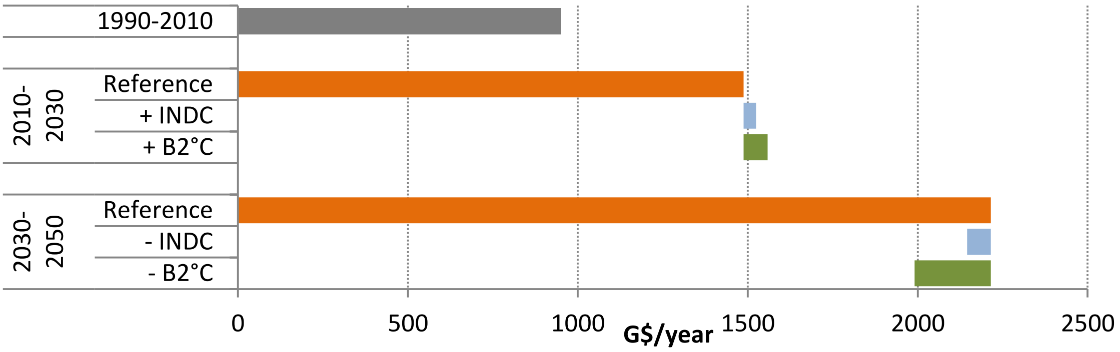
6.1 Energy system costs

6.1.1 Investment in energy supply

The total investments ([66]) required in the energy sector for supply and energy transformation (fossil fuel production, power, hydrogen, biofuels) would reach 30 trillion dollars (tn$) over 2010-2030 (1.5 tn$/year on average) and 43 tn$ over 2030-2050 (2.2 tn$/year on average) (INDC scenario), compare

d to 19 tn$ invested over 1990-2010 (0.9 tn$/year on average), see Figure 77. Energy supply and transformation investments would still represent about 7% of total investment levels of the economy throughout the projection period (that share was about 7-8% over 1990-2015) ([67]).

Figure 77: Average annual world investment in energy supply and transformation



The expected investment needs in the energy sector are increasing over time to sustain growing energy needs, most notably in non-OECD regions, as well as a shift towards capital-intensive production means in the power sector and more expensive fossil fuel production.

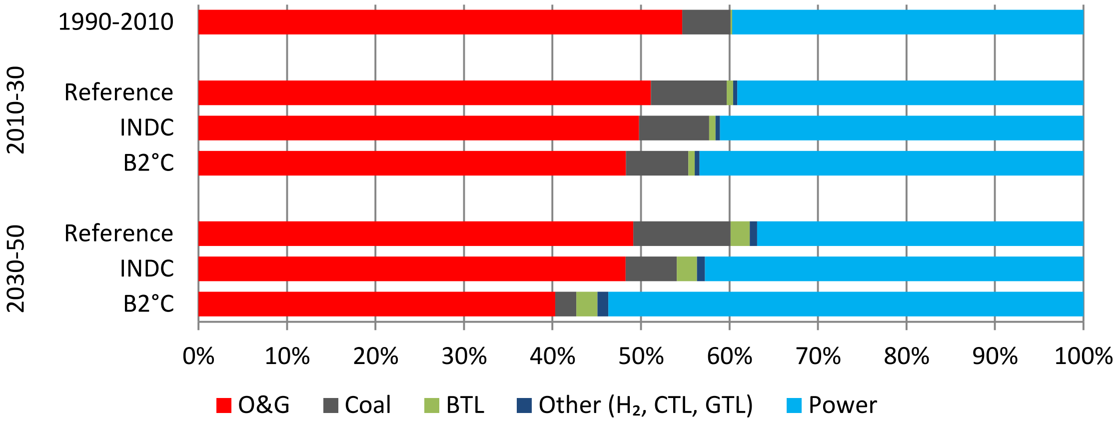
Figure 78 shows the distribution of these investments by supply and transformation sector. Over the 2010-2030 period total investment costs are similar across scenarios, with slightly higher totals as more stringent climate policies are applied (30-31 tn$ depending on the scenario). With stronger climate policies, the share of the power sector in total energy investments increases (and that in fossil fuels decreases): this reflects the transition towards a low-carbon energy system, with a stronger electrification of the final energy mix and a more capital-intensive power production cost structure.

([66]) Investment volumes in this report are given in real USD of 2015, non-levelized.

([67]) Historical figures are gross capital formation from World Bank (2017); projections used the GEM-E3 model (see Annex 2).

Beyond 2030 there is greater difference between scenarios, driven by a reduced energy demand that lowers the needs in supply and transformation when ambitious climate policies are in place. Investments range 40-44 tn$ over the 2030-2050 period, i.e. an 11% difference between Reference and B2°C scenarios. The shift away from fossil fuels to the power sector accelerates after 2030.

Figure 78: World investment in energy supply and transformation, shares



Note: BTL: biomass-to-liquids, H2: hydrogen, CTL: coal-to-liquids, GTL: gas-to-liquids.

These investments refer to the energy supply and transformation sectors. They do not, however, represent the total investments in the energy sector since they do not include investments in transmission infrastructures nor in the energy demand sector to improve the efficiency of consuming equipment (in transport, industry and buildings) and to improve insulation in buildings. In particular, additional investments in more energy efficient building envelopes over 2015-2050 could reach 19 tn$ globally in the scenarios with climate policies, rising in importance over time and amounting to around half the total investment needs in the power sector or around a third of the total investment needs in energy supply and transformation by 2050 (68).

Investment in the power sector

Global investments in new power capacities are projected to rise in all scenarios, as the global electrification trend is expected to occur in all three scenarios (Figure 79). Investments during the 2010-2020 decade are already expected to be 50% higher than those made in 2000-2010. Climate policies favour technologies with higher capital costs and lower operating (fuel) costs; as a result, investments are higher in the INDC and B2°C scenarios. Cumulated total investments over 2015-2050 are 10% and 25% higher than in the Reference scenario, respectively. Over the 2015-2030 period, investments are expected to range from 8.6 to 10.5 tn$. As a result, investments in power production are a larger share of total investments in energy supply with stronger climate policies.

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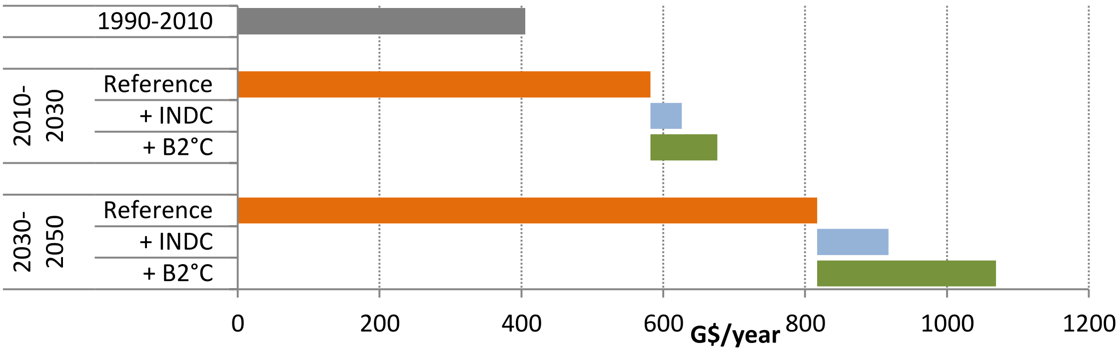
(68) These figures are comparable to IEA figures for investments over 2015-2040 in buildings (10 tn$) compared to power generation (15 tn$, excluding T&D) (IEA, 2015). Note that the situation in the EU would be different, as the EU exhibits higher demand-side investments due to higher building insulation needs because of its colder climate, as well as less power sector investment needs due to a more moderately increasing power demand (EC, 2016).

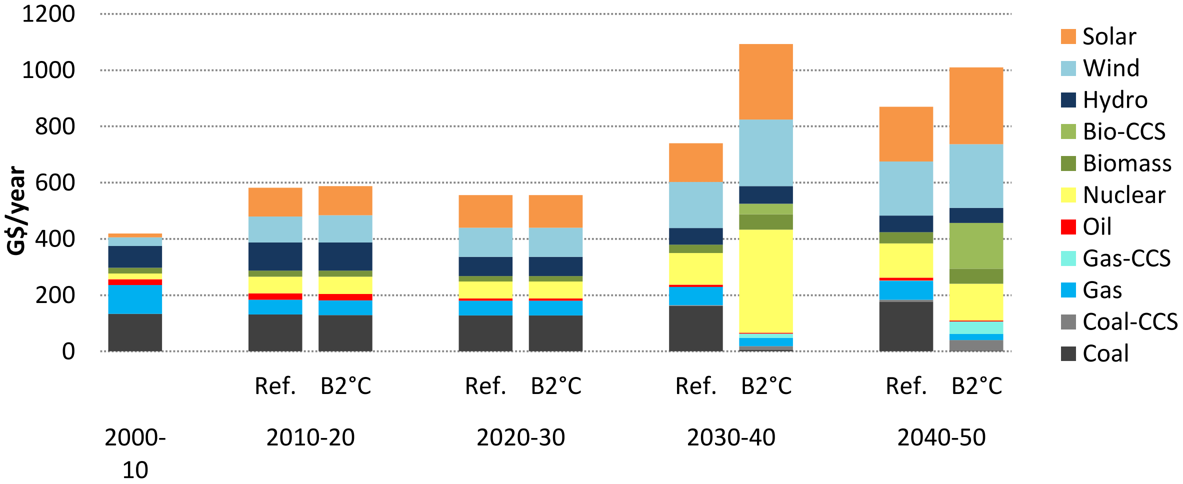
Figure 79: World investments in power generation capacities



In all scenarios, the deployment of renewables increases over time, and this trend would be further enhanced in the framework of ambitious GHG mitigation policies: most investments go to solar and wind, followed by nuclear and CCS technologies (coupled with coal, gas or biomass), as shown in Figure 80.

On the other hand, while coal would attract for some time the largest investments without climate policies (followed by wind and solar), it would almost disappear from the investment landscape in the B2°C scenario, despite the deployment of CCS.

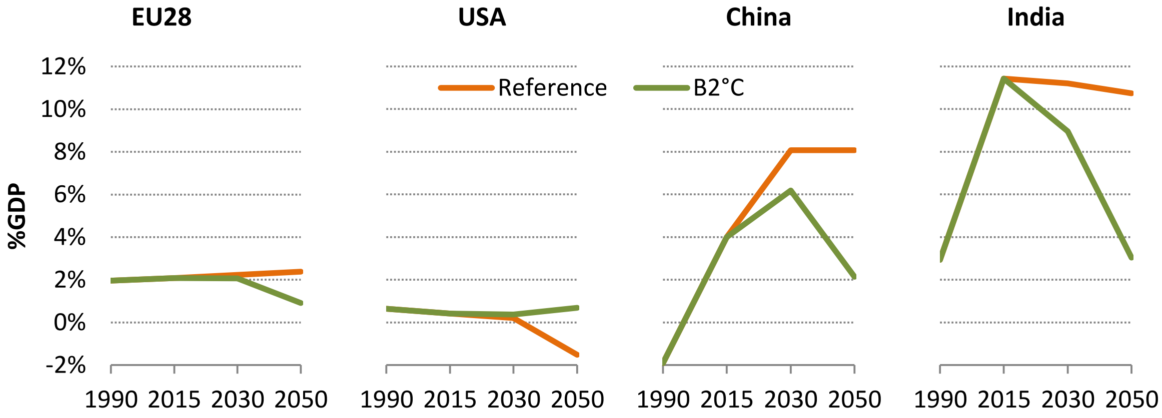
Figure 80: World investments in power generation capacities per technology



6.1.2 Energy trade costs

World energy trade would intensify in the future in all scenarios, with regional differences in the structure of exporters and importers over time and across scenarios (Figure 81). Changes in energy demand and energy efficiency with ambitious climate policies would limit this growth: the value of total international energy trade in the 2040-50 decade compared to the 2010-20 decade could be multiplied by a factor of as much 3.5 in the Reference scenario, and only grow by 20% in the B2°C scenario. Lowering the domestic consumption in relative terms and relying more on local renewable energy resources would contribute to mitigate the external energy bill and improve indicators on security of supply.

Figure 81: Total net energy trade as a percentage of GDP, Reference and B2°C scenarios (69)



Note: Includes trade of oil, gas, coal and solid and liquid biomass.

Energy trade entails a financial burden to energy importing countries that amounts to a significant percentage of those countries' economies. Importing countries would experience different trends in their energy import bill as the result of their own domestic demand and international prices. Ambitious climate policies significantly contribute in limiting energy import expenditure. The EU's import bill would remain over the period on average at about 2% of the region's GDP, as observed since 1990 (70), or progress towards zero in the B2°C scenario. In the Reference scenario, the USA would move towards becoming a net energy exporter (mostly due to gas and coal exports). China would experience a strong growth in energy import expenditure by 2030, in volume and as a share of its GDP, but it would be able to reverse that trend over the long term with ambitious climate policies.

6.2 Greenhouse gas mitigation and macro-economic growth

This section presents an estimate of the macroeconomic cost of the climate change mitigation policies in line with Section 4 with the JRC-GEM-E3 model. Here, climate policies are implemented via a stylized cap-and-trade system, with emission permits grandfathered in all sectors (71). Government budget deficits relative to GDP are kept at the levels of the Reference through lump sum transfers to households.

The policies in the INDC scenario are consistent with robust economic growth, and only marginally affect annual GDP growth rates for several regions between 2020-2030 (Table 15). On a global level, GDP growth remains roughly stable compared to the Reference levels with annual growth rates at approximately 2.75% in the INDC scenario for the 2020-2030 period.

The results for the B2°C scenario indicate that more ambitious GHG emission reductions typically require stronger economic efforts to transition to a low-carbon system. Importantly, lower-income countries such as India and China continue to experience sustained economic growth comparable to Reference projections, even in the B2°C scenario.

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(69) Trade volumes are in real USD of 2015; shares of GDP were calculated with volumes using GDP MER.

(70) The cost of energy imports, and most notable of oil imports, depend on the oil price and can fluctuate significantly in the short term: for instance while oil imports represented close to 1.5% of EU GDP over 1990-2015 on average, it ranged from 0.5% in 1998 to 2.8% in 2011.

(71) Except the European power sector where the permits are auctioned, following the legislation in place.

Table 15: Annual GDP growth rates (%) under different climate policy scenarios

	2020-2030		
	Reference	**INDC**	**B2°C**
World	2.77	2.75	2.73
World (PPP)	3.54	3.52	3.49
EU28	1.36	1.36	1.35
USA	1.94	1.92	1.92
CHN	4.96	4.91	4.86
IND	6.60	6.60	6.55
RUS	2.05	2.05	1.90
BRA	2.66	2.66	2.63
CAN	1.99	1.99	1.98
JPN	0.91	0.91	0.89
AUS	2.63	2.63	2.62
NAM	3.97	3.96	3.87
UBM	3.33	3.34	2.38
RET	2.65	2.65	2.62
ROW	4.18	4.16	4.11

Note: Growth rate of GDP expressed in MER ($2005) unless indicated otherwise. NAM: North Africa and Middle East; UBM: Ukraine, Belarus and Moldova; RET: Rest of Europe (EFTA, Balkans, Turkey); ROW: Rest of the world. See Table 20 in Annex 2 for the definition of acronyms. The GDP growth rates of the Reference are based on exogenous projections as explained in Section 2.1.

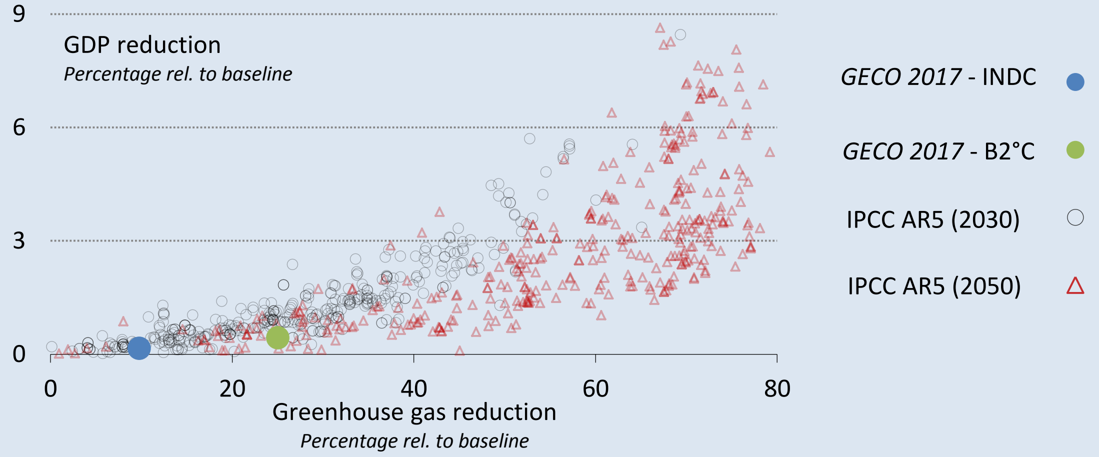
Interpreting the costs of mitigation

Importantly, the results presented here do not include the (avoided) impacts of changing climate conditions such as sea level rise or heat-related mortality (see section 6.6) or associated co-benefits (see section 6.3 for an analysis of co-benefits on avoided air pollution), but rather focus on the cost side of greenhouse gas abatement alone. The approach adopted here uses the Computable General Equilibrium (CGE) model JRC-GEM-E3 (see Annex 2), an economy-wide sectoral model with global coverage. This type of models is based on the assumption of long-term full rationality of optimising agents: welfare-maximising households and profit-maximising firms in each region. Consequently, this modelling set-up per definition implies that imposing restrictions on the economic system (e.g. a limit on greenhouse gases) leads to negative economic impacts if not compensated for by improvements in other market imperfections (e.g. externalities, spill-overs, and incomplete information) or lowering economic distortions (e.g. taxes and subsidies). Therefore, CGE models are widely used to assess the cost side of climate and energy policies, and are useful tools to compare results across scenarios and regions. Section 6.6 provides an overview of research on the impacts of climate change and discusses the costs of inaction, which are not covered in this section. The macroeconomic costs of mitigation via land use, land use change and forestry is not covered here.

Studying a time horizon longer than 30 years comes with substantial uncertainty from various sources in addition to inherent political uncertainty – which are not just limited to the CGE methodology. A first category relates to **methodological** issues. Input-output data for one historical year is the basis to project economic structure into the future. Although we capture some dynamics in sector composition of the economy, such as a shift to service sectors typically observed in the development stages of a country, this approach may introduce some rigidities (e.g. the breakthrough of totally new sectors or inter-sectoral interactions). Second, climate policy may unlock **technological advances** by providing finance streams and by shifting long-term strategic investments in the private sector. Ambitious climate action endogenously affects technological progress, a feature not captured by the macroeconomic modelling presented in this report. Furthermore, potentially important technologies such as biomass energy with CCS and electric vehicles are not well represented in the version of the JRC-GEM-E3 model used here. In addition, to what extent the falling cost of batteries may facilitate the electrification of the energy system on a large scale is yet to be explored. A third aspect that is important for long-run analyses relates to **behavioural change**. The assumption that future generations behave in the same way as past generations, especially when enjoying increasing income, might prove to be conservative if better information and greater awareness leads to changes in diet, transport use, housing choices and price-responsiveness. Fourth, the cost of climate change mitigation will depend on the specifics of the **policy implementation**. Insofar as current energy use and corresponding emissions arise from distorting policies such as energy subsidies, there could be scope for policy measures enhancing economic growth and reducing greenhouse gas emissions simultaneously (Coady et al., 2017). Auctioning tradeable emission permits or levying carbon taxes raises revenues for the government budget, which can be used to foster economic development, for instance by reducing other (possibly more distortionary and inefficient) taxes. Furthermore, market failures may give rise to an 'energy efficiency gap', indicating that even some energy-saving projects with a positive payoff are currently not undertaken due to a variety of barriers. The abovementioned options are currently not included in the macroeconomic modelling but could change the cost estimate significantly. On the other hand side, reaching emission reduction targets via sector-specific regulation or policies would be more costly than with the assumed economy-wide cap-and-trade system (Aldy et al., 2010). A final point relates to the related work of the scientific community.

It is only fair to acknowledge that the assessment of climate change mitigation costs is a **research field continuously in progress**, as any other scientific area. Figure 82 below present the results presented in this report compared to numerical simulations included in the IPCC's Fifth Assessment Report database (IIASA, 2015). Placing our results in the range of estimates included by the IPCC provides some validation, perspective and context to our work.

Figure 82: The scientific community estimates of mitigation cost



Note: All results shown are global. GECO 2017 results represent the year 2030 and exclude LULUCF emission reductions and corresponding macroeconomic cost.

6.3 Benefits of improved air quality

Climate policies lead to lower emissions and concentrations of air pollutants (see Section 5). Better air quality brings several benefits, of which three main categories are considered here: avoided premature mortality, avoided morbidity (illness costs and labour days lost) and increased agricultural productivity.

To what extent the transition in the energy system will lead to reductions in air pollution will depend on how pollution-intensive activities are in the first place. The differences between a *FROZ* scenario, with air quality controls fixed at 2010 levels, and a *PROG* scenario, in which the stringency of air pollution policies increase over time, are discussed in Section 5.1.1. Because of a lack of information on the costs of air pollution policies in the *PROG* scenario, the remainder of the report focuses on the co-benefits under the assumption of *FROZ* air quality technologies.

In the calculation of health benefits, we do not distinguish between emissions by source, although research indicates that particulate matter deriving from coal combustion is more harmful than from other sources (Thurston et al., 2016).

The impacts of reduced $PM_{2.5}$ and ozone concentrations on a global level are presented below. Currently, the results do not include direct health impacts of NO_2; only indirect effects via the formation of secondary $PM_{2.5}$ and ozone are taken into account.

6.3.1 Global co-benefits

A greenhouse gas trajectory that is consistent with limiting global average temperature change to below 2°C can reduce 'equivalent attributable deaths' ([72]) (referred here simply as **avoided premature deaths**) by nearly 1.5 million cases annually compared to the Reference scenario in the year 2050 (Figure 83 panel A). Already in 2030 under climate action as presented in the INDCs, avoided premature mortality reaches nearly 100,000 excess equivalent deaths. The calculation is based on non-linear exposure-response functions for $PM_{2.5}$ and log-linear functions for ozone as in the Global Burden of Disease study (GBD, 2015). Mortality causes considered here are ischaemic heart disease, cerebrovascular disease (strokes), lung cancer and lower respiratory infections for $PM_{2.5}$, and chronic obstructive pulmonary disease for both $PM_{2.5}$ and ozone.

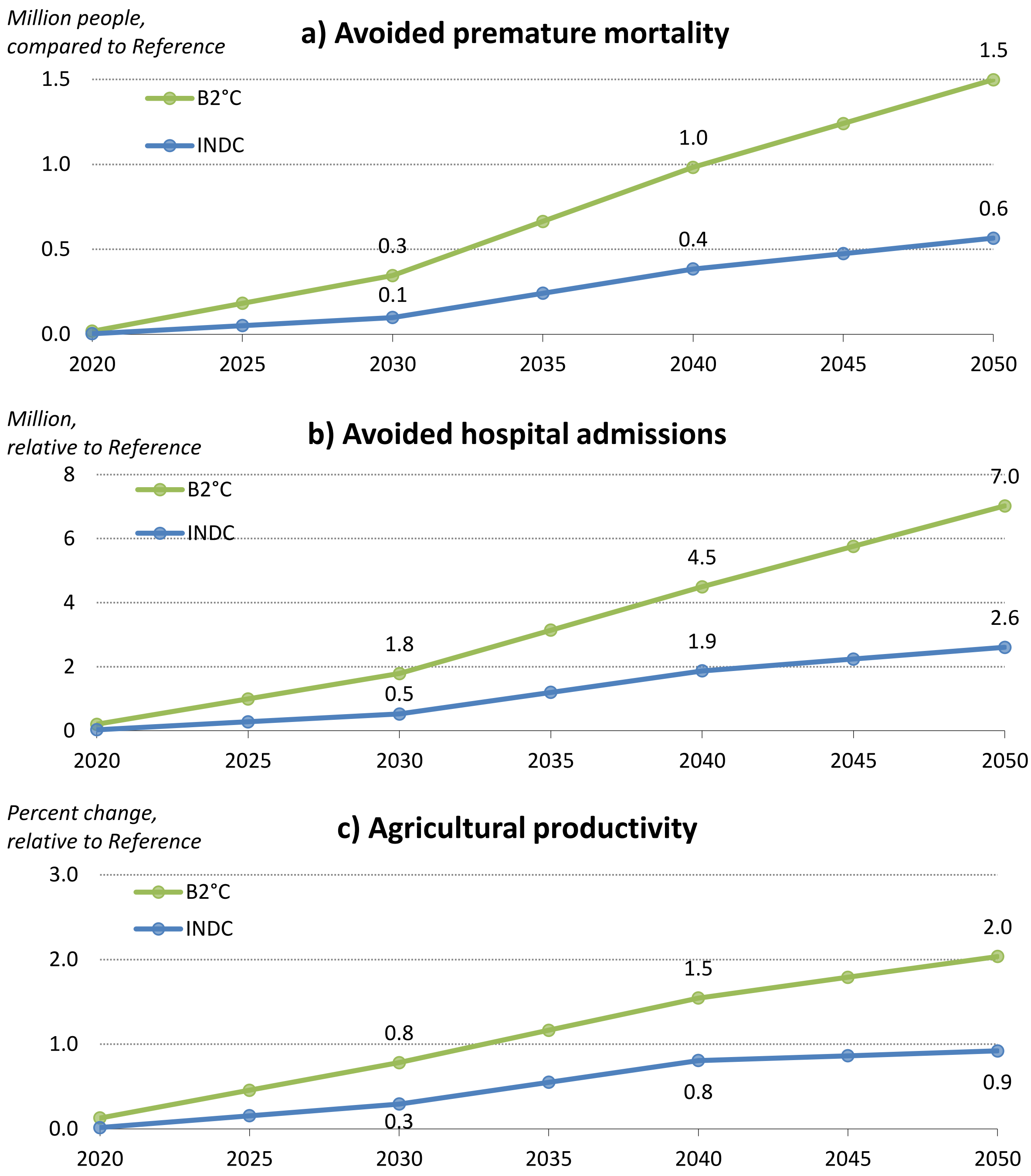
In terms of **morbidity**, better air quality implies a reduction of more than half a million equivalent hospital admissions in the INDC scenario in 2030, and of more than 7 million in the B2°C scenario in 2050, as compared to the Reference scenario. The results presented in Figure 83 (panel B) cover hospital admissions cardiovascular and respiratory illnesses from exposure to $PM_{2.5}$ (in the general population) and ozone exposure (for people aged above 64). In addition, improved air quality also leads to fewer incidences of bronchitis and asthma (children), chronic bronchitis and loss of work days (adults), and reduced number of restricted activity days (across all ages) when ill-health causes someone to change his/her otherwise normal daily routine. The estimated impact on the abovementioned morbidity indicators are calculated by using mortality-to-morbidity multipliers (Annex 4).

Lower concentrations of ozone contribute to better plant growth, improving total **agricultural productivity** by approximately 0.9% and 2.0% globally in 2050 in the INDC and B2°C scenario respectively, compared to the Reference scenario. The effect on productivity in Figure 83 (panel C) is expressed for the total agricultural sector, including livestock and crops for which there is no evidence of the impact of ozone on growth.

([72]) It is wrong to claim (in the majority of cases) that any individual has died from air pollution alone. Air pollution will act with various other stresses on the body (poor diet, lack of exercise, smoking behaviour, etc.) that accumulate as we age and influence life expectancy. Following COMEAP (2010), we interpret estimates of air pollution deaths as 'equivalent attributable deaths': the total number of people whose death is linked to air pollution exposure is likely higher than indicated, but the typical loss of life expectancy for each affected individual attributable to air pollution is likely in the order of months rather than years.

Therefore, the aggregate numbers conceal potentially large effects for certain crops, regions or farms. The relative yield losses are derived from crop-specific exposure-response function using the three-monthly growing season mean of daytime ozone. The crop-specific exposure-response functions for wheat, maize, rice and soy are based on Van Dingenen et al. (2009), while other crops are classified into high, medium and low ozone sensitivity based on Mills et al. (2009). Crops covered represent around 40% of the value of the agricultural sector on a global level (2009-2013).

Figure 83: Global co-benefits due to improvements of air quality as a consequence of climate policy: a) Avoided premature mortality; b) avoided morbidity expressed as hospital admissions; and c) improved total agricultural productivity.



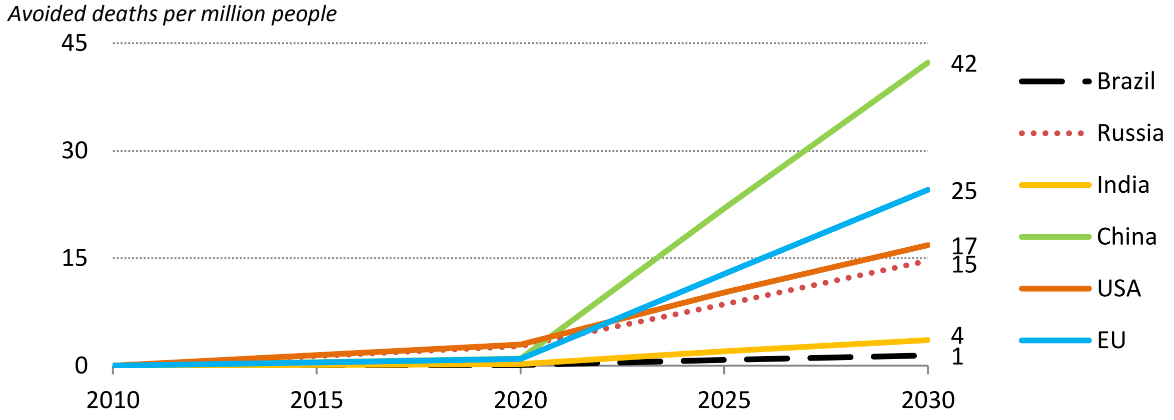
Note: Figures obtained using air pollutant emissions under the assumption of "FROZ" air pollution policy (see Section 5.1.1).

6.3.2 Avoided premature mortality: breakdown by region and pollutant

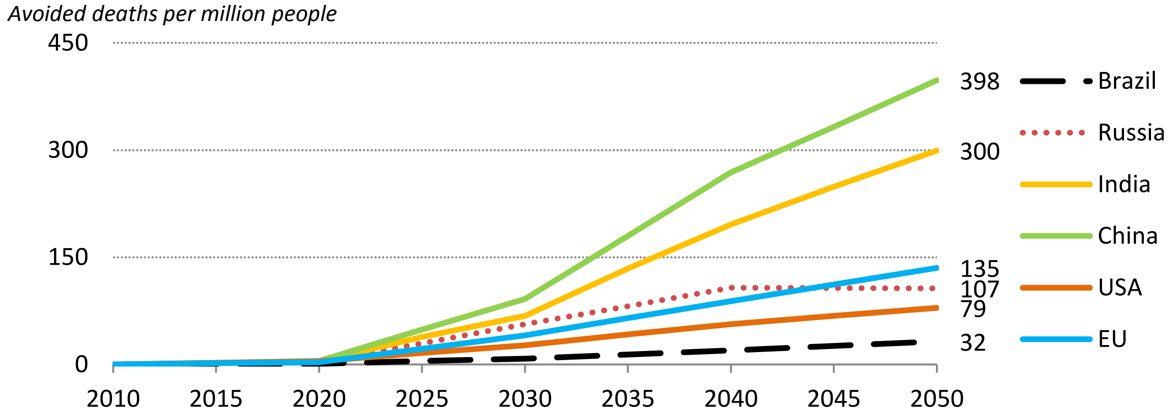
Figure 84 zooms in on a number of key regions with respect to the avoided mortality impact. The results show that China and India are countries with high avoided mortality co-benefits in the B2°C scenario.

Figure 84: Yearly avoided premature mortality per region due to lower concentrations of $PM_{2.5}$ and ozone as a consequence of climate policies

a) as a consequence of INDC climate policies



b) as a consequence of B2°C climate policies



Note: Figures obtained using air pollutant emissions under the assumption of "FROZ" air pollution policy (see Section 5.1.1).

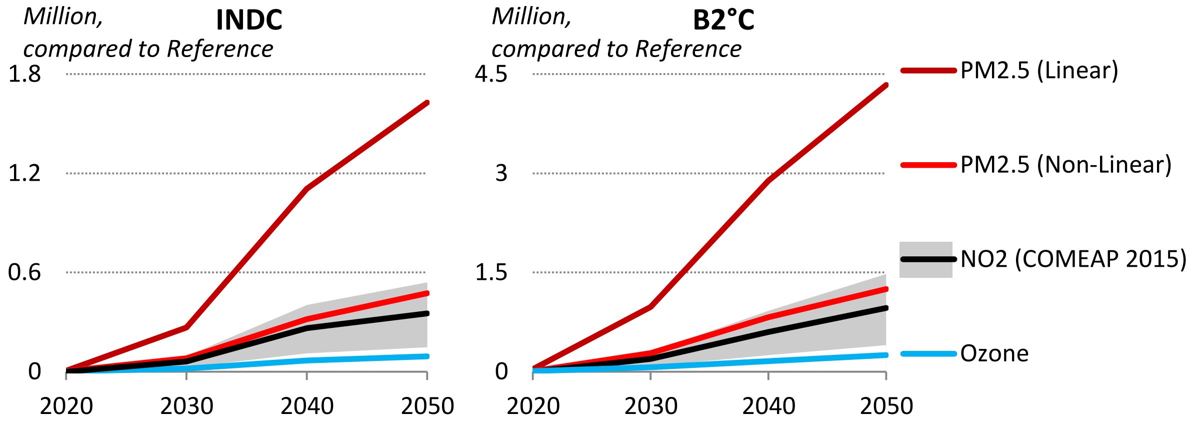
The literature assessing the health impacts of air pollution is constantly evolving. Substantial uncertainty remains in the size and channels of impacts. This section sheds some light on the ongoing discussions in the field and provides some context to the central scenarios presented in other sections.

Figure 85 presents the avoided premature mortality results for different pollutants and various exposure-response functions. For $PM_{2.5}$, the central scenarios presented in other sections of this report are based on the non-linear exposure-response functions of the Global Burden of Disease Project (Annex 4). Alternatively, a linear relation between $PM_{2.5}$ concentration and mortality could be considered: based on the log-linear relative risk curves in the study of Health Effects Institute (HEI; see Krewski et al., 2009), the avoided premature mortality in the B2°C scenario reaches more than 4 million equivalent deaths in 2050.

The results presented in previous sections only include NO_2 impacts indirectly, as NO_2 is a precursor for ozone and secondary particulate matter. However, there is recent evidence in the epidemiological literature of a direct health effect of NO_2 on long-term mortality, although there is still significant uncertainty of the potential magnitude of the health impact. To reveal both the potential importance and the uncertainty of NO_2 as a direct source of air pollution related co-benefits, Figure 85 shows avoided premature mortality due to lower NO_2 concentrations using exposure-response functions from the Committee on the Medical Effects of Air Pollutants (COMEAP, 2015). Results indicate that avoided premature mortality cases due to NO_2 reductions can range from roughly 400,000 to nearly 1.5 million in the B2°C scenario in 2050 (shaded area indicates 95% confidence interval).

Other channels that are not considered in this study include: the potential causal link between air pollution and Alzheimer ([73]), worker productivity (Zivin and Neidell, 2012; Chang et al., 2016), diabetes (Puett et al., 2011; Hansen et al., 2016; He et al., 2017), road safety (Sager, 2016), buildings, acidification, eutrophication and ecosystems.

Figure 85: Avoided premature mortality cases for different pollutants and exposure-response functions



Note: Figures obtained using air pollutant emissions under the assumption of "FROZ" air pollution policy (see Section 5.1.1).

6.3.3 Avoided illness

Air pollution affects the heart, the lungs and the brain. A body of literature provides evidence for the health impacts of air pollution, while the scientific community continues to discuss the strength of various pollutant-health pairings and to explore additional channels through which air quality relates to human health. For this report, in line with Hunt et al. (2016), we include the following impact categories for morbidity:

- Respiratory and cardiovascular hospital admissions due to $PM_{2.5}$ and, in case of the elderly population, ozone;
- Restricted activity days and work loss days for $PM_{2.5}$, and minor restricted activity days for ozone;
- Acute bronchitis incidences and asthma symptom days for children, and chronic bronchitis for adults due to $PM_{2.5}$.

Although currently not included in the central scenario results presented elsewhere in this report, the direct impact of reduced NO_2 concentrations on bronchitis (children) and respiratory hospital admissions have been calculated and are shown below. There is evidence that links NO_2 to respiratory problems independent of other pollutants, but disentangling the effects of $PM_{2.5}$ and NO_2 is statistically challenging because they typically co-exist. Indirectly, NO_2 contributes to the health impacts as it is a precursor for

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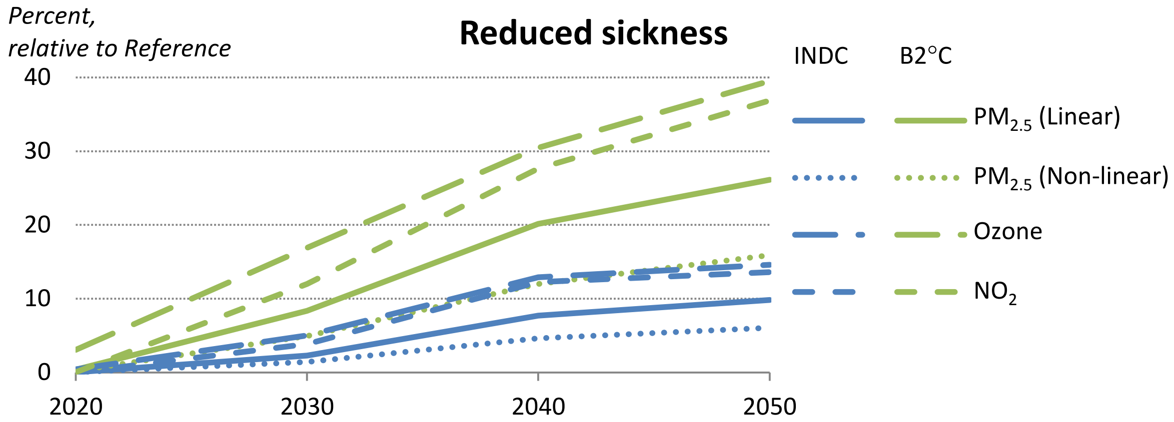
([73]) See "The polluted brain. Evidence builds that dirty air causes Alzheimer's, dementia", Science (January 26th 2017), http://www.sciencemag.org/news/2017/01/brain-pollution-evidence-builds-dirty-air-causes-alzheimer-s-dementia

$PM_{2.5}$ and ozone. In addition, Figure 86 includes estimates of the direct implications of NO_2 concentrations for illness.

Climate policies that limit global warming to below 2°C imply a reduction of air pollution-related illnesses by 15-40% in 2050 (Figure 86). For the INDC scenario, morbidity indicators are reduced by 1-5% in 2030 and 6-15% in 2050. The global results shown in Figure 86 vary by pollutant, but apply to all abovementioned pollutant-specific illness categories, irrespective whether the illness metric is expressed as days, incidences or hospital admissions.

Figure 86: Air quality impacts on morbidity, global average



Note: Figures obtained using air pollutant emissions under the assumption of "FROZ" air pollution policy (Section 5.1.1).

6.3.4 Crop productivity

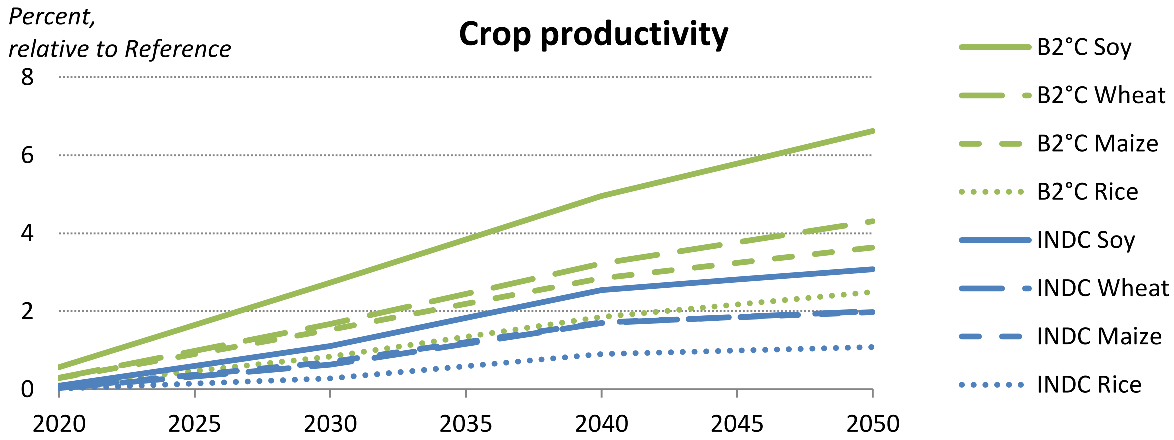
Ground-level ozone is absorbed by leaves, damaging plant metabolism (reduced CO_2 assimilation rates) and hindering plant growth. As a result, high concentrations of ground-level ozone harm agricultural crop yields and reduce farmers' income. Whether or not tropospheric ozone affects forests' capacity of sequestering and storing CO_2 is a topic for ongoing debate (Fuhrer et al., 2016); this feedback channel is not considered here.

By reducing emissions of ozone precursors NO_x, NMVOCs and CO, climate policies raise agricultural yields (Figure 87). The INDCs imply a productivity increase between 0.3% (rice) and 1.1% (soy) in 2030, which further increases to 1.1% and 3.1% in 2050. Crop productivity increases roughly double in the B2°C scenario compared to the INDC scenario. Soybean and wheat are typically more sensitive to ozone concentration, which is reflected by the results presented in Figure 87. Maize and rice are relatively less affected by ozone. Geographic patterns of production and climate action also play a role. For instance, China and the United States are important producers of maize globally. Substantial reductions in ozone concentrations in these countries in the INDC scenario lead to significant improvements of maize yield globally. In the B2°C scenario, strong ozone reductions in India and China give more weight to yield improvements for important crops in these countries, notably rice.

Translating changes in ground-level ozone concentrations to yield impacts is done through exposure-response functions. These crop-specific functions relate ozone exposure to yield and are mainly based on Van Dingenen et al. (2009) for wheat, maize, rice and soy. Three generic classes of exposure-response functions were estimated for high, medium and low sensitivity crops. Based on the meta-analysis of Mills et al. (2009), another 25 crops were allocated to these generic categories. Crop productivity impacts have been aggregated across regions using five-year average (2009-2013) gross production values from FAOSTAT.

We emphasize that the impact of climate change on crop productivity is not included in this study. Research by Lobell et al. (2011) indicates that maize and wheat production has already declined due to climate trends over the period 1980-2008, whereas Zampieri et al. (2017) note that heat and water stress are important factors explaining wheat yield variability. Estimating the size of the CO_2 fertilization effect remains an important avenue for future research.

Figure 87: Ozone impacts on productivity for key crops, global average



Note: Figures obtained using air pollutant emissions under the assumption of "FROZ" air pollution policy (Section 5.1.1).

6.4 Macro-economic impacts of avoided air pollution

To assess the macro-economic impacts of lower concentrations of $PM_{2.5}$ and ozone ([74]), we include three market impacts (work lost days, agricultural productivity and healthcare expenditures) and one non-market impact (mortality). The abovementioned market impacts are introduced in the JRC-GEM-E3 model:

- The changes in work lost days are implemented in the model by adjusting the available labour supply.
- Agricultural productivity in each of the scenarios is reflected by the total factor productivity in the agricultural sector.
- The reduction in healthcare expenditures is modelled by changing the minimum (also labelled 'subsistence' or 'obliged') consumption levels for healthcare, such that more income is available for consumption of other goods.

Avoided premature deaths are valued economically outside of the JRC-GEM-E3 model, using the statistical value of life (VSL), also known as the value of a prevented fatality (VPF), which is not a measure of the intrinsic value of a person's life, but rather represents society's collective willingness to pay for a small reduction in the annual risk of death for an anonymous individual exposed to air pollution.

The benefits of air pollution co-benefits of climate policy reach more than 2% of globally aggregated GDP in the B2°C scenario in 2050. Substantial differences are found across regions, with values reaching as much as 5% for China (INDC and B2°C) and India (B2°C).

Of all co-benefits considered, avoided premature mortality is the most significant one, as illustrated by the results in Figure 88. These results use the non-linear exposure-response functions (as in the Global Burden of Disease project, GBD 2015) and assume that air quality policies are frozen at 2010 levels. The economic valuation of mortality depends on income, reflecting differences in society's willingness and capability to pay for the loss of a life. Ideally, national or regional studies should be used to value economic benefits for a reduction in ambient air pollution. In the absence of such data, however,

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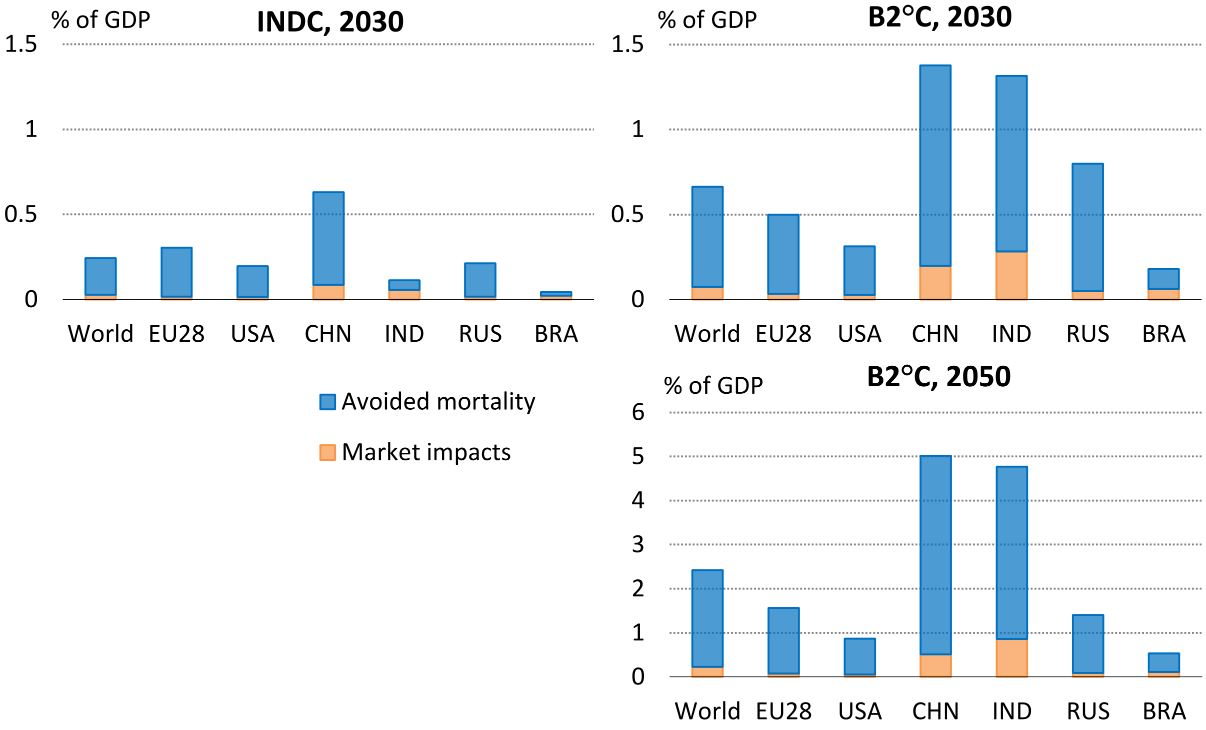
([74]) Only indirect NO_2 effects are included ($PM_{2.5}$ and ozone formation).

the central scenario assumes a VSL of 5 million US $ for the USA in 2005 (75), while the value of statistical life for other regions and years is calculated in line with the "benefit-transfer" methodology proposed by OECD (2012) according to the following equation (year t, region i, income I, income elasticity α=0.8):

$$VSL_i^t = VSL_{USA}^{2005} * \left(\frac{I_i^t}{I_{USA}^{2005}}\right)^{\alpha}$$

The adjustment takes into account differences in income levels between regions, all other socioeconomic conditions are assumed to be similar (ceteris paribus). Here, I is the GDP per capita (at PPP prices), and α is an income elasticity factor, which is a measure of the change in price for a marginal increase in income. Cost adjustment over time (income growth effect) is included, such that the valuation of mortality evolves in line with per capita income. Furthermore, the future co-benefits presented in this report are undiscounted.

Figure 88: Macro-economic impact of lower air pollution concentration levels as a consequence of climate policy, World and selected countries



Note: Figures obtained using air pollutant emissions under the assumption of "FROZ" air pollution policy (Section 5.1.1) and linear $PM_{2.5}$ *exposure-response function.*

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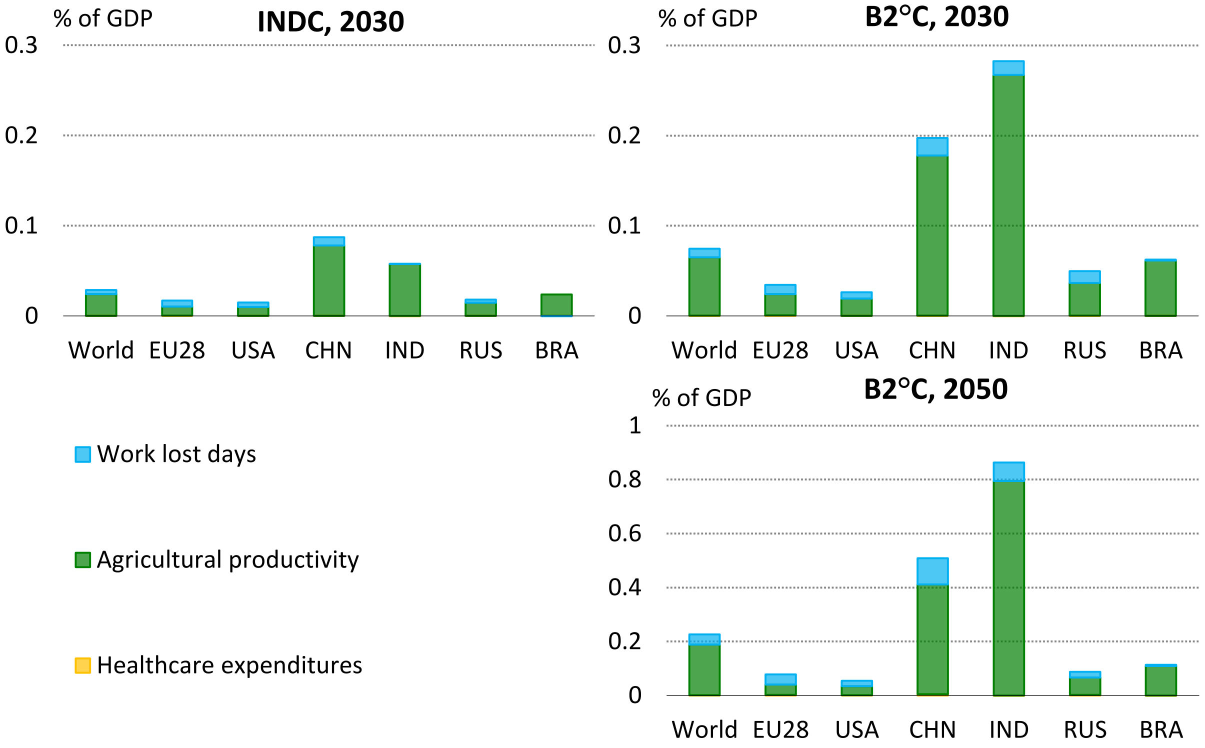
(75) References and sensitivity included at the end of this section.

Among the market impacts, the benefits on the labour supply and agricultural markets dominate over the avoided healthcare costs (Figure 89). Avoided work days lost appear to be relatively more important in high-income countries, while some low-income regions with a sizeable agricultural sector (India, Brazil) experience larger benefits due to improved agricultural productivity. The reduction in healthcare expenditures, which induces a shift in expenditure from healthcare towards other goods and services, has a relatively small impact on GDP.

Figure 89: Macro-economic market impacts of lower air pollution concentration levels as a consequence of climate policy, World and selected countries



Note: Figures obtained using air pollutant emissions under the assumption of "FROZ" air pollution policy (Section 5.1.1) and linear $PM_{2.5}$ *exposure-response function.*

Table 16 below presents some sensitivity analyses for the largest effect, i.e. avoided premature mortality co-benefits. Using a range of base VSL_{Base} values (for USA 2005, in million US $ 2005) and a range of income elasticities (α) based on relevant literature, the tables show the sensitivity of the valuation of avoided premature mortality as a share of globally aggregated GDP. The values for VSL_{Base} include 2.5 (West et al., 2013; low), 4 (OECD, 2016; IMF, 2014), 5 (this report), 6 (Thompson et al., 2014), 7 (Shindell et al., 2016) and 7.5 million US $ 2005 (West et al., 2013; high). The income elasticity values include 0.4 (Shindell et al., 2016), 0.5 (West et al., 2013), 0.8 (OECD, 2016; IMF, 2014 and this report), 0.9 and 1 (both OECD, 2016). This report uses rather conservative central values.

Table 16: Value of avoided premature mortality, expressed as percent of global GDP

a) INDC 2030

VSL_{Base} \ α	0.4	0.5	0.8 *GECO 2017*	0.9	1
2.5	0.13	0.12	0.11	0.10	0.10
4	0.21	0.20	0.17	0.16	0.16
5 *GECO 2017*	0.26	0.25	**0.21**	0.20	0.19
6	0.32	0.30	0.26	0.24	0.23
7	0.37	0.35	0.30	0.28	0.27
7.5	0.40	0.37	0.32	0.31	0.29

b) B2°C 2030

VSL_{Base} \ α	0.4	0.5	0.8 *GECO 2017*	0.9	1
2.5	0.41	0.37	0.29	0.27	0.26
4	0.65	0.60	0.47	0.44	0.41
5 *GECO 2017*	0.81	0.75	**0.59**	0.55	0.51
6	0.97	0.90	0.71	0.66	0.61
7	1.14	1.05	0.82	0.77	0.71
7.5	1.22	1.12	0.88	0.82	0.77

c) B2°C 2050

VSL_{Base} \ α	0.4	0.5	0.8 *GECO 2017*	0.9	1
2.5	1.24	1.20	1.10	1.07	1.04
4	1.99	1.92	1.76	1.71	1.67
5 *GECO 2017*	2.48	2.40	**2.20**	2.14	2.09
6	2.98	2.88	2.64	2.57	2.51
7	3.48	3.36	3.07	3.00	2.92
7.5	3.73	3.60	3.29	3.21	3.13

6.5 Combining GHG mitigation cost with air quality co-benefits

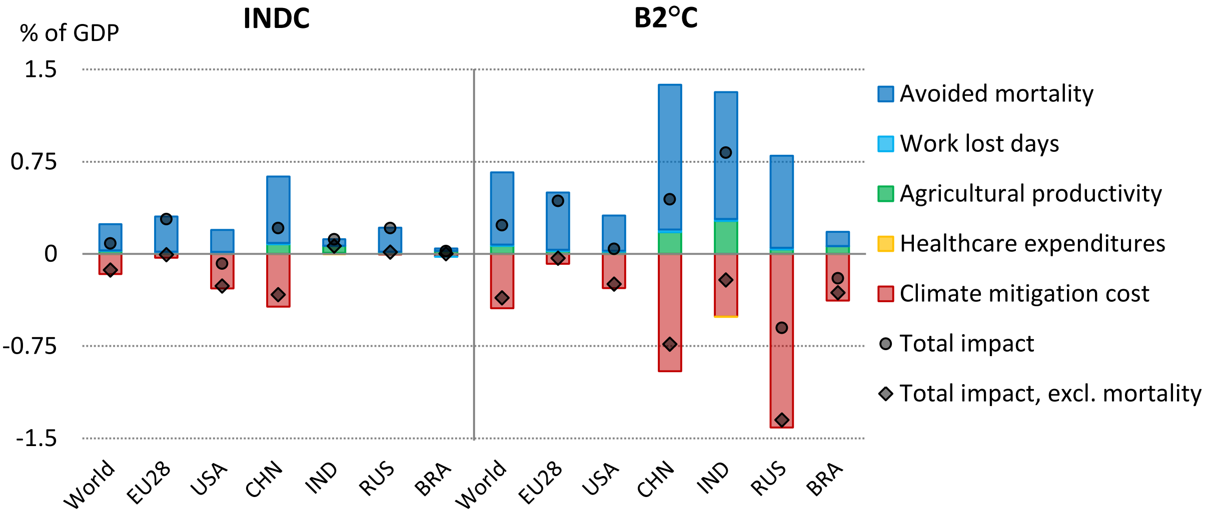
This section brings together the macro-economic cost of climate change mitigation and the health co-benefits via improved air quality. The benefits of avoided climate impacts are not quantified here, but the next section discusses some of the relevant literature. Figure 90 presents the main results for the INDC and the B2°C scenarios in 2030. Regarding the mitigation costs, the same caveats as presented in Section 6.2 apply (see Box: Interpreting the costs of mitigation). The list of co-benefits included is not exhaustive and excludes potential channels of clean air benefits, notably the direct health effects of lowered NO_2 concentrations.

On a global level, the cost of climate change mitigation is more than compensated by air pollution co-benefits in 2030, both in the INDC and in the B2°C scenario. Results for different regions show substantial variation both in terms of mitigation costs and in co-benefits. Various factors contribute to this heterogeneity. The bottom-up nature of the INDC policies entails the absence of effort harmonization across regions. Correspondingly, regions with more ambitious GHG reduction targets will experience both higher mitigation costs and larger local co-benefits. Figure 90 shows the mitigation cost compared to the Reference, which includes current policies. For regions where the currently implemented climate and energy policies are already ambitious, such as the EU, a comparison between the INDC and the Reference therefore shows only limited additional mitigation costs, although the effort undertaken is substantial. Furthermore, the cost and the potential scope of various mitigation options depend on region-specific characteristics. In Brazil, for instance, avoiding deforestation is a crucial instrument in climate policy, but the feedbacks of land-use changes to local air pollutants are not included in this study.

Both mitigation costs and air quality co-benefits are not restricted to domestic policies. Climate policies undertaken in other regions can give rise to domestic costs or benefits via international trade in two ways. First, the relative ambition level of a country's climate policy, and the means of implementation, may affect the competitive position of export-oriented industries. Second, the structural economic changes implied by ambitious climate policies may affect export markets: countries that produce clean technologies may benefit from growing global demand, while shrinking international markets may imply a challenging transition for fossil fuel exporting countries.

In terms of additional co-benefits of local air pollutants, a region gains from ambitious climate policies in neighbouring regions: although air pollutants are local, the distance between source and receptor may be large enough to cross jurisdictional borders, especially for ozone but also for $PM_{2.5}$. Although this was not singled out in this study, transboundary circulation of air pollutants was included in the modelling. Other research shows that the premature mortality associated with transboundary transport of $PM_{2.5}$ can reach over 10% of all mortality cases related to $PM_{2.5}$ (Zhang et al. 2017).

Figure 90: Comparison of mitigation cost and air quality co-benefits in 2030



Note: Cost and co-benefits related to land use, land-use change and forestry are not included in this figure.

Direct comparisons of the costs and benefits of climate policy have been difficult to implement due to the mismatch between the timing of the costs (now) and the moment to harvest the benefits (one-two generations ahead). The analysis presented here is not a direct cost-benefit analysis of climate policy, but rather widens the scope to include the co-benefits of the transformation of the energy system on air quality. Including the air pollution co-benefits, immediate, important impacts such as lower mortality can be factored in, delivering robust evidence of substantial synergies between climate policy and air quality for a wide set of regions in the world. In addition to other co-benefits, such as hedging against oil price fluctuations (Rozenberg et al., 2010, Maisonnave et al., 2012), incentivizing a healthier diet (Springmann et al., 2017) and spurring innovation (Jaffe et al., 2005), the climate policy-induced improvements in air quality and associated health benefits further strengthen the economic case for the ongoing global energy transition (see also IEA/IRENA, 2017).

6.6 The cost of inaction

Arguably the main trigger behind climate change mitigation policies is the damage that arises due to anthropogenic global warming. The economic and social impact of changing climatic conditions is not studied in this report, but its importance must be stressed, since it is the main rational for climate mitigation policy action, in addition to the co-benefits assessed in this report.

A growing literature is assessing these impacts from a top-down perspective and increasingly from bottom-up analyses zooming on specific sectors and/or regions.

Although it can vary across regions and coverage, impact cost estimates for end of the century range from 2% to 20%, hence in the order of magnitude or beyond the climate mitigation cost (to which must be added the co-benefits, i.e. the avoided cost of reduced air pollution).

Recent studies that encompass a wide range of impacts include:

- Sectoral economic analyses: Ciscar et al. (2014) for the EU (2% by 2080); Hsiang et al. (2017) for the US (1.2% per °C by late 21st century);
- Global economic analyses: OECD (2015) (2-10% by 2100); Burke et al. (2015) (23% by 2100);
- Other type of analyses, on heat-related deaths: Mora et al. (2017) (share of the population exposed to climatic conditions exceeding deadly threshold for at least 20 days a year: from 30% today to 74% by 2100) and Forzieri et al. (2017) (point out that heat-related mortality in Europe could rise to more than 150,000 by the end of the century).

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List of abbreviations and definitions

Acronyms & Abbreviations

AR5: Fifth Assessment Report of the IPCC

BAU: Business As Usual

BECCS: Bio-Energy combined with Carbon Capture and Sequestration

BGR: German Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe)

BTL: Biomass-To-Liquids

CCS: Carbon Capture and Sequestration

COM: Communication from the European Commission

COP: Conference Of the Parties

CDR: carbon dioxide removal

CGE: Computable General Equilibrium model

CTL: Coal-To-Liquids

CSP: Concentrated Solar Power

DOE: US Department Of Energy

EC: European Commission

EFTA: European Free Trade Association

EIA: US Energy Information Administration

ETS: Emission Trading Scheme

GDP: Gross Domestic Product

GECO: Global Energy & Climate Outlook

GHG: Greenhouse Gases

GTAP: Global Trade Analysis Project

GTL: Gas-To-Liquids

ICE: Internal Combustion Engine

IEA: International Energy Agency

IIASA: International Institute for Applied Statistical Analysis

ILO: International Labour Organization

IMF: International Monetary Fund

INDC: Intended Nationally Determined Contribution

IPCC: Intergovernmental Panel on Climate Change

JRC: Joint Research Centre of the European Commission

LNG: Liquefied Natural Gas

LULUCF: Land Use, Land Use Change and Forestry

MER: Market Exchange Rate

NDC: Nationally Determined Contribution

NREL: US National Renewables Energy Laboratory

OECD: Organisation of Economic Co-operation and Development

OICA: Organisation Internationale des Constructeurs d'Automobiles

OMR: IEA Oil Monthly Report

PPP: Purchasing Power Parity

PV: Photovoltaics

REN: Renewable Energy

R/P: ratio Reserves by Production

UN: United Nations

UNFCCC: United Nations Framework Convention on Climate Change

USGS: US Geological Survey

WEC: World Energy Council

WG I, II, III: Working Group I, II, III of the IPCC

Regional codes

Balk: other Balkans countries, includes Albania, Bosnia-Herzegovina, Kosovo, Macedonia, Montenegro, Serbia

C Am: Central America, includes: Bahamas, Barbados, Belize, Bermuda, Costa Rica, Cuba, Dominica, Dominican Republic, El Salvador, Grenada, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, NL Antilles and Aruba, Panama, St Lucia, St Vincent and Grenadines, Trinidad and Tobago

CIS: Commonwealth of Independent States, includes: Armenia, Azerbaijan, Belarus, Kazakhstan, Kyrgyz Rep., Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan. Georgia is also included here (although withdrawn from CIS since 2008)

EFTA: Iceland, Liechtenstein, Norway, Switzerland

EU28: European Union with 28 Member States (as of June 2017). Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom

Europe: EU28, EFTA, Other Balkans (Albania, Bosnia-Herzegovina, Kosovo, FYR of Macedonia, Montenegro, Serbia)

LDC: Least Developed Countries (UN concept). Refer here to regions where income is inferior to 5 k$/cap in 2030, i.e.: Rest of Central America, Egypt, Rest of Sub-Saharan Africa, India, Rest of South Asia, Indonesia, Vietnam, Rest of South-East Asia, Pacific Islands, according to POLES-JRC

OECD: Australia, Austria, Belgium, Canada, Chile, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Latvia, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States

OPEC: Organization of the Petroleum Exporting Countries, includes (as of June 2017): Algeria, Angola, Ecuador, Equatorial Guinea, Gabon, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, United Arab Emirates, Venezuela

Pacif: Pacific, includes: Fiji Islands, Kiribati, Papua New Guinea, Samoa (Western), Solomon Islands, Tonga, Vanuatu

R CIS: Rest CIS, CIS excluding Russia and Ukraine

R Gulf: Rest Gulf, includes Bahrain, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Syria, United Arab Emirates, Yemen

S Am: South America, includes Argentina, Bolivia, Brazil, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela

S Asia: South Asia, includes Afghanistan, Bangladesh, Bhutan, Maldives, Nepal, Pakistan, Sri Lanka

SE Asia: South-East Asia, includes: Brunei, Cambodia, Indonesia, Korea (PR), Lao PDR, Malaysia, Mongolia, Myanmar, Philippines, Singapore, Taiwan, Thailand, Vietnam

SS Afr: Sub-Saharan Africa (Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Congo DR, Cote d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe)

Glossary

Agriculture sector includes the energy consumed in agriculture, forestry and fishing. It covers the exploitation of vegetal and animal natural resources (growing of crops, raising and breeding of animals, harvesting of timber and other plants).

Electric processes & appliances: energy demand for end-uses where electricity is necessary. Covers electric industrial processes, white and grey appliances, lighting, space cooling. Does not include electricity demand for space heating and cooking.

Energy for Power Generation covers energy for electricity and heat production. It covers fuel use in electricity plants, heat plants and combined heat and power (CHP) plants. Self-consumption is included.

Final Energy Demand is the sum of energy consumption by the different end-use sectors. It is broken down into the energy demand in the following sectors: Agriculture; Industry; Transport; Residential; and Services. It excludes international marine and aviation bunkers, except at world level where they are included in the transport sector. It can also be broken down into the energy demand in the following end-uses: Heat uses; Electric processes & appliances; Mobility; and Non-energy uses.

Heat uses: energy demand for end-uses for the production of low- and high-temperature heat. Covers thermal industrial processes and space heating.

Industry sector includes manufacturing industry, construction and mining; it does not include energy transformation activities; it includes non-energy uses of energy fuels. It consists of the following sub-sectors:

- Iron and Steel industry (includes blast furnaces and coke final consumption);
- Non-Metallic Minerals;
- Chemicals (consumption for energy uses of chemicals and petrochemicals industry);
- Other Industry (energy uses in other manufacturing industry, construction and mining);
- Non-Energy Uses (non-energy uses of energy fuels in rubber and plastics and chemical feedstocks production).

The energy used for transport by industry is not included here but reported under transport.

Mobility: energy demand for mobility end-uses. Coincides with the energy demand of the Transport sector.

Non-energy uses: non-energy end-uses of energy fuels in rubber and plastics and chemical feedstocks production. Consumed along with the energy uses of fuels in the Chemicals sector in Industry.

Other Energy Transformation & Losses is the energy own use and losses of the energy transformation industry not shown elsewhere, such as energy for fossil fuel and uranium extraction, refining, transport and distribution (including gasworks); coal-, gas- and biomass-to-liquids production; hydrogen production; coke ovens. Also includes transfers and statistical differences. Losses include losses in energy distribution, transmission and transport.

Primary Energy Demand represents the total energy demand, including net imports. It is the sum of energy demand for power generation, other energy transformation sector & losses and total final demand.

Residential sector includes all household energy uses.

Services sector includes commercial energy uses (office buildings, hotels, shopping centres, IT centres, …), and public services energy uses (public street lighting).

Transport sector includes all fuels (oil, gas, biomass, coal, hydrogen, electricity) used for transport, for all passenger and freight transport, irrespective of the economic sector within which the activity occurs. It covers domestic aviation, road, rail, waterways, and domestic navigation. Road transport includes light goods vehicles, heavy goods vehicles, light duty vehicles and passenger carrying vehicles for public and private transport. Country and regional balances refer to domestic consumption; international air and maritime bunkers are included only in the world total balance. It does not include pipeline transport of energy goods and related losses.

Units

Energy

EJ	Exajoule	1000 000 000 000 000 000 J

toe	tonne of oil equivalent	
ktoe	thousand tonnes of oil equivalent	1000 toe
Mtoe	million tonnes of oil equivalent	1000 000 toe
Gtoe	giga tonnes of oil equivalent	1000 000 000 toe

Mbl/d	million barrels per day	1000 000 bl/d
Tbl	tera barrels	1000 000 000 000 bl

Gt	giga metric tonnes	1000 000 000 t
Mt	million metric tonnes	1000 000 t

Electricity

GW	gigawatts	1000 000 000 W
TWh	terawatt-hours	1000 000 000 000 Wh

Prices

$/bbl	$ per barrel of oil
$/boe	$ per barrel of oil equivalent

Emissions and related

tCO_2	tonne CO_2	
tCO_2e	tonne CO_2-equivalent	
$MtCO_2e$	million tonnes of CO_2e	1000 000 tCO_2e
$GtCO_2e$	giga tonnes of CO_2e	1000 000 000 tCO_2e
ppm	particulates per million	
μm	micrometre ($1x10^{-6}$ metre)	
μgm^{-3}	microgram ($1x10^{-6}$ gram) per cubic metre	

Monetary units

k$	thousand dollars	1000 $
M$	million $	1000 000 $
bn$	billion $	1000 000 000 $
tn$	trillion $	1000 000 000 000 $

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Annex 1 Description of the energy/GHG model POLES-JRC

For a fuller description of the model, see Keramidas and Kitous (2017b) and http://ec.europa.eu/jrc/poles.

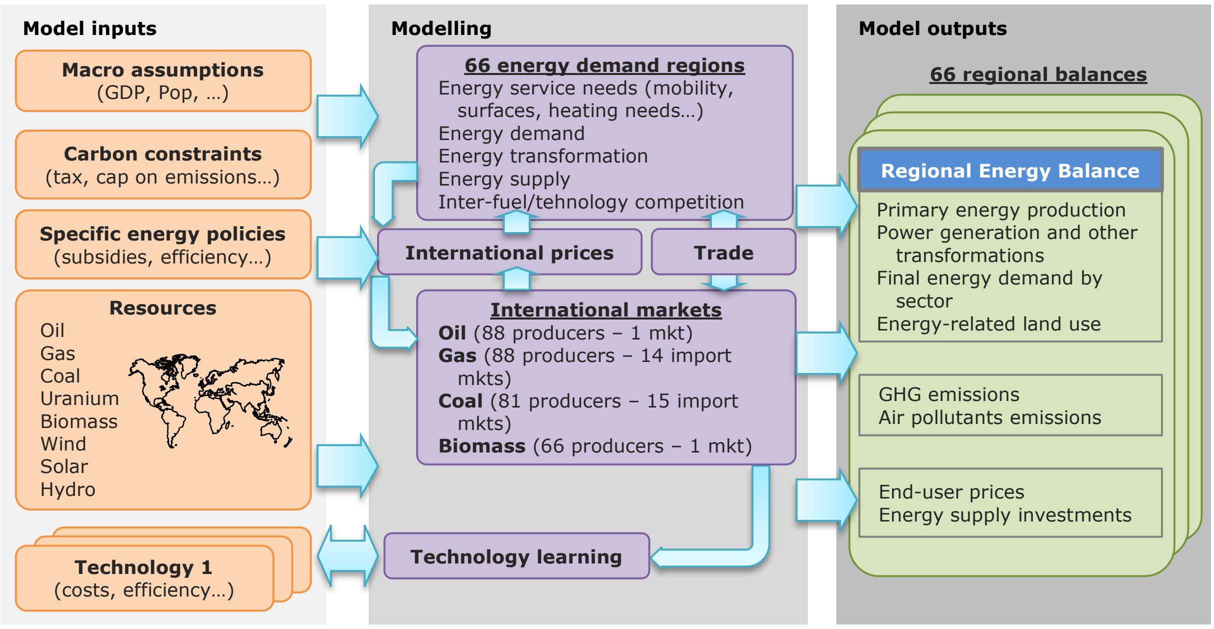
Model

POLES-JRC is a world energy-economy partial equilibrium simulation model of the energy sector, with complete modelling from upstream production through to final user demand. It follows a year-by-year recursive modelling, with endogenous international energy prices and lagged adjustments of supply and demand by world region, which allows for describing full development pathways to 2050 (see general scheme in Figure 91).

The model provides full energy and emission balances for 66 countries or regions worldwide (including detailed OECD and G20 countries), 14 fuel supply branches and 15 final demand sectors.

This exercise used the EC POLES-JRC 2017 version. Differences with other exercises done with the POLES-JRC model by EC JRC, or with exercises by other entities using the POLES model, can come from different i/ model version, ii/ historical data sets, iii/ parameterisation, iv/ policies considered.

Figure 91: POLES-JRC model general scheme



Final demand

The final demand evolves with activity drivers, energy prices and technological progress. The following sectors are represented:

- industry: chemistry (energy uses and non-energy uses are differentiated), non-metallic minerals, steel, other industry;
- buildings: residential, services (specific electricity uses are differentiated, different types of buildings are considered);
- transport (goods and passengers are differentiated): road (motorcycles, cars, light and heavy trucks – different engine types are considered), rail, inland water, international maritime, air domestic and international;
- agriculture.

Power system

The power system describes capacity planning of new plants and operation of existing plants.

The planning considers the existing structure of the power mix (vintage per technology type), the expected evolution of the load demand, the production cost of new technologies, and resource potential for renewables.

The operation matches electricity demand considering the installed capacities, the variable production costs per technology type, the resource availability for renewables.

The electricity demand curve is built from the sectoral distribution over typical days.

Electricity price by sector depend on the evolution of the power mix, of the load curve and of the energy taxes.

Other transformation

The model also describes other energy transformations sectors: liquid biofuel (BTL), coal-to-liquid (CTL), gas-to-liquid (GTL), hydrogen (H_2).

Oil supply

Oil discoveries, reserves and production are simulated for producing countries and different fuel types.

The market is structured along the market power of the different countries: non-OPEC, OPEC, Gulf.

International oil price depend on the evolution the oil stocks in the short term, and on the production cost and spare capacity in the Gulf in the longer run.

Gas supply

Gas discoveries, reserves and production are simulated for individual producers and different resource. They supply regional markets through inland pipeline, offshore pipelines or LNG.

Gas price depends on the transport cost, the regional R/P ratio, the evolution of oil price and the development of LNG (integration of the different regional markets).

Coal supply

Coal production is simulated for individual producers. They supply regional markets. Coal delivery price for each route depends on the production cost and the transport cost.

Biomass supply

The model differentiates various types of primary biomass: energy crops, short rotation crop (lignocellulosic) and wood (lignocellulosic). They are described through a potential and a production cost curve – information on lignocellulosic biomass (short rotation coppices, wood) is derived from look-up tables provided by the specialist model GLOBIOM-G4M (Global Biosphere Management Model*)*. Biomass can be traded, either in solid form or as liquid biofuel.

Wind, solar and other renewables

They are associated to potentials and supply curves per country.

GHG emissions

CO_2 emissions from fossil fuel combustion are derived directly from the projected energy balance. Other GHGs from energy and industry are simulated using activity drivers identified in the model (e.g. sectoral value added, mobility per type of vehicles, fuel production, fuel consumption..) and abatement cost curves. GHG from agriculture and LULUCF are derived from GLOBIOM-G4M lookup tables.

Countries and regions

The model decomposes the world energy system into 66 regional entities: 54 individual countries and 12 residual regions (Figure 92, Table 17 and Table 18), to which international bunkers (air and maritime) are added.

Figure 92: POLES-JRC model regional detail map (energy balances)

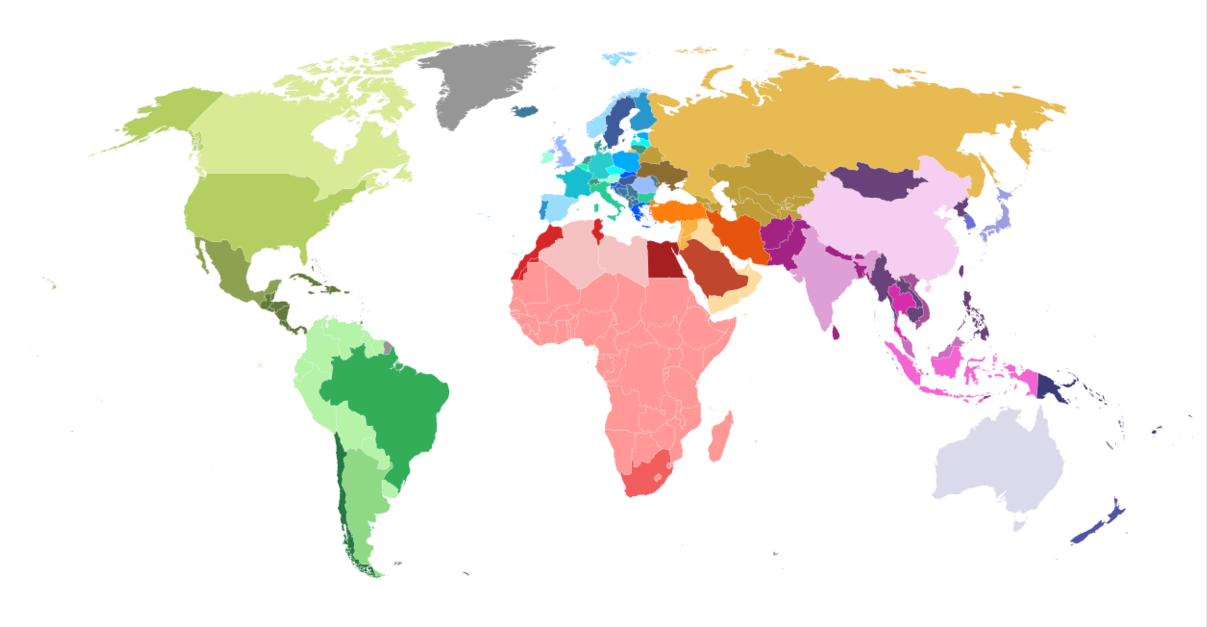


Table 17: List of 54 individual countries represented in POLES-JRC (energy balances)

Non-EU individual countries	EU28 Member States
Argentina	Austria
Australia	Belgium
Brazil	Bulgaria
Canada	Croatia
Chile	Cyprus
China	Czech Republic
Egypt	Denmark
Iceland	Estonia
India	Finland
Indonesia	France
Iran	Germany
Japan	Greece
Malaysia	Hungary
Mexico	Ireland
New Zealand	Italy
Norway	Latvia
Russia	Lithuania
Saudi Arabia	Luxembourg
South Africa	Malta
South Korea	Netherlands
Switzerland	Poland
Thailand	Portugal
Turkey	Romania
Ukraine	Slovak Republic
United States	Slovenia
Vietnam	Spain
	Sweden
	United Kingdom

Note: Hong-Kong and Macau are included in China

Table 18: Country mapping for the 12 regions in POLES-JRC (energy balances)

Rest Central America	Rest Balkans	Rest Sub-Saharan Africa (continued)	Rest South Asia
Bahamas	Albania	Burkina Faso	Afghanistan
Barbados	Bosnia-Herzegovina	Burundi	Bangladesh
Belize	Kosovo	Cameroon	Bhutan
Bermuda	Macedonia	Cape Verde	Maldives
Costa Rica	Moldova	Central African Republic	Nepal
Cuba	Montenegro	Chad	Pakistan
Dominica	Serbia	Comoros	Seychelles
Dominican Republic	**Rest CIS**	Congo	Sri Lanka
El Salvador	Armenia	Congo DR	**Rest South East Asia**
Grenada	Azerbaijan	Cote d'Ivoire	Brunei
Guatemala	Belarus	Djibouti	Cambodia
Haiti	Georgia	Equatorial Guinea	Lao PDR
Honduras	Kazakhstan	Eritrea	Mongolia
Jamaica	Kyrgyz Rep.	Ethiopia	Myanmar
Nicaragua	Tajikistan	Gabon	North Korea
NL Antilles and Aruba	Turkmenistan	Gambia	Philippines
Panama	Uzbekistan	Ghana	Singapore
Sao Tome and Principe	**Mediterranean Middle East**	Guinea	Taiwan
St Lucia	Israel	Guinea-Bissau	**Rest Pacific**
St Vincent & Grenadines	Jordan	Kenya	Fiji Islands
Trinidad and Tobago	Lebanon	Lesotho	Kiribati
Rest South America	Syria	Liberia	Papua New Guinea
Bolivia	**Rest of Persian Gulf**	Madagascar	Samoa (Western)
Colombia	Bahrain	Malawi	Solomon Islands
Ecuador	Iraq	Mali	Tonga
Guyana	Kuwait	Mauritania	Vanuatu
Paraguay	Oman	Mauritius	
Peru	Qatar	Mozambique	
Suriname	United Arab Emirates	Namibia	
Uruguay	Yemen	Niger	
Venezuela	**Morocco & Tunisia**	Nigeria	
	Morocco	Rwanda	
	Tunisia	Senegal	
	Algeria & Libya	Sierra Leone	
	Algeria	Somalia	
	Libya	Sudan	
	Rest Sub-Saharan Africa	Swaziland	
	Angola	Tanzania	
	Benin	Togo	
	Botswana	Uganda	
		Zambia	

Data sources

Table 19: POLES-JRC model historical data and projections

Series		Historical data	GECO Projections
Population		UN, Eurostat	UN (medium fertility)
GDP, growth		World Bank	EC, IMF, OECD
Other activity drivers	Value added	World Bank	POLES-JRC model
	Mobility, vehicles, households, tons of steel, …	Sectoral databases	
Energy resources	Oil, gas, coal	BGR, USGS, WEC, sectoral information	
	Uranium	NEA	
	Biomass	GLOBIOM model	
	Hydro	Enerdata	
	Wind, solar	NREL, DLR	
Energy balances	Reserves, production	BP, Enerdata	
	Demand by sector and fuel, transformation (including. power), losses	Enerdata, IEA	
	Power plants	Platts	
Energy prices	International prices, prices to consumer	Enerdata, IEA	POLES-JRC model
GHG emissions	Energy CO_2	Derived from POLES-JRC energy balances	POLES-JRC model
	Other GHG Annex 1	UNFCCC	POLES-JRC model, GLOBIOM model
	Other GHG Non-Annex 1 (excl. LULUCF)	EDGAR	POLES-JRC model, GLOBIOM model
	LULUCF Non-Annex 1	National inventories, FAO	POLES-JRC model, GLOBIOM model
Air pollutants emissions		GAINS model, EDGAR, IPCC, national sources	GAINS model, national sources
Technology costs		POLES-JRC learning curves based on literature, including but not limited to: EC JRC, WEC, IEA, TECHPOL database*	

**: developed in several European research projects: SAPIENT, SAPIENTIA, CASCADE MINTS*

Annex 2 Description of the economic model JRC-GEM-E3

The GEM-E3 model, a Computable General Equilibrium (CGE) model, is used to assess the direct and indirect impacts of mitigation efforts until the year 2030. The GEM-E3 model is a multi-sector, multi-region model that includes the interactions between the energy system, the economy and the environment. It is built on sound microeconomic foundations and integrates multiple data sources such as trade statistics, input-output data and information on emissions of greenhouse gasses. Furthermore, existing tax structures and unemployment mechanisms are incorporated. The version of the model used here is global (13 regions, see Table 20) and covers all industry sectors, disaggregated into 31 sectors, of which 10 electricity generating technology sectors.

In a general equilibrium framework, results regarding impacts of imposed policies are presented comparatively with the Reference projections of the economy, thus in terms of percentage differences from the Reference scenario. The GEM-E3 Reference is constructed on the basis of a variety of data sources. First, the future path of GDP is based on projections done by the OECD (Dellink et al., 2014) for all regions in the world. Second, population projections are taken from the UN (2015). Third, the input-output tables and the data on bilateral trade flows are derived from the GTAP 8 database. Fourth, the emission levels of greenhouse gasses (totals and by sector) and the shares of electricity generation technologies are harmonised with the Baseline in the POLES model. For the EU, the Baseline is consistent with the 2013 reference of the PRIMES model. Importantly, for the EU this Baseline already includes substantial policy measures. In particular, Europe complies with the "20-20-20 Package" and is in line with the "EU Energy, Transport and GHG emission trends to 2050; update 2013" (EC, 2013). For the other regions, policy measures that are already put in place are included, in line with section 2. Additional data sources include labour statistics from ILO and energy statistics from IEA.

The GEM-E3 model is a recursive dynamic CGE model representing multiple regions, sectors and agents. The interactions between three types of agents are included: households, firms and governments. Household behaviour derives from the maximisation of a Stone-Geary (Linear Expenditure System) utility function. Unemployment is modelled via a wage curve mechanism. Firms maximise profits subject to sector-specific nested constant elasticity of substitution production technologies. The behaviour of governments is exogenous, and government budget balance relative to GDP is assumed to be at the level of the Reference in all scenarios.

Table 20: Regional aggregation in the JRC-GEM-E3 model

Region	***Code***
European Union	EU28
USA	USA
China	CHN
India	IND
Russia	RUS
Brazil	BRA
Canada	CAN
Japan	JPN
Australia	AUS
North Africa and Middle East	NAM
Ukraine, Belarus and Moldova	UBM
Rest of Europe (Switzerland, Norway, Albania, Iceland, Bosnia, Serbia, Turkey…)	RET
Rest of the world	ROW

Source: GEM-E3 model

Annex 3 Description of the source-receptor model TM5-FASST

In general, air quality source-receptor models (AQ-SRM) link emissions of pollutants in a given source region with downwind impacts, implicitly using underlying knowledge of meteorology and atmospheric chemistry and physics processes. The source region is any point or area from which emissions are considered; the receptor is any point or area at which the pollutant concentration and impact is to be evaluated. Primary pollutants do not undergo chemical transformation during their atmospheric lifetime and are only affected by dry and wet removal from the atmosphere (e.g. elemental carbon, mineral dust). Secondary pollutants are formed from reactions of primary emissions, e.g. NO_2 forms nitrate aerosol but also leads to the formation of ozone; emitted SO_2 is transformed into sulphate aerosols. An AQ-SRM will need to include a functional relationship between each precursor and each relevant pollutant or pollutants metric, for each source region and each receptor region.

TM5-FASST has been designed as a reduced-form SRM: the relation between the emissions of compound *i* from source *x* and resulting concentration (or burden) of pollutant *j* (where *j* = *i* in case of a primary component) at receptor *y* is expressed by a simple functional relation that mimics the underlying meteorological and chemical processes. In the current version TM5-FASST the function is a linear relation expressing the change in pollutant concentration in the receptor region upon a change in precursor emissions in the source region with the generic form $dC_y = SRC \times dE_x$ where dC_y = the change in the pollutant concentration compared to a reference concentration in receptor region *y*, dE_x = the change in precursor emission compared to a reference emission in source region *x*, and SRC the source-receptor coefficient for the specific compound and source-receptor pair. The source-receptor (SR) coefficients are implemented as matrices with dimension $[n_x,n_y]$ with n_x and n_y the number of source and receptor regions respectively. A single SR matrix is available for each precursor and for each resulting component from that precursor. Table 1 gives an overview of all precursor – pollutant links that have been included.

For TM5-FASST we defined 56 source regions, as shown in Figure 1. The choice of regions has been made to obtain an optimal match with integrated assessment models such as IMAGE, MESSAGE (Riahi et al., 2007), GAINS (Höglund-Isaksson and Mechler, 2005) as well as the POLES model (Russ et al., 2007; Van Aardenne et al., 2007). Most European countries are defined as individual source regions, except for the smallest countries, which have been aggregated. In the current version, the US, China and India are treated as a single emission regions, i.e. without break-down in states or provinces. Although most integrated assessment models cover Africa, South America, Russia and South-East Asia as a single socio-economic entity, it was decided to sub-divide these regions, to account for climatological difference in these vast continents. Apart from the 56 regions, source-receptor coefficients were calculated between global international shipping and aviation as sources, and the global grid as receptor, hence $n_x = 58$. The set of receptor regions can range from the 1°x1° native resolution of the TM5 model output, to customized aggregated receptor regions. A common aggregation is the one identical to the 56 continental source regions. For the current work we make use of the highest available spatial resolution, i.e. global 1°x1° gridmaps.

The SR matrices, describing the concentration response in each receptor grid upon a change in emissions in each source region, have been derived from a set of runs with the full chemical transport model TM5-CTM by applying 20% emission perturbations for each of the 56 defined source regions (plus shipping and aviation), for all relevant precursor components, in comparison to a set of unperturbed simulations, hereafter denoted as 'base simulations'. TM5-CTM explicitly solves the mass balance equations of the species using detailed meteorological fields and sophisticated physical and chemical process schemes at 1°x1° resolution within customizable zoom areas, which are 2-way nested via an intermediate 3°x2° and global 6°x4° base resolution (Krol et al., 2005) . The global continents are covered with the 1°x1° resolution by defining 13 1°x1° master zoom areas for which the base runs are performed separately, and which are pasted into one global 1°x1° resolution base field. This is the so-called native resolution at which base simulation and perturbation fields are available.

As base run emissions we use the community generated representative pathway concentration (RCP) emissions for the year 2000 prepared for IPCC 5th Assessment (Lamarque et al., 2010). The meteorological fields are from the European Centre for Medium-Range Weather Forecast (ECMWF) operational forecast (OD), representative for the year 2001.

For each receptor point *y* (i.e. each model vertical level 1°x1° grid cell), the change in concentration of component *i* in receptor *y* resulting from a 20% perturbation of emitted precursor *j* in source region *x*, is expressed by a unique SR coefficient $A_{ij}[x,y]$:

$$A_{ij}[x,y]=\frac{\Delta C_j(y)}{\Delta E_i(x)} \text{ with } \Delta E_i(x)=0.2E_{i,base}(x) \qquad (1)$$

The total concentration of component *j* in receptor region *y*, resulting from arbitrary emissions of *all* n_i precursors *i* at *all* n_x source regions *x,* is obtained as a perturbation on the base-run concentration, by summing up all the respective SR coefficients scaled with the actual emission perturbation:

$$C_j(\boldsymbol{y})=C_{j,base}(\boldsymbol{y})+\sum_{\boldsymbol{n_x}}\sum_{\boldsymbol{n_i}}A_{ij}[x,y]\cdot\left[E_i(x)-E_{i,base}(x)\right] \quad (2)$$

Pollutants include particulate matter components (SO_4, NO_3, NH_4, BC, particulate organic matter – POM), trace gases (SO_2, NO, NO_2, NH_3, O_3, CO), and deposition fluxes of BC, N and S species. In the case of *j*=ozone, the n_i precursors in equation (2) would comprise [NO_x, NMVOC, CO, CH_4]. The set of linear equations (2) with associated source-receptor matrices (1) for all components and all source and receptor regions thus emulates the 'full' TM5-CTM, and constitutes the 'kernel' of TM5-FASST_V0.

Emissions of sea-salt and mineral dust are included in the base simulation using emission schemes from Dentener et al. (2006), but they are not affected in the perturbation runs where we consider only perturbations of anthropogenic components. Although for most health and ecosystem impacts only the surface level fields are required, base run and perturbed pollutants concentrations were calculated and stored for the 25 vertical levels of the model as monthly means, and some air-quality relevant parameters as hourly/daily fields. For the present version of TM5-FASST the monthly perturbations are aggregated to annual emission-concentration SR matrices. Surface ozone (and NO_2) fields were stored at hourly intervals allowing for the calculation of specific vegetation and health related ozone metrics, often based on thresholds of hourly ozone concentrations, or concentrations during daytime. The hourly ozone surface fields were converted into specific ozone metrics responses to annual emissions, including accumulated hourly ozone above a threshold of 40 ppbV during a 3 months crop growing season (AOT40), 3-monthly mean of 7 hr or 12 hr daytime ozone during crop growing season (M7, M12), maximum 6-monthly running average of daily maximum hourly ozone (M6M), the sum of daily maximal 8hr ozone mean concentrations above 35ppbV (SOMO35).

BC and POM emissions are assumed not to interact with other pollutants, in particular their atmospheric lifetime is assumed not to be affected by mixing with other soluble species like ammonium salts. Secondary biogenic POM (SOA) was included following the AEROCOM recommendation (Dentener et al., 2006; Kanakidou et al., 2005) which parameterized SOA formation from natural VOC emissions as a fixed fraction of the primary emissions. SOA from anthropogenic emission was not explicitly included in the current simulations. This is a topic for future developments of the model.

Health impact metrics

TM5-FASST provides output of annual mean $PM_{2.5}$ and ozone health metrics (3-monthly and 6-monthly mean of daily maximum hourly ozone (M3M, M6M), and the sum of the maximal 8-hourly mean above 35 ppbV (SOMO35)), as well as annual mean NO_x and SO_2 concentrations at grid resolution of 1°x1°, including customizable exposure threshold. The population-weighted pollutant exposure metrics grid maps, in combination with consistent population grid maps are thus available for human health impact assessment.

Crop impacts

TM5-FASST provides gridded crop ozone exposure metrics (averaged or accumulated over the crop growing season) which can be overlaid with crop production grid maps to evaluate cop relative yield losses for 4 major crops (wheat, rice, maize, soybean). The methodology used is described in detail by Van Dingenen et al. (2009), however gridded crop data (growing season and crop production grid maps) have been updated using Global Agro-Ecological Zones data set (IIASA and FAO, 2012).

Mapping POLES-JRC regions to TM5-FASST source regions

As described above, FASST takes as input annual emissions from each of 56 continental source regions + shipping and aviation (Figure 93). For this study, input emissions were generally prepared at a higher regional aggregation (although for Europe individual country data were provided), therefore the POLES regional aggregation had to be remapped the predefined FASST regions. Individual country level POLES emissions are first estimated per sector by multiplying the POLES regional emission with a country and sector-specific weight factor λ_i, the latter calculated from available RCP gridded emissions for the corresponding year:

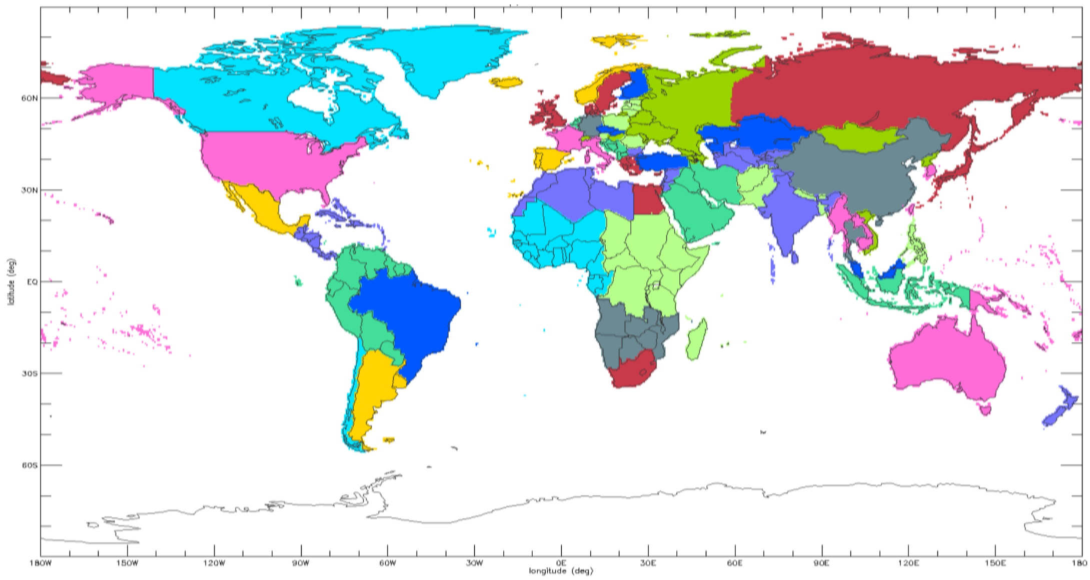
$$EM\_CNTRY_i = \lambda_i \, EM\_REG_{POLES}$$

with $\lambda_i = \frac{EM\_RCP_i}{\sum_j EM\_RCP_j}$

and $\sum_j \lambda_j = 1$

and subsequently re-aggregated to the FASST regions.

Figure 93: 56 continental source regions of the TM5-FASST model



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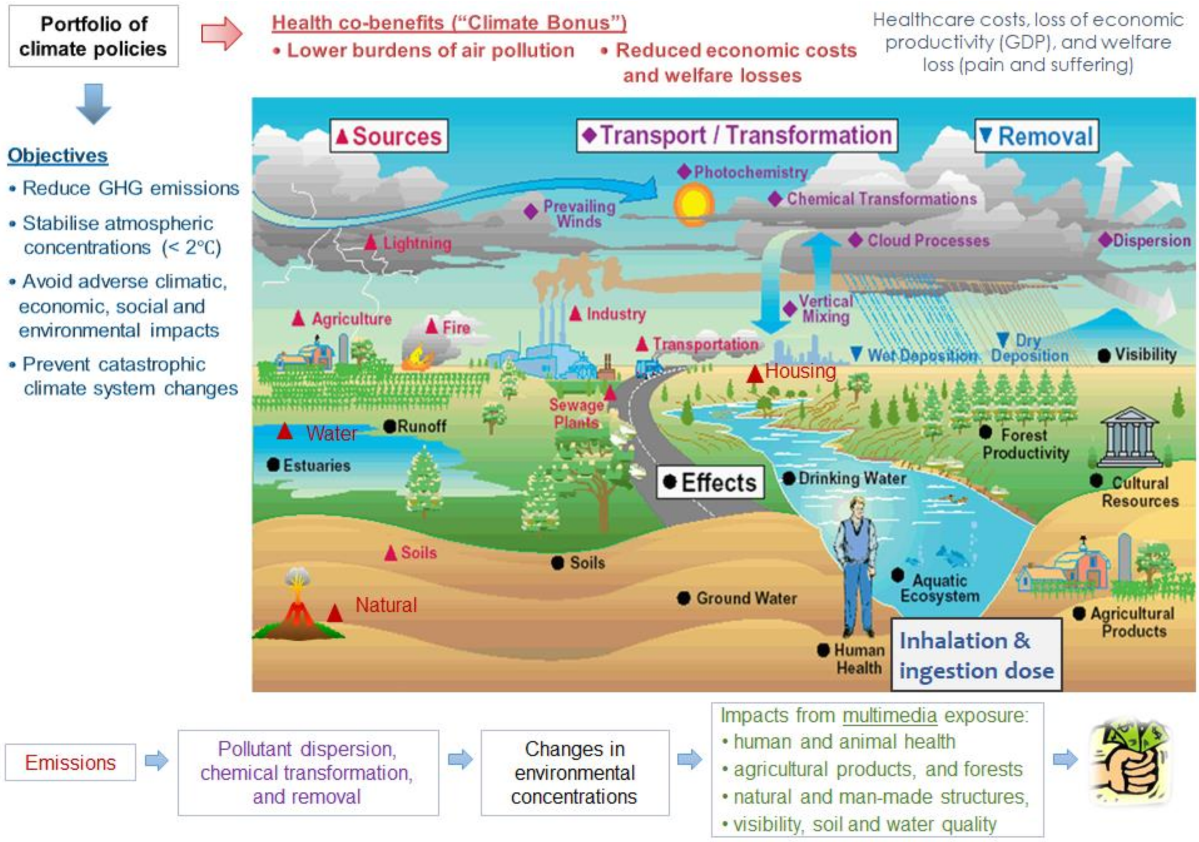
Annex 4 Air pollution health impacts methodology

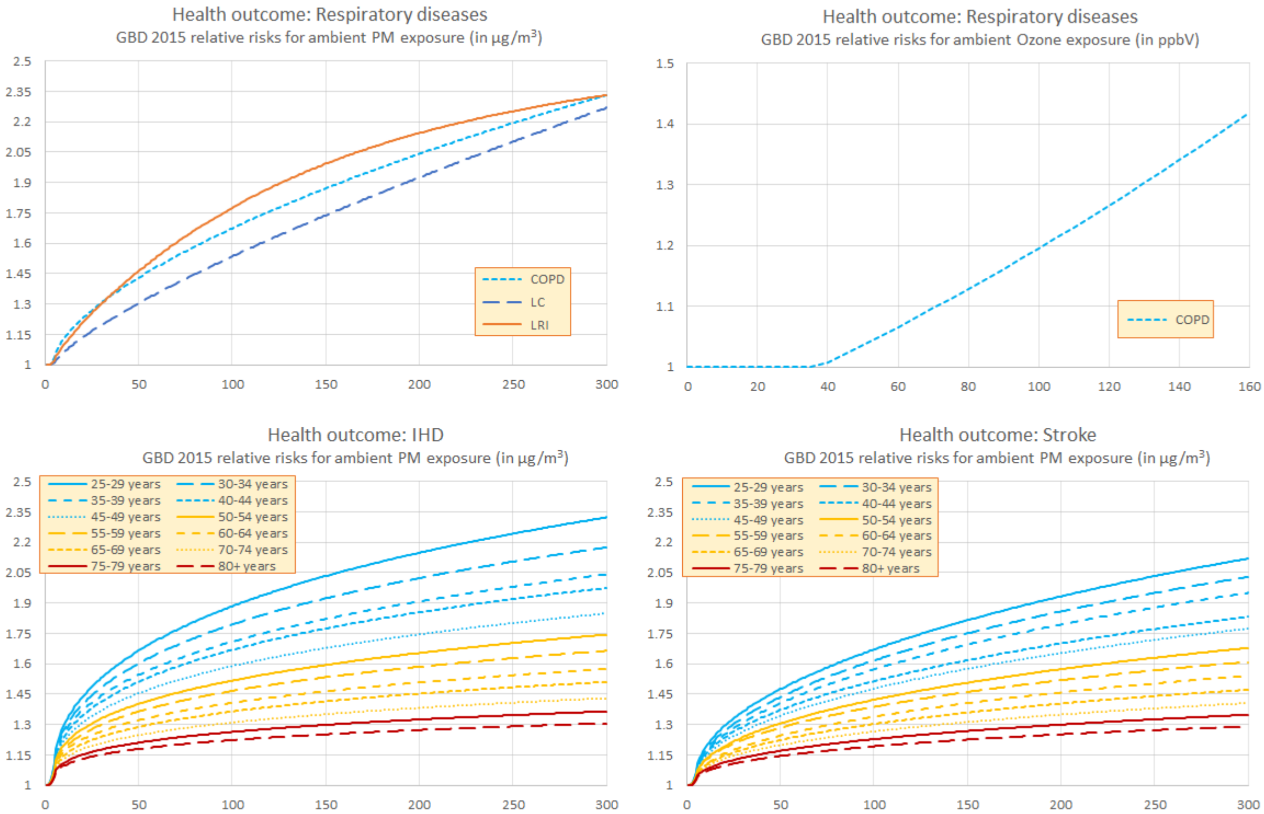
Health impacts are calculated using an "impact pathway" analysis, which explicitly traces the fate of pollutants from the moment they are released into the environment, followed by atmospheric dispersion, and removal by deposition and chemical transformation (Figure 94). Vulnerable population subgroups, such as the sick, children and the elderly, who are exposed to atmospheric contaminants via inhalation and/or ingestion pathways are at a higher risk of suffering from adverse health symptoms, ranging from mild discomfort to more serious life-threatening conditions. Quantified health benefits of reduced emissions include avoided cases of illness (health morbidity), and saved premature deaths. Health effects include bronchitis and asthma attacks in children, chronic bronchitis and work lost days (WLD) in adults, and other illnesses that affect a person's normal daily routine (restricted activity days, RAD), or worse yet may require hospitalization (HA) because of cardio-pulmonary system complications.

Figure 94: Methodology framework for assessing health co-benefits of air quality and climate policies (Impact pathways analysis).



Physical benefits are calculated using epidemiological associations (relative risks, RR) linking ambient air concentration to specific adverse health outcomes in the general public. The relative risk is defined as the ratio of health events in a risk group that is exposed to air pollution and a control group that is unexposed. RR of unity signifies no difference between the two populations. The exposure response functions of the Global Burden of Disease Study 2015 (GBD 2015) for PM2.5 and ozone are illustrated in Figure 95 for various cause-specific mortality outcomes. The excess mortality is calculated using a population attributable fraction (PAF = 1−1/RR), which measures the attributable share of the total burden of disease that is ascribed to ambient air pollution. Multiplying PAF by the baseline mortality rate (values are cause-, age-, and country-dependent) yields the premature deaths from air pollution. Air pollution attributable cases of illness are estimated using morbidity-to-mortality multiplier factors (Table 21).

Figure 95: Exposure response functions of the Global Burden of Disease (GBD) Study 2015 for PM and ozone related mortality calculations.



IHD = Ischaemic Heart Disease; COPD = Chronic Obstructive Pulmonary Disease; LC = Lung Cancer; LRI = Lower Respiratory Infections

Source: Own reconstruction based on personal communication with Dr. Richard Burnett from Health Canada (Ottawa, Ontario, Canada) and information from Institute for Health Metrics and Evaluation, IHME (http://ghdx.healthdata.org/gbd-2015).

Table 21: Morbidity-to-mortality multiplier factors for calculating cases of illness related to ambient air pollution (morbidity = multiplier factor × Total cause-specific deaths).

Illness	$PM_{2.5}$ (Non-Linear)	$PM_{2.5}$ (Linear model)	Ozone
Bronchitis, children [6 to 12 years]	4.82	3.04	
Asthma Symptom Days, children [5 to 19 years]	50.9	32.1	
Chronic bronchitis, adults [older than 27 years]	1.43	0.90	
Work Lost Days, workers [15 to 64 years]	547	345	
Hospital admissions [aged 64+ for ozone]	1.13	0.71	22.48
Minor Restricted Activity Days			23,215
Restricted Activity Days	1,967	1,240	

Annex 5 Detailed energy and climate policies

The following tables provide a full list of the policies considered in the GECO2017 scenarios (see also section 2 for a discussion on how these policies were implemented). The INDC scenario includes the policies already included in the Reference scenario; the B2°C scenario includes all policies included in the INDC and Reference scenarios.

The objectives of all these policies were reached, except in the following cases (noted *in red italic* in the tables below) where they are either superseded by more recent policies or not in track with more recent evolution of the countries' energy system and related emissions:

- 2020 emissions (all scenarios):
    - Norway, Switzerland (emissions result from the same carbon price as for EU28 ETS sectors, reflecting the single EU ETS market)
    - Canada (2020 objective superseded by more recent policy)
    - Mexico (conditional)
    - South Korea (2020 objective superseded by more recent policy)
    - Kazakhstan
- 2025-2030 emissions (INDC and B2°C scenarios):
    - Iceland, Norway, Switzerland (emissions result from the same carbon price as for EU28 ETS sectors, reflecting the single EU ETS market)
    - Morocco & Tunisia (conditional INDC policies very constraining in terms of the effort necessary to reach the target; the policy effort was capped by using the highest carbon value applied in any other country / region by 2030)
- Energy (all scenarios):
    - Several 2020 policies on renewables in transport: EU28, USA, Argentina, China, Indonesia, Thailand, Ukraine, South Africa
    - South Korea (share of renewables 2020-2035)
    - China (share of non-fossil 2020 reached in INDC, not Reference; share of gas 2020 not reached)
    - Malaysia (share of renewables 2020)
    - Thailand (share of renewables 2036)
    - Russia (share of renewables 2020, nearly reached)
    - Turkey (energy efficiency 2020, nearly reached; nuclear capacities 2030: slower development than planned)
    - South Africa (CCS from coal-to-liquids: slower development than planned)
    - Several targets for countries not modelled individually were considered but not necessarily reached (Ecuador, Papua New Guinea, Bangladesh, Jordan, Algeria, Cameroon)
- Other:
    - Several targets expressed for the LULUCF sector not related to emissions were considered but not modelled (Brazil, Chile, Ecuador, Japan, Cambodia, China, India, Vietnam)

An Excel version of these tables along with further detail is available in the GECO website, see: www.ec.europa.eu/jrc/geco.

Table 22: GHG policies in and around 2020 in the Reference scenario

UN Party	GHG coverage	Sectoral coverage	Metric	Base year	Target year	Objective	Source
Europe							
EU28	All GHGs	All excl. LULUCF	Emissions	1990	2020	-20%	EU 2020 Climate and Energy Package (European Commission, 2008)
EU28	All GHGs	ETS sectors	Emissions	2005	2020	-21%	EU 2020 Climate and Energy Package (European Commission, 2008) + 2021-2050 cap linear reduction factor of -1.74%/year
EU28	HFCs	All	Emissions	2012	2019-2036	-10% to -85% over time	Kigali Amendment to the Montreal Protocol
Norway	All GHGs	All	Emissions	1990	2020	-30%	National Communication 6 (UNFCCC, 2014)
Switzerland	All GHGs	All	Emissions	1990	2020	-20%	National Communication 6 (UNFCCC, 2014)
North America							
Canada	All GHGs	All	Emissions	2005	2020	-17%	Copenhagen Accord (UNFCCC, 2009)
Canada	CO2	Power sector	Emissions	2015	2015	*420 gCO_2/kWh for new power plants*	CO_2 standard for new power plants (2012)
Mexico	All GHGs	All	Emissions	2020 (BAU)	2020	*-30%*	Copenhagen Accord (UNFCCC, 2009); National Communication 4 (UNFCCC, 2009)
USA	All GHGs	All	Intensity of GDP	2005	2020	-17%	Climate Action Report (US Department of State, 2014) / National Communication 6 (UNFCCC, 2014)
Central & South America							
Brazil	All GHGs	All	Emissions	2020 (BAU)	2020	-36.1% to -38.9%	Copenhagen Accord (UNFCCC, 2009); National Communication 2 (UNFCCC, 2010)
Chile	All GHGs	All	Emissions	2020 (BAU)	2020	-20%	Copenhagen Accord (UNFCCC, 2009)
Pacific							
Australia	All GHGs	All	Emissions	2000	2020	-5% (conditional: up to -25%)	National Communication 6 (UNFCCC, 2013)
Japan	All GHGs	All	Emissions	2005	2020	-3.8%	Ministry of the Environment (COP19, 2013)
New Zealand	All GHGs	All	Emissions	1990	2020	-5% (conditional: -10% to -20%)	Copenhagen Accord (UNFCCC, 2009); National Communication 6 (UNFCCC, 2013)

South Korea	All GHGs	All excl. LULUCF	Emissions	2020 (BAU)	2020	*-30%*	Copenhagen Accord (UNFCCC, 2009); National Communication 3 (UNFCCC, 2012); Green Grown Act (2016)
Asia							
China	CO_2	All excl. LULUCF	Intensity of GDP	2005	2020	-40% to -45%	Copenhagen Accord (UNFCCC, 2009)
India	GHG	All excl. agriculture	Intensity of GDP	2005	2020	-20% to -25%	Copenhagen Accord (UNFCCC, 2009)
Indonesia	CO_2	Energy, LULUCF	Emissions	2020 (BAU)	2020	-26%	Copenhagen Accord (UNFCCC, 2009); National Communication 2 (UNFCCC, 2012)
Malaysia	All GHGs	All	Intensity of GDP	2005	2020	-40%	National Communication 2 (UNFCCC, 2011)
Thailand	All GHGs	Energy, transport	Emissions	2020 (BAU)	2020	-7% to -20%	Copenhagen Accord (UNFCCC, 2009); Development trajectory (ADBI, 2012)
CIS							
Kazakhstan	All GHGs	All	Emissions	1990	2020	*-15%*	Copenhagen Accord (UNFCCC, 2009)
Russia	All GHGs	All	Emissions	1990	2020	-15% to -25%	Copenhagen Accord (UNFCCC, 2009)
Ukraine	All GHGs	All	Emissions	1990	2020	-20% (conditional: -30%)	Copenhagen Accord (UNFCCC, 2009)
Africa							
South Africa	All GHGs	All	Emissions	2020 (BAU)	2020	-34%	Copenhagen Accord (UNFCCC, 2009); National Communication 2 (UNFCCC, 2011)

Table 23: Energy policies in and around 2020 in the Reference scenario

UN Party	Technology	Metric	Target year	Objective	Source
Europe					
EU28	Renewables	Share in gross final demand	2020	20%	European Commission , DG Energy
EU28	Renewable fuels	Share in transport demand	2020	*10%*	European Commission , DG Energy
EU28	Private vehicles emissions	Emissions, in g/km	2021	95	European Commission , DG Energy
EU28	Energy demand	% reduction vs. BAU	2020	-20% (primary: 1.5 Gtoe, final: 1.1 Gtoe)	European Commission , DG Energy
Switzerland	Renewables	Share in primary demand	2020	24%	Energy Strategy 2050
North America					
Canada	Private vehicles emissions	Emissions, in g/km	2025	88	Canadian Environmental Protection Act
Mexico	Non-fossil + cogeneration	Share in power capacities	2018	34.6%	National Development Plan 2014-2018
Mexico		Capacity targets	2018	Nuclear: 1.4 GW Renewables: 23.3 GW	National Development Plan 2014-2018
Mexico	Non-fossil	Share in power production	2024	35%	Energy Transition Law 2015
USA	Wind, Solar, Geothermal	Power production	2020 vs. 2012	Doubling	White House
USA	Private vehicles emissions	Consumption, miles/gal	2020	54.5	US EPA
USA	Renewables	Production target	2022	*Renewable fuel blended in transport: 36 billion gallons*	Renewable fuel standard (2015)
Central & South America					
Argentina	Renewables	Share in power production	2025	25%	RenovAr, 2016
Argentina	Renewables	Share in transport demand	2016	*12%*	Biofuels Law (2016)
Brazil	Renewables	Share in power production	2020	16%	National Plan on Climate Change (2008)

Brazil		Capacity targets	2024	Biomass: 18 GW Hydro: 117 GW + small hydro 8 GW Nuclear: 3 GW Solar: 7 GW Wind: 24 GW	Decenal Energy Expansion Plan (2024)
Chile	Renewables	Share in power capacities	2025	20% (excl. hydro) (12% in 2020, 18% in 2024)	Non-Conventional Renewable Energy Law (2013)
Chile	Energy demand	% reduction vs. BAU	2020	-12%	Energy Efficiency Action Plan (2012)
Pacific					
Australia	Renewables	Share in power production	2020	23.5%	Australian Government, Department of Environment
Japan	Renewables	Share in power production	2030	24% (13.5% by 2020); 21% for nuclear	Basic Energy Plan (2014)
Japan	Renewables	Capacity targets	2020	Biomass: 5.5 GW Solar: 28 GW Wind: 6 GW	Ministry of Economics, Trade and Industry
Japan	Private vehicles emissions	Consumption, km/l	2020	20.3 (from 16.8 in 2015)	Top Runner Programme (1999)
New Zealand	Renewables	Share in power production	2025	90%	New Zealand Energy Efficiency and Conservation Strategy 2011-2016
S.Korea	Renewables	Share in primary demand	2035	*11% (5% by 2020, 9.7% by 2030)*	4th Basic Plan on New and Renewable Energies (2014)
S.Korea	Renewables	Share in power production	2035	13.4% (10% by 2024, 11.7% by 2029)	7th Basic Plan for Long-term Electricity Supply and Demand (2014)
S.Korea	Private vehicles emissions	Emissions, in g/km	2020	97 (from 140 in 2015)	Fuel efficiency standard (2005)
Asia					
China	Non-fossil	Share in primary demand	2020	*15%*	Copenhagen Accord (UNFCCC, 2009)

China	Renewables	Capacity targets	2020	Hydro: 380 GW Nuclear : 58 GW Solar: 110 GW Wind: 210 GW Biomass: 30 GW	Energy Development Strategy Action Plan (2014-2020)
China	Total energy	Cap	2020	5.0 Gtce	13th Five Year Plan (2016-2020)
China	Coal	Cap	2020	4.2 Gtce	Energy Development Strategy Action Plan (2014-2020)
China	Gas	Share in primary energy	2020	*10%*	Energy Development Strategy Action Plan (2014-2020)
China	Renewables	Production target	2020	*Liquid biofuels: 12 Mt*	Energy Development Strategy Action Plan (2014-2020)
India	Renewables	Capacity targets Additional vs. 2010	2022	Biomass: +10 GW Solar: +100 GW Wind: +60 GW	India's Union Budget 2015-2016
Indonesia	Renewables	Share in power production	2019	19%	Energy and Mineral Resources Ministry
Indonesia	Renewables	Share in transport demand	2025	*15%*	Biofuel targets (2013)
Malaysia	Renewables	Share in power capacities	2020	*10%*	National Renewable Energy Policy and Action Plan (2010)
Malaysia		Capacity targets	2020	Biomass: 0.8 GW Hydro (small): 0.5 GW Solar PV: 0.2 GW	National Renewable Energy Policy and Action Plan (2010)
Thailand	Renewables	Share in primary demand	2036	*30%*	Alternative Energy Development Plan (2015-36) (2015)
Thailand	Renewables	Share in power production	2036	20%	Power Development Plan (2015-36) (2015)
Thailand	Renewables	Share in transport demand	2036	*35%*	Alternative Energy Development Plan (2015-36) (2015)

Thailand	Energy demand	% reduction of energy intensity vs 2010	2036	-30%	Energy Efficiency Plan (2015-36) (2015)
Vietnam	Renewables	Share in primary demand	2020	5%	National Energy Development Strategy 2020 (2013)
Vietnam	Renewables	Share in power production	2020	4.5%	Power Development Plan 2011-2020 (2013)
CIS					
Russia	Renewables	Share in power production	2020	*2.5% (excl. large hydro)*	Renewable energy targets (2013)
Ukraine	Renewables	Share in final consumption	2020	11%	National Action Plan for Renewable Energy (2014)
Ukraine	Renewables	Share in transport demand	2020	*10% (5% by 2014-2015; 7% by 2016)*	Law on Alternative Liquid and Gaseous Fuels (2012)
Ukraine	Renewables	Capacity targets	2020	Biomass: 1 GW Hydro: 5.4 GW Solar: 2.3 GW Wind: 2.3 GW	National Action Plan for Renewable Energy (2014)
Middle East					
Turkey	Energy demand	% reduction of energy intensity vs 2008	2023	*-20%*	Energy Efficiency Law (2012)
Turkey	Renewables	Share in gross final energy consumption	2023	20.5%	National Renewable Energy Action Plan (2014)
Turkey		Capacity targets	2023	Hydro: 34 GW Solar: 5 GW Wind: 20 GW Biomass: 1 GW Geothermal: 1 GW	National Renewable Energy Action Plan (2014)
Turkey	Renewables	Share in power production	2023	30%	Energy Strategy Plan 2010-2014 (2011)
Saudi Arabia	Renewables	Capacity targets	2023	9.5 GW	Vision 2030 (2016)

Africa					
Egypt	Renewables	Share in power production	2020	20%	Egypt Regional Center for Renewable Energy and Efficency
South Africa	Renewables	Capacity targets	2030	Solar: 9.4 GW Wind: 8.5 GW	Integrated Resource Plan (2010, updated 2013)
South Africa	Renewables	Share in transport demand	2007	*2%-10% for bio-ethanol; >5% for biodiesel*	Biofuels Industrial Strategy (2007)

Table 24: Additional GHG policies in 2025-2030 in the INDC scenario

Source: INDCs, unless otherwise noted

UN Party	GHG coverage	Sectoral coverage	Metric	Base year	Target year	Target	BAU emissions at Target year (Mt)
All	HFCs	All sectors	Emissions	Kigali Amendment to the Montreal Protocol: trajectory to -85% of BAU depending on country group			
Europe							
Albania	CO_2	Energy, industrial processes	Emissions	2030 (BAU)	2030	-11.5%	5.9
EU28	All GHGs	All sectors	Emissions	1990	2030	-40%	
EU28	All GHGs	ETS sectors	Emissions	2005	2030	-43% - European Commission , DG Energy + 2021-2050 cap linear reduction factor of -2.2%/year	
Iceland	All GHGs	All sectors	Emissions	1990	2030	-40%	
Macedonia (FYROM)	CO_2	FF combustion	Emissions	2030 (BAU)	2030	-36%	17.7
Norway	All GHGs	All sectors (LULUCF net-net)	Emissions	1990	2030	-40%	
Serbia	All GHGs	All sectors	Emissions	1990	2030	-9.8%	
Switzerland	All GHGs	All sectors	Emissions	1990	2030	-50%	
North America							
Canada	All GHGs	All sectors (LULUCF net-net)	Emissions	2005	2030	-30%	
Mexico	All GHGs	All sectors	Emissions	2030 (BAU)	2030	-36%	973
USA	All GHGs	All sectors (LULUCF net-net)	Emissions	2005	2025	-28%	
USA	CO_2	Power sector	Emissions	2005	2030	-32% - Clean Power Plan (2014)	
USA	CH_4	Oil and gas production	Emissions	2012	2025	-45% - Climate Action Plan: Strategy to Reduce Methane Emissions (2016)	
Central & South America							
Argentina	All GHGs	All sectors	Emissions	2030 (BAU)	2030	-30%	670
Brazil	All GHGs	All sectors	Emissions	2005	2025	-37%	

Chile	All GHGs	All sectors excl. LULUCF	Intensity of GDP	2007	2030	-45%	
Colombia	All GHGs	All sectors	Emissions	2030 (BAU)	2030	-30%	335
Costa Rica	All GHGs	All sectors	Emissions	2012	2030	-25%	
Dominican Republic	CO_2, CH_4, N_2O	All sectors	Emissions	2010	2030	-25%	
Ecuador	CO_2, CH_4, N_2O	Energy	Emissions	2025 (BAU)	2025	-45.8%	n/a
Grenada	CO_2, CH_4	Electricity, Transport, Waste, Forestry	Emissions	2010	2025	-30%	
Peru	CO_2, CH_4, N_2O	All sectors	Emissions	2030 (BAU)	2030	-30%	298
Venezuela	CO_2	Energy	Emissions	2030 (BAU)	2030	-20%	340
Pacific							
Australia	All GHGs	All sectors	Emissions	2005	2030	-28%	
Japan	All GHGs	All sectors excl. sinks	Emissions	2013	2030	-26%	
Korea (Republic)	All GHGs	All sectors excl. LULUCF	Emissions	2030 (BAU)	2030	-37%	851
Marshall Islands	CO_2, CH_4, N_2O	All sectors	Emissions	2010	2025	-32%	
New Zealand	All GHGs	All sectors (LULUCF net-net)	Emissions	2005	2030	-30%	
Asia							
Afghanistan	CO_2, CH_4, N_2O	All sectors	Emissions	2030 (BAU)	2030	-13.6%	48.9
Bangladesh	All GHGs	Power, transport and industry	Emissions	2030 (BAU)	2030	-15%	234
Cambodia	CO_2, CH_4, N_2O	Energy	Emissions	2030 (BAU)	2030	-27%	11.6
China	CO_2	Energy	Intensity of GDP	2005	2030	-65%	
China	CO_2	All sectors	Emissions		2030	Peak around 2030	
India	All GHGs	All sectors	Intensity of GDP	2005	2030	-35%	

Indonesia	All GHGs	All sectors	Emissions	2030 (BAU)	2030	-41%	2881
Malaysia	CO_2, CH_4, N_2O	All sectors	Intensity of GDP	2005	2030	-45%	
Philippines	All GHGs	All sectors	Emissions	2030 (BAU)	2030	-70%	n/a
Singapore	All GHGs	All sectors	Intensity of GDP	2005	2030	-36%	
Thailand	All GHGs	All sectors excl. LULUCF	Emissions	2030 (BAU)	2030	-25%	555
Vietnam	All GHGs	All sectors	Emissions	2030 (BAU)	2030	-25%	787
CIS							
Azerbaijan	All GHGs	Energy, agriculture, waste, LULUCF	Emissions	1990	2030	-35%	
Belarus	All GHGs	All sectors excl. LULUCF	Emissions	1990	2030	-28%	
Kazakhstan	All GHGs	All sectors	Emissions	1990	2030	-25%	
Moldova	All GHGs	All sectors	Emissions	1990	2030	-67%	
Russian Federation	All GHGs	All sectors	Emissions	1990	2030	-30%	
Tajikistan	CO_2, CH_4, N_2O	All sectors	Emissions	1990	2030	-35%	
Ukraine	All GHGs	All sectors excl. LULUCF	Emissions	1990	2030	-40%	
Middle East							
Iran	All GHGs	All sectors	Emissions	2030 (BAU)	2030	-12%	n/a
Iraq	CO_2, CH_4, N_2O		Emissions	2035 (BAU)	2035	-15%	305
Israel	All GHGs	All sectors excl. LULUCF	Emissions	2030 (BAU)	2030	-22.6%	106
Lebanon	CO_2, CH_4, N_2O	All sectors	Emissions	2030 (BAU)	2030	-30%	43.6
Saudi Arabia	All GHGs	All sectors excl. LULUCF	Emissions	2030 (BAU)	2030	-130 $MtCO_2e$	n/a

Turkey	All GHGs	All sectors	Emissions	2030 (BAU)	2030	-21%	1175
Africa							
Algeria	CO_2, CH_4, N_2O	All sectors	Emissions	2030 (BAU)	2030	-22%	n/a
Burkina Faso	CO_2, CH_4, N_2O	All sectors	Emissions	2030 (BAU)	2030	-18.2%	118
Cameroon	CO_2, CH_4, N_2O	Energy, agriculture, forestry, waste (no LULUCF)	Emissions	2035 (BAU)	2035	-32%	104
Central African Republic	CO_2, CH_4, N_2O	All sectors	Emissions	2030 (BAU)	2030	-5%	110
Congo (Dem. Rep.)	CO_2, CH_4, N_2O	Energy, agriculture, forestry (no LULUCF)	Emissions	2030 (BAU)	2030	-17%	430
Côte d'Ivoire	All GHGs	All sectors excl. LULUCF	Emissions	2030 (BAU)	2030	-36%	34
Equatorial Guinea	CO_2, CH_4, N_2O	All sectors	Emissions	2010	2030	-20%	
Ethiopia	CO_2, CH_4, N_2O	All sectors	Emissions	2030 (BAU)	2030	-64%	400
Gambia	All GHGs	All sectors excl. LULUCF	Emissions	2010	2030	-45.4%	
Ghana	All GHGs	All sectors	Emissions	2030 (BAU)	2030	-45%	74
Guinea	All GHGs	Energy, agriculture	Emissions	2030 (BAU)	2030	-13%	53
Kenya	CO_2, CH_4, N_2O	All sectors	Emissions	2030 (BAU)	2030	-30%	143
Madagascar	CO_2, CH_4, N_2O	All sectors (net of sinks)	Emissions	2030 (BAU)	2030	-14%	214
Morocco	CO_2, CH_4, N_2O	All sectors	Emissions	2030 (BAU)	2030	*42%*	170
Niger	CO_2, CH_4, N_2O	All sectors	Emissions	2030 (BAU)	2030	-34.6%	96
Nigeria	CO_2, CH_4, N_2O	All sectors	Emissions	2030 (BAU)	2030	-45%	850

Sao Tome and Principe	CO_2, CH_4, NO_x	All sectors	Emissions	2030 (BAU)	2030	-24%	240
South Africa	All GHGs	All sectors	Emissions		2030	2020-2035: plateau at 398-614 MtCO2e	
Tanzania	All GHGs	All sectors (gross emissions)	Emissions	2030 (BAU)	2030	-20%	146
Tunisia	All GHGs	All sectors	Intensity of GDP	2010	2030	*-41%*	
Zambia	CO_2, CH_4, N_2O	Energy, Agriculture, Waste, LULUCF	Emissions	2030 (BAU)	2010	-47%	80

Table 25: Additional energy policies in 2025-2030 in the INDC scenario

Source: INDCs, unless otherwise noted

UN Party	Technology / Sector	Metric	Target year	Objective
Europe				
EU28	Renewables	Share in gross final demand	2030	27% - European Commission , DG Energy
Central & South America				
Brazil	Renewables	Share in of liquid biofuels	2030	18%
Brazil	Renewables	Share in primary energy	2030	45%
Brazil	Renewables excl. hydro	Share in primary energy	2030	28-33%
Brazil	Renewables excl. hydro	Share in power production	2030	23%
Pacific				
Japan	Nuclear	Share in power production	2030	20-22%
Japan	Renewables	Share in power production	2030	22-24%
Asia				
China	Non-fossil fuels	Share in primary energy	2030	20%
India	Non-fossil fuels	Share in new power capacity	2030	40%
Indonesia	Renewables	Share in primary energy	2025	23%
Middle East				
Turkey	Renewables	Capacity	2030	Wind: 16 GW Solar: 10 GW
Turkey	Nuclear	Capacity	2030	*Commissioning of a nuclear power plant*
Africa				
South Africa	Coal-to-liquids	CO2 captured and stored	2050	*23 Mt* CO_2
South Africa	Plug-in vehicles	Share in vehicles	2030	20%

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