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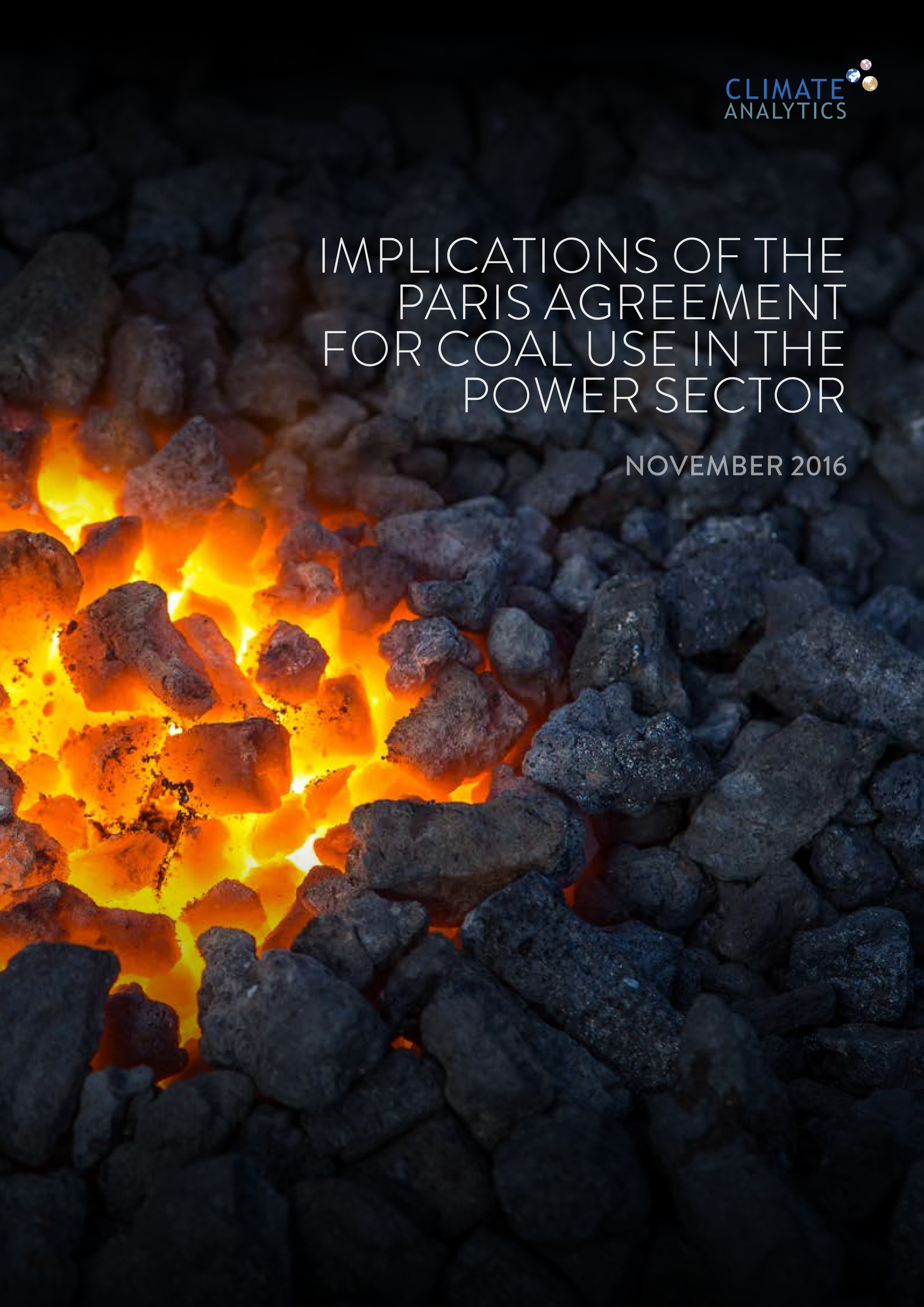

IMPLICATIONS OF THE PARIS AGREEMENT FOR COAL USE IN THE POWER SECTOR

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CLIMATE ANALYTICS

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KEY FINDINGS

The long-term temperature goal adopted in the Paris Agreement (PA) of holding temperature increase to "well below 2°C and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels" requires a rapid decarbonisation of the global power sector.

Energy-system models show that the phase out of unabated coal-fired power plants needs to take place around mid-century globally. Under a least-cost strategy, coal phase out dates differ across regions in the world: the EU and the OECD would need to phase out coal by 2030, China by 2040 and the rest of the world, including the majority of emerging economies, would need to phase out coal by 2050.

The OECD and the EU, with earlier phase out dates, need to take the lead worldwide in implementing policies and a process to move away from coal. From a fairness perspective, overall emissions reductions in these regions need to be complemented by financial transfers for mitigation measures in developing regions.

Current coal plans worldwide are inconsistent with the Paris Agreement and point to a large risk that economies and societies are running if they were to implement current plans.

For all regions assessed here, the need for coal phase out on the next decades to meet the Paris Agreement long term temperature goal stands in strong contrast with the current and planned coal-based generation capacity.

- Cumulative emissions from current coal capacity (operating and under construction) of 2.308 GW exceed the cost-optimal CO_2 emissions budget in line with the Paris Agreement long-term temperature goal until the end of the century.
- We estimate the world is currently planning on building 1082 new (permitted or pre-permitted) coal-fired power plants with combined capacity of around 596GW, which would go on top of the already exceeding capacity from operating plants. If this new capacity would be built, it would lock-in the energy infrastructure of many countries on a carbon-intensive pathway for at least the next 40 years.

The longer the world continues to use coal as currently planned, the higher the reliance will be on negative emissions technologies in the second half of the century. Early, ambitious and concerted action is needed worldwide to hedge against the risk that negative emissions technologies will not deliver within the timeframe and scale needed and the associated technical, sustainability and other challenges.

To achieve the Paris Agreement temperature goal, countries will have to implement early retirement of power plants, reduce their utilization rate, and refrain from building new capacity.

This report finds that the available tools to model the global energy system, including IAMs but also other types of energy system models such as the IEA World Energy Model, IRENA and Greenpeace Revolution models, provide broadly consistent results in terms of emissions reductions during the first half of the century (although different models will achieve emissions reductions in very different ways).

These studies all show that a rapid energy transition is possible now.

Numerous alternatives to coal exist and the development of renewable energy sources is gaining momentum as many of them offer benefits and opportunities that go beyond emissions reduction, such as cleaner air, increased energy security, independence and access.

There is an increasing coal vulnerability in different parts of the world that is clearly visible in the fact that in 2015 coal production decreased for the first time since the 1990s. Apart from climate change concerns this is driven by factors including that coal is the lead cause of air pollution, especially in the case of the open-pit mining, destruction of whole ecosystems and the fact that its import has negative impacts on trade balance of the importing countries.

Even though more coal-fired power plants continue to be built globally, the utilization rate of the current coal fleet continues to decline in several countries such as the USA, China, India and others. This is affecting the willingness of energy companies to invest in new coal-fired projects and is also decreasing their credit ranking, thus increasing the costs of debt and making major investments more expensive and vulnerable.

Strengthening government's commitment to climate policy by ambitious yet feasible NDCs, removing subsidies for fossil fuels, and building support for renewables and energy efficiency offer new opportunities for developed and the developing countries to build a low-carbon economy in line with the commitments made in Paris. This would at the same time avoid the risks and costs of stranded assets, encourage large institutional investors to increase their involvement in the low-carbon economy and move away from exposure to risky coal investments.


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BACKGROUND AND OBJECTIVE

At the 21ST session of the Conference of Parties (COP21) in December 2015, 195 countries adopted the Paris Agreement, which obliged its signatories to strengthen their efforts in fighting against climate change and its consequences. At its core the Agreement includes a goal of **holding global warming to "well below 2°C and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels".**

This long-term temperature goal is linked to another goal of bringing global greenhouse gas emissions to effectively zero in the second half of the 21ST century. The exact timeframe shall be developed on the basis of the best available scientific evidence. The Paris Agreement has been ratified in record time and will enter into force on 4 November 2016.[1]

While the technologies needed for reducing emissions to achieve 2°C are the same as those necessary to limit global warming to maximum 1.5°C by 2100, they need to be deployed faster and be complemented by actions decreasing energy demand (Schleussner et al., 2016).

According to the most recent scientific literature[2], meeting the Paris Agreement goal requires a rapid decarbonisation of the power sector, with the share of unabated coal, i.e. coal-fired power plants without carbon capture and storage, declining rapidly from today's levels until they are phased out completely around mid-century globally.

Longer utilization of unabated coal than currently projected in the models will have to be compensated by respectively higher negative emissions in the second half of the century. Should the availability of negative emissions be limited due to technological or sustainability reasons, coal phase out will be necessary much earlier to achieve the Paris Agreement long-temperature goal.

The necessity of a quick coal phase out in the next decades stands in strong contrast with the current and planned coal-based generation capacity.

A recent analysis of the "Coal Gap" by the Climate Action Tracker (Climate Action Tracker, 2015) highlighted that even with no new construction, emissions from existing coal-fired power plants in 2030 would be 150% higher than what is consistent with scenarios limiting warming to below 2°C above pre-industrial levels globally. The analysis comes to the conclusion that if the planned new coal capacity estimated by the Global Coal Plant Tracker (GCPT) were to be built, the emissions would exceed the remaining carbon budget for coal use by 400%.[3]

The goal of this report is to provide reliable and detailed information on the implications of the Paris Agreement long-term temperature goal (and for comparative purposes of the previous below 2°C target) for current and planned coal capacity globally and in specific regions such as the OECD, EU28 and China.

Given their relatively long retirement age (the global average lifetime of a coal power plant is of around 40-50 years), any additional coal-fired power plants built today represent an important lock-in in emissions that is not in line with the Paris Agreement long-term temperature goal. It is therefore crucial to inform policymakers responsible for the energy policy that they need to consider the role of coal in the energy mix of their respective countries and adjust policies accordingly.

Currently, there still appears to be a "gap between what politicians have signed up to in Paris and what markets and fossil fuel companies are assuming" (Zenghelis & Stern, 2016). From a financial perspective, this means that there is a need for investors to carefully analyse the risks to such high-carbon assets to avoid additional wasted capital and stranded assets (Carbon Tracker Initiative, 2013) and for policymakers to send clear policy signals.

1 As of 14 October 2016, 191 countries signed the Agreement, meaning these countries are now obliged to refrain from acts that would defeat the treaty's object and purpose; another 76 countries both signed and ratified, thereby signaling their intent to be legally bound by the terms of the treaty.

2 Scenarios consistent with limiting warming to below 2°C or 1.5°C in the IPCC Fifth Assessment Report (IPCC, 2014a)

3 The budget for coal is calculated using the AR5 Integrated Assessment Model Scenarios.

ANALYTICAL FRAMEWORK

To provide information about the compatibility between the existing and planned coal-fired power plants and the long-term climate goals stated in the Paris Agreement in the European Union (EU)[4], OECD[5], China and the rest of the world,[6] we performed the following analysis:

First, the *capacity* and *resulting emissions* of the *existing and planned* coal-fired power plants was estimated using the Global Coal Plant Tracker (GCPT) database. The GCPT provides information on every known coal-fired electrical generating unit ever installed, including location, status, investor, capacity, combustion technology and fuel (Global Coal Plant Tracker, 2016).

Second, we estimated coal-related CO_2 emissions in line with the Paris Agreement long-term temperature goal using the Integrated Assessment Model (IAM) MESSAGE.[7] Given their high complexity, IAMs stipulate least-cost pathways at a regional level. In order to obtain specific regional and country results, we downscaled results for the aggregated coarse IAMs regions using Climate Analytics' in-house model SIAMESE (Simplified Integrated Assessment Model with Energy System Emulator). For details on the downscaling method and on SIAMESE, refer to Annex V: SIAMESE.

In addition, the emissions from existing and planned coal-fired power plants are compared to emissions allowances in line with equity. It differs from the least cost approach as it takes into consideration not only the lowest costs, but also a number of different elements, such as historic responsibility, mitigation potential and capability of a country or region to take action. The approach employed here to evaluate emissions allowances in line with equity is based on a range of equity proposals, criteria and metrics put forward by the scientific community and different countries.

Lastly, the report offers some insights into the alternatives that could replace conventional[8] coal-fired power generation capacity, based on a range of energy-system models.

I. TRANSLATING THE PARIS AGREEMENT INTO EMISSIONS SCENARIOS

The energy-economic scenarios analysed in this report, as well as those referred to in the IPCC's Working Group III part of the Fifth Assessment Report, identify the technical and economic conditions required to achieve the Paris Agreement long-term temperature goals. These scenarios lay out the technological options and estimate increases or decreases in overall costs if certain options (like energy efficiency improvements, availability of negative emissions technologies or nuclear power) were to be included, excluded, or limited.

The scenario literature provides ample energy-system emissions scenarios consistent with holding warming to below 2°C, with various degrees of likelihood of exceeding this level, which reflect the uncertainty around temperature responses of the Earth's system to changes in greenhouse gas concentrations in the atmosphere.

Based on the scientific literature and consensus built over the years, the Cancun Agreements goal of holding warming below 2°C is interpreted consistently with the "likely below" 2°C class scenarios, that is, **2°C scenarios that have a 66% chance, or greater, of staying below a 2°C global mean warming** above pre-industrial levels throughout the 21[ST] century.

More than two decades of international climate negotiations laid the groundwork for the legally binding goals of the Paris Agreement[9]. The Paris Agreement goes well beyond the below 2°C limit of the Cancun Agreements both substantively and legally. The Paris Agreement long term temperature goal is a legally binding and set within the

4 Includes the 28 member states of the European Union in 2015.

5 Includes: Australia, Austria, Belgium, Canada, Chile, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Israel, Italy, Japan, Mexico, Netherlands, New Zealand, Poland, Slovakia, Slovenia, South Korea, Spain, Sweden, Turkey, United Kingdom and United States.

6 All countries not part in the OECD region and China. There is an overlap between the regions EU28 and the OECD.

7 The MESSAGE model provides a flexible framework for the comprehensive assessment of major energy challenges and has been applied extensively for the development of energy scenarios and the identification of socioeconomic and technological response strategies to these challenges. Further details on the model can be found at http://www.iiasa.ac.at/web/home/research/modelsData/MESSAGE/MESSAGE.en.html

8 We do not consider coal power plants with Carbon Capture and Sequestration (CCS) as this technology is still in its early stages. There are a few planned power plants in the GCPT data base that shall be equipped with CCS, but are excluded from our analysis since CCS represents a very different technology compared to non-CCS plants. Retrofitting existing plants with CCS might be viable for a certain share of the global coal power plants fleet and would present an alternative option to early retirement of the existing capacity.

9 Mace, M.J., 2016. Mitigation Commitments Under the Paris Agreement and the Way Forward. Climate Law, 6, pp.21–39.

context of legally binding treaty, whereas the Cancun Agreements were only part of a UNFCCC COP Decision. The Paris Agreement has the goal of hold warming to *well below* 2°C and to pursue efforts to limit temperature increase to 1.5°C.[10] Whilst is should be noted that the range and depth of literature available for the evaluation of 1.5°C limit is not as ample as for the "likely below" 2°C class of scenarios, sufficient scenarios are available to allow a first order and robust analysis of the differences between these two temperature goals .

The vulnerable countries have argued that the Paris Agreement long-term temperature goal means limiting global mean warming to 1.5°C above pre-industrial, without overshoot. Scenarios that limit warming to 1.5°C (or below) throughout the 21ST century are only now entering the literature and are not available for this analysis[11]. The lowest scenarios published to date overshoot a 1.5°C global mean warming above preindustrial in the 21ST century by about 0.1 to 0.2°C, before returning to 1.5°C or below in 2100 with a 50% likelihood (median warming in 2100 of 1.4°C).

We have used these available scenarios, which **hold warming below 2°C with 85% probability, or greater, and with a more than 50% chance of remaining below 1.5°C by 2100**[12], as a proxy for 1.5°C consistent scenarios, recognising that many countries may view scenarios that overshoot the 1.5°C limit as being inconsistent with the Paris Agreement long-term temperature goal.

This interpretation of the Paris Agreement temperature goal requires that global GHG emissions are reduced by 70-95%[2] below 2010 (which is equivalent to 65-90% below 1990) levels by 2050, and reach globally aggregated zero GHG emissions by 2060-2080. In contrast, the Cancun Agreements goal implied that global greenhouse gas emissions need to be reduced by 40-70%[13] in 2050 below 2010 (which is equivalent to 35-55% below 1990) levels and reach globally aggregated zero emissions by 2080-2100.

To ensure maximum relevance of this analysis for policymaking focused on the post-2020 timeframe, we require scenarios with global GHG emissions by 2020 as close as possible to current emissions projections. We opt therefore to select from a class of scenarios in the literature that are often called "delayed action" scenarios, as opposed to those that are often termed "immediate action" scenarios.

Delayed action scenarios usually assume that countries will meet their Copenhagen Accord pledges for 2020, before beginning deeper action to meet a long-term temperature goal, as opposed to immediate action scenarios, which assume strong global concerted climate action starting all in 2010[14]. In such scenarios emissions in 2020 are significantly lower than those that are implied by full implementation of the Copenhagen Accord 2020 pledges. All scenarios used in this report are from the MESSAGE model. For more detailed information on the scenarios selection refer to: Integrated Assessment Model scenarios selection.

Based on the considerations described in the previous section, we selected the following scenarios from the Integrated Assessment model MESSAGE (IIASA, 2016), which form the basis of this analysis:

- **Paris Agreement 1.5°C scenario with overshoot**: Pathway that accelerates global action from 2020 onwards and temporarily allows for an increase in temperature by more than 1.5°C in the 21ST century. However, due to reduction in emissions and later CO_2 removal from the atmosphere, the average increase in temperature goes down to 1.5°C by 2100 with 50% probability.

- **Cancun Agreements 2°C scenario:** Pathway that accelerates global action from 2020 onwards to hold warming below 2°C by 2100 with probability of at least 66%.

10 A discussion of the history of the Paris Agreement long term temperature goal can be found in Annex I

11 Results of the ADVANCE project (http://www.fp7-advance.eu) are consistent with the scenario results used here under drawn from a wider range of Integrated Assessment Models.

12 The 1.5°C scenarios underlying the emissions numbers here have a more than 50% chance of returning to below 1.5°C by 2100 and simultaneously have a probability of about 85% to hold warming below 2°C during the 21ST century.

13 These numbers are drawn directly from the IPCC AR5 Working Group III Summary for Policymakers (2014). The other numbers in this section draw from all scenarios assessed by the IPCC Fifth Assessment Report and the 2014 UNEP Emissions Gap Report (2014)and follow the methodologies of the 2014 UNEP Emissions Gap Report, to enable a direct comparison of these other numbers with the information provided in the 2014 UNEP Emissions Gap Report for 2 °C.

14 IAMs usually compute results for periods of five or ten years. MESSAGE has 10 year intervals from 2010 onwards. Since the scenarios prepared for AR5 were run before 2014 – the year when AR5 was published – the first period for which *immediate* climate policy is assumed is 2010, whereas it is 2020 for *delayed* climate policy.

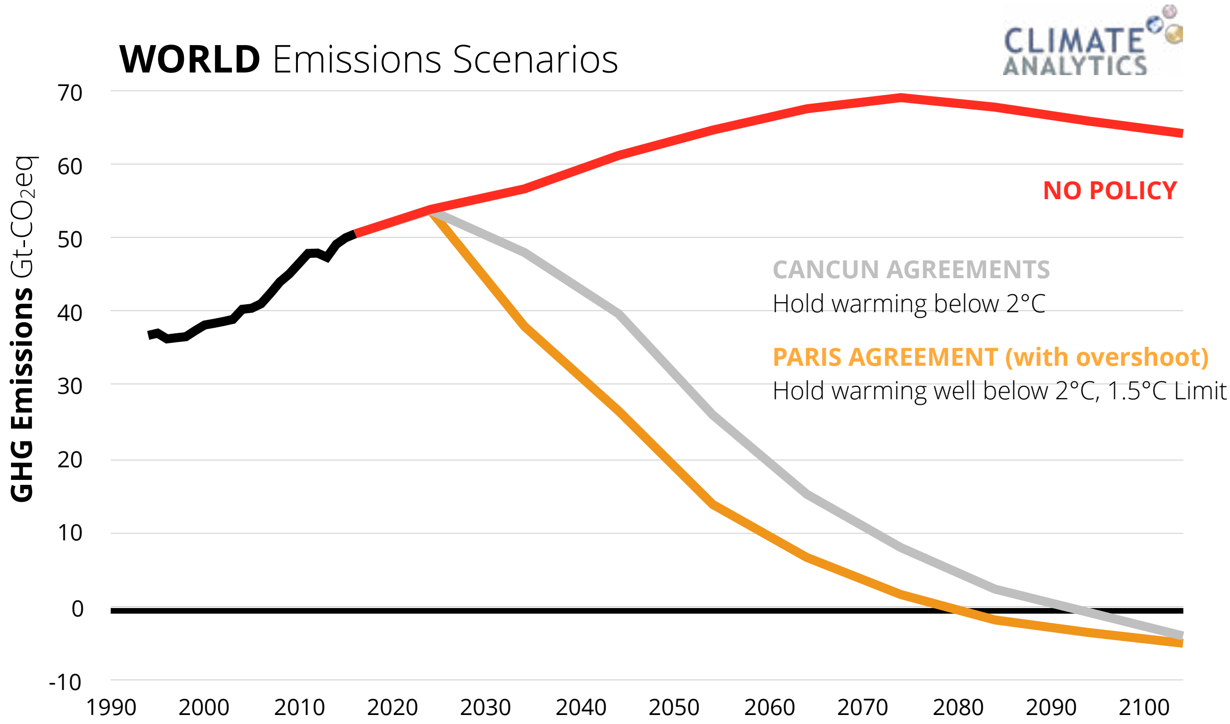

Figure 1: Global policy-relevant emissions scenario cases. GHG emissions, including LULUCF. Source IIASA/Joeri Rogeli

II. COAL EMISSIONS IN LINE WITH THE PARIS AGREEMENT

Based on the chosen global emissions scenarios, we derived the pathways from electricity generation from coal in line with the Paris Agreement 1.5°C temperature limit (and for comparative purpose for the Cancun Agreements 2°C goal). While coal is used in various other sectors, such as iron and steel production and the cement industry, the vast majority of coal is used in power generation. Moreover, due to the recent rapid decrease in the costs of low-and zero-carbon alternatives, power generation constitutes the sector where coal can be replaced the most rapidly and with the greatest co-benefits.

The emissions scenarios used for estimating coal emissions in line with the Paris Agreement achieve emissions reductions through the deployment of a number of technologies. Among these technologies, the model includes the use of carbon capture and storage (CCS) in coal power stations. In this report, we focus on the relevance of coal-fired power stations for Earth's climate. In the MESSAGE model coal power plants with CCS are assumed to emit little or no CO_2 into the Earth's atmosphere, and hence are not relevant for emissions budget considerations. In reality, coal power plants with CCS are very likely to emit around a tenth[15] of the average emissions in comparison to an installation without CCS. In much of the following analysis we consider that deployment of CCS for fossil fuel power plants is unlikely given the reduction in efficiency and high costs, especially with the costs of alternatives decreasing rapidly.

Figure 2 shows the cost-optimal global emissions from coal power plants over the remainder of the 21ST century. According to these pathways, worldwide emissions from coal need to become (close to) zero by 2050 to be in line with the Paris Agreement and around 2060 to be in line with the Cancun Agreements.[16]

Emissions need to decline very rapidly in both scenarios after 2020: for the Paris Agreement compatible pathway, global emissions from coal need to fall by around three quarters from close to 10 $GtCO_2$ per year in 2020 to around 2.5 $GtCO_2$ per year in 2030. The following sections show that this can only be achieved with early retirement of operating power plants, so there is no rationale for supporting the construction new plants.

15 http://www.iea.org/topics/ccs/

16 Year of reductions of 90% or more below 2010 levels - analogous to assessment of emissions from energy supply sector in IPCC AR5 WG3 (SPM)

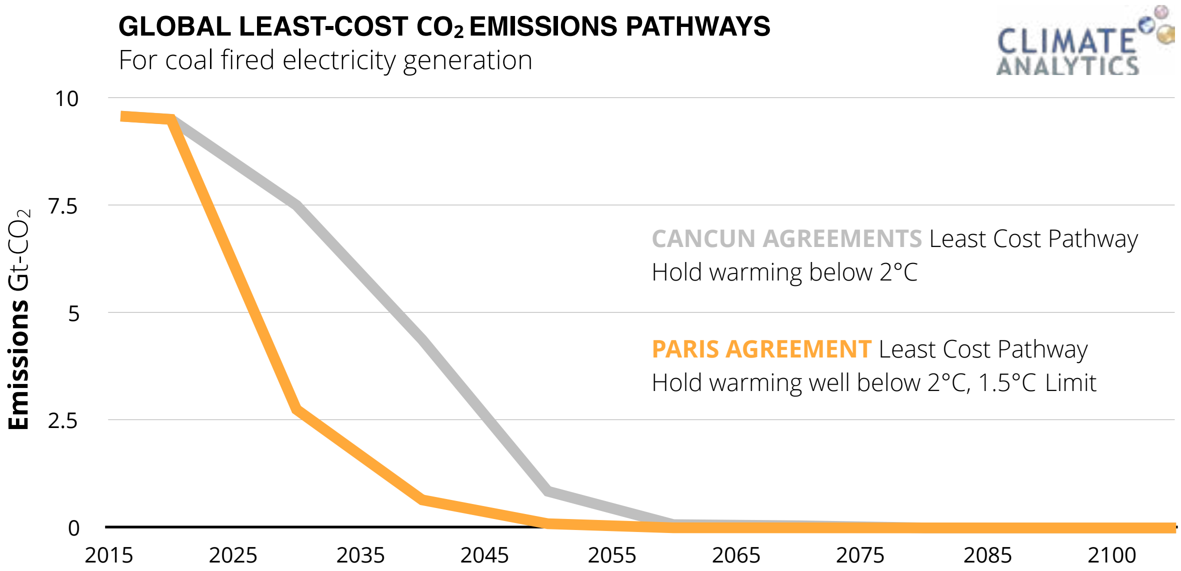

Figure 2: Global least–cost CO2 emissions pathways for coal fired electricity generation. Source IIASA/Joeri Rogeli, own calculations

III. IAM SCENARIO LIMITATIONS AND COMPARISON WITH OTHER ENERGY SYSTEM MODELS

IAM models and limitations

IAMs combine the current knowledge of energy systems and climate-model projections to identify economically and technologically feasible emissions pathways consistent with a temperature limit, while minimising global costs. **IAMs consider a timeframe spanning from the recent past until the end of the 21ST century** and divide the world into about a dozen regions. IAMs provide so-called optimal **"least-cost" or "cost-optimal" pathways**, as the results are based on a global cost-minimisation approach.

IAMs explicitly encompass the interplay between the increasing economic activity, the energy sector, and the implications for climate change. Each of those is usually represented in dedicated modules.

The economy module consists of a stylised representation of economic activities like GDP, consumption, investments, and trade between regions. The energy module calculates future energy demand, based on socioeconomic projections (GDP and population) and energy prices. A land use module takes into account other physical trade-offs, such as the availability of biomass. Finally, total GHG emissions are used to compute the reaction of Earth's climate using the climate model.

A solution algorithm maximizes an economic utility function under a set of constraints. **By imposing a constraint on the carbon budget, radiative forcing or global temperature increase, IAMs provide global least-cost mitigation pathways, i.e. they find the globally cheapest way to achieve the climate target.**

According to the literature on IAMs results, the earlier strong climate action is implemented, the cheaper the combined global cost of meeting a temperature limit over the whole of the century. This conclusion is quite robust across all IAMs.

However, as model updates are time consuming, IAMs often rely on outdated information regarding for example the near-term effect of current developments in energy, air pollution and climate policies, and recent developments in energy technologies and markets, like the price of renewables which is now decreasing at a faster pace than expected. An outdated representation of the latter usually results in higher penetration rates of CCS technologies to the detriment of renewables in the short term. Another limitation is the lack of co-benefits considerations (like decreased air pollution and avoided damages like less sea-level rise), which are not accounted for monetarily in those models.

Also, IAMs assume perfect markets with mitigation scenarios often being implemented via a global emissions trading scheme, which usually leads to large financial transfers from high-income countries to lower income regions where mitigation is cheaper. **These models may therefore result in deeper emissions reductions in low-income countries in comparison to approaches that take into account fairness principles.** Therefore, IAM results should be taken with a "grain of salt" as non-economic considerations associated with such financial transfers could be seen as unrealistic or undesirable.

Finally, IAMs do not model "short-term" dynamics. These models typically assume "perfect foresight" (that is, all relevant information over the whole model time horizon is available and taken into account) and therefore find the optimal solution throughout the whole century, unless near-term dynamics are explicitly prescribed (such as near-term mitigation "delay" compared the cost-optimal, early action pathway). Notably, most IAMs provide projections only for time steps of 5 or 10 years apart. In this regard, **other models can complement IAMs results and provide more relevant insights in the short term.**

IAMs vs other energy-system models

While IAMs provide collectively state-of-the-art knowledge of energy system, and are the basis of the scientific work supporting the adoption of long-term temperature goals, as discussed above, they are not perfect. Here we analyse in a step-wise and transparent manner the advantages and disadvantages of using IAMs in comparison to the WEO (IEA: Directorate of Global Energy Economics, 2015), IRENA (IRENA, 2016) and Greenpeace Revolution (Greenpeace, 2015). It must be noted that at this moment, only IAMs have produced the data on 1.5°C scenarios currently available in the scientific literature. Other sources (e.g. IRENA, IEA) are in the process of producing new scenarios and are expected to deliver full, or partial assessments of 1.5°C in the course of 2017, alongside an expected much broader assessment base of the IAM "community".

The WEM (World Energy Model) developed by the International Energy Agency is at the core of the World Energy Outlook projections. WEM provides valuable information for specific countries (covering the majority of emissions) under different scenarios (typically a Current Policies Scenario (CPS), New Policies Scenario (NPS) and a 450 ppm scenario). Key results include the energy (and electricity) mix and the associated CO_2 emissions.

However, the time horizon of the IEA WEM is only around 25 years and results are provided through to 2040 which makes it difficult to compare with long-term temperature goals. Apart from its short time horizon, a key limitation of the WEM is the lack of interaction between the supply and energy demand. Higher energy prices are a key incentive for energy efficiency improvements that ultimately lower energy demand and those types of feedback loops are not taken into account by WEM (those feedbacks are reflected in IAMs). Overall, while WEM provides very useful information to complement our understanding of energy systems in the short-term, it cannot answer key questions regarding long-term mitigation strategies, such as the trade-off between short-term mitigation actions and the reliance on, or limits to Carbon Dioxide Removal (CDR) technologies in the longer term, as IAMs do.

Posing another basic question, other institutions like Greenpeace and IRENA put forward scenarios that essentially provide storylines for how very high penetration rates of renewable energy can be achieved by 2050, as a determining factor in limiting warming below 2°C in the longer term. According to Greenpeace, renewables could meet 75-95% of energy demand by 2050, whereas IRENA set this at 50-75%. MESSAGE instead relies heavily on CCS technologies, which are expected to come on line in 2030, and has a comparatively lower penetration rate of renewable energy technologies in the first half of the century. For additional information refer to the "Replacement for coal and the way forward" section.

In order to better understand how these different models relate to and complement each other, we looked into the resulting pathways for energy-related emissions until 2050 (Figure 3), and compare them to an IAM (MESSAGE) pathway consistent with a 1.5°C global temperature goal by 2100 as referenced in the Paris Agreement. The carbon budget (total CO_2 emissions) associated with the 1.5°C scenario analysed here is around 450 $GtCO_2$ for the period 2010-2100 (Rogelj et al. 2013).

It is important to note, all the scenarios depicted in Figure 3 already emit around 1000 $GtCO_2$ for the period 2010-2050 (twice the allowable budget for the full century). This leads to a simple – although very important – conclusion: all these scenarios require negative emissions in the second half of the century to prevent an increase in temperature above 1.5°C by 2100 (under a reasonable probability – e.g. 50% chance).

Coal CO_2 emissions in the MESSAGE model decrease faster than in the other energy-system models assessed here (Figure 3). A detailed analysis of the alternatives for coal in the different models is provided in the upcoming Chapter "Replacement for coal and the way forward".

Unless other CDR technologies will emerge in the near future as a consequence of R&D investments. If negative emissions do not take place after 2050, the consequence would be missing the 1.5°C global temperature increase by 2100, under all of these pathways, with possible catastrophic impacts of climate change for many regions in the world and for vulnerable countries like LDCs (Least Developed Countries) and SIDS (Small Island Development States) in particular.

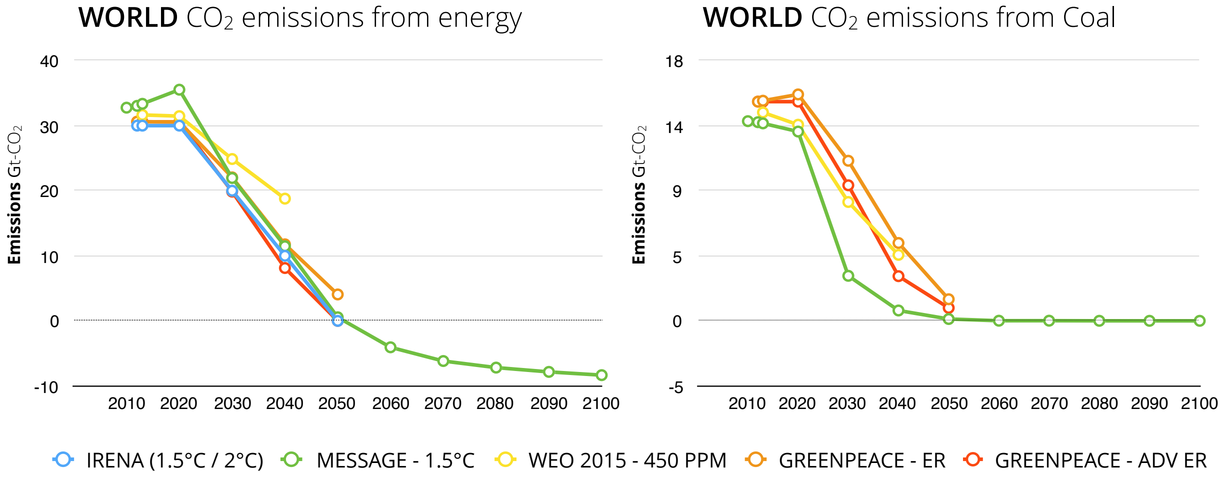

Figure 3: CO2 emissions from energy (left panel) and from coal in the power sector (right panel) in a least-cost pathway (MESSAGE) in line with 1.5°C, WEO, IRENA and Greenpeace Revolution. Note that the higher 2020 level in MESSAGE is in line with Copenhagen pledges and therefore also in line with currently implemented worldwide policies.

It is important to note that particularly for 1.5°C scenarios, but also for 2°C scenarios, large scale utilization of technologies providing negative CO_2 emissions, such as BECCS (used in MESSAGE, other models may also use different technologies like *Direct Air Capture or Enhanced Weathering*) are needed (Smith et al., 2015) even after taking into account the assumed potential for carbon sequestration in forests and soils realized mainly through afforestation.

It is therefore clear that delaying mitigation action does not only increase the overall mitigation costs and undermine the probability of limiting warming to the agreed level, **but also increases reliance on negative CO_2 emissions.**

This leads to the very important conclusion that, regardless of the model considered **energy efficiency measures and coal replacement by low-carbon alternatives decrease the need for later compensation by negative CO_2 emissions and thus also the environmental, social and political costs of their implementation. Also, earlier emissions reductions hedge against the risk that negative emissions technologies will not deliver at the scale currently implied by the models.**

Research in the scientific community is ongoing in many of these areas, including in relation to the consequences of limitations of use and deployment of certain technologies for sustainability, or other considerations, in achieving global warming limits. These issues are not covered in this report, but remain important to any real-world deployment of options described here.

PARIS AGREEMENT IMPLICATIONS FOR THE FUTURE OF COAL

I. THE STATUS QUO OF PLANNED AND EXISTING COAL CAPACITY

Coal power plants have a long economic lifetime, often over forty years. Due to high investment costs, every new coal-fired power plant means the lock-in of a large amount of CO_2 emissions if run over its economic lifetime. **In order to avoid the costs of stranded assets resulting from early retirement of such plants and instead to use investment cycles wisely to decarbonize the power sector, it is crucial to understand the implications of the Paris Agreement for planned coal capacity.**

The Global Coal Plant Tracker (GCPT) provides information on every known coal-fired power generation unit, including location, status, investor, capacity, combustion technology[17] and fuel, year of opening and planned retirement. For this report we use the information provided in the March 2016 version of the GCPT.

Regarding the power plant status, the database distinguishes between, operating, under construction, permitted, pre-permitted and announced plants. In this report, we distinguish:

- **Currently operating capacity**: operating and under construction units, whose "site preparation and other activities are underway", given the certainty about their existence and the related sunk cost.
- **Planned capacity**: emissions from permitted and pre-permitted coal power plants constitute planned capacity. Permitted projects have "secured all environmental permits but have not broken ground"; pre-permitted projects "have actively moved forward in one or more of the following ways: applying for environmental permits; acquiring land, coal, water rights, transmission arrangements; or securing financing" (End Coal, 2016).

The GCPT database also includes an additional "announced plants" category which "have appeared in corporate or governmental planning documents but have not yet moved actively forward by applying for permits or seeking land, coal, or financing" (End Coal, 2016). Existing analysis has shown that an increasing number of coal-fired power plants are cancelled due to, among other reasons, competition with renewables or environmental concerns (Shearer, Ghio, Myllyvirta, & Nace, 2015). To avoid overestimating the overall planned capacity, we do not include the "announced plants" into the planned capacity.

Currently operating coal capacity

There are currently 7,273 operating coal-fired power plants in the world with combined installed capacity of 1,964 GW. Additional 719 plants, representing 344 GW of new combined capacity, are currently under construction. Table 1 summarizes the regional distribution[18] of both operating and under construction coal-fired power plants.

More than a third of all currently operating coal-fired power plants are situated in China, representing nearly half of global installed capacity. Another third operates in the OECD countries, from which around 30% corresponds to European countries. The remaining third is distributed between all the other countries of the world, which together account for only around a fifth of global installed capacity. However, the installed capacity global distribution will change once the currently under construction plants start operating. While China and the rest of the world will continue building new capacity by adding jointly further 671 plants, the OECD and EU will lose importance.

Planned coal capacity

Regarding planned capacity, 70% represents coal power plants that are either in pre-permitted state and 30% are in permitted stage. **If these 1082 power plants were to be built, they would represent more than 596 GW of new generation capacity that would lock-in the energy infrastructure of many countries on a carbon-intensive pathway for at least the next 40 years.** The remaining planned capacity are announced plants,

17 The database distinguishes between different combustion technologies in the following categories: subcritical, supercritical and ultra-supercritical without or with CCS, ranking from least to most efficient respectively. For example, MIT's "Future of Coal" study (Massachusetts Institute of Technology, 2007) estimated the following representative efficiencies for plants burning Illinois #6 coal, a bituminous grade of coal with 25,350 kJ/kg heat rate: Subcritical: 34.3%; Supercritical: 38.5%; Ultra-supercritical: 43.3%. We do not consider coal fired power plants retrofitted with CCS technology further in our analysis.

18 Most of the power plants in the region EU28 are also included in the OECD region since most of the European countries are also OECD countries. Therefore the aggregation of the quantity and capacity of coal-power plants presented in this section for the four individual regions results in larger numbers than the total global. The rest of the world region is defined as all countries that are not part of the European Union or the OECD, excluding China.

Table 1: Regional distribution of current coal power plant capacity

	Operating		Construction		Current Total	
Region	Units	Capacity (GW)	Units	Capacity (GW)	Units	Capacity (GW)
China	2 895	917	367	195	**3 262**	**1 112**
OECD	2 109	608	48	25	**2 157**	**634**
EU28	902	177	14	9	**916**	**186**
Rest of the World	2 269	438	304	124	**2 573**	**563**

Table 2 - Regional distribution of planned coal power plant capacity (permitted and pre-permitted) and announced capacity

	Pre-permitted		Permitted		Announced	
Region	Units	Capacity (GW)	Units	Capacity (GW)	Units	Capacity (GW)
China	353	215	105	55	360	247
OECD	99	57	23	11	47	50
EU28	9	6	2	1	3	5
Rest of the World	298	159	211	101	269	191

which are the least likely to be built as the land or environmental permits have not been obtained.

Almost half of all the planned coal-based capacity (45%) is concentrated in China. Around 43% of the combined planned capacity would be installed in countries outside the EU28, OECD and China. In contrast, only around 11% of all planned coal-fired power plants are in OECD countries, which currently represent about 50% of the global GDP (OECD Website, 2016).

Resulting emissions from current and planned coal capacity

Figure 4 shows the resulting emissions from operating and planned coal power plants. Almost all of the CO_2 emissions in the EU28 and the OECD arise from existing coal-fired power plants. Still, the currently operating capacity, if not retired early, would run until the early 2060s.

This would be extended to around 2080 for the EU and 2070 for the OECD if new planned capacity were to be built. Currently operating capacity in China, if not retired early, would also run until 2060. A large amount of capacity would be added to the system in the next 15 years if the planned capacity were to be built: in China, this added planned capacity would increase current capacity by 33% and for the rest of the world, the added planned capacity would double current capacity levels.

Coal power plant lifetime and load factor assumptions

Emissions from currently operating and planned capacity were calculated based on a range of known (provided in the database) or estimated parameters. Notably, load factors and lifetime for the power plants are key for estimating emissions. For those plants where a retirement date was not explicitly provided in the database, we either used global lifetime averages (46 years) or a country-level average lifetime based on historical trends.

Table 3 shows the average timeline used for the countries that deviated significantly from the historical average. For all other countries and regions (incl. the EU, China, Poland, Germany and others not included in the table) in the world we applied the global average, as their average lifetime did not deviate significantly from it. Note that while a large share of currently operating capacity is in China and rest of the world, the fleet in these countries is new and does not provide enough historic information for inferring country-specific lifetimes and we also applied average lifetime for these countries.

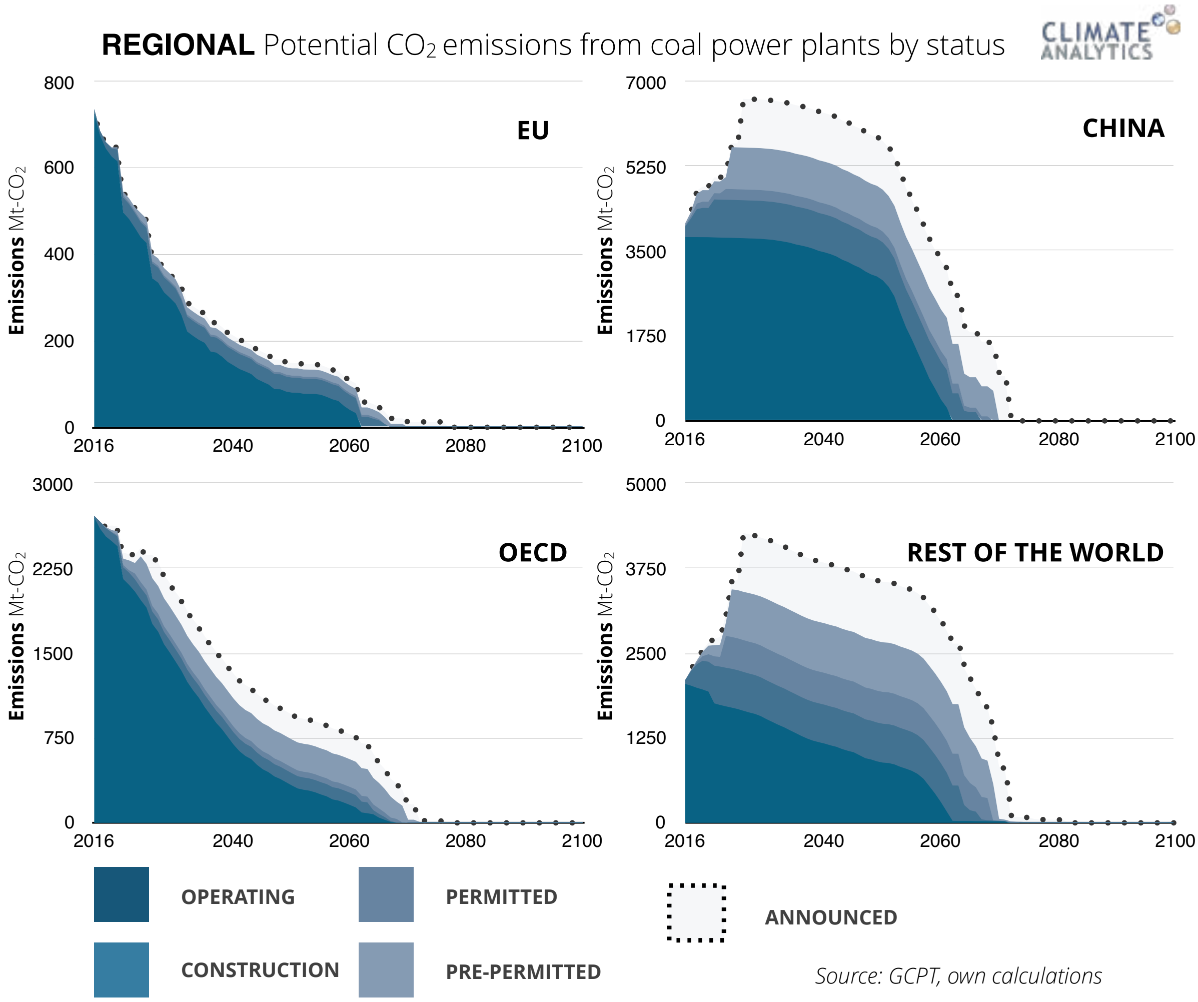

Figure 4: Regional emissions pathways for operating and different stages of planned coal power plants. Announced capacity is depicted with a dotted to indicate that the lower likelihood that these plants come online in comparison to permitted and pre-permitted plants.

We assumed an average capacity factor of 55.8% for the EU, 63% for the OECD countries, 56.9% for China and 64.1% for the rest of the world. All these capacity factors are based on data for from the International Energy Agency (IEA, 2015)[19]. For more information on the GCPT data and details on emissions calculations from existing and planned coal capacity, see Annex II.

Table 3: Country-specific and global coal plant average lifetime (and values less than one standard deviation from the mean) based on historical trend.

Country	Av. Lifetime (min-max)
Australia	41 (39-44)
Canada	40 (35-45)
Bulgaria	51 (46-55)
Romania	29 (22-36)
Russia	56 (51-61)
USA	54 (44-65)
Global	**46 (32-60)**

19 Capacity factors used here are based on historic representative regional values (IEA, 2015). It must be noted that these factors may change over time and have decreased in some countries, e.g. China. Predicting the variability of these factors is challenging given regional heterogeneity and the uncertainty over the next decades, so we opted to assume fixed parameters for the whole projection period. This uncertainty arises from the fact that capacity factors depend, among other factors, on the actual capacity installed and retired in each region. It is likely that in case the planned capacity is shelved, operating plants will increase their capacity factor, reversing the recently observed trend in this parameter.

BOX 1: CHINA'S COAL CAPACITY BUBBLE

The Chinese government has pledged to reach a 20% non-fossil energy target by 2030 (National Development and Reform Commission, 2015) and has consequently increased its investment in renewable and nuclear power capacity. This has resulted in non-fossil fuel sources covering largely the electricity demand growth and a decline in the average utilisation of coal-fired plants.

In 2015 China's thermal power capacity increased by around 72GW while coal-fired generation decreased by around 3%. This meant a decrease in the utilization of the coal-fired power plants by around 8% (Myllyvirta et al., 2016). Indeed coal-fired capacity utilisation has been constantly declining in China since 2011 from around 60% to less than 50% in 2015 (Shearer et al., 2015).

In 2015, China's Ministry of Environmental Protection and provincial Environmental Protection Bureaus gave positive permitting decisions to a total of 210 coal-fired power plants with a total capacity of 169 GW (Myllyvirta, Shen, & Lammi, 2016). In this context expanding coal-based capacity will likely result in coal-fired generators facing further reductions in operating hours and increased difficulty in recovering their capital costs (International Energy Agency, 2016).

Taking into account the 2030 non-fossil energy target and the fact that electricity production from coal in China has not been increasing since 2011, it becomes clear that there is no space for additional coal-fired power generation in the market, at least in the medium term. As a consequence, it is expected that additional coal capacity added in the country will lead to losses in power generators and shut down of the older power plants (Myllyvirta et al., 2016).

The closure of smaller and less efficient plants to be replaced by newer and more efficient ones has been the approach of the Chinese government in recent years (Small Plant Replacement Policy) to justify coal capacity additions (Shearer et al., 2015). Figure 5 shows the increasing mean capacities of the power plants from 195 to 635, for each 5-year period between 1990 and 2030.

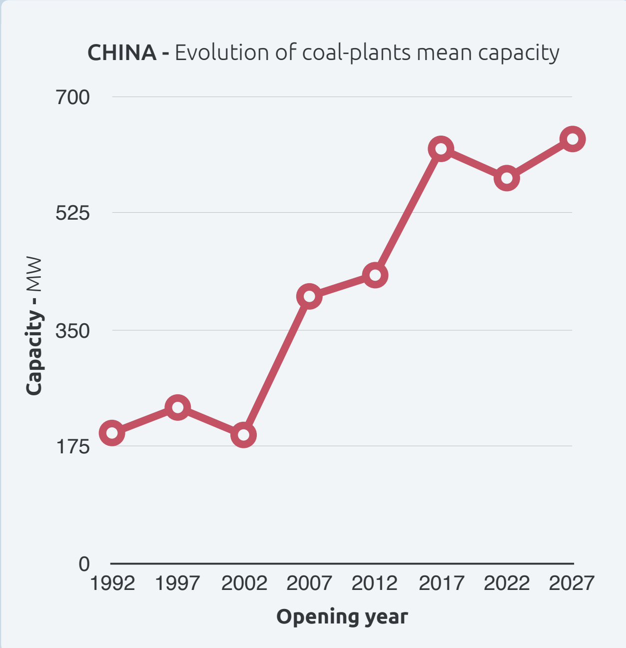

Figure 5: Mean capacity of Chinese power plants

Therefore, if historical pathways continue in the country, additional investment in coal-fired power plants will not necessarily result in increasing CO_2 emissions for many decades as usually observed in other countries. However, it will likely result in a massive amount of stranded assets, and a missed opportunity to channel the investment spending into renewable energy enabling even faster growth in their installed capacity (Myllyvirta, Shen, & Lammi, 2016).

II. PARIS AGREEMENT VS PLANNED AND EXISTING COAL CAPACITY

For all regions in the world, CO_2 emissions from currently operating capacity largely surpass emissions budgets in line with the Paris Agreement and the Cancun Agreements goals. Building additional planned capacity would be completely inconsistent with any development in line with meeting the Paris Agreement temperature goal.

The cost-optimal pathways show that to be in line with the Paris Agreement, the OECD and the EU need to phase out coal the fastest – by around 2030. Phase out needs to happen about a decade later to achieve the Cancun Agreements goals. For China and the rest of the world, coal emissions would need to be phased out around 2040 and 2050 respectively to be in line with the Paris Agreement (Table 4). Under the Cancun Agreements consistent pathway, coal emissions in China would need to start declining after 2030, whereas under the Paris Agreement scenario, these emissions need to start steeply reducing from 2020 onwards (Figure 6).

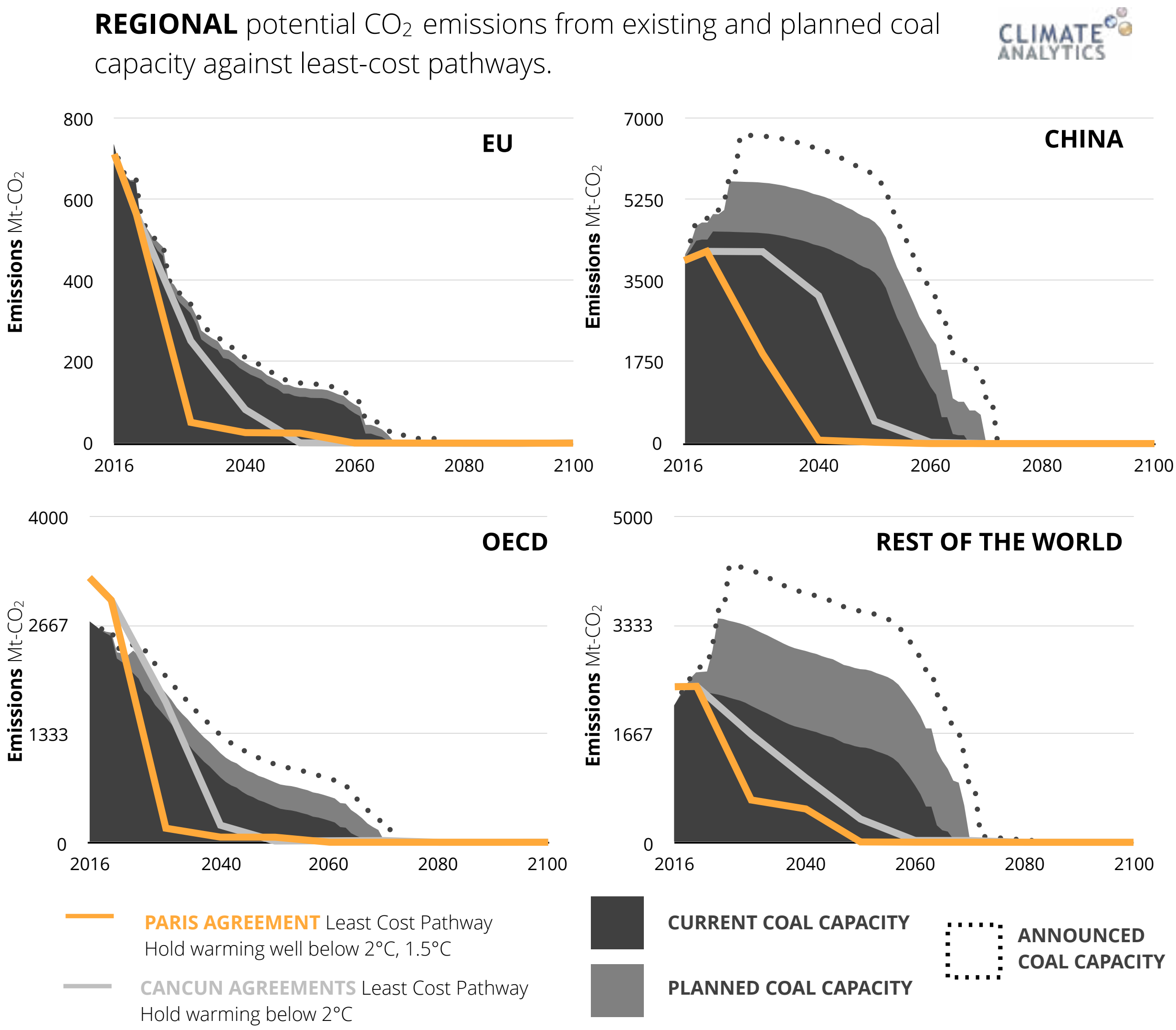

Figure 6: Emissions from existing and planned coal-fired power plants compared with the coal emissions pathways in line with the Paris Agreement and the Cancun Agreements temperature goals. To calculate the cost optimal regional/country level pathways from electricity generation from coal in line with the Paris Agreement long-term temperature goal, we downscaled the aggregated coarse IAMs regions using Climate Analytics' SIAMESE model to subregions which we then again aggregated to the target regions OECD, EU28 and China and rest of the world representing all other countries. As SIAMESE outputs are in energy units, we converted them into emissions pathways using the implicit conversion factor from the MESSAGE model (MESSAGE emissions factor equals 25.8 tC/TJ*44/12). For more details on the SIAMESE model, refer to Annex V. The discrepancy in CO2 emissions from the coal power plants between modelled and observed levels in the OECD region around 2015 arises mainly from the recent retirement of the power plants, which was not taken into account in the model predictions. Globally, the difference between observed and modelled CO2 emissions from the coal power plants is of 650 MtCO2 in 2016. From these, 441 MtCO2 are the avoided emissions from plants that retired between 2009 and 2015 worldwide from which 380 MtCO2 are avoided emissions in the OECD region alone.

Table 4: Coal phase out dates. Country and regional coal phase out dates in line with the Paris Agreement. Phase out year is year of reductions of 90% or more below 2015 levels - similar to assessment of emissions from energy supply sector in IPCC AR5 WG3 (SPM)

Coal power phase out date depending on scenario	China	EU28	OECD	Rest of the world
Paris Agreement 1.5°C	2040	2030	2030	2050
Cancun Agreements 2°C	2050	2040	2040	2060

In order to achieve the Paris Agreement long-term temperature goal, this analysis suggests that **countries will have to implement early retirement of power plants, reduce their utilization rate, stop the construction of currently planned capacity** or use a combination of these measures.

As explained in the previous section, our central estimate for emissions resulting from currently operating and planned capacity in this report are estimated based on assumptions regarding the lifetime of the coal power plants and load factor. The consequences of different operating lifetimes on emissions linked to currently operating and planned capacity are presented in Figure 7, with the lower end of the range representing short lifetimes, upper end the long lifetimes, in addition to our best estimate already shown in Figure 6.

Reducing the power plants' lifetime to the minimum historically observed in the European Union would lead to a steep emissions decrease in the short-term. However, by around 2030 coal power plants would need to be switched off even earlier or their utilization rates would need to be decreased significantly. In China, these short-term effects of reduced lifetimes are hardly observed given the young nature of the fleet: pronounced impacts

POTENTIAL REGIONAL CO_2 EMISSIONS

Based on currently operating and planned coal power plants.

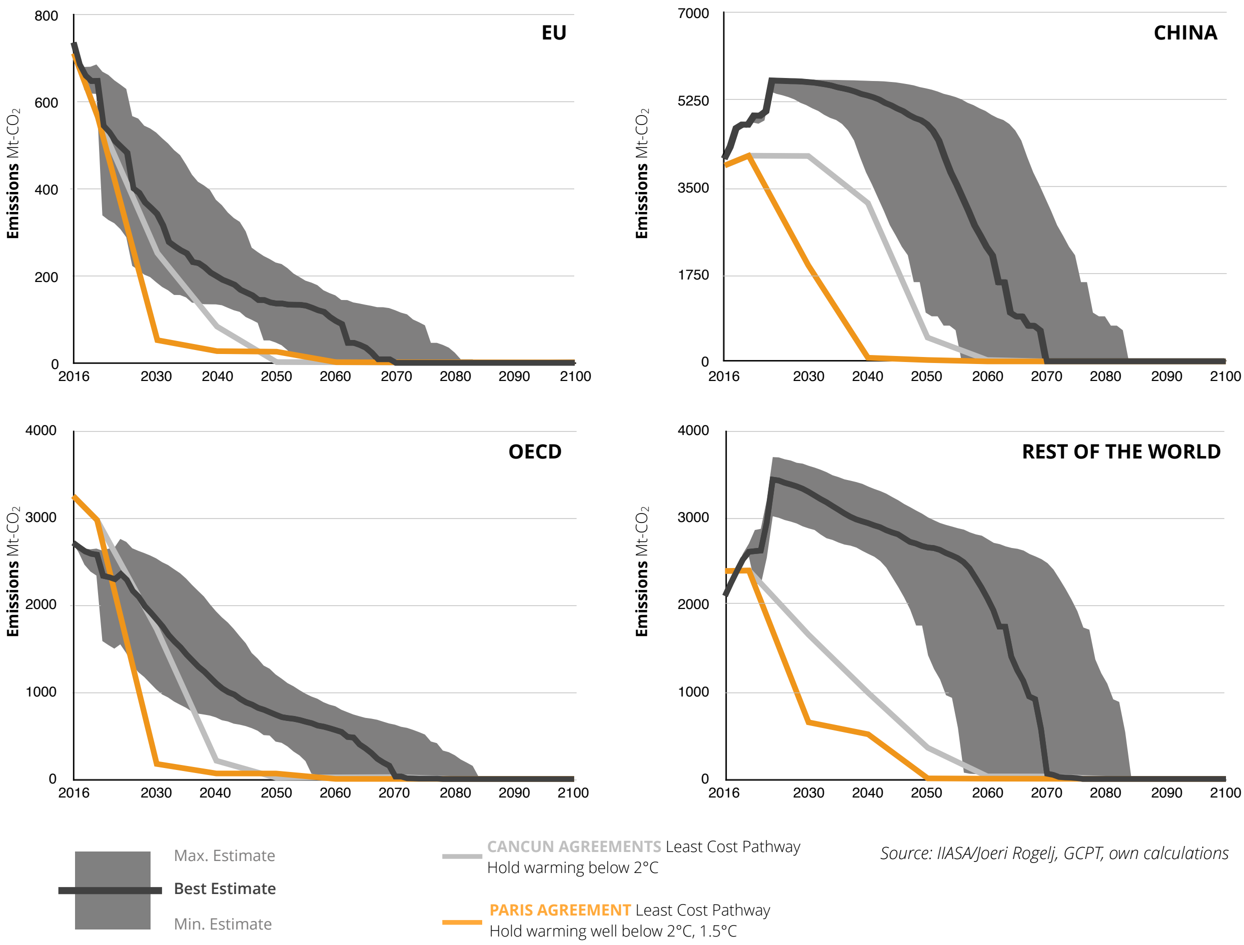

Figure 7: Regional level sensitivity analysis for emissions from current and planned coal-fired power plants. The lower and upper end of the emissions range results from calculating emissions from the coal fleet using lifetime parameters one standard deviation below and above the historical mean respectively. Specific lifetime parameters used in sensitivity analysis are shown in Table 3.

of reducing lifetime could only be observed from around 2030 onwards, by when emissions would have largely surpassed the level of emissions in line with the Paris Agreement.

The upper end of the range would mean that coal-fired power plants run for a much longer time than they have on average in the past and can be seen as proxy for a scenario of leniency of policies (e.g. ineffective Emissions Trading Scheme system) where emissions would grow without practical constraints. In other words, the present weak EU ETS settings would appear consistent with a long-term continuation of coal in Europe rather than the rapid reduction required by either the 2°C or 1.5°C pathways. Changing this trajectory would therefore require measures which shorten the life of existing coal power plants as well as reducing operating capacity, including major improvements in the EU ETS scheme with much lower emissions allowances.

Table 5 below shows the regional cumulative emissions from currently operating and planned capacity until 2050 and 2100, respectively, and how these relate to the Paris Agreement and Cancun Agreements least-cost budgets. Globally, the currently operating capacity would already emit more than twice what would be in line with the Paris Agreement temperature limit. Currently planned capacity in China would emit 2.5 times more than the allowances for the country.

For the world to achieve the Paris Agreement temperature goal, many of the currently operating plants will need to be switched off before the investment costs could be recovered or used with much lower load factors than necessary to ensure their profitability. We must note that the latter is already occurring due to slower than expected increase in power demand in some countries, competition from renewables with negligible running costs, or a mix of both.

The large discrepancy between current coal plans worldwide and developments that would be in line with the Paris Agreement stresses the risk that economies and societies are running if they were to implement current plans.

Table 5: Cumulative CO_2 emissions form currently operating and planned coal power plants (Gt CO_2e) and relation to Paris Agreement (PA) and Cancun Agreements (CA) cost-optimal budgets. Source: IIASA/Joeri Rogelj, GCPT, own calculations

	Until 2050			Until 2100		
Region	**Cumulative emissions**	**Share of PA budget**	**Share of CA Budget**	**Cumulative emissions**	**Share of PA Budget**	**Share of CA Budget**
China current	150	255%	131%	177	299%	151%
+ planned	182	309%	175%	226	383%	194%
+ announced	207	352%	215%	273	461%	233%
EU28 current	11	168%	123%	12	182%	136%
+ planned	12	178%	130%	13	196%	146%
+ announced	12	182%	133%	14	204%	153%
OECD current	49	155%	102%	53	167%	109%
+ planned	57	182%	119%	67	210%	137%
+ announced	63	200%	131%	77	241%	158%
Rest of the World current	68	199%	134%	83	242%	156%
+ planned	102	298%	200%	139	402%	260%
+ announced	125	364%	245%	180	522%	337%
World current	**268**	**214%**	**125%**	**314**	**250%**	**143%**
+ planned	**342**	**273%**	**160%**	**432**	**344%**	**197%**
+ announced	**396**	**317%**	**185%**	**530**	**422%**	**242%**

BEYOND LEAST-COST PATHWAYS - EQUITY IMPLICATIONS

As IAMs do not account for factors such as different levels of mitigation capability (e.g. wealth) or historical responsibility for GHG emissions between countries, policymakers should take into account alternative approaches to determine adequate national emissions reduction levels.

In this section we present one alternative approach for splitting emissions reductions consistent with a long-term temperature goal across countries and regions, based on fairness principles. This ensures that no country does comparably more or less than another on the basis of equity.

We determine emissions levels reductions for a country or region according to a wide range of equity indicators, such as a country's historical responsibility for global climate change, or its capability to contribute to global emissions reduction efforts. Instead of limiting the analysis to any particular one of these views, our approach considers many equity proposals, based on different criteria and metrics, which have been put forward by the scientific community and by governments. For further details on our equity methodology, refer to Annex VI: Equity Methodology.

The discrepancy between emissions levels in line with the least-cost pathways and emissions allowances in line with equity indicates that **while strong emissions reductions are required by equity, it may be technologically and economically beneficial for developed countries to achieve a share of these reductions abroad, that is, to invest in reducing emissions in other regions where mitigations costs are lower.**

In this sense, equity approaches imply a need for investment and/or finance by wealthier countries in emissions reduction in countries with lower capacity and lower mitigation costs. However, keeping in mind the significant emissions reduction needed, **financing mitigation action in developing countries cannot replace but has to complement domestic emissions reduction efforts.**

What remains clear is that the OECD and the EU with earlier coal phase out dates need to take the lead globally in implementing policies and a process for move away from coal. From a fairness perspective, emissions reductions need to be complemented by financial transfers for mitigation measures in developing regions.

Table 6: GHG emissions reductions in line with equity approaches consistent with the Paris Agreement (based on GHG emissions excluding emissions from LULUCF) Source: Own calculations using PRIMAP and Climate Analytics' Equity Tool Note that rows are not additive as EU28 largely overlaps with OECD

GHG emissions – $MtCO_2e$	2020	2030	2050
China	13 994	10 568	5 973
EU28	4 744	1 620	-3 962
OECD	15 577	6 994	-9 290
Rest of the World	20 310	16 726	12 410
World	**50 197**	**34 480**	**9 026**

Table 6 shows the emissions allowances for 2020, 2030 and 2050 for the OECD, the EU, China and rest of the world in line with the long-term global temperature goal of the Paris Agreement[20], according to a full range of equity criteria. These results need to be interpreted in light of the results presented earlier in the report, which consider the feasibility of emissions reductions taking into account characteristics of the energy system in different regions.

In order to meet the Paris Agreement temperature goal, total GHG emissions could still be positive at the global level in 2050 (with CO_2 emissions close to zero). However, by this point in time, equitable emissions reduction would require some countries of the world to have negative emissions, while others could keep emitting. In general equity-based emissions reduction levels are more stringent for developed countries than for developing countries, because the first group of countries is in general characterized by high historical responsibility, capability and emissions levels per capita which all lead to relatively higher obligations in comparison to developing countries.

20 For equity-approach results in line with the Cancun Agreements long-term temperature goal, refer to Annex VII: Equity approach results for Cancun Agreements temperature goal.

At any point in time and for any region, or country, emissions levels calculated using the least-cost methodology on the one hand, and equity considerations on the other, will differ.

Emissions allowances estimated using the least-cost approach are often lower than emissions allowances resulting from equity approaches for countries in the European Union and the OECD. Under the least-cost approach, these two regions are still allowed to emit during the first half of the century while equity-based allowances would require emissions to be largely negative already by 2050.

This is explained by the fact that IAMs search for a *global* least-cost strategy (and not country-level fairness indicators), reducing first emissions where it costs less to reduce and later where it costs more (and the latter regions would include OECD and the EU).

Similar to the least-cost approaches, the equity approach indicates that in order to achieve the Paris Agreement long-term temperature goal, a considerable majority of the countries will have to implement early retirement of the coal-fired power plants and stop the construction of currently planned capacity. Moreover, the equity analysis suggests that for countries exceeding already their equity-based allowances (e.g. EU28 and OECD) investment in reducing emissions in other regions of the world would be necessary to compensate for the emissions of their current coal capacity.

REPLACEMENT FOR COAL AND THE WAY FORWARD

While coal needs to be phased out over the coming decades, other energy sources need to be phased in.

As previously pointed out in this report (section on "IAM scenario limitations and comparison with other energy system models"), different energy-system models in the literature achieve close to zero energy-related CO_2 emissions by 2050 through the deployment of different carriers, energy efficiency measures and technologies over different time frames. In this section, we analyse and compare how various models, specifically IAM (MESSAGE), the World Energy Model (IEA: Directorate of Global Energy Economics, 2015), the Greenpeace revolution model (Greenpeace, 2015) and the IRENA model (IRENA, 2016), achieve those emissions reductions and how the different storylines from these models complement each other.

IRENA

According to IRENA (IRENA, 2016), renewables would reach 50-75% of the energy mix by 2050, depending on assumptions regarding the electrification rates of the transport and building sectors. In their 2016 report, IRENA stresses the current lack of CCS infrastructures, which provides a strong argument for phasing out coal as soon as possible. IRENA found that renewables would mainly displace coal-based power plants, and that a doubling of renewables by 2030 would be needed to put the world on track with a 1.5°C emissions pathway. Despite the fact that IRENA recognises the importance of negative emissions to achieve the long-term goal of the Paris Agreement, it does not provide any specific information on future CCS pathways.

Greenpeace

Greenpeace projections achieve deep emissions reduction mainly through energy efficiency improvements and renewable energy. Under its most ambitious "advanced RE" scenario, renewables would meet 95% of the energy demand by 2050. Coal and nuclear energy will be completely phased out by 2050. At the same time, energy savings are expected to reduce energy consumption below current levels by 2050. While CCS technologies are not considered in the analysis, negative emissions would still be needed in the second half of the century to achieve a 1.5°C compatible pathway, and would therefore need to be quickly phased in towards the end of the first half of the century.

IEA WEM model

In comparison to the above models, the WEM takes a more conservative approach regarding the deployment of renewables as they account for 30% of the energy demand by 2040 (450-ppm scenario). Although no data are provided regarding the CCS penetration rate, WEM assumes CCS deployment to start in 2020 or 2025, especially in China and India. Coal will be partly displaced by renewables and nuclear, even though it will still meet 15% of the energy mix in 2040. Nuclear is projected to increase significantly by 2040, almost by a factor compared to 2013. Further energy efficiency improvements will reduce energy consumption and CO_2 emissions below current levels by 2040. WEM models phase out coal in the OECD by 2035 and in China by 2045 to be in line with a 2°C goal (2DS scenario).[21] This is broadly in line with phase out dates provided in this report.

MESSAGE model

Figure 8 summarises how the MESSAGE model scenario primary energy composition changes over the coming decades to achieve the Paris long-term temperature goal. Taking into consideration the rapidly decreasing costs of the alternatives and the high carbon intensity of coal, coal phase out in the power sector is the "low-hanging fruit" of limiting emissions.

Under low-carbon scenarios, the MESSAGE model projects CCS technologies to come online already in 2030. Renewables (including BECCS) will account for roughly 50% of energy demand by 2050. Energy demand will remain stable until 2050, as opposed to other energy-system models where energy consumption decreases through high levels of energy savings and efficiency. Some fossil fuels without CCS will remain in the primary energy mix, they will be partly offset by negative emissions.

By comparing all the models discussed so far, different storylines emerge on how to replace coal to meet a 1.5°C emissions pathway. The MESSAGE model scenarios seem plausible only if CCS technologies take off and are deployed already at commercial scale in 2030, which remains highly debatable and requires additional research. Otherwise, the 1.5°C emissions pathway will be most likely similar to those provided by WEM, IRENA or Greenpeace, depending on public acceptance of nuclear power

21 http://www.slideshare.net/MatthewGray16/cop21-and-beyond-coalfired-power-and-longterm-climate-goals?qid=42570c92-307b-427e-97c4-fc02e7017277&v=&b=&from_search=1

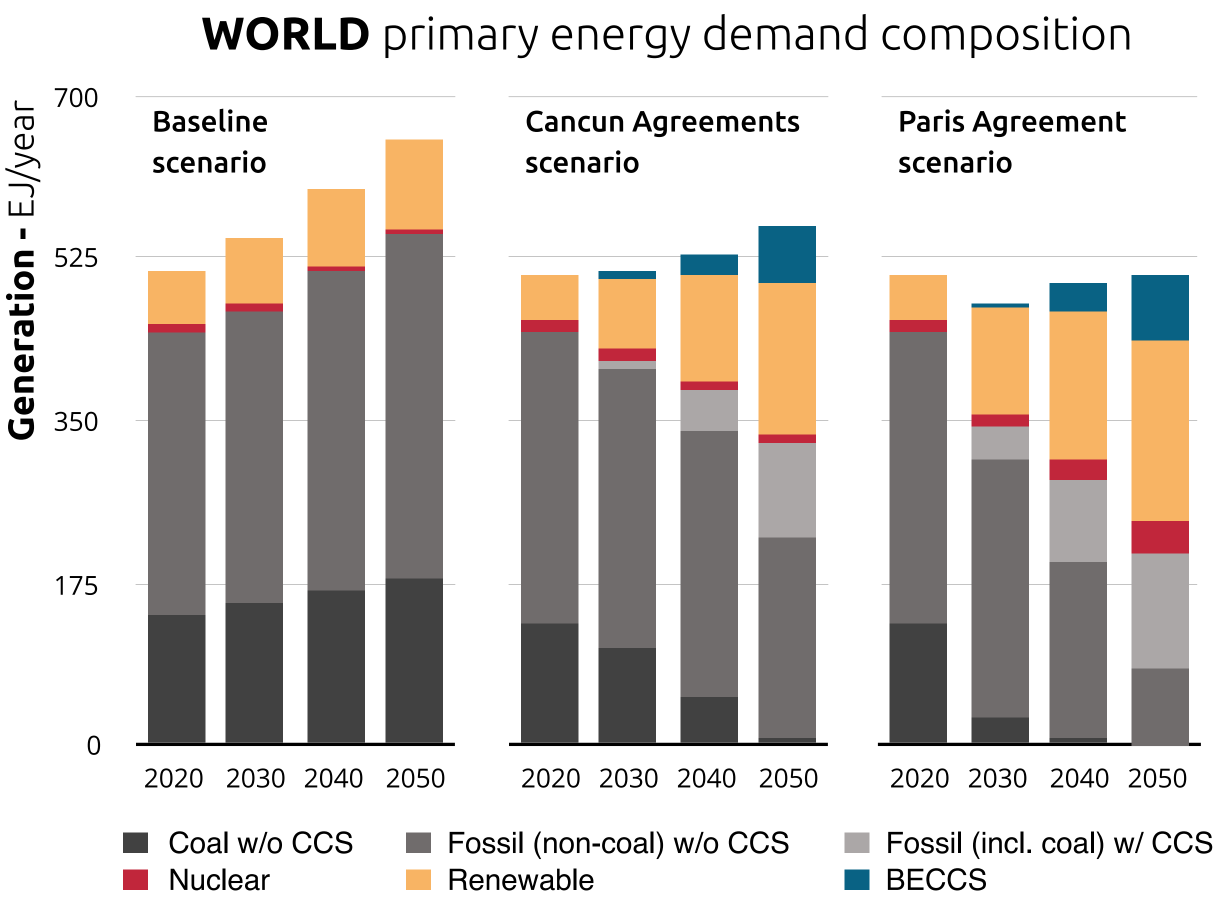

Figure 8: Global primary energy demand composition from the MESSAGE model

plants (WEM) or future deployment of renewables coupled with energy efficiency improvements (IRENA and GREENPEACE).

Beyond contributing to climate change, coal is also the lead cause of air pollution and, especially in the case of open-pit mining, destruction of whole ecosystems. Furthermore, it has negative impacts on trade balance of the importing countries and increases the vulnerability of coal exports to changes in the commodity prices. **This has led to increasing coal vulnerability in different parts of the world clearly visible in the fact that in 2015 coal production decreased for the first time since the 1990s.**[22]

While governments still plan significant new coal capacity, the alternatives to coal are gaining momentum. The combined capacity of renewables, excluding hydropower, increased from 182 GW in 2005 (Renewable Energy Policy Network for the 21ST Century, 2006) to 785 GW in 2015 (REN 21, 2016). Between 2004 and 2014 the share of installed capacity in low-carbon sources of energy, including nuclear and hydro energy, increased from 31% to 36% (The Shift Project Data Portal., 2016). Between 2005 and 2015 the share of renewable sources of energy in the power sector, except for hydro energy, increased from 1% to 8% in the OECD countries.[23] Initially driven by support mechanisms for renewables, in recent years renewables gained momentum due to rapidly decreasing prices and the increasing attention paid to the external costs of fossil fuels, not only in terms of their contribution to climate change, but also in the more immediate air pollution impacts (International Energy Agency (IEA), 2016).

Coal-fired power plant capacity is increasing, with almost 108 GW of newly operating capacity added in 2015 alone (End Coal Website, 2016), Despite this increase in generation capacity, power plant utilization rates have decreased, in the United States from over 60% in 2014 to below 55% in 2015 (US Energy Information Administration (EIA), 2016), below 45% in China in early 2016 (Stanway & Pullin, 2016) and in India reduced to 60% (Sharma, 2015). This is not only influencing the willingness of energy companies to invest in new coal-fired projects, but is also decreasing their credit ratings (Moody's Investors Service, 2016) thus increasing the costs of financing and making major investments more expensive.

22 https://euracoal.eu/library/coal-market-reports/

23 Own calculations based on the IEA' Monthly Electricity Statistics. The numbers do not include Estonia, Slovakia and Chile, which were not part of the OECD in 2005.

At the same time, low interest rates significantly decrease the costs of investments in installations where the bulk of costs are incurred upfront, such as wind and solar energy, as well as in energy efficiency (Channell et al., 2015).

Strengthening government's commitment to climate policy by ambitious and feasible NDCs, followed by the removal of subsidies for fossil fuels and continuous support for renewables and energy efficiency, would also encourage large institutional investors to increase their involvement in the low-carbon economy. That would offer new opportunities especially for developing countries, which then would not have to bear the costs of stranded assets and could instead develop a cost-effective low-carbon economy (Fay et al., 2015).

There is no doubt, that the energy sector of the future will look very different from the current one. The models come up with a much more diverse mix of energy sources that complement each other. The energy system in the OECD, the EU28 and in China will experience a strong shift towards clean sources of energy, which will dominate the energy system in these regions.

ANNEXES

Photo © Weerachai Khamfu

ANNEX I: CONCEPTUALIZING THE PARIS AGREEMENT TEMPERATURE GOAL

More than two decades of international climate negotiations laid the groundwork for the Paris Agreement and it is with this rich history in mind this treaty should be understood and conceptualized, particularly with regards to the long-term temperature goal.

At the Earth Summit in Rio de Janeiro in 1992 the UN Framework Convention on Climate Change (UNFCCC) was adopted with the ultimate objective being the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (United Nations, 1992). Importantly, it had neither been clarified what level of climate change is to be considered "dangerous", nor was there an agreement on the exact concentration levels required to reach that objective. It was only in the Copenhagen Accord from 2009 that the first long-temperature goal of limiting the global temperature increase to **below 2 degrees Celsius** was mentioned (UNFCCC, 2010). During the subsequent COP16 in Cancun in 2010 the Parties adopted the 2°C limit, expressed as the aim "to hold the increase in global average temperature below 2°C above preindustrial levels".[1]

Notwithstanding this decision, in 2010 the UNFCCC established a review process to evaluate whether the long-term global temperature goal of holding warming below 2°C was adequate to avoid dangerous climate change and to consider "strengthening the long-term global goal on the basis of the best available scientific knowledge, including in relation to a global average temperature rise of 1.5°C". In 2015 the Structured Expert Dialogue ended with the conclusion that a warming of 2°C cannot be considered safe (UNFCCC, 2015b). This has ultimately led to the Paris Agreement objective to "pursue efforts to limit" global warming to 1.5°C above preindustrial, while holding warming to **"well below 2°C".**

The Paris Agreement long-term temperature goal therefore goes beyond the Cancun Agreements 2°C temperature limit and has important implications for the long-term emissions reductions goal mentioned in the Paris Agreement (Article 4).

The Paris Agreement (UNFCCC, 2015a) long-term temperature (Article 2) and emissions (Article 4) goals have specific implications for the global emissions and energy transition pathways. It is therefore crucial to carefully consider the formulation of the Paris Agreement long-term goals and find how they can be best reconciled with the most recent scientific knowledge, given that, by necessity, much of this knowledge is based on scientific publications predating the Paris Agreement.

Under the long-term temperature goal (Article 2.1) of the Paris Agreement, Parties agreed to "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognising that this would significantly reduce the risk and impacts of climate change". This article is accompanied by Article 4.1, that specifies that "(i)n order to achieve the long-term temperature goal set out in Article 2, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country Parties, and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty."

The Paris Agreement thus stipulates that in the second half of the century the ***global*** aggregate amount of direct human induced emissions must be counterbalanced by sinks of greenhouse gases. This, however, does not mean that the global aggregate amount of sources and sinks needs to be zero ***at the same time*** in ***every region*** of the world but that as some regions on balance may be sinks other regions may still be sources. The timing of this balancing is to be based on the "best available science".

1 Decision 1.CP/16 Paragraph 4 http://unfccc.int/resource/docs/2010/cop16/eng/07a01.pdf

ANNEX II: ESTIMATING CO_2 EMISSIONS FROM COAL PLANTS

The Global Coal Plant Tracker data used in this report contains detailed information per plant, per country, its capacity, status and combustion technology. We estimate CO_2 from these plants, using the following formula:

$$\textit{Annual } CO_2 \textit{ (in Mt)} = \textit{capacity} \times \textit{capacity factor} \times \textit{heat rate} \times \textit{emissions factor} \times \Phi^1$$

The **capacity** describes the amount of power a plant can produce and is measured in Megawatt (MW). For each plant in the database, the capacity is given, ranging from 0 to 8000MW. These are however merely theoretical values, as in reality the capacity factor, that is the amount of power that a plant produces compared with the capacity, is lower than 100% due to variations in demand and other technical considerations such as routine maintenance. In our calculations for the central estimate we assumed an average capacity factor of 55.8% for the EU, 63% for the OECD countries, 56.9% for China and 64.1% for the rest of the world. All these capacity factors are based on data for from the International Energy Agency (IEA, 2015).

The **heat rate** describes how efficiently a plant converts energy from coal into electricity and it is usually expressed as the amount of energy used by a power plant to generate one kilowatt hour (kWh) of electricity. This rate is derived by comparing the quantity of energy contained in coal as it enters the plant site to the quantity of energy contained in the electricity that exits the plant side into the grid. The heat rate in our analysis is expressed through Btu/kWh ant it varies from 7.528 Btu/kWh to 8.921 Btu/kWh depending on factors like the type of combustion technology, the type of coal and the size of the plant (Sargent & Lundy, 2009)

The emissions factor refers to the average amount of CO_2 emissions resulting of burning coal to produce a certain quantity of energy. For our analysis, we use emissions factors based on the International Energy Agency (B.D. Hong and E. R. Slatick, 1994) for the different types of coal that are used in each power plant included in the GCPT:

- Lignite (i.e. brown coal): 216.3 pounds of carbon dioxide per million Btu
- Subbituminous coal: 211.9 pounds of carbon dioxide per million Btu
- Bituminous coal: 205.3 pounds of carbon dioxide per million Btu
- Anthracite: 227.4 pounds of carbon dioxide per million Btu

Based on the formula above we calculated the emissions on a per plant basis, which were then aggregated at a regional or country level and distinguished by their status, taking into account the plants that are either operating, under construction, announced, permitted or pre-permitted.

Moreover, in order to calculate the emissions for each plant, due to some missing information in the GCPT database regarding retirement date, type of fuel, etc. for some power plants we made the following assumptions:

- Information on the type of coal burned in the power plant was missing for a considerable portion of the planned coal plants (24% of total operating and under construction capacity). In order to not bias the estimates artificially assigning a too high or too low emissions factor to the plant with missing fuel information we assigned an average emissions factor to those plants, namely (211 $lbCO_2$/million Btu), which is the emissions factor of subbituminous coal.

- For power plants that did not have an opening date yet, we applied the following rule to estimate their entry date: for plants under construction we assume an opening date in 2020; for permitted plants we assumed 2022 taking into account the average construction time of a power plant; for pre-permitted plant we assume an operation start date in 2023; and for announced plants we assume 2025.

1 Φ represents an units conversion factor (3.97347 x 10^-9) which basically represents 8760 hours per year (to calculate the annual electricity output) divided by 2,202.31 lb/tonne (to calculate the emissions in the standard tonnes unit.

- For power plants that are currently operating despite the fact that their planned retirement date was earlier we applied the following rule to estimate the year of retirement: taking into account that all these power plant were supposed to be retired a while ago we assume they will be online for another 5 years but not beyond that.

- For power plants that did not have a retirement date, we applied the following rule to estimate the year of retirement: for the central estimate we assume that these power plants will have a lifetime that is exactly the average lifetime of power plants that have been already retired in the country. When this historical information is not available, or in case it is available but does not differ substantially from the world average (all countries except for Australia, Canada, USA, Bulgaria, Romania and Russia) we assume the average lifetime to be 46 years for the best estimate. Moreover, for our sensitivity analysis presented in the main report, we changed this average lifetime by adding or subtracting one standard deviation to the mean lifetime for each of the countries in order to obtain a maximal and minimal estimate of the emissions of current and future coal power plants in the following years.

Finally, in order to build emissions pathways for the regions in the following decades we assume the observed global mean average lifetime to be the best estimate of the future observed lifetime of power plants. However, being aware that the specific average lifetime assumed for the calculation of the emissions pathway is one of the most relevant parameter to determine cumulative emissions for the different regions we give specific country level average lifetime parameters to the countries where this indicator is known and deviates significantly from the global average. The specific lifetime parameters used in our emissions pathways calculations are summarized in Table 3 in the main report.

Regarding the EU, specific lifetimes were calculated based on the retired plants in the GCPT database. For the large majority of countries (except for Romania and Bulgaria) the average lifetime did not significantly deviate from the global average and the latter was considered for calculating emissions.

Acknowledging the uncertainty surrounding the future lifetime of coal power plants globally we make a sensitivity analysis for emissions pathways in each of the regions studied. This analysis consists in estimating the resulting emissions pathways in a best-case scenario (all plants run with the minimal observed lifetime), a worst-case scenario (all plants run with the maximal observed lifetime) and a best-estimate scenario (all plants run with the observed average lifetime). Results for the emissions pathways resulting from the sensitivity analysis are shown in Figure 7 in the main report.

ANNEX III: INTEGRATED ASSESSMENT MODEL SCENARIOS SELECTION

In order to select 1.5°C and 2°C consistent scenarios from all the MESSAGE scenarios available, we made use of a scenario selection process consisting in computing the maximum probabilities of exceeding temperature goals of 1.5°C and 2°C over the 21ST century and exceedance probabilities in 2100 for the available scenarios, using the MAGICC reduced form climate model (Meinshausen, Raper, & Wigley, 2011). From these scenarios we chose those that achieved global warming of 1.5°C or less in 2100 with a probability of at least 50 percent. Further, we selected only scenarios in which climate policy compliant with the respective temperature goal is delayed until 2020 since we deemed this more realistic. This selection process led to the three MESSAGE scenarios shown in Box1:

- The No Policy scenario is the baseline scenario assuming no further climate action after 2020 but a low energy intensity/high energy efficiency.
- The Cancun Agreement (CA) scenario and the Paris Agreement (PA) scenario are scenarios compatible with 2°C and 1.5°C, respectively.

It must be noted that all MESSAGE scenarios assumed full technological availability, i.e. all technologies that are present in the model are deployed at rates determined by the model under the respective constraints – e.g. fossil fuel resources or renewable energy potentials.

The 1.5°C consistent scenarios published to date overshoot a 1.5°C global mean warming above preindustrial levels in the 21ST century by about 0.1 to 0.2°C, before returning to 1.5°C or below in 2100 with a 50% likelihood (median warming in 2100 of 1.4°C). There is a range of new scenarios under consideration and in preparation by different research groups which limit warming to 1.5°C with a higher probability and with a corresponding peak warming somewhat lower than indicated above. These are not yet in the publication phase and therefore cannot be cited or used with confidence at this point.

In this report, we opt to select from a class of scenarios in the literature that are often called **"delayed action" scenarios**, as opposed to those that are often termed "immediate action" scenarios. Delayed action scenarios usually assume that countries will meet their Copenhagen Accord pledges for 2020, before beginning deeper action to meet the 2°C or 1.5°C long-term temperature goal, as opposed to immediate action scenarios, which assume strong global concerted climate action starting all in 2010. In effect, using immediate-action scenarios would imply that full global climate action to meet the 2°C or other limit started more than 5 years ago and that emissions levels in 2020 would be much lower than presently projected. Such scenarios, whilst useful for analytical purposes, are unrealistic in the analysis conducted here. It is important to note, however, that if climate action were to be ramped up in the pre-2020 period, would relieve pressure on the post-2020 targets.

ANNEX IV: SCENARIO LIMITATIONS OF IAMS

The MESSAGE scenarios are based on high efficiency (low primary energy demand) and full technology availability. The latter means that technology such as nuclear power, fossil fuel CCS and negative CO_2 emissions technology, all of which may have important sustainability and other constraints, are assumed to be available for mitigation. Particularly for 1.5°C scenarios (such as the Paris Agreement 1.5°C), negative CO_2 emissions are now essential if this warming limit is to be met. Negative CO_2 emissions are also required to hold warming below 2°C with a likely probability (such as Cancun Agreements 2°C scenario studied in this report). After taking into account the assumed potential for carbon sequestration in forests and soils, there still remains a large need for industrial scale negative CO_2 emissions using technologies such as BECCS or Direct Air Capture. BECCS is the technology used in MESSAGE — and other IAMs — to achieve negative CO_2 emissions at scale.

In practice, there may be non-direct economic constraints placed upon technologies. For example, if there is a large need for negative CO_2 emissions to meet global warming goals, then policy makers may restrict this application only to geologically secure repositories. There may also be sustainability constraints placed upon the deployment of biomass energy systems, which have the potential for leading to land use and other environmental concerns, unless properly managed and deployed in a sustainable manner. Concerns with nuclear power in many jurisdictions are well known and may limit future deployment in at least some regions.

Research in the scientific community is ongoing in many of these areas, including in relation to the consequences of technology limitations for sustainability, or other considerations, in achieving global warming limits. These issues are not covered in this report, but remain important to any real-world deployment of options described here.

ANNEX V: SIAMESE

The **S**implified **I**ntegrated **A**ssessment **M**odel with **E**nergy **S**ystem **E**mulator (SIAMESE) tries to address the complexity challenges of most present-day IAMs with its simple model structure. This allows SIAMESE to scale the regional results of IAMs down to a country or sub-regional level. This downscaling technique greatly extends the field of application of IAMs and making it more useful for country policy analysis.

In order to downscale the MESSAGE regional output to the EU, China, OECD and rest of the world regions, the results of the MESSAGE model are inputted to the SIAMESE model, in terms of GDP and energy consumption. At the base year (2010), the model is calibrated to replicate observed energy consumption. In a way, this calibration process sets some preferences regarding the energy mix composition. More precisely, SIAMESE allocates energy consumption in the regions by equalising the marginal utility of energy, under a welfare maximisation approach. Energy prices are endogenous in the model[1] and coincide with the marginal utility of energy.

In terms of equations, SIAMESE mimics the structure of Integrated Assessment Model. Similarly to other IAMs, the economic output (GDP) is a function of capital, labour and energy consumption and TFP (total factor productivity), by using a CES (Constant Elasticity of Substitution) production function. The basic idea behind the CES production function is that it would be possible, to some extent (and at increasing cost), to replace one factor of production with another (e.g. capital with energy consumption). Therefore, GDP is an endogenous variable. In order to provide realistic results, we harmonise the GDP with external projections by changing the TFP assumptions. The TFP is exogenous and it can be interpreted as a proxy of technological progress.

Labour force is also an exogenous variable. For sake of simplicity SIAMESE assumes that labour coincides with total population. Finally, Capital for production of final goods, is modelled via a capital accumulation equation, and can be increased by means of investments.

The focus of SIAMESE is on CO_2 emissions (excluding LULUCF) and on primary energy consumption. SIAMESE does not cover other GHG such (e.g. CH_4, N_2O etc.). Other gases emissions can be downscaled by using a simple (proportional) downscaling technique.

1 SIAMESE determines the energy prices for each fuel, based on energy consumption levels from the MESSAGE model.

ANNEX VI: EQUITY METHODOLOGY

Description of the Equity Analysis Tool

The PRIMAP group at the Potsdam Institute for Climate Impact Research (PIK) developed the Potsdam Real-time Integrated Model for the probabilistic Assessment of emissions Paths (PRIMAP model) (Potsdam Institute of Climate Impact Research, n.d.). The Emissions Module (Nabel et al., 2011) the emissions module of the Potsdam Real-time Integrated Model for the probabilistic Assessment of emissions Paths (PRIMAP has been developed as part of this model and allows for the flexible combination of data sources into composite datasets, and the calculation of national, regional and global emissions pathways following various emissions allocation schemes. At the core of the Emissions Module is a custom-built emissions database, the so-called PRIMAPDB.

Climate Analytics and the PRIMAP group developed an Equity Analysis Tool for the assessment of equity principles and indicators, embedded in the Emissions Module. Currently implemented in the tool we have the following published equity methodology proposals:

- Greenhouse Development Rights (Kartha, Baer, Athanasiou, & Kemp-Benedict, 2009)
- South North Proposal (Ott et al., 2004) with own methodology for downscaling emissions from groups to country level based on GDP and population projections (details available upon request)
- Per capita convergence (Agarwal & Narain, 1991; Meyer, 2000)
- South-African Proposal (Winkler, Letete, & Marquard, 2013)
- Chinese proposal (BASIC Experts, 2011)

Building on a range of methodologies and equity criteria put forward by the scientific community and Parties for sharing the burden of reducing emissions, the PRIMAP equity tool also offers a modality that allows users to emulate equity regimes based on various equity criteria - and for each criterion a range of possible empirical metrics to quantify them is available. The equity criteria selected and the different empirical metrics available to evaluate them in the Equity Tool are:

Historical Responsibility: this remains the main argument often used by many developing countries that the greenhouse gas problem is primarily caused by emissions from industrialized countries. The metrics used as a proxy for historical responsibility in this exercise are based on per capita cumulative emissions i.e. the quotient of cumulative emissions for each country and its cumulative population within the pre-set time frame:

- Cumulative greenhouse gases emissions per capita, excluding deforestation emissions: starting and end years for accounting cumulative emissions are flexible
- Cumulative greenhouse gases emissions per capita, including deforestation emissions: starting and end years for accounting cumulative emissions are flexible

Capacity to mitigate: the overall capacity to mitigate in a country is often related to a country's wealth or degree of development, as these relate to the country's ability to pay for and implement measures to reduce greenhouse gases emissions. Metrics available to evaluate this criterion are:

- GDP Purchasing Power Parity (PPP) per capita
- Human Development Index (HDI) at a certain year

Potential to mitigate: is a measure of the actual room for improvement existing in a country. Among proposals that consider potential as a criteria are the Triptych methodology[1] and the South North Proposal. The following intensities can be used to estimate a country's potential to mitigate:

- Emissions intensity: Energy related greenhouse gas emissions per unit of GDP
- Emissions per capita: Total national greenhouse gas emissions per capita, including deforestation emissions.
- Carbon intensity: greenhouse gas emissions per unit of energy production

Weights can be attributed to each one of the criteria selected. This means that allocation regimes based on only one of the criteria, e.g. responsibility, or based on more than one criterion, and assuming either equal or different weighting among the different criteria can be studied. For each criterion, one or a set of empirical measures to evaluate them can be selected, also with different weights. Such an approach allows for full flexibility of assumptions in regard to criteria and metrics.

Another important feature of the tool is that is that it allows for the calculation of ranges of responsibilities for countries, based on the different indicators. To calculate ranges, (1) random weights are attributed to each indicator and measure, (2) resulting emissions pathways calculated and finally (3) calculations are repeated multiple times to define a range of possible pathways. Such an approach allows capturing the full range of emissions allowances of a country and to determine how different criteria and metrics influence its outcome.

BOX 2: DATA COLLECTION

Data availability and quality represents a major challenge for this exercise. Even though the Equity Analysis Tool is embedded in the PRIMAP database (Nabel et al., 2011), which offers a wide range of choices of data sources, a few restrictions prevent a free choice. First, as we are interested in the relative contribution of countries to a certain qualitative metric, top-down data provides a more adequate frame for comparison, as it usually implies that a set of requirements have been met to ensure quality and comparability of data (as opposed to data provided on a national level, following e.g. own – nonstandard – inventory methodologies). Second, for each metric resulting from two single metrics e.g. emissions per GDP, we consistently used data from the same data source. For the current exercise, we have used the following data sources: UNFCCC Common Reporting Framework (CRF) GHG data, World Development Indicators 2013, Carbon Dioxide Information Analysis Center (CDIAC), International Energy Agency (IEA) data for energy, United Nations 2012 for population and Human Development Index (HDI).

The data used here are from state-of-the-art sources and are regularly updated in the PRIMAP database. We have consistently used the same datasets across all scenario runs, ensuring that the differences between emissions allowances across scenarios arise from criteria/metric choices alone and not through data divergences. For business-as-usual projections, we used RCP8.5 scenario downscaled to country level using SSP scenarios. From the few SSP scenario families, we have used the PIK implementations of the SSP2 narrative (for detail, refer to detailed methodology), which provides a global median of estimates. The RCP regional emissions are downscaled to country level using the SSP GDP pathways for individual countries, the IPAT equation and the assumption of (partial) convergence of regional emissions intensities. The methodology is based on van Vuuren et al. (2007).

Index Calculation: The selected quantitative measures are weighted, normalized and added, to obtain an interim index. The split of the mitigation burden is calculated proportionally to a final index, which is obtained by normalizing and weighting the interim index by the population share of each country. To avoid using projections, we calculated the index based on the last common historical year shared between all selected metrics, which was 2010. The index is calculated for as many countries as possible, which is the number of common countries available for all selected metrics. Because the index is the result of the

1 The Triptych methodology contains elements of cost–effectiveness in that those with high specific emissions (i.e. high potential for reductions) have to reduce more. It was used as a basis to share the emissions reductions of the first commitment period for the Kyoto Protocol within the EU.

normalization of variables, we investigated the presence of extreme countries in each one of the metrics and excluded those countries (potentially a different set of countries at each iteration of the model) to avoid the over or underestimation of countries' share of responsibility

Global mitigation burden: Equity methodologies often fit global emissions to levels that are in line with temperature targets. The two target scenarios investigated in this report are the Paris Agreement 1.5°C and the Cancun Agreements 2°C scenarios, which are delayed-action least-cost scenarios consistent with maintaining temperatures at 1.5°C in 2100 with a 50% probability and below 2°C with a 66% probability in the 21ST century respectively. Based on the selected low-carbon scenario, an emissions mitigation burden is calculated as the difference between global business-as-usual emissions (here, RCP8.5) and an emissions trajectory that avoids the worst effects of global warming (here consistent with the Paris Agreement 1.5°C and the Cancun Agreements 2°C scenarios).

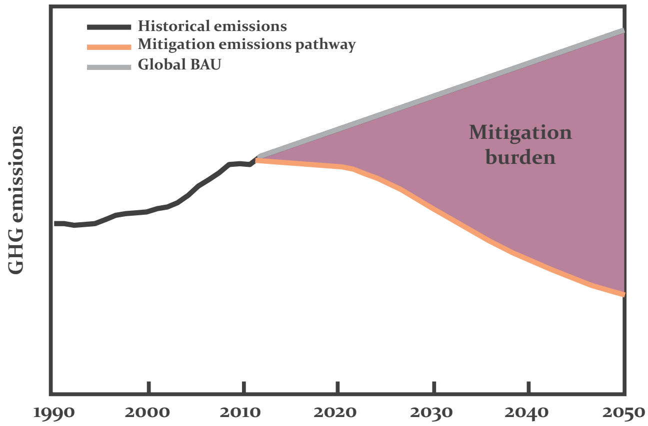

Figure 9: Mitagation burden

Calculation of emissions allowances: The index calculated using the methodology described above is then used to split the mitigation burden across countries, in such way that the country's index share of the sum of all indices will be proportional to its share of the mitigation burden. Countries with high indices will be attributed a high share of the mitigation burden and vice-versa. The share of the global mitigation burden of a country is subsequently subtracted from this country's business-as-usual emissions to obtain its final emissions allocations.[2]

The assessment of fairness of all commitments was done against emissions allowances excl. land-use, land-use change and forestry (LULUCF) emissions. This is due to two main reasons. First, emissions projections in the LULUCF sector are generally highly doubtful and would add a considerable amount of uncertainty to the overall assessment. Second, while the LULUCF sector requires important emissions reductions (and increasing sinks), a pathway towards 1.5°C requires decarbonisation of the world energy system. The use of sinks to achieve targets may mask e.g. an increase in emissions from the energy and industrial emissions which would be inconsistent with a low carbon, transformational pathway towards 1.5°C goal. Real, substantial reductions in emissions from all sectors need to be made by all countries to set the world on a pathway towards a decarbonised economy. The emissions allowance ranges presented in this report constitute the 20th to 80th percentile of the overall range, which is consistent with IPCC AR5 methodology (Höhne, den Elzen, & Escalante, 2014).

Emissions levels within the equity range that guarantees the target scenario is met: The goal of the present analysis is to evaluate a range of responsibility for the countries of interest. Given the large variability of equity proposals, criteria and metrics, we can have wildly different outcomes for a country leading to very wide equity ranges. However, even if all outcomes behind the equity ranges were in line with the target scenario in question, if all countries would meet reductions in line with the top of the ranges, the resulting global emissions would be far higher than the emissions levels in that scenario. It is therefore crucial to determine the maximum level of emissions within countries' equity ranges, which when aggregated, would result in the target scenario. This level is determined as follows:

- Calculate emissions levels consistent with:
  - > **a global equity best case scenario:** where all countries choose to reduce emissions in line with the very bottom of their equity range. The combination of all these individual country equity minima would result in a global minimum. In other words, overall temperature increase would be held below the global target.

2 Such an approach allows for attribution of negative emissions allocations.

- **a global equity worst case scenario:** where all countries choose to reduce emissions only to the top of their equity range, which is numerically equivalent to the total of the maxima of all countries' equity ranges. In other words, overall temperature increase would be much above the global target.

- In a next step the Paris Agreement 1.5°C (or Cancun Agreements 2°C) pathway is then overlaid with the global equity range to determine the intersection between global equity scenarios and the target scenario. We calculate what the relative level of that intersection.

- Apply that relative level to all countries' equity ranges in order to determine the minimal emissions reduction level that would be required in order to make sure that the global target is met without relying in other countries making a comparably bigger effort to reduce emissions.

- On a final step, when necessary, we calculate a regional aggregation based on the calculated individual countries emissions levels ranges using the following rule: the region's full equity range will be bounded by the sum of individual countries max/min emissions allowances (independently from the equity proposal, criteria, or metric that this max/min allowance represents for each country). Then the relative level calculated for global emissions will be applied to the region's full equity-range in order to determine the minimal emissions reduction level that would be required in the region to meet the global target without relying in other countries making a comparably bigger effort to reduce emissions.

Selection of scenarios

Based on the range of equity proposals, criteria and quantification metrics described above, **we defined roughly 40 equity regimes to allocate mitigation efforts across countries** in the world, with the goal of capturing the widest possible range of and outcomes in terms of emissions reductions for the studied regions. These regimes are based on the following proposals, criteria and metrics:

- Different methodologies: GDR, per capita convergence, South North Proposal, South African proposal, Chinese proposal, proposal based solely on historical responsibility, proposal based on historical responsibility and capability, proposal based on potential, historical responsibility, and capability.

- Different starting years for historical period (1950, 1970, 1990)

- Different weighting schemes for the criteria (e.g. 50/50 responsibility and capability vs 75/25

- Different metrics for the criteria (e.g. capability measures in terms of HDI or GDP-PPP and their different impacts)

ANNEX VII: EQUITY APPROACH RESULTS FOR CANCUN AGREEMENTS TEMPERATURE GOAL

Similarly to the emissions allowances in line with the Paris Agreement, emissions allowances (excluding LULUCF) compatible with the Cancun Agreements could still be positive at the global level in 2050. However the EU and OECD regions would need to achieve negative emissions on an equity basis for both Cancun and Paris Agreement scenarios (Table 7).

Table 7: GHG emissions reductions in line with equity approaches consistent with the Cancun Agreements (based on GHG emissions excluding emissions from LULUCF). Own calculations using PRIMAP and Climate Analytics Equity Tool

GHG emissions – $MtCO_2e$	2020	2030	2050
China	13 994	12 524	7 352
EU28	4 745	3 180	-1 995
OECD	15 578	11 199	-3 493
World	**50 199**	**44 514**	**21 183**

For this long-term temperature goal, emissions reductions estimated using the equity approach are also more stringent than the ones resulting from a least-cost approach for countries in the European Union and the OECD. Independent from the temperature goal considered, emissions reductions, from an economic perspective, could be more likely achieved at lower cost in most countries outside these two regions.

In addition, with the Cancun Agreements long-term temperature goal as global target, the main finding for current and planned coal power plants derived from equity-considerations does not change: a considerable majority of the countries will have to implement early retirement of the coal-fired power plants and stop the construction of currently planned capacity in order to meet the global warming goal.

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