CLIMATE ACTION TRACKER

Climate Action Benchmarks:
Mid-2018 analysis exploring the highest plausible ambition for countries and sectors

Phase 1 Scoping Report

Final report – July 2018

Note:

This report was created in the first half of 2018, i.e. before publication of the IPCC Special Report on Global Warming of 1.5°C (SR 1.5). The work draws on a set of Integrated Assessment Modelling (IAM) mitigation pathways predating the publication of SR 1.5. The aim of the study was to assess highest plausible ambition on a number of indicators to contribute to limiting warming to below 1.5°C. To this end, we drew from current technological, economic and policy trends, back-casting scenarios, forecasts, and the most ambitious IAM mitigation pathways available at the time. To understand the results in this report, it is important to note that in the context of the SR 1.5 the IAM pathways in this benchmark report are typically P4 (high overshoot) pathways, as few P1–3 type pathways were available at the time, and even at this point in time are not generally available at the sectoral and geographical resolution required for the purpose of this report. P1-3 type pathways with no- or limited overshoot of 1.5°C generally have faster emissions reductions over the next few decades, hence lower emission levels around 2030 and faster transformations in all sectors than P4 type pathways in this report. This is most relevant for global total greenhouse gas emissions by 2030, which are most directly linked to IAM pathways and are too high in this report, and hence not ambitious enough, compared to values reported in IPCC SR 1.5.

A report by the Climate Action Tracker with support from the ClimateWorks Foundation, the European Climate Foundation and the We Mean Business Coalition

1 Executive summary

This report summarises the main outcomes of Phase 1 (pilot phase) of the project "Climate Action Benchmarks" developed by the Climate Action Tracker (CAT) team with support from the ClimateWorks Foundation, the European Climate Foundation and the We Mean Business Coalition.

The key objectives of this first phase were (1) to test the opportunity to define **shared Paris compatible benchmarks** globally and for 5 key countries (China, EU, India, US and Indonesia) and for 3 sectors (overall economy, power and transport) based on available public data and (2) to define a more comprehensive process for the next phase of the project.

The question we aim to answer is: "**What level of achievement is in line with the Paris Agreements long-term goals for a given country, sector and indicator?"**

The main challenge in answering this question is that a global temperature goal cannot unambiguously be translated into individual actions. Different strategies could be used to meet the long- term goal; e.g. by assigning more reductions to specific sectors than others, as long as the overall emission budget is met (since the overall budget determines the long-term temperature increase). However, the degrees of freedom are limited, as the available emissions budget is small, and it is clear from the Paris Agreement's temperature and emissions goals that all sectors will eventually have to reduce emissions to zero, the questions being when and how.

As an unambiguous translation of the global long-term goal to individual actors is not possible, we chose the approach of ***"highest plausible ambition"*** for each indicator. This means that we ended up choosing, in some instances, the fastest transition provided across different analysis perspectives, namely energy-economic scenarios from integrated assessment models (IAMs), back-casting scenarios (designed to meet e.g. 100% renewables or 1 tCO_2/cap without an explicit link to the Paris Agreement long-term goals), or current technological, economic and policy trends and forecasts. This decision was based on our own expert judgement and initial consultations with project partners. With such a set of indicators of *"highest plausible ambition"*, we ensured that in total the Paris Agreement long-term goals are met with high likelihood.

We have used the following steps to define the benchmarks representing the *"highest plausible ambition"* for each indicator based on available data:

1. The starting point is the **highest-level of ambition from global scenarios that meet the Paris Agreement long-term goals** and distribute reductions across sectors in a globally least-cost way, namely scenarios from Integrated Assessment Models and the International Energy Agency (IEA). To consider the significant uncertainties around Carbon Dioxide Removal, we include only model results with Carbon Dioxide Removal limited to a maximum of about 10–15 Gt per year globally, from a combination of BECCS and afforestation/reforestation—excluding available model scenarios that lead to up to twice this level.
2. Where **back-casting model results** are more ambitious, they are used as a point of reference for what some stakeholders believe is technically, politically and/or economically feasible.
3. **Projections based on current policies and developments** defined by industry, research organisations or national projections are used to adjust model-based results, when they indicate that a faster development is possible. These results are also used to derive at least some direction towards 1.5°C compatible results when no model results are available.
4. **Finally, we review benchmarks per sector across countries.** This step calibrates the results for the fact that for some countries more data may be available than for others.

Figure 1 presents the proposed 5 benchmarks that are the result of our analysis based on publicly available data. A further elaborated version for the indicator "coal phase out" is included in chapter 2.

GHG emissions	2014	2020	2030	2050	Net-0 year
	Gt CO_2e				Year
Global	49	45-50 (51-52)	30-40 (56-59)	5-15 (-)	2055-2060
China	11.5	11-12 (12)	6-8 (12-14)	~0 (-)	2050-2055
EU	4.2	4 (4)	2-3 (3-5)	0 (-)	2045-2050
India	2.7	3 (3.5)	2-3 (5-6)	0-2 (-)	2050-2055
USA	6.7	6-7 (7)	3-4 (7)	0 (-)	2045-2050

RES share	2014	2020	2030	2050
	%			
Global	23%	27% [-]	40-50% [-]	70-85% [-]
China	23%	26% [-]	40-50% (28-36%)	70-75% [-]
EU	29%	35-40% (36%)	50-65% (42-52%)	75-95% (55%)
India	15%	23% (22%)	40-45% (20-35%)	70-75% [-]
USA	13%	20-25% (19%)	40-45% (22-25%)	75-90% (27%)

Coal phase-out	Phase-out year
Global	2040-2050
China	2040
EU	2030
India	2040-2050
USA	2030-2035

CO_2 intensity	2014	2020	2030	2050
	gCO$_2$ / kWh			
Global	572	450-500 [-]	180-310 [-]	0 [-]
China	774	660 (662)	280-460 (500-601)	0 [-]
EU	370	200-260 (262)	60-140 (200-203)	0 [-]
India	813	650 (791)	160-260 (600-670)	0 [-]
USA	492	360-440 (454)	80-170 (340-400)	0 [-]

EV sales share	2015	2020	2030	2050	>95% sales	>95% stock
	%				Year	
Global	0.7%	10% (2-6%)	50-100% (12-24%)	100% (90%)	2030-2040	2045-2055
China	1.0%	20% (9%)	50-100% [-]	100% [-]	2030-2040	2055
EU	1.6%	15% [-]	90-100% [-]	100% [-]	2030-2035	2045
India	0.1%	5% (0.3%)	50-100% [-]	100% [-]	2030-2040	2055
USA	0.8%	10% (9%)	90-100% [-]	100% (65%)	2030-2035	2045
Indonesia	[-]	[-] [-]	50-100% [-]	100% [-]	2040	[-]

Figure 1: Overview of all the proposed benchmarks (and level of current policy projections in brackets)

Indicator definitions:

- GHG emissions refer to total economy-wide greenhouse-gas emissions, including from land use, land-use change and forestry.
- RES share refers to Renewable Energy Share in the power sector, including biomass.
- Coal phase-out refers to phase-out year in the power sector.
- CO_2 intensity refers to CO_2 emissions intensity in the power sector.
- EV sales share refers to share of Electric Vehicles in total annual sales of light-duty vehicles. Benchmarks for Indonesia are printed grey, to indicate very limited data availability compared to other countries (except EV sales share).

The following key elements need to be considered in the interpretation and use of the results. Paris-compatible model runs provide a good basis for some indicators (e.g. GHG emissions) but a very poor basis for others (e.g. EV share), for reasons explained in this report. This stresses the need for a complementary approach adapted to each indicator that we have deployed here.

Most benchmark levels are globally consistent across countries in the long term (e.g. long term benchmarks levels are very similar across countries for CO_2 intensity and EV sales-share).

Several challenges and gaps have been encountered during the data collection and benchmark definition processes in this first phase of the project. Comparability of the model results at country level and transparency of the model cost and technology assumptions are the main limitations that need to be considered in the interpretation of some of the benchmark results.

Despite the challenges, i**t is possible to derive preliminary benchmarks based on available models results and the broader literature**. These benchmarks can provide a robust starting point for guiding stakeholder consultations and mobilising higher ambition in countries and sectors, with the understanding that benchmarks can and should be refined, in the context of new data availability and updates of technological, economic and political developments and with inclusion of a wider stakeholder group. The main challenges were overcome by:

- Additional analysis and complementary data sources to ensure that the gathered scenarios can be compared (e.g. adding non-CO_2 gases where only CO_2 was considered);
- Showing ranges that could be narrowed as more data and analysis becomes available;
- Adapting results given for regions comprised of several countries, if appropriate (e.g. a particular model includes in its North America region both the USA and Canada, with the former clearly dominating the region's results).
- The determination of the benchmarks ultimately requires decisions because the global goals of the Paris Agreement cannot unambiguously be translated into sector goals. We intended to make these decisions as robust as possible through transparent description of a four-step method. Ultimately it should be a joint decision-making process by a larger group of users.

The preliminary benchmarks are the results of the project' pilot phase, including expert inputs for the collection of the data sources. Our recommendations for future work include additional data collection and analytical work, with a focus on stakeholder consultation and the following 4 points:

1. The current data sources should be complemented by collection of new integrated assessment model results that will become available soon, providing more basis for benchmarks and to reconcile e.g. 100% RES back-casting model results with IAMs, as they roughly seem to be converging.
2. The current approach should be continued and complemented with additional and updated alternative data gathering, in particular for indicators that have limited availability of Paris-compatible model results (e.g. EV sales share).
3. The current approach should also be complemented by modelling and analytical work, in particular for indicators with good availability of Paris-consistent model results that require further harmonisation to derive robust country level results (incl. beyond just the largest emitters). Data from step 2 is essential to feed into this step, to reconcile national-scale modelling with up-to-date national-specific circumstances (incl. costs, technological and political trends and projections).
4. Ultimately, it should be a joint decision-making process by a larger group of users to determine the benchmarks to translate the global goals of the Paris Agreement into sector goals.

We will continue engaging with the ClimateWorks Foundation, the European Climate Foundation and the We Mean Business Coalition to support them in the stakeholder consultation process and to define next steps towards the next phase.

2 Example output for indicator “coal phase out”

Identifying Paris-consistent benchmarks for coal phase-out in the power sector

Coal plays a large role in the world energy system, and is at the same time the most CO_2 intensive fossil fuel. Although the coal share in power generation has decreased in many countries in recent years, it is still growing in some large countries such as India and Indonesia.

To comply with the Paris Agreement’s warming limit, the power sector needs to reach zero carbon dioxide emissions globally around 2050 (Kuramochi et al., 2018). Low-emissions scenarios for the future energy system require transitioning away from unabated coal-fired power. Because other sectors face similar or even greater challenges in decarbonising completely, a fast phase-out of emissions from power is required to use our remaining carbon budget responsibly. Therefore, we define the following question as the basis for our benchmark, which we call “highest plausible ambition”: **What is the earliest feasible phase-out year for (unabated) coal from the power sector, globally and for some of the most important countries to meet the Paris Agreement’s target?** We recognize that some countries may need support to reach this level.

To answer this question, we first look at scenarios[1] that aim to limit global temperature increase and select only the scenarios that (1) are in line with Paris Agreement’s temperature limit and (2) avoid high reliance on large-scale availability of CDR (CO_2 removal) and particularly BECCS. Then, we compare the results with other sources, such as back-casting scenarios and projections based on current policies and developments, to take into account results that are considered technically and politically feasible. Finally, we harmonise country level results as the data availability differs and to ensure consistency of the ambition level, also in view of differentiation between countries.

The figure below shows the resulting suggested benchmarks of what is the “highest plausible ambition” for a global and country level phase-out of (unabated) coal from the power sector in line with the Paris’ Agreement.

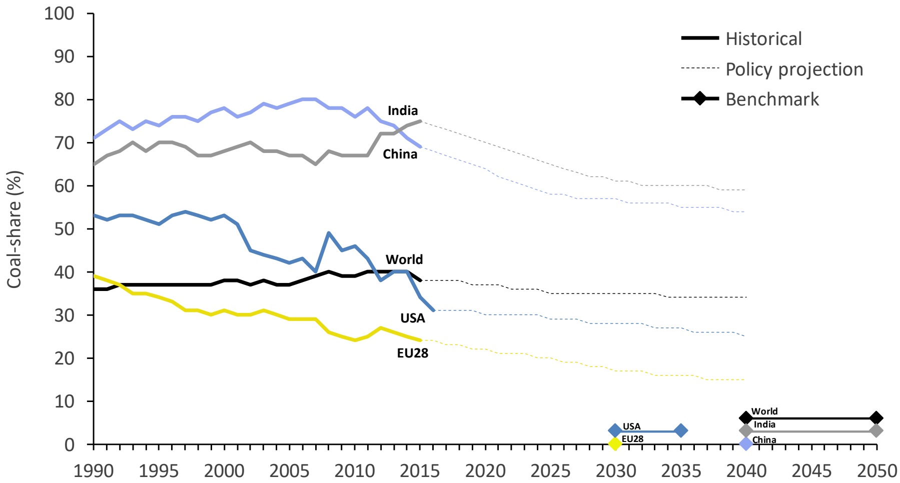

Figure 2: Coal-share (%) in the power sector, historical data (IEA, 2017d), policy projection (IEA, 2017c) and proposed benchmarks

[1] From integrated assessment models and models from the International Energy Agency (IEA)

When reviewing the literature, we found that global integrated assessment models only provide a limited numbers of Paris-compatible model runs for this indicator (D. van Vuuren et al., 2018; Rogelj et al., 2015; IEA, 2017a). We had to apply regional phase-out years to individual countries. A study with a large set of model scenarios has just been published (Rogelj et al 2018) and confirms the findings at a global level, but regional and national data from these new scenarios are not publicly available yet. Country-level analysis from back-casting models (Greenpeace, 2015; Deep Decarbonization Pathways Project, 2015) are in line or less ambitious than the Paris-compatible model runs. This reflects the fact that these stakeholders consider that the coal phase-out ambition level required to reach Paris Agreement long term goal is possible, but technically, politically and/or economically challenging. Projections based on current policies and developments are not available for this indicator. In a final step, we harmonised country specific results to reflect some country specificities and selected the most ambitious part of the range of EU and US results.

The results show that emissions from coal-fired power stations must be phased out globally between 2040 and 2050, with the phase-out occurring first in OECD countries by 2030 (for EU) or maximum 2035 (for US), followed by China in 2040 and India by maximum 2050. In recent years, China, USA, EU have shown a good trend towards achieving the benchmark, although those development are not yet supported by current policies, meaning that the long-term achievement is still very much uncertain. On the other hand, India's recent trend is going in the wrong direction. Recent policy changes are positive but not yet ambitious enough. There are not enough publicly available data for Indonesia to draw relevant conclusion for this benchmark.

We identified key challenges and gaps in defining the benchmark:

- The definition of the benchmarks ultimately requires decisions, because the global goals of the Paris Agreement cannot unambiguously be translated into sector goals. We intended to make these decisions as robust as possible through transparent description of a four-step method. Ultimately, it should be a joint decision-making process by a larger group of users.
- Model scenarios that are consistent with the Paris long-term temperature goal are still limited. A larger number of scenarios would give more robust insights on uncertainties around the wide variety of assumptions (in particular whether coal will be used along with CCS and the extent to which negative-emissions technologies are available and compensate for remaining emissions from coal).
- Paris-compatible data is particularly limited for "smaller countries". Regional scenario data can be downscaled via a relatively simple representation of the national energy system, which subsequently can benefit from the opportunity to reflect national circumstances. Additional data collection is required to guide the latter on recent developments in technology costs, policies, priorities and projections regarding the national energy mix, etc.

A next phase of the project would need to regularly update this benchmark in the light of new insights available, and involvement of a larger stakeholder group in the determination of the benchmark. Given the key role played by a coal phase-out in low-emissions scenarios, in the next phase, careful attention should be paid to issues of stranded assets in the coal power and mining sectors and how these, and inertia effects, will influence the rapidity of a phase-out.

Contents

3 Introduction

3.1 Context

3.1.1 Background

Under the Paris Agreement the world has agreed to take action collectively to hold the global average temperature increase "well below 2°C" and "pursuing efforts" to limit it to 1.5°C, peaking emissions as soon as possible, achieving a rapid decline thereafter, and reaching globally aggregate zero greenhouse gas emissions in the second half of this century[2].

To meet these ambitious goals, mitigation actions will be needed at every level and hence the big question is now what actions are needed by countries, sectors, businesses, cities and the general public. Related to this is the issue of whether current developments and future trajectories of countries and sectors are compatible with transitions that need to happen to meet Paris Agreement goals. And, how will the regulatory framework changes accompanying these transitions impact businesses, cities and others and how might these actors respond?

To limit the risks from climate change, acknowledged by the ratifying Parties of the Paris Agreement, the stringency of the Agreement's temperature and emissions reductions goals significantly constrains the levels of freedom to distribute emission reductions across sectors, countries and over time. As a result of the limited remaining carbon budget, combined with inertia in the energy, transport, and industrial systems, and the difficulty of reducing emissions in some sectors, global energy models find only a small set of possible emissions pathways, . On the other hand, zero-carbon technologies are developing very rapidly, with costs reducing faster than assumed in many energy system models, or even market forecasts, so that more ambitious action becomes possible and acceptable in, for example, the power and transport sectors, but increasingly in other sectors as well.

3.1.2 Objective of the project

The objective of this project is to develop, in a collaborative dialogue process with representatives from different actors' groups, a set of climate action benchmarks for i.a. countries, sectors, subnational entities that can be shared by a broad range of actors. The benchmarks should help users to assess if recent developments and future actions or targets of countries and non-state actors are compatible with the Paris long-term temperature goal. Possible users include policymakers to help determine and evaluate actions and policies required for decarbonisation, as well as businesses, cities and campaigners to inform themselves and engage in discussions with stakeholders on the level of actions and prepare their own organisations for expected developments. Businesses could also use the results to explore likely regulatory and/or market constraints on their own sectors or sectors covering their supply chains.

3.1.3 Scope and definitions

In this first phase, we focus on five indicators in three sectors:

1. Economy-wide indicator
- **GHG emissions**
  = total GHG emissions at economy-wide level (tCO_2e)

2. Power sector indicators
- **Renewable electricity share in the power sector**

[2] For the purpose of this report, the term "globally aggregate zero greenhouse-gas emissions" is used to reflect the actual text in Article 4 of the Paris Agreement: "... balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases ..."

= Renewable energy share in generated electricity (% TWh) (all RE, incl. Bio and Hydro)

- **Expected year of coal phase-out in the power sector**
  = year in which share of unabated coal <5% in generated electricity (year)[3]
- **CO_2 intensity of the power sector**
  = CO_2 emissions intensity of generated electricity (tCO_2 / kWh)

3. Transport sector indicator

- **EV sales share**
  = number of Electric Vehicles (EVs) as a fraction of Light Duty Vehicles (LDVs) (% EV)

The benchmarks cover three points in time (2020, 2030 and 2050) for the following five countries: USA, EU, China, India, Indonesia.

3.2 Selecting the right data for the right indicator

Our approach to defining suggested benchmarks is to use a variety of sources, taking advantage of their individual relative strengths:

- **IAM core sources** for indicators close to the "problem space", validated with broader literature, historical trends and bottom-up studies
  - Indicators close to the "problem space" are those most directly linked to a high level of global warming, which needs to be avoided. The linkage is primarily via geophysical mechanisms, and indicators are relatively directly constrained by particular carbon budgets and warming limits. Indicators include total GHG emissions and the phase-out of unabated coal. Once a temperature limit of 1.5°C is set, the ranges of values of indicators compatible with that limit is comparatively small and hence degrees of freedom for policy targets and benchmarks are very limited.
- **Broader literature core sources** for indicators grounded in the "solutions space", if possible further guided by IAM results under particular constraints, such as technology portfolio, regional/national circumstances etc.
  - Indicators close to the "solution space" are those closely related to the many different, and rapidly developing options that define our zero-emissions future. These indicators represent the actions we can take to replace high-emissions technologies and change GHG emissions trajectories, such as increasing the share of electric vehicles. The range of values of these indicators compatible with 1.5°C is comparatively large. Note, however, that benchmark values need to be drawn from the more ambitious part of the range for a particular indicator, to avoid the need for other benchmarks to over-deliver and to hedge against the risk that other benchmarks may under-deliver.

Data availability for Paris compatible (well below 2/1.5°C) scenarios is also a key consideration for the selection of the right data sources. The figure below illustrates the data availability of the selected indicators.

[3] The reason for applying this 5% rule (instead of actually zero), which is also used by the IPCC, is that many IAMs, due to the underlying mathematical optimisation, tend to keep small amounts of specific energy transformation technologies in the overall energy supply system.

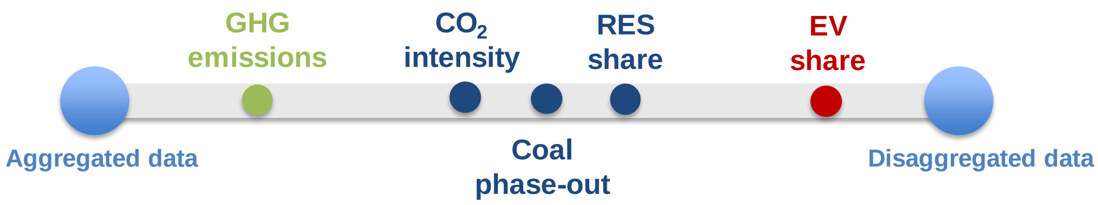

Figure 3: Illustration of the data availability of the selected indicators

3.3 Key characteristics of Integrated Assessment Models

Uncertainties exist in the response of the climate to increases in atmospheric GHG concentrations and changes in other anthropogenic influences (aerosols, land-surface characteristics). In Integrated Assessment Models this uncertainty is often not directly accounted for. If there is a representation of the climate system, this is usually limited to a single projection of global warming. However, IAM emissions scenarios can be evaluated with coupled carbon-cycle/climate models that take into account these uncertainties, as was done for all emissions scenarios assessed in IPCC's Fifth Assessment Report. This provides an ex-post analysis of probabilities of exceeding, or staying below, certain warming limits representative of the latest climate science. Some uncertain aspects remain outside of the scope of these assessments, which was also the case for the large complex Earth system models used in IPCC's AR5. An example is methane release from thawing permafrost (MacDougall, Zickfeld, Knutti, & Matthews, 2015).

Emission pathways generally achieve a range of probability and temperature limits simultaneously. Of particular importance in the context of the Paris Agreement long-term temperature goal is the general observation (see Appendix) that global emissions pathways can simultaneously achieve a probability of:

- About 85% to hold warming below 2°C throughout the 21st century,
- About 70% to hold warming below 1.75°C throughout the 21st century,
- About 50% to limit warming to 1.5°C by 2100.

From sources with multiple scenarios (AR5 database; Rogelj et al 2015) we were able to select such scenarios (See table 1). We have also included the most recent modelling results publicly available, from two individual models, that achieve higher probabilities than these (IMAGE, GCAM).

Another critical issue in the interpretation of mitigation scenarios is how much they rely on Carbon Dioxide Removal (CDR) from the atmosphere. Nearly all published scenarios rely on the large-scale deployment of afforestation/reforestation and technological means to remove CO_2 from the atmosphere, usually by using BioEnergy with Carbon Capture and Storage (BECCS). This technology is heavily debated as it remains to be proven to work on the scale of several gigatonnes CO_2 removed per year and due to its possible interference with food security and biodiversity because of land (and fresh water) requirements.

Table 1 summarises these two key characteristics for the IAM results included in this report. Published results (van Vuuren et al 2018) suggest the total annual CDR in the IMAGE SSP2-RCP19 scenario reaches around 10–15 GtCO2/yr during the second half of the century.

Table 1: Key characteristics of IAM scenarios used in this work

Model or model source	Cumulative CDR (Gt CO_2)	Probability of staying below 2°C during 21st century	Probability of staying below 1.5°C in 2100
IMAGE	~750[a)]	87%[b)]	73%[b)]
GCAM	– [c)]	~85%[b)]	~66%[b)]
AR5/SSP-IAM	– [d)]	~80–85%[e)]	50%[f)]
Rogelj et al (2015)	450–1000[g)]	~80%[h)]	50–55%[h)]

a) Van Vuuren et al (2018) Figure 2
b) Rogelj et al (2018) Figure 1d
c) Available data only contains total GHG emissions, without separation between gases
d) Methodology (ordinary least squares fit of variable of interest on median temperature in 2100) does not allow for computation of these values
e) Derived from 50% chance of below 1.5°C by 2100 (right column) and general associated probability for 2°C as explained in text
f) Results for 1.5°C warming in 2100 are derived by ordinary least-squares fit with median temperature in 2100 as the independent variable. Median temperature corresponds to a 50%-probability of exceeding 1.5°C in that context
g) Range for all scenarios in Rogelj et al (2015) noting that precise CDR data for the five scenarios selected for this report is not available
h) For the five scenarios selected for this report

IEA models also include important assumptions on negative emissions. In both the 2DS and B2DS scenarios defined by IEA, BECCS is deployed at a large scale, delivering 36 GtCO2 of cumulative negative emissions in the 2DS and 72 GtCO2 in the B2DS in the period to 2060. Generally, in 1.5 and 2°C scenarios, the largest amount of negative emissions is achieved post 2060, so that IEA scenarios can be assumed reach substantially higher cumulative amounts by the end of the century. Negative emissions would likely need to be greater in the case of a 1.5°C trajectory compared to the 2DS and B2DS scenarios.

For further details on probability levels and a more in-depth discussion of the issue of negative emissions please see the Appendix.

4 Benchmark definitions

4.1 Methodology to define the proposed benchmarks

The objective of the analysis is to define shared benchmarks that are compatible with the long-term goals of the Paris Agreement. The level of the benchmarks must therefore be in line with a "well below 2°C" or "pursuing 1.5°C" trajectory and achieve globally aggregate zero GHG emissions in the second half of the century.

The main obstacle to answering this question is that the global goals cannot unambiguously be translated into individual actions. Different strategies could be used to meet the long- term goal; e.g. by assigning more reductions to specific sectors than others, as long as the overall emission budget is met (as it determines the long-term temperature increase). The strategies also differ in how much the budget can be "overspent" and later compensated by negative emissions. But the degrees of freedom are limited, as the available emission budget is very limited. It is clear from the Paris Agreements goals, that eventually all sectors have to reduce emissions to zero, the question is when and how (Kuramochi et al., 2018).

Several types of analysis are available to draw upon. Integrated Assessment Models and the model results from the IEA define technically feasible and globally cost-optimal trajectories that are compatible with the Paris Agreement's warming limit target (see section 2.3). However, they sometimes appear "conservative", or outdated. For some indicators, the resolution of Integrated Assessment Models may not be sufficient. IAMs show a large spread of possible values for many indicators, which is due to the large (though still limited) number of models and scenarios, including different relative technology costs, and variations in deployment of negative emissions to compensate fossil fuel related emissions. Alternately, models based on "back-casting" can be used, where it is assumed that a particular goal of e.g. 100% renewables is met by a certain date, without necessarily considering overall cost effectiveness of achieving a particular warming limit or emissions level. Finally, current policies and developments can be faster (or slower) than model assumptions, as changes in these trends may not yet have propagated t updated assumptions in the models.

As an unambiguous translation of the global long-term goal to individual actors is not possible, we chose the approach of the **"highest plausible ambition"** for each indicator. This may mean that we choose in some instances the fastest transition provided in IAMs, back-casting scenarios and recent trends. With our chosen indicators of *highest plausible ambition*, we ensure that the overall Paris Agreement long-term goals are met with high likelihood.

As a result of these considerations, we have used the following four steps to define our suggested benchmark levels:

1. The starting point is the **highest-level of ambition from global scenarios that meet the Paris Agreement long-term goals** and distribute reductions across sectors in a globally least-cost way, namely scenarios from Integrated Assessment Models and the International Energy Agency (IEA). To consider the significant uncertainties around Carbon Dioxide Removal, we include only model results with Carbon Dioxide Removal limited to a maximum of about 10–15 Gt per year globally, from a combination of BECCS and afforestation/reforestation—excluding available model scenarios that lead to up to twice this level.
2. Where **back-casting model results** are more ambitious, they are used as a point of reference for what some stakeholders believe is technically, politically and/or economically feasible.
3. **Projections based on current policies and developments** defined by industry, research organisations or national projections are used to adjust model-based results, when they indicate that a faster development is possible. These results are also used to derive at least some direction towards 1.5°C compatible results when no model results are available.
4. **Finally, we review and harmonise benchmarks per sector across countries.** This step calibrates the results based on internal and qualitative expert review for the fact that for some countries more data may be available than for others and to resolve inconsistencies between data sources for a given country.

Below is the colour code used in the tables in the next section to indicate the hierarchy level of each source and how the source has been used in the benchmark definition indicated at the end of the table.

Paris compatible model results

Back-casting model results

Projections based on current policies and developments

4.2 GHG emissions

4.2.1 Introduction

The first benchmark is for **total economy-wide GHG emissions from all sources in GtCO₂e/year**. The GHG emissions comprise emissions of all gases covered in the Kyoto Protocol: CO_2, CH_4, N_2O, HFCs, PFCs and SF_6, expressed in CO_2-equivalents (using 100-year Global Warming Potentials to weight a greenhouse-gas's effect on global warming relative to CO_2, when evaluated over a 100-year time horizon).

The benchmark also includes "Net-0 year" which is the year when total GHG emissions are expected to reach 0. The net zero year is calculated as the first year in which total GHG emissions are below 5% of 2010 value.

Current emissions of GHGs are approximately 49 $GtCO_2e$/year, with approximately 37 Gt being carbon dioxide and the remainder coming from other contributions, primarily methane and nitrous oxide (Climate Action Tracker, 2017). Although emissions have been rising relatively slowly over the past few years, total emissions have risen by nearly 50% since the reference date of 1990 usually used as a baseline, with particularly strong growth in emissions in China (Figure 4).

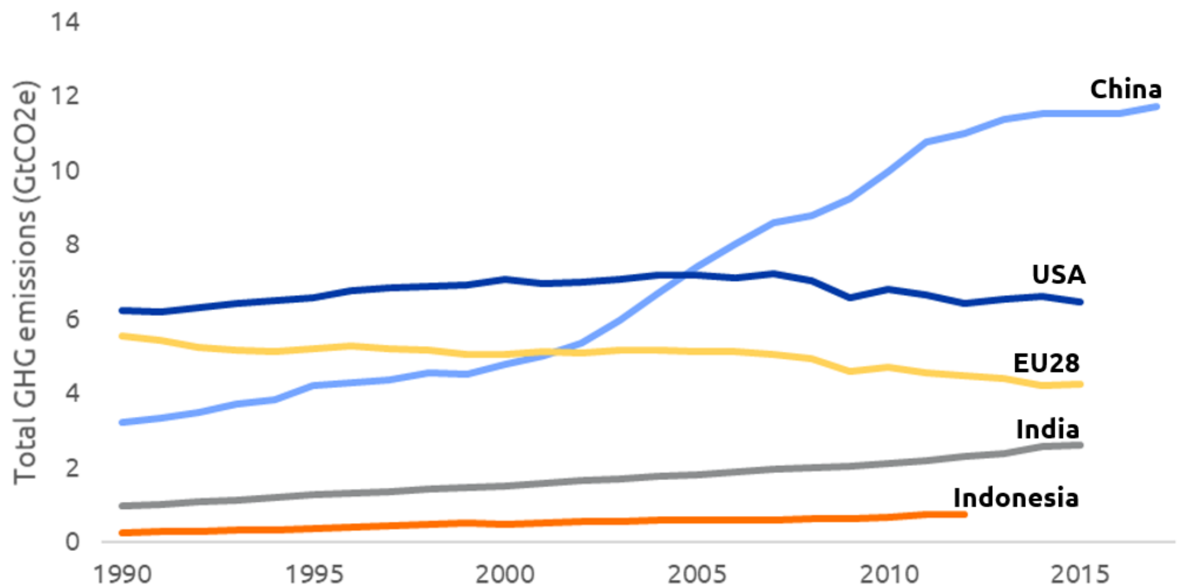

Figure 4: Annual total GHG emissions in focus countries, 1990–2017. Source: CAT Country Assessments. Shown are latest data points available.

4.2.2 Presentation of results

Since total global emissions are one of the key indicators in the climate science community, most models and other summaries will report this quantity. The data sources used in the definition of the benchmark are listed below; for details about the different approaches, please refer to the appendices.

- Integrated Model to Assess the Global Environment, "IMAGE 2018" (D. van Vuuren et al., 2018)
- Global Change Assessment Model, "GCAM 2017" (Joint Global Change Research Institute, 2017)
- Fifth Assessment Report, "IPCC AR5" (Intergovernmental Panel on Climate Change, 2014)
- Energy system transformations for limiting end-of-century warming to below 1.5 °C, "Rogelj, et al. 2015" (Rogelj et al., 2015)
- IEA Energy Technology Perspectives 2017, "IEA ETP" (IEA, 2017a)
- Greenpeace, The Energy [R]evolution, 2015, "Greenpeace" (Greenpeace, 2015)
- Deep Decarbonization Pathways, Country Reports, 2015, "DDP" (Deep Decarbonization Pathways Project, 2015)
- Climate Action Tracker, Decarb Portal, 2017, "CAT" (Climate Action Tracker, 2017)
- Carbon Transparency Initiative, 2016, "CTI" (Carbon Transparency Initiative, 2016)
- Carbon Transparency Initiative, EU results, 2018, "CTI EU" (Cornet et al., 2018)

The tables below present the result of our data collection and the suggested benchmark level based on the approach described in section 4.1.

Table 2: Overview of results for GHG emissions global benchmark

Global	2020	2030	2050	Net-0 year	Remarks
	Gt CO_2e			year	
Benchmark	**45-50**	**30-40**	**5-15**	**2055-2060**	
Paris compatible model results					
IMAGE	47	31	6	2054	
GCAM	44	42	17	2075-2080	• GCAM4.2 scenario for RCP 1.9 without BECCS restriction (negative emissions level considered very high and therefore not taken into account)
AR5/SSP	49	38	13	[-]	• Econometric estimation of 1.5°C value from AR5 and SSP IAM databases
Rogelj et al. (2015)	49	38	14	2060-2070	• Median value of 5 "delayed action" scenarios
IEA ETP	~45	~30	~4	[-]	• B2D scenario (energy related CO_2 emissions) + other emissions from IMAGE model
Back-casting model results					
Greenpeace	~46	~30	~11	[-]	• Advanced Energy Revolution scenario (CO_2 emissions) + other emissions from IMAGE model
Projections based on current policies and developments					
CAT	51-52	56-59	[-]	[-]	• Current policy scenario

Table 3: Overview of results for GHG emissions benchmark for China

China	2020	2030	2050	Net-0 year	Remarks
	Gt CO_2e			year	
Benchmark	**11-12**	**6-8**	**~0**	**2050-2055**	
Paris compatible model results					
IMAGE	11.3	8.1	0	2045	
GCAM	9.7	9.2	2.1	2060-2065	• GCAM4.2 scenario for RCP 1.9 without BECCS restriction (negative emissions level considered very high and therefore not taken into account)
Rogelj et al. (2015)	10.5	7.8	2.7	2080-2090	• Results are for MESSAGE region CPA (Centrally Planned Asia) including China but also other countries such as Cambodia and Viet Nam and therefore not taken into account
IEA ETP	~12	~6	~0	2050	• B2D scenario (energy related CO2 emissions) + other emissions from IMAGE
Back-casting model results					
DDP	[-]	[-]	5.2	[-]	• Central scenario
Greenpeace	~11	~8	~1	>2050	• Advanced Energy Revolution scenario (CO2 emissions) + other emissions from IMAGE
Projections based on current policies and developments					
CAT	12	12-14	[-]	[-]	• Current policy projection
CTI	[-]	14	[-]	[-]	• Current Development Scenario, based on current policies, decarbonisation trends and energy-related investments

Table 4: Overview of results for GHG emissions benchmark for the EU

EU	2020	2030	2050	Net-0 year	Remarks
	Gt CO_2e			year	
Benchmark	**4**	**2-3**	**0**	**2045-2050**	
Paris compatible model results					
IMAGE	4.3	2.7	0.9	2051-2066	• EU countries contained within model regions Central Europe (CE) and Western Europe (WE)
GCAM	4.4	3.9	1.3	2085-2090	• EU countries contained within model regions EU-15 and EU-12 • GCAM4.2 scenario for RCP 1.9 without BECCS restriction (negative emissions level considered very high and therefore not taken into account)
Rogelj et al. (2015)	5.6	3.7	1.1	2080->2100	• EU countries are scattered across WEU and EEU regions that contain EU and non-EU countries (incl. Turkey) and therefore not taken into account
IEA ETP	~4	~2	~0	2050	• B2D scenario (energy related CO_2 emissions) + other emissions from IMAGE (CE + WE regions)
Back-casting model results					
DDP	[-]	[-]	[-]	[-]	• No valid data for EU
Greenpeace	~4	~2	~1	2050	• Advanced Energy Revolution scenario (only CO2 emissions; including some non-EU countries such as Israel and Turkey and excluding others such as Croatia or Lithuania) + other emissions from IMAGE (CE + WE regions)
CTI EU	[-]	2.1	[-]	[-]	• Best practice policy scenario for the EU-28
Projections based on current policies and developments					
CAT	3.9–4.0	3.4–3.9	[-]	[-]	• Current policy projections
CTI	[-]	4.6	[-]	[-]	• Current Development Scenario, based on current policies, decarbonisation trends and an evaluation of energy-related investments

Table 5: Overview of results for GHG emissions benchmark for India

India	2020	2030	2050	Net-0 year	Remarks
	Gt CO_2e			year	
Benchmark	**3**	**2-3**	**0-2**	**2050-2055**	
Paris compatible model results					
IMAGE	3.1	2.3	0	2044	
GCAM	3.1	3.2	2.1	2080-2085	• GCAM4.2 scenario for RCP 1.9 without BECCS restriction (negative emissions level considered very high and therefore not taken into account)
Rogelj et al. (2015)	4.9	5.1	3.5	after 2100	• India is part of MESSAGE region SAS (South Asia) consisting of India but also other countries such as Bangladesh or Pakistan and therefore not taken into account
IEA ETP	~3	~3	~2	> 2050	• B2D scenario (energy related CO_2 emissions) + other emissions from IMAGE.
Back-casting model results					
DDP	[-]	[-]	1.9	[-]	• Sustainable scenario
Greenpeace	~3	~3	~1	> 2050	• Advanced Energy Revolution scenario (CO_2 emissions) + other emissions from IMAGE
Projections based on current policies and developments					
CAT	3.5	5.1–5.4	[-]	[-]	• Current policy projections
CTI	[-]	6.2	[-]	[-]	• Current Development Scenario, based on current policies, decarbonisation trends and an evaluation of energy-related investments

Table 6: Overview of results for GHG emissions benchmark for the USA

USA	2020	2030	2050	Net-0 year	Remarks
	Gt CO_2e			year	
Benchmark	**6-7**	**3-4**	**0**	**2045-2050**	
Paris compatible model results					
IMAGE	5.5	3.0	0	2039	
GCAM	6.1	5.7	1.2	2060-2065	• GCAM4.2 scenario for RCP 1.9 without BECCS restriction (negative emissions level considered very high and therefore not taken into account)
Rogelj et al. (2015)	7.0	4.4	0	2050	• USA are part of model region NAM (North America) consisting of the USA and Canada. The results are considered valid for US and taken into account
IEA ETP	~6	~3	~0	2050	• B2D scenario (energy related CO_2 emissions) + other emissions from IMAGE
Back-casting model results					
DDP	[-]	[-]	0.7	[-]	• Mixed scenario
Greenpeace	~6	~3	~0	2050	• Advanced Energy Revolution scenario (only CO2 emissions; includes Canada and Mexico) + other emissions from IMAGE (North-America)
Projections based on current policies and developments					
CAT	6.7	6.7	[-]	[-]	• Current policy projections
CTI	[-]	7.4	[-]	[-]	• Current Development Scenario, based on current policies, decarbonisation trends and an evaluation of energy-related investments

Table 7: Overview of results for GHG emissions benchmark for Indonesia

Indonesia	2020	2030	2050	Net-0 year	Remarks
	Gt CO_2e				
Benchmark	**1.6**	**0.9**	**~0**	**2050-2055**	• Based on 1 source only
Paris compatible model results					
IMAGE	1.6	0.9	0	2045	
GCAM	1.2	1.3	1.3	2085-2090	• GCAM4.2 scenario for RCP 1.9 without BECCS restriction (negative emissions level considered very high and therefore not taken into account)
Rogelj et al. (2015)	[-]	[-]	[-]	[-]	• Indonesia is part of model region Other Pacific Asia (PAS) which is considered as not a representative region
IEA ETP	[-]	[-]	[-]	[-]	• No available data for Indonesia
Back-casting model results					
DDP	[-]	[-]	0.4	[-]	• Renewable scenario
Greenpeace	[-]	[-]	[-]	[-]	• No available data for Indonesia
Projections based on current policies and developments					
CAT	1.0	1.3	[-]	[-]	• Current policy projections
CTI	[-]	[-]	[-]	[-]	• No available data for Indonesia

4.2.3 Conclusions

As a result of the present analysis, the table below shows our suggested benchmarks for an "highest feasible ambition" level of GHG emissions level that would enables us to stay within the limit of a "well below 2°C" temperature increase.

The suggested benchmarks levels were defined based on the following 4 steps:

1. **Highest-level of ambition from IAMs and IEA:** several Paris compatible model runs are available for this indicator. However, some results are not taken into account because the level of negative emissions is considered too high (GCAM) or regional results are not applicable for some of the countries (Rogelj et al. 2015). IEA ETP CO_2-only data were complemented with non-CO_2 and other emissions from IMAGE to enable comparability of results. The net-zero year for the EU is relatively late compared to other countries, which could have a variety of reasons (differences in cost assumptions, differences in non-CO2 emissions, differences in amount of BECCS, etc.). With an eye to "highest feasible level of ambition", IEA ETP values determine the EU zero year, rather than the later IAM-based values.
2. **Back-casting model-based results** are in line with, or only slightly less ambitious than, Paris consistent results from IAMs. Even if the results are not fully consistent with the limit of well below 2 or 1.5°C temperature increase, they suggest that the model results

from "step 1" could be considered by the related stakeholders as technically, politically or economically feasible.

3. **Projections based on current developments** are less ambitious than model results and do not reflect the level of ambition required to reach Paris Agreement long term goal.
4. **Harmonisation of country specific results:** to ensure consistency of the benchmarks across countries in light of limited data availability, and with our aim of finding the "highest plausible ambition", we have defined the EU net-0 year based on the more ambitious US benchmark level (2045–2050) and we selected the higher end of the range for India and China (2050–2055). This earlier net-0 year for developed countries reflects the need for developed countries to take the "lead" in climate action. This is also in line with 1.5°C scenario data that will be published together with the IPCC SR1.5. The broader and most recent 1.5°C literature shows that in 1.5°C pathways, while the net-0 year for *CO_2 emissions* in Asia is very close to the net-0 year for OECD countries, the net-0 year for *total GHG emissions* is typically 5–10 years later. Other developing country regions have net-0 years close to OECD for both CO_2 and total GHGs. The "delay" for Asia is explained mostly by methane emissions, with China, India and Indonesia all among the top global CH_4 emitters.

The results show that global GHG emissions must be reduced rapidly to reach a net-zero level between 2055 and 2060. The countries in scope show consistent results as all the benchmarks are set to reach net-zero emissions around 2050, with US and EU set to achieve this earlier than China and India. There are not enough publicly available data for Indonesia to draw relevant conclusion for this benchmark.

Table 8: Overview of our suggested benchmarks for GHG emissions

GHG emissions	2014	2020	2030	2050	Net-0 year	Remarks
	Gt CO_2e				Year	
Global	49	45-50 (51-52)	30-40 (56-59)	5-15 (-)	2055-2060	
China	11.5	11-12 (12)	6-8 (12-14)	~0 (-)	2050-2055	
EU	4.2	4 (4)	2-3 (3-5)	0 (-)	2045-2050	
India	2.7	3 (3.5)	2-3 (5-6)	0-2 (-)	2050-2055	
USA	6.7	6-7 (7)	3-4 (7)	0 (-)	2045-2050	
Indonesia	0.8	1.6 (1.0)	0.9 (1.3)	~0 (-)	2050-2055	Based on 1 source only

Remark: the 2014 level is based on CAT data; the smaller numbers in brackets denote current policy projections.

The key challenges and gaps encountered in defining the benchmark are:

- Limited number of scenarios in line with 1.5°C, in particular at country level
- Difficulties in comparing model results:

- IAMs cover only larger individual countries and defined regions, with those definitions not necessarily being the same between models. For some models (including AR5) we could not define appropriate proxy regions and therefore did not include this source in country benchmarks. Furthermore, none of the models provide results that exactly correspond to the scope of the EU region and usually include additional countries such as Turkey. Results of the EU region are therefore overestimated.
- IEA scenarios only provide results for energy-related CO_2 emissions. We have added other CO_2 and non-CO_2 emissions from IAMs sources to enable a basic comparison.

Making benchmark results more robust would require additional data and analytical work on the following aspects:

- Differentiation of results in terms of weak vs strong dependency on negative emissions technologies. Although deployment of negative emissions technologies is evident in all currently available data sources that relate to the Paris Agreement and to its well-below 2°C/1.5°C limit, available data is too limited to make a useful distinction.
- Downscaling of results from regions to individual countries. Ideally, we would do so based on GDP per capita country projections for each scenario of each model, or more sophisticated downscaling approaches at energy system level, followed by adjusting the associated representation of the national energy system to reflect recent developments and planned policies at country level.
- More insights and actionable benchmarks could be based on additional indicators at sector level, e.g. energy related CO2, total emissions from agriculture etc.

For Phase 2 of this project, there will be more scenarios from the IAM community, assessed in the IPCC 1.5°C Special Report to be released in October 2018. As the focus on Paris Agreement-compatible scenarios and ambitions increases, more effort will be made to understand some of the differences between aspirational scenarios indicating the feasibility of rapid transformation toward a 100% renewable energy and the more cautious results that arise from complete energy-economy system models such as IAMs for which results can be evaluated directly against the Paris Agreement global temperature and emissions goals.

4.3 RES share

4.3.1 Introduction

The second benchmark is based on the indicator Renewable Energy Source (RES) share in the power sector and is defined as the ***RES share in generated electricity (% TWh)***. This includes renewable energy from biomass and hydroelectric power.

In the EU and, more recently, in China and the USA, the RES share in the power sector has been growing steadily in recent years (Figure 5). In developing countries such as India and Indonesia, the shares have been declining since 1990 in the face of rising electricity demand.

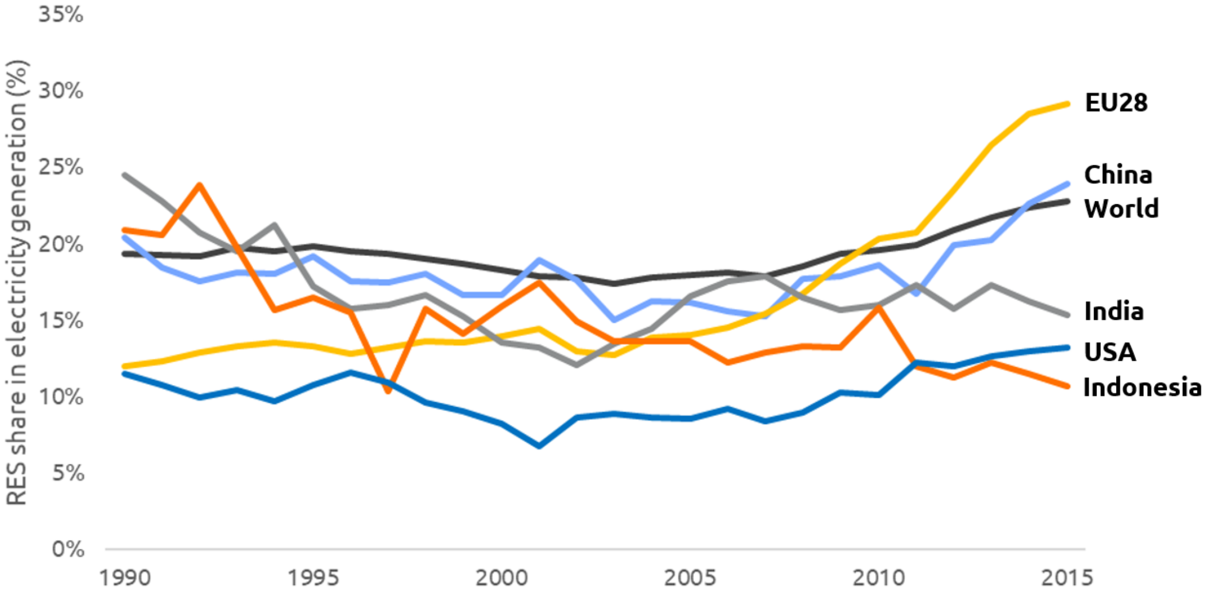

Figure 5: RES share in electricity generation in focus countries, 1990–2016. Source: CAT Decarb Portal based on IEA data from Energy Statistics and Balances 2016 OECD/IEA [2016], www.iea.org/statistics, Licence: www.iea.org/t&c; as modified by the Climate Action Tracker.

4.3.2 Presentation of results

The available literature shows that the electricity sector is an especially critical area for decarbonisation efforts, and therefore for meeting the Paris targets (e.g. Rogelj et al 2018). An array of technologies exists for moving toward a low-carbon electricity system, and options to convert demand from other sectors (heating of buildings, transportation) to electricity are increasing. The electrification of these sectors potentially carries with it an increase in efficiency, and therefore a possible decrease in final energy consumption for a given level of services. At the same time, renewable energy capacities have been consistently increasing at much higher rates globally than was believed possible only a few years ago.

Data sources used for renewable energy shares in the electricity sector include:

- Integrated Model to Assess the Global Environment 2018, “IMAGE” (D. van Vuuren et al., 2018)
- Fifth Assessment Report, “IPCC AR5” (Intergovernmental Panel on Climate Change, 2014)
- Energy system transformations for limiting end-of-century warming to below 1.5 °C, “Rogelj, et al. 2015” (Rogelj et al., 2015)
- IEA Energy Technology Perspectives 2017, “IEA ETP” (IEA, 2017a)
- Greenpeace, The Energy [R]evolution, 2015, “Greenpeace” (Greenpeace, 2015)
- Deep Decarbonization Pathways, Country Reports, 2015, “DDP” (Deep Decarbonization Pathways Project, 2015)
- Climate Action Tracker, Decarb Portal, 2017, “CAT” (Climate Action Tracker, 2017)
- Carbon Transparency Initiative, 2016, “CTI” (Carbon Transparency Initiative, 2016)
- Carbon Transparency Initiative, EU results, 2018, “CTI EU” (Cornet et al., 2018)
- IRENA, Global Energy Transformation – A roadmap to 2050, 2018, “IRENA” (IRENA, 2018)

In addition, we also screened the following reports. However, data projections in these reports were not used to inform the benchmark decision as they had e.g. short time horizons or because they did not match the benchmark definition.

- REN21, Global Status Report, 2017 (REN21, 2017)

- IRENA, The Power to Change: Solar and Wind Cost Reduction Potential to 2025, 2016 (IRENA, 2016b)
- Global Wind Energy Council, Global Wind Report, 2016 (Global Wind Energy Council, 2016)
- EIA, International Energy Outlook, 2017 (EIA, 2017)

The tables below present the result of our data collection and the suggested benchmark level.

Table 9: Overview of results for RES share global benchmark

Global	2020	2030	2050	Remarks
		%		
Benchmark	**27%**	**40-50%**	**70-85%**	
Paris compatible model results				
IMAGE	19%	38%	76%	
IPPC AR5	21%	28%	58%	
Rogelj et al. (2015)	21%	37%	60%	
IEA ETP	[-]	47%	74%	• B2D Scenario
Back-casting model results				
IRENA	[-]	[-]	85%	• REmap scenario
Greenpeace	32%	64%	100%	• Advanced Energy Revolution scenario
Projections based on current policies and developments				
IEA ETP	27%	33%	41%	• Reference Technology Scenario (~planned policy pathway)

Table 10: Overview of results for RES share benchmark for China

China	2020	2030	2050	Remarks
		%		
Benchmark	**26%**	**40-50%**	**70-75%**	
Paris compatible model results				
IMAGE	15%	28%	74%	
Rogelj et al. (2015)	18%	23%	48%	• Results based on overall CPA region (not only China) and therefore not taken into account
IEA ETP	[-]	49%	70%	• B2D scenario
Back-casting model results				
DDP	[-]	[-]	51%	• Central scenario
Greenpeace	27%	50%	100%	• Advanced Energy Revolution scenario
Projections based on current policies and developments				
CAT	[-]	28%	[-]	• Current policy projections
CTI	[-]	36%	[-]	• Current Development Scenario, based on current policies, decarbonisation trends and an evaluation of energy-related investments
BNEF	[-]	55%		• Central scenario in 2040
IEA ETP	26%	32%	43%	• Reference Technology Scenario (~planned policy pathway)

Table 11: Overview of results for RES share benchmark for the EU

EU	2020	2030	2050	Remarks
		%		
Benchmark	**35-40%**	**50-65%**	**75-95%**	
Paris compatible model results				
IMAGE 2018	11-33%	14-45%	81-93%	• EU countries contained within model regions Central Europe (CE) and Western Europe (WE)
Rogelj et al. (2015)	14-27%	29-39%	57-59%	• Results based on overall WEU and EEU regions (also non EU, incl. Turkey)
IEA ETP	[-]	59%	75%	• B2D scenario
Back-casting model results				
DDP	[-]	[-]	[-]	• Model does not cover EU
Greenpeace	42%	70%	100%	• Advanced Energy Revolution scenario (including some non-EU countries such as Israel and Turkey and excluding others such as Croatia or Lithuania)
CTI EU	[-]	74%	[-]	• Best practice policy scenario for the EU-28 based on new model projection
Projections based on current policies and developments				
CAT	36%	42%	55%	• Current policy projections
CTI	[-]	52%	[-]	• Current Development Scenario, based on current policies, decarbonisation trends and an evaluation of energy-related investments
BNEF	[-]	74%		• Central scenario in 2040 for GERMANY only
IEA ETP	38%	50%	63%	• Reference Technology Scenario (~planned policy pathway)

Table 12: Overview of results for RES share benchmark for India

India	2020	2030	2050	Remarks
	%			
Benchmark	**23%**	**40-45%**	**70-75%**	
Paris compatible model results				
IMAGE	23%	43%	69%	
Rogelj et al. (2015)	24%	42%	59%	• Results based on overall SAS (South Asia) region (not only India) and therefore not taken into account
IEA ETP	[-]	42%	75%	• B2D scenario
Back-casting model results				
DDP	[-]	[-]	60%	• Central
Greenpeace	23%	65%	100%	• Advanced Energy Revolution scenario
Projections based on current policies and developments				
CAT	22%	20–26%	[-]	• Current policy projections
CTI	[-]	35%	[-]	• Current Development Scenario, based on current policies, decarbonisation trends and an evaluation of energy-related investments
BNEF	[-]	49%		• Central scenario in 2040
IEA ETP	19%	23%	27%	• Reference Technology Scenario (~planned policy pathway)

Table 13: Overview of results for RES share benchmark for the USA

USA	2020	2030	2050	Remarks
		%		
Benchmark	**20-25%**	**40-45%**	**75-90%**	
Paris compatible model results				
IMAGE	15%	43%	92%	
Rogelj et al. (2015)	23%	42%	78%	• Results based on overall NAM (North America) consisting of the USA and Canada. The results are considered valid and taken into account
IEA ETP	[-]	33%	66%	• B2D scenario
Back-casting model results				
DDP	[-]	[-]	57%	• Central
Greenpeace	35%	73%	100%	• Advanced Energy Revolution scenario, includes Canada and Mexico
Projections based on current policies and developments				
CAT	19%	22%	27%	• Current policy projections
CTI	[-]	25%	[-]	• Current Development Scenario, based on current policies, decarbonisation trends and an evaluation of energy-related investments
BNEF	[-]	38%		• Central scenario in 2040
IEA ETP	19%	28%	34%	• Reference Technology Scenario (~planned policy pathway)

Table 14: Overview of results for RES share benchmark for Indonesia

Indonesia	2020	2030	2050	Remarks
	%			
Benchmark	**15%**	**45%**	**70-75%**	• Based on 1 source only
Paris compatible model results				
IMAGE	4%	43%	70%	
Rogelj et al. (2015)	7%	37%	41%	• Results based on model region Other Pacific Asia (PAS), not only Indonesia and therefore not taken into account
IEA ETP	[-]	[-]	[-]	• No public data available on Indonesia
Back-casting model results				
DDP	[-]	[-]	49%	• Central
Greenpeace	[-]	[-]	[-]	• No public data available on Indonesia
Projections based on current policies and developments				
CAT	13–17%	18–26%	[-]	• Current policy projections
CTI	[-]	[-]	[-]	• Current Development Scenario, based on current policies, decarbonisation trends and an evaluation of energy-related investments

Only a few of the “broader” sources assessed during the project provide data for the time horizon used in this study. Additionally, the comparisons of expected solar based power generation in 2025 by Navigant Research with IEA’s ETP scenarios even suggest that the B2DS scenario underestimates the short-term expansion of solar generation (Table 15), suggesting that the IEA ETP projections could be revised upwards.

Table 15: Overview of global solar electricity generation (TWh) in expected development scenarios compared to IEA ETP scenarios

Solar based electricity production (TWh)	Global 2025
Navigant Research (Base)	1,712
IEA ETP (B2DS)	1,252

4.3.3 Conclusions

In its "Ten steps" report[4], the Climate Action Tracker showed that, to be in line with the Paris Agreement's warming limit target, the electricity generation sector will first need to make a rapid transition away from coal, and then, in the next few decades, from natural gas, towards renewables and other zero and low carbon energy sources. Zero and low carbon energy sources are mostly represented by renewable power, nuclear power or power CCS. Of these options, renewables are the most promising as they show high growth rates, provide truly zero carbon power, and have a comparatively low environmental footprint.

As a result of the present analysis, the table below shows our suggested benchmarks for an achievable level of RES shares in the power sector that would enables us to stay within the well below 2/1.5°C limit.

The suggested benchmarks levels were defined based on the following 4 steps:

1. **Highest-level of ambition from IAMs and IEA:** the large range for the EU reflects the disparities between Western and Eastern Europe. The large differences between the model results within each region reflects the disparities between model assumptions. Models assume that most of the newly built capacity in all countries is renewable, but with different costs assumptions for the different regions (e.g. analysis of results shows that cost assumptions in some models might be higher for Western Europe than for other regions).
2. **Back-casting model based results** vary a lot, being less ambitious (DDP) or more ambitious (Greenpeace and CTI) than the results from Step 1. This reflect the variety of stakeholders' views on what is considered a technically, politically and/or economically feasible RES development in the different regions. CTI EU and Greenpeace results have been taken into account to reflect that a higher level of ambition is possible in the EU for 2030 and 2050. At the global level, the recently published report by IRENA provides a more ambitious level of RES development for 2050 which we selected as higher range of the global benchmark.
3. **Projections based on current policies and developments:** current policy projections are less ambitious and do not reflect the level of ambition required to reach the Paris Agreement long term goal. However, industry projections (BNEF or others displayed in separate tables because of scoping differences) are significantly higher than other observed projections, suggesting that a higher level of ambition is possible for most regions.
4. **Harmonisation of country specific results:** to reflect differences in data availability as well as most recent developments, we selected the higher end of the range of EU and US results. Observed growth in China or India is already high and IAMs and IEA probably assume growth rates to continue to be significantly higher than in EU and USA based on current cost assumptions. This results in more RES capacity expected to be built in China and India and the renewables share increasing faster. This might not be considered as realistic given recent developments or fair in the longer term in light of the need for developed countries to take the lead. With decreasing costs and more ambitious policies, we expect more renewables will also be built in the EU and the USA.

The results show that global power generation based on RES must be ramped-up rapidly to reach 40–50% by 2030 and 70–85% by 2050. Country benchmark levels are quite different between OECD and non-OECD countries, with US and EU showing higher ambition level but also

[4] Refer to report "THE TEN MOST IMPORTANT SHORT-TERM STEPS TO LIMIT WARMING TO 1.5°C" available HERE

a larger range of results (between 75 and 90 to 95% respectively) and China and India at a similar level of ambition of 70 to 75%. There are not enough publicly available data for Indonesia to draw relevant conclusion for this benchmark.

Table 16: Overview of our suggested benchmarks for RES share

RES share	2014	2020	2030	2050	Remarks
	%				
Global	23%	27% [-]	40-50% [-]	70-85% [-]	
China	23%	26% [-]	40-50% (28-36%)	70-75% [-]	
EU	29%	35-40% (36%)	50-65% (42-52%)	75-95% (55%)	
India	15%	23% (22%)	40-45% (20-35%)	70-75% [-]	
USA	13%	20-25% (19%)	40-45% (22-25%)	75-90% (27%)	
Indonesia	[-]	15% (13-17%)	45% (18-26%)	70-75% [-]	Based on 1 source only

Remark: the 2014 level is based on IEA data; the smaller numbers in brackets denote current policy projections.

The key challenges and gaps encountered in defining this benchmark are:

- Limited number of scenarios at country level in line with well below 2/1.5°C.
- Difficulties in comparing models results:
  - IAMs models cover only specific regions. Region definition is different in each model and makes it difficult to reconcile with the country selection here.

Making benchmark results more robust would require additional data and analytical work on the following aspects:

- Downscaling of results from regions to individual countries and subsequent national energy-system modelling to reflect national circumstances and development (as highlighted in previous section)
- Differentiating results in terms of weak vs strong dependency on negative emissions technologies (as highlighted in previous section)
- Challenging results of IAMs to assess if assumptions used are in line with current developments (e.g. on LCOE). However, data availability for long term projections and assumptions is limited.
- Also consider other indicators, such as "shares of newly built" or RES flow year (to convey messages such as "All new build power capacity should be RES by the year YYYY").

4.4 Coal phase-out

4.4.1 Introduction

This benchmark is based on the indicator "coal phase-out expected year" which represents the year in which share of unabated coal <5%[5] in generated electricity (year).

Coal plays a large role in the world energy system, and is at the same time the most CO_2 intensive fossil fuel. Although the coal share in power generation has decreased in many countries in recent years, it is still growing in e.g. India or Indonesia (Figure 6).

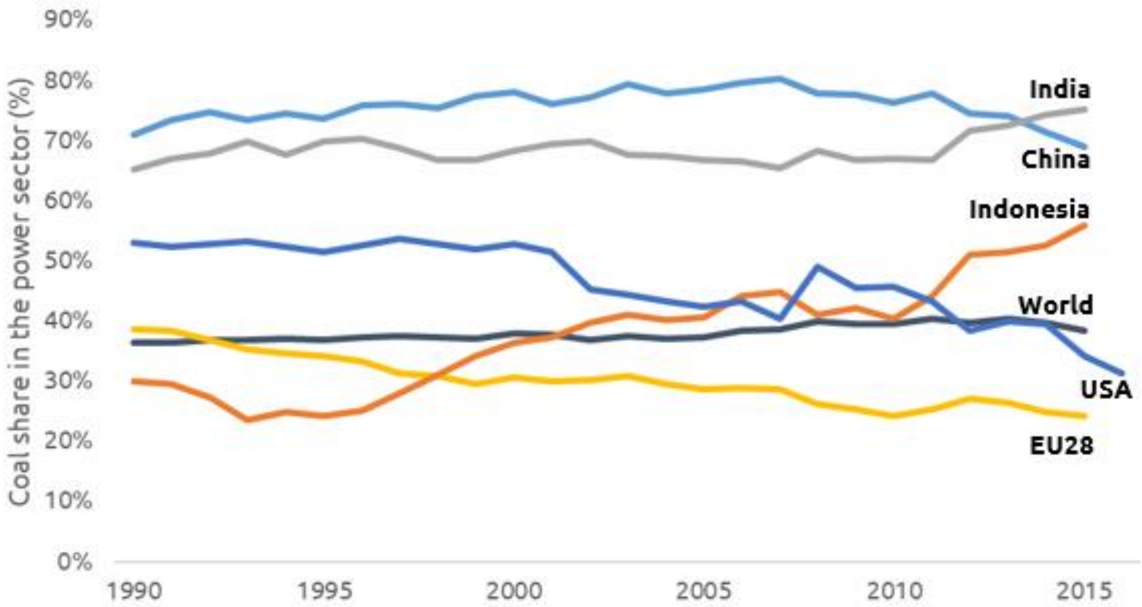

Figure 6: Coal share in the power sector in focus countries, 1990–2016. Source: Energy Statistics and Balances 2016 OECD/IEA [2016], www.iea.org/statistics, Licence: www.iea.org/t&c

Because of its major contribution to global CO_2 emissions, low-emissions scenarios for the future rely heavily on transitioning away from coal-fired power, in particular. Figure 6 illustrates the challenge of both reducing coal emissions from existing capacity for power generation, as well as the risks involved for power producers in planning future coal expansion. The solid line shows a typical pathway for emissions from coal power in a future compatible with the Paris Agreement, with the area under the curve represents the total coal-emissions budget. The pathway is consistent with the latest literature with a broad set of models (Rogelj et al 2018, Supplementary Information Figure 14b). In contrast, the black area in Figure 6 represents estimated emissions from existing coal-power plants, which are significantly larger than that budget. Adding the additional power plants currently planned further exacerbates the problem, as shown by the lighter shaded area.

[5] The reason for applying this 5% rule (instead of actually zero), which is also used by the IPCC, is that many IAMs, due to the underlying mathematical optimisation, tend to keep small amounts of specific energy transformation technologies in the overall energy supply system.

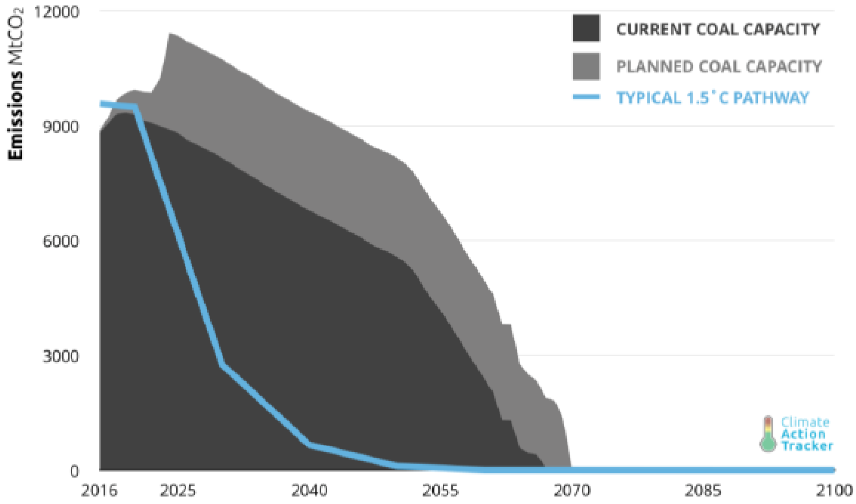

Figure 7: Potential CO2 emissions from existing and planned coal capacity compared to a typical 1.5C pathway. Source: Climate Action Tracker

4.4.2 Presentation of results

We look in more detail at the results for coal phase-out timing from different models. The sources used in the definition of the benchmark include:

- Integrated Model to Assess the Global Environment, "IMAGE 2018" (D. van Vuuren et al., 2018)
- Energy system transformations for limiting end-of-century warming to below 1.5 °C, "Rogelj, et al. 2015" (Rogelj et al., 2015)
- IEA Energy Technology Perspectives 2017, "IEA ETP" (IEA, 2017a)
- Greenpeace, The Energy [R]evolution, 2015, "Greenpeace" (Greenpeace, 2015)
- Deep Decarbonization Pathways, Country Reports, 2015, "DDP" (Deep Decarbonization Pathways Project, 2015)
- Carbon Transparency Initiative, EU results, 2018, "CTI EU" (Cornet et al., 2018)

The tables below present the result of our data collection and the suggested benchmark level. The results include unabated coal only, i.e. coal power without CCS. Coal with CCS as a nearly emissions neutral power source could be significant in some model results as explained in Section 6.3.2.

Table 17: Overview of results for coal phase-out year global benchmark

Global	Phase-out year	Remarks
Benchmark	**2040-2050**	
Paris compatible model results		
IMAGE	2040	
Rogelj et al. (2015)	2050	
IEA ETP	2040	• B2D scenario
Back-casting model results		
Greenpeace	2050	• Advanced Energy Revolution scenario
Projections based on current policies and developments		
IEA ETP	N/A	• Reference Technology Scenario (~planned policy pathway)

Table 18: Overview of results for coal phase-out year benchmark for China

China 	Phase-out year	Remarks
Benchmark	**2040**	
Paris compatible model results		
IMAGE	2040	
Rogelj et al. (2015)	2040	
IEA ETP	2040	• B2D scenario
Back-casting model results		
DDP	2050	• Central scenario
Greenpeace	2050	• Advanced Energy Revolution scenario
Projections based on current policies and developments		
IEA ETP	N/A	• Reference Technology Scenario (~planned policy pathway)

Table 19: Overview of results for coal phase-out year benchmark for the EU

EU	Phase-out year	Remarks
Benchmark	**2030**	
Paris compatible model results		
IMAGE	2050	
Rogelj et al. (2015)	2030	
IEA ETP	2030	• B2D scenario
Back-casting model results		
DDP	[-]	• No public data available on EU
Greenpeace	2040	• Advanced Energy Revolution scenario • Model results includes some non-EU countries such as Israel and Turkey and excludes others such as Croatia or Lithuania
CTI EU	2030	• Best practice policy scenario for the EU-28 based on new model projection
Projections based on current policies and developments		
IEA ETP	>2050	• Reference Technology Scenario (~planned policy pathway)

Table 20: Overview of results for coal phase-out year benchmark for India

India	Phase-out year	Remarks
Benchmark	**2040-2050**	
Paris compatible model results		
IMAGE	<2040	
Rogelj et al. (2015)	2050	
IEA ETP	2035	• B2D scenario
Back-casting model results		
DDP	2050	• Central scenario
Greenpeace	2040	• Advanced Energy Revolution scenario
Projections based on current policies and developments		
IEA ETP	N/A	• Reference Technology Scenario (~planned policy pathway)

Table 21: Overview of results for coal phase-out year benchmark for the USA

USA	Phase-out year	Remarks
Benchmark	**2030-2035**	
Paris compatible model results		
IMAGE	2040	
Rogelj et al. (2015)	2030	
IEA ETP	2035	• B2D scenario
Back-casting model results		
DDP	2050	• Central scenario
Greenpeace	2030	• Advanced Energy Revolution scenario • Model results includes Canada and Mexico
Projections based on current policies and developments		
IEA ETP	N/A	• Reference Technology Scenario (~planned policy pathway)

Table 22: Overview of results for coal phase-out year benchmark for Indonesia

Indonesia	Phase-out year	Remarks
Benchmark	**2040-2050**	• Based on 1 source only
Paris compatible model results		
IMAGE	2040	
Rogelj et al. (2015)	2050	• Results based on model region Other Pacific Asia (PAS), not only Indonesia and therefore not taken into account
IEA ETP	[-]	• No public data available on Indonesia
Back-casting model results		
DDP	2050	• Central scenario
Greenpeace	[-]	• No public data available on Indonesia
Projections based on current policies and developments		
IEA ETP	[-]	• Reference Technology Scenario (~planned policy pathway)

4.4.3 Conclusions

In its "Ten steps" report, we found that, to be in line with the Paris Agreement's warming limit target, the global power sector needs to decarbonise ten years earlier than under a 2˚C pathway, meaning that the sector needs to reach zero carbon dioxide emissions globally around 2050.

As a result of the present analysis, the table below shows our suggested benchmarks for the achievable year for global and country coal phase-out that would enables us to stay within the limit of well below 2°C temperature increase.

The suggested benchmarks levels were defined based on the following 4 steps:

1. **Highest-level of ambition from IAMs and IEA:** regional phase-out years are applied as an estimate of the latest phase-out year per country in the models. Some results are not taken into account because regional results are not applicable for the country (e.g. Indonesia).
2. **Back-casting model based results** are in line with or less ambitious than IAMs and IEA results. This reflects that some stakeholders consider that the coal phase-out ambition level required to reach Paris Agreement long term goal is technically, politically and/or economically challenging.
3. **Projections based on current policies and developments**: only the IEA ETP Reference Technology Scenario is available and most countries do not phase-out coal in the time scale of the scenario (2060).

4. **Harmonisation of country specific results:** to reflect the need for developed countries to take the lead, we selected the most ambitious part of the range of EU and US results. Similar to the RES share benchmark, some models might assume faster coal phase-out in non-OECD countries than in OECD countries based on current cost assumptions. This might not be considered as realistic or fair in the longer term in light of differentiation principles. With decreasing costs of RES and more ambitious policies, we expect more coal capacity to be shut down before the end of its life in the EU and the USA. To achieve these early shutdowns, the models' assumptions should be reviewed and constrained by up-to-date policies at national level and/or explicitly reflect high costs of coal-fired power plants currently externalised (e.g. impact of air pollution).

The results show that emissions from coal-fired power stations must be phased out globally between 2040 and 2050, with the phase-out occurring first in OECD countries by 2030 (for EU) or maximum 2035 (for US), followed by China in 2040 and India in 2050 latest. There are not enough publicly available data for Indonesia to draw relevant conclusion for this benchmark, but phase out should at least be consistent with the global phase out by 2050.

Table 23: Overview of our suggested benchmarks for coal phase-out year

Coal phase-out	Phase-out year	Remarks
Global	2040-2050	
China	2040	
EU	2030	
India	2040-2050	
USA	2030-2035	
Indonesia	2040-2050	Based on 1 source only

The key challenges and gaps encountered in defining the benchmark are:

- The limited number of available scenarios in IAMs that are consistent with the Paris target
- Wide variety of assumptions in IAMs as to whether coal will be used along with CCS
- Extent to which negative-emissions technologies are available and able to compensate for remaining emissions from coal

Given the key role played by a coal phase-out in low-emissions scenarios, in the next phase, careful attention should be paid to issues of stranded assets in the coal power and mining sectors and how inertia effects and lock-ins will influence the rapidity of a phase-out.

4.5 CO_2 intensity

4.5.1 Introduction

A clear measure of the decarbonisation of the energy system is CO_2 intensity in the power sector, measured in grammes of CO_2 emitted per kWh of electricity generated (g/kWh) or equivalent units. As a very rough indication, coal-fired power results in 1000 g/kWh and natural gas power about half that amount. The CO_2 intensity is a complementary indicator to that of renewable energy share in the power sector and is clearly connected to the rate of coal phase-out.

CO_2 intensities in the power sector have decreased in many countries in recent years, but continue to remain at high levels e.g. in India and China (Figure 8).

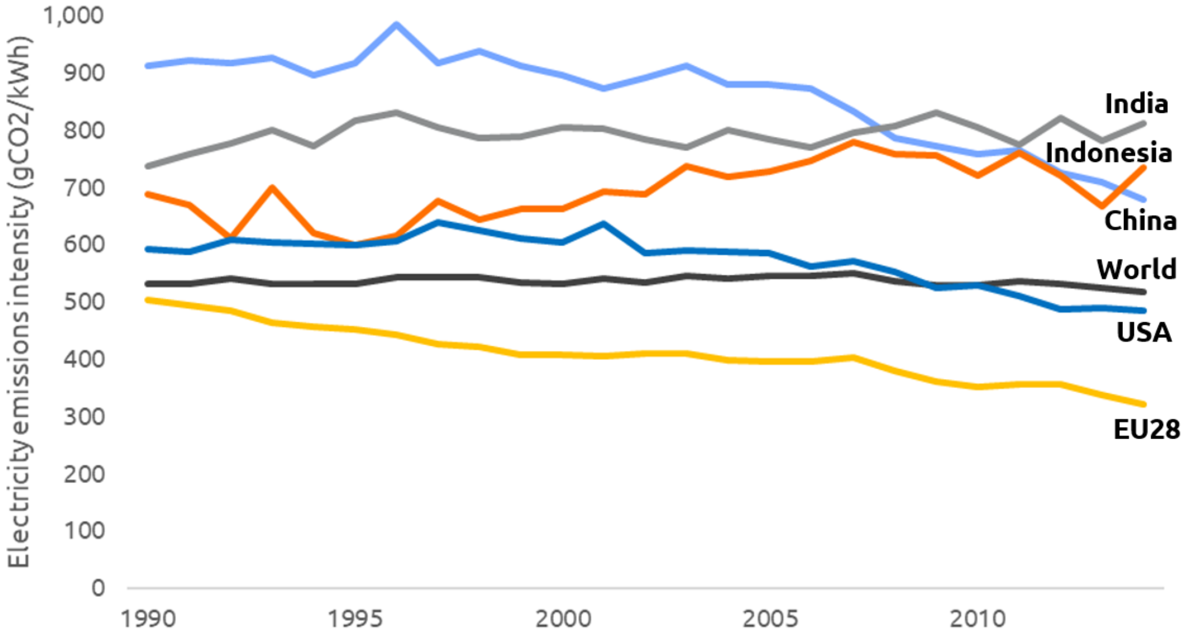

Figure 8: Electricity emissions intensity in focus countries, 1990–2015. Source: CAT Decarb Portal based on IEA data from Energy Statistics and Balances 2016 OECD/IEA [2016], www.iea.org/statistics, Licence: www.iea.org/t&c; as modified by the Climate Action Tracker.

4.5.2 Presentation of results

The tables shown below provide a summary of data from various sources of the CO_2 intensity for our six geographies.

The sources used in the definition of the benchmark include:

- Integrated Model to Assess the Global Environment, “IMAGE” (D. van Vuuren et al., 2018)
- Fifth Assessment Report, “IPCC AR5” (Intergovernmental Panel on Climate Change, 2014)
- Energy system transformations for limiting end-of-century warming to below 1.5 °C, “Rogelj, et al. 2015” (Rogelj et al., 2015)
- IEA Energy Technology Perspectives 2017, “IEA ETP” (IEA, 2017a)
- Greenpeace, The Energy [R]evolution, 2015, “Greenpeace” (Greenpeace, 2015)
- Deep Decarbonization Pathways, Country Reports, 2015, “DDP” (Deep Decarbonization Pathways Project, 2015)
- Climate Action Tracker, Decarb Portal, 2017, “CAT” (Climate Action Tracker, 2017)
- Carbon Transparency Initiative, 2016, “CTI” (Carbon Transparency Initiative, 2016)
- Carbon Transparency Initiative, EU results, 2018, “CTI EU” (Cornet et al., 2018)

Table 24: Overview of results for CO_2 intensity global benchmark

Global	2020	2030	2050	Remarks
	gCO_2 / kWh			
Benchmark	**450-500**	**180-310**	**0**	
Paris compatible model results				
IMAGE	495	235	0	
AR5/SSP	463	306	0	
Rogelj et al. (2015)	448	179	0	
IEA ETP	[-]	229	0	• B2D scenario
Back-casting model results				
Greenpeace	463	224	0	• Advanced Energy Revolution scenario
Projections based on current policies and developments				
IEA ETP	500	402	309	• Reference Technology Scenario (~planned policy pathway)

Table 25: Overview of results for CO_2 intensity benchmark for China

China	2020	2030	2050	Remarks
	gCO$_2$ / kWh			
Benchmark	**660**	**280-460**	**0**	
Paris compatible model results				
IMAGE	666	464	0	
Rogelj et al. (2015)	823	438	16	• CO_2 intensity of the CPA region (not only China) and therefore not taken into account
IEA ETP	[-]	277	0	• B2D scenario
Back-casting model results				
DDP	[-]	[-]	68	• Central scenario
Greenpeace	644	400	0	• Advanced Energy Revolution scenario
Projections based on current policies and developments				
CAT	662	601	[-]	• Current policy projections
CTI	[-]	500	[-]	• Current Development Scenario, based on current policies, decarbonisation trends and an evaluation of energy-related investments
IEA ETP	647	480	319	• Reference Technology Scenario (~planned policy pathway)

Table 26: Overview of results for CO_2 intensity benchmark for the EU

EU	2020	2030	2050	Remarks
	gCO_2 / kWh			
Benchmark	**200-260**	**60-140**	**0**	
Paris compatible model results				
IMAGE	224-573	138-384	0	• EU countries contained within model regions Central Europe (CE) and Western Europe (WE)
Rogelj et al. (2015)	206-542	56-118	1-5	• Results based on overall WEU and EEU regions (also non EU, inc. Turkey); thus low end of range used in benchmark
IEA ETP	[-]	78	0	• B2D scenario
Back-casting model results				
DDP	[-]	[-]	[-]	• Central scenario
Greenpeace	269	141	0	• Advanced Energy Revolution scenario • Model results includes some non-EU countries such as Israel and Turkey and excludes others such as Croatia or Lithuania
CTI EU	[-]	40	[-]	• Best practice policy scenario for the EU-28 based on new model projection
Projections based on current policies and developments				
CAT	262	203	[-]	• Current policy projections
CTI	[-]	200	[-]	• Current Development Scenario, based on current policies, decarbonisation trends and an evaluation of energy-related investments
IEA ETP	285	173	78	• Reference Technology Scenario (~planned policy pathway)

Table 27: Overview of results for CO_2 intensity benchmark for India

India	2020	2030	2050	Remarks
	gCO_2 / kWh			
Benchmark	**650**	**160-260**	**0**	
Paris compatible model results				
IMAGE	651	156	0	
Rogelj et al. (2015)	589	285	6	• Results based on overall SAS (South Asia) region (not only India) and therefore not taken into account
IEA ETP	[-]	256	33	• B2D scenario
Back-casting model results				
DDP	[-]	[-]	56	• Central scenario
Greenpeace	690	268	0	• Advanced Energy Revolution scenario
Projections based on current policies and developments				
CAT	791	670	[-]	• Current policy projections
CTI	[-]	600	[-]	• Current Development Scenario, based on current policies, decarbonisation trends and an evaluation of energy-related investments
IEA ETP	738	642	473	• Reference Technology Scenario (~planned policy pathway)

Table 28: Overview of results for CO_2 intensity benchmark for the USA

USA	2020	2030	2050	Remarks
	gCO_2 / kWh			
Benchmark	**360-440**	**80-170**	**0**	
Paris compatible model results				
IMAGE	439	170	0	
Rogelj et al. (2015)	360	83	1	• Results based on overall NAM (North America) consisting of the USA and Canada. The results are considered valid and taken into account
IEA ETP	[-]	232	0	• B2D scenario
Back-casting model results				
DDP	[-]	[-]	13.5	• Central scenario
Greenpeace	338	106	0	• Advanced Energy Revolution scenario • Results include Canada and Mexico
Projections based on current policies and developments				
CAT	454	340	[-]	• Current policy projections
CTI	[-]	400	[-]	• Current Development Scenario, based on current policies, decarbonisation trends and an evaluation of energy-related investments
IEA ETP	432	327	282	• Reference Technology Scenario (~planned policy pathway)

Table 29: Overview of results for CO_2 intensity benchmark for Indonesia

Indonesia	2020	2030	2050	Remarks
	Mt CO_2e			
Benchmark	**620**	**60**	**0**	• **Based on 1 source only**
Paris compatible model results				
IMAGE	625	62	0	
Rogelj et al. (2015)	504	126	0	• Results based on model region Other Pacific Asia (PAS), not only Indonesia and therefore not taken into account
IEA ETP	[-]	[-]	[-]	• No public data available on Indonesia
Back-casting model results				
DDP	[-]	[-]	50	• Central scenario
Greenpeace	[-]	[-]	[-]	• No public data available on Indonesia
Projections based on current policies and developments				
CAT	[-]	[-]	[-]	• No data available on Indonesia
CTI	[-]	[-]	[-]	• No public data available on Indonesia
IEA ETP	[-]	[-]	[-]	• Reference Technology Scenario (~planned policy pathway)

4.5.3 Conclusions

As a result of the present analysis, the table below shows our suggested benchmarks for an achievable level of CO_2 intensity in the power sector that would enables us to stay within the limit of well below 2°C temperature increase.

The suggested benchmarks levels were defined based on the following 4 steps:

1. **Highest-level of ambition from IAMs and IEA:** most models project a CO_2 intensity level for the power sector in 2050 close to 0 for all regions. IEA ETP projects still relatively high emissions intensity in 2050 for India, despite a suggested earlier coal phase-out. This can be explained by the still relatively high share of natural gas without CCS in the production mix (6%).
2. **Back-casting model based results**: Greenpeace is in line with IAMs and IAE results, reflecting they consider that the ambition level required to reach the Paris Agreement long term goal is technically, politically and/or economically feasible. CO_2 intensity projection by CTI EU is even lower for 2030 (40 gCO_2/kWh) and reflect that a higher level of ambition could be possible in the EU. DDP is less ambitious but we consider that it

does not reflect the level of ambition required to reach the Paris Agreement long term goal.

3. **Projections based on current policies and developments** are less ambitious and we consider that they do not reflect the level of ambition required to reach the Paris Agreement long term goal. Only EU 2030 upper-end range level was adapted to reflect the lower projection level set by IEA ETP Reference Technology Scenario.
4. **Harmonisation of country specific results:** in alignment with the ambition level of the RES share and coal phase-out indicators, we have selected the most ambitious end of the range of EU and US results. Similar to the other two indicators, some models might assume faster power sector decarbonisation in non-OECD countries than in OECD countries based on current cost assumptions. This might not be considered as realistic given recent developments or fair in the longer term in light of differentiation principles.

Globally, the power sector currently has an emissions intensity of approximately 450 gCO_2/kWh, with strong regional and country variations, representing a generation mix in roughly equal measures of coal, natural gas and low-carbon sources (nuclear power and renewables). The targets for coal phase-out, the transition from coal to gas, followed by a phase out of gas, and the continued increase in renewable energy in the electricity sector are the drivers for reducing the overall emissions intensity.

Global and country specific ambition is showing broadly similar trajectories, with CO_2 intensity decreasing by roughly half by 2030 and aligning towards a carbon neutral power system by 2050. Similar to coal phase-out trajectories, China, USA, EU are showing a good trend towards achieving the long-term CO_2 intensity benchmark. India remains in a more challenging situation. There are not enough publicly available data for Indonesia to draw relevant conclusion for this benchmark.

Table 30: Overview of suggested benchmarks for CO_2 intensity

CO_2 intensity	2014	2020	2030	2050	Remarks
	gCO_2 / kWh				
Global	572	**450-500** [-]	**180-310** [-]	**0** [-]	
China	774	**660** (662)	**280-460** (500-601)	**0** [-]	
EU	370	**200-260** (262)	**60-140** (200-203)	**0** [-]	
India	813	**650** (791)	**160-260** (600-670)	**0** [-]	
USA	492	**360-440** (454)	**80-170** (340-400)	**0** [-]	
Indonesia	[-]	620 [-]	60 [-]	0 [-]	Based on 1 source only

Remark: the 2014 level is based on IEA data; the smaller numbers in brackets denote current policy projections.

The key challenges and gaps encountered in defining the benchmark are:

- The limited number of available scenarios in IAMs that are consistent with the Paris target and the lack of country-level resolution limit the ability to compare model outputs to other available data
- Differences in the assumed potential rate of substitution of high-emissions with low-emissions electricity generation.

This benchmark is closely related to the actionable targets of enabling a coal phase-out and promoting increasing shares of renewable energy for electricity generation. It does add a useful perspective to those other indicators, however, and given the fairly good availability of data for monitoring the benchmark, we suggest keeping this benchmark alongside these others. As opposed to some other indicators, CO_2 intensity is firmly and physically linked to the source of electricity, since to a good approximation, if the source is known, so is the emissions intensity.

4.6 EV sales share

4.6.1 Introduction

The last benchmark assessed in this report is the Electric Vehicle (EV) sales share and is defined as the number of EV light duty vehicles (LDVs), i.e. passenger cars, sold in the total of LDVs in road transport sector, expressed as the **% of overall sales**. Our definition of EVs includes both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs).

EVs sales have only started to become relevant in recent years. Figure 9 below from the CAT portal shows that EV stocks, i.e. EVs per capita, have only started to increase (sharply) since 2010, at first in the USA and in Europe, with China more recently starting to catch up. Most recent data shows China doubling its number of EVs per 1000 inhabitants just in the year 2016 (IEA, 2017b). Particular countries and states seem to have a solid lead in terms of EV fleet, including Norway reaching 22 EVs/1,000 cap in 2016, The Netherlands reaching 7 EVs/1,000 cap by that year and California reaching 7 EVs/1,000 cap in 2016 and 9 EVs/1,000 cap by February 2018[6].

[6] Auto Alliance https://autoalliance.org/energy-environment/advanced-technology-vehicle-sales-dashboard/

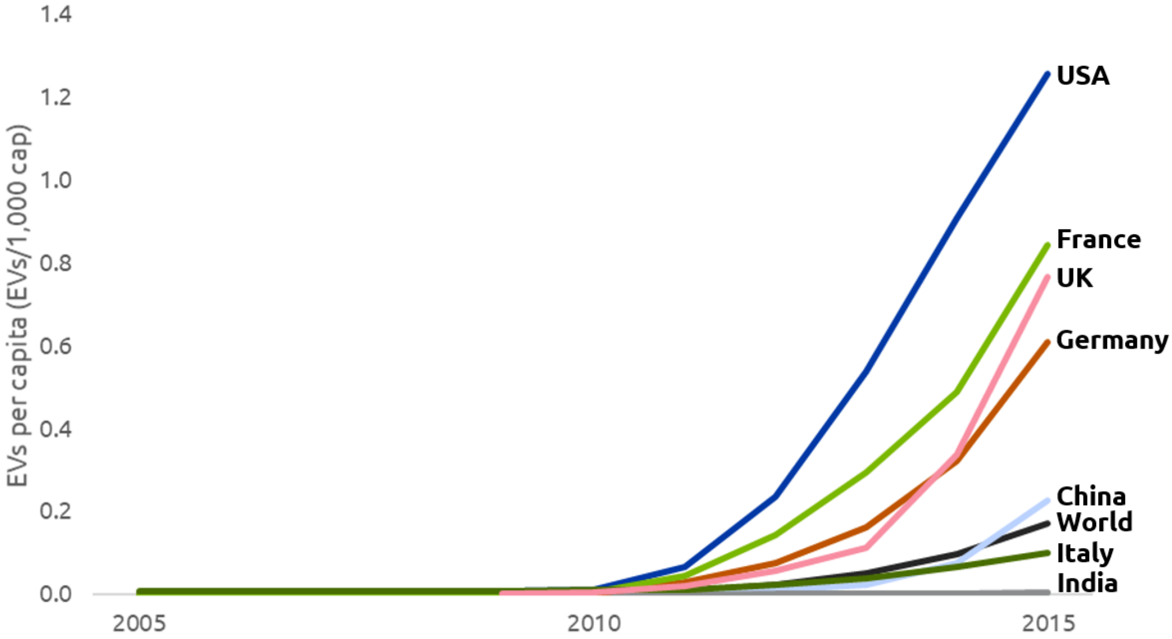

Figure 9: EVs per capita (EVs/1000 cap), 1990–2015. Source: CAT Decarbonisation Data Portal

IAMs models do not provide any public data on EVs sales share. Therefore, we rely mostly on IEA Mobility Model data (which is the model used for the Global EV Outlook 2017 report) and on projections based on current developments from market and industry research organisation or from government planned policies.

The tables below present the result of our data collection and show the suggested benchmark level. In addition to EV sales shares in 2020, 2030 and 2050, we also show years in which EVs dominate LDV sales and stocks with respective shares above 95%, where available.

The approach to define EV benchmarks is an example where we have very limited information on 1.5°C compatible levels of EV sales share and the limited existing sources may well lag behind real developments. It is also the indicator for which the highest number of examples exist of planned policies that are in line with 1.5°C (according to our "ten steps" work). Therefore, we have defined the benchmark levels primarily to be in line with plausible trajectories based on recent trends and planned targets already agreed by leading countries in this sector.

4.6.2 Presentation of results

The transport sector is still highly dependent on fossil fuels. A shift from internal combustion engine vehicles to low carbon alternatives and EVs in particular is thus imperative for limiting the global temperature increase to 1.5°C–2°C. This shift needs to be accompanied by new mobility solutions which limit private car ownership. While EV shares in stocks have only been increasing slowly, EV sales shares have been rising quickly in recent years. Consequently, EV sales projections have been revised regularly reflecting e.g. declining battery costs and rising R&D budgets.

Data sources used for EV sales include:

- IEA, Mobility Model, 2017, "IEA GEVO 2017" (IEA, 2017b)
- BNEF, EV Outlook, 2017, "BNEF" (BNEF, 2017)

- Navigant Research, EV Market Forecast, 2017, “Navigant Research” (Navigant Research, 2017)
- UBS, Evidence Lab, 2017, “UBS” (UBS, 2017)
- BofA Merrill Lynch EV Report, 2017, “BofA Merrill Lynch” (Bank of America Merrill Lynch, 2017)
- BP, Energy Outlook, 2018, “BP” (BP, 2018)
- Energy Innovation, Research Note, 2017, “Energy Innovation” (Energy Innovation, 2017)
- Carbon Transparency Initiative, EU results, 2018, “CTI EU” (Cornet et al., 2018)

In addition, we also screened the following reports. However, data projections in these reports were not used to inform the benchmark decision as they did not match the benchmark definition.

- IRENA, REmap, 2016 (IRENA, 2016a)
- RethinkX, Disruption, Implications and Choices, 2017 (RethinkX, 2017)
- ExxonMobil, Outlook for Energy, 2017 (ExxonMobil, 2017)

The tables below present the result of our data collection and the suggested benchmark level. In addition to EV sales shares in 2020, 2030 and 2050, we also show years in which EVs dominate LDV sales and stocks with respective shares above 95%, where available.

Table 31: Overview of results for EV sales share global benchmark

Global	2020	2030	2050	>95% sales	>95% stock	Remarks
	%			Year		
Benchmark	**10%**	**50-100%**	**100%**	**2030-2040**	**2045-2055**	
Paris compatible model results						
IEA GEVO 2017	11%	31%	91%	2055	2065	• B2D scenario
Projections based on current policies and developments						
BNEF	3%	24%	[-]	[-]	[-]	• Central scenario
Navigant Research	6.1%	[-]	[-]	[-]	[-]	• Base scenario
BofA Merrill Lynch	[-]	[-]	90%	[-]	[-]	• Base scenario
BP	2%	12%	[-]	[-]	[-]	• Evolving Transition scenario
UBS	16%		[-]	[-]	[-]	• Base scenario in 2025
Car manufacturers	20-25%		[-]	[-]	[-]	• Share of EVs in VW, Daimler and BMW car sales in 2025

Table 32: Overview of results for EV sales share benchmark for China

China	2020	2030	2050	>95% sales	>95% stock	Remarks
	%			Year		
Benchmark	**20%**	**50%-100%**	**100%**	**2030-2040**	**2055**	
Paris compatible model results						
IEA GEVO 2017	18%	36%	95%	2045	2065	B2D scenario
Projections based on current policies and developments						
Navigant Research	9.1%	[-]	[-]	[-]	[-]	Base scenario
Planned policies	[-]	[-]	[-]	[-]	[-]	China has defined electric vehicle quota for car manufacturers but no country targets

Table 33: Overview of results for EV sales share benchmark for the EU

EU	2020	2030	2050	>95% sales	>95% stock	Remarks
	%			Year		
Benchmark	**15%**	**90-100%**	**100%**	**2030-2035**	**2045**	
Paris compatible model results						
IEA GEVO 2017	16%	36%	96%	2050	2055	• B2D scenario
Back-casting model results						
CTI EU	50%	90%	[-]	[-]	[-]	• Best practice policy scenario for the EU-28 based on new model projection
Projections based on current policies and developments						
Planned policies	[-]	[-]	[-]	2030–2040	[-]	• (Planned) ban of sales of new petrol and diesel cars in NL (2030), FR (2040) and UK (2040)

Table 34: Overview of results for EV sales share benchmark for India

India	2020	2030	2050	>95% sales	>95% stock	Remarks
	%			Year		
Benchmark	**5%**	**50-100%**	**100%**	**2030-2040**	**2055**	
Paris compatible model results						
IEA GEVO 2017	3%	27%	93%	2055	2060	• B2D scenario
Projections based on current policies and developments						
Navigant Research	0.3%	[-]	[-]	[-]	[-]	• Base scenario
Planned policies	[-]	[-]	[-]	2030	[-]	• (Planned) target to sell only EVs by 2030

Table 35: Overview of results for EV sales share benchmark for the USA

USA	2020	2030	2050	>95% sales	>95% stock	Remarks
	%			Year		
Benchmark	**10%**	**90-100%**	**100%**	**2030-2035**	**2045**	
Paris compatible model results						
IEA GEVO 2017	10%	38%	97%	2045	2050	B2D scenario
Projections based on current policies and developments						
Navigant Research	8.8%	[-]	[-]	[-]	[-]	Base scenario
Energy Innovation	[-]	[-]	65%	[-]	[-]	Base scenario
Planned policies	[-]	[-]	[-]	[-]	[-]	No country specific target

Table 36: Overview of results for EV sales share benchmark for Indonesia

Indonesia	2020	2030	2050	>95% sales	>95% stock	Remarks
	%			Year		
Benchmark	**[-]**	**50-100%**	**100%**	**2040**	**[-]**	
Paris compatible model results						
IEA GEVO 2017	[-]	[-]	[-]	[-]	[-]	No data on Indonesia
Projections based on current policies and developments						
Planned policies	[-]	[-]	[-]	2040	[-]	Planned ban of sales of new petrol and diesel cars by 2040

4.6.3 Conclusions

In our "Ten Steps" report, we found that the rapid introduction of zero emission vehicles is key to the decarbonisation of passenger transport that is required by 2050 to stay within the limits of Paris agreement. To only have zero emission cars on the road by 2050, the last fossil fuel powered car would have to be sold roughly before 2035, assuming an average lifetime of 15 years. Such a transition will be much easier with a reduction—and modal shift—of demand for personal transport.

The suggested benchmarks levels were defined based on the following 4 steps:

1. **Highest-level of ambition from IAMs and IEA:** in this category only the IEAs Global Electric Vehicle Outlook "beyond 2 degrees" scenario (GEVO B2D) provides insights. The model results are considered as already outdated and new results are expected to be published later this year. The GEVO B2D assumes nearly 100% EV sales by 2050 for all regions. Integrated assessment models do not have the resolution to consider EVs separately or do not provide public data on their shares.
2. **Back-casting model based results** are not available except for the EU with recently published CTI results up to 2030. The model displays a much higher level of ambition than GEVO B2D, demonstrating that higher level of EV sales may be possible. We expect similar level of ambition to be feasible for the US.
3. **Projections based on current policies and developments** are only slightly less ambitious than the GEVO B2D. (2030: 24% of new sales from BNEF compared to 31% in GEVO B2D or 2050: 90% in BofA compared to 91% in GEVO B2D). Car manufacturers' projections for 2025 are also in line with GEVO B2D short term projections. These projections are much higher than GEVO's base case scenario, suggesting that a higher level of ambition is certainly possible. Planned policies at country level are a good indicator of the ambition of some countries towards the phase-out of fossil based cars. The results show that the policy ambition between countries differs from no goals to 100% electric vehicle sales as soon as 2025 or 2030. These targets only cover some countries in the scope of our analysis and none of the announced targets have so far been enshrined in laws or regulations. But they are considered as a good indication of the level of ambition considered as achievable and are therefore taken into account.
4. **Harmonisation of country specific results:** cars are a global commodity and therefore changes in one country can easily spread to other markets as global manufacturers

change their practices. There are now several countries that are taking or at least planning to take a much faster route towards banning fossil fuel cars in near future. Therefore we believe the "highest plausible ambition" is broadly aligned in all countries, with the more ambitious end of the range, 100% EV sales share in 2030, being defined by these early movers, while also considering the leading role to be played by OECD countries.

As a result, we suggest a global benchmark of 100% electric vehicles sales by 2030 to 2040, with the EU and the USA phasing out ICE cars faster (90 to 100% EV sales share in 2030) than China, India or Indonesia (50 to 100% EV sales share in 2030). We recommend updating this benchmark very regularly to take into account most recent developments.

Table 37: Overview of our suggested benchmarks for EV sales share

EV sales share	2015	2020	2030	2050	>95% sales	>95% stock
	%				Year	
Global	0.7%	10% (2-6%)	50-100% (12-24%)	100% (90%)	2030-2040	2045-2055
China	1.0%	20% (9%)	50-100% [-]	100% [-]	2030-2040	2055
EU	1.6%	15% [-]	90-100% [-]	100% [-]	2030-2035	2045
India	0.1%	5% (0.3%)	50-100% [-]	100% [-]	2030-2040	2055
USA	0.8%	10% (9%)	90-100% [-]	100% (65%)	2030-2035	2045
Indonesia	[-]	[-] [-]	50-100% [-]	100% [-]	2040	[-]

Remark: the 2014 level is based on IEA data; the smaller numbers in brackets denote current policy projections.

The key challenges and gaps encountered in defining the benchmark are:

- Only 1 main source is giving Paris compatible results, the IEA GEVO 2017. It is already recognised by IEA that the sector is evolving so rapidly that projections are not up to date anymore. New projections are expected to be published in IEA GEVO 2018 in May–June this year.
- Limited country specific projections based on current development.

In the next phase, projections based on current developments could be more widely used to challenge IEA Mobility Model results. However, given the difference in time horizons between the longer-term IEA projections and typical short-term forecasts, this analysis may require comparisons of underlying drivers in addition, such as battery costs and battery energy capacity development.

If access can be gained to underlying assumptions, we could add robustness to our data set by comparing it with studies on the impact of different battery costs on EV sales or the relationship between climate policy projections and EV sales (Edelenbosch, 2018; van Exter, 2017).

5 Recommendations for Phase 2

5.1 Important considerations

Several challenges and gaps have been encountered during the data collection and benchmark definition processes and should be considered in the interpretation of the results:

- **Not all models and projections publish values for all indicators and all countries.** The lack of multiple sources makes it difficult to derive robust benchmarks for some indicators.
- **IAMs do not generally resolve scenarios at country level.** Even if data is available for some individual countries, in particular the largest emitters, this is generally not publicly available. Data regions covered by models are usually not sufficient to use as a proxy (for example Western Europe is generally not suitable as proxy for EU28).
- **Assumptions behind models and projections results are often not systematically communicated and partly not reported at all.** A lack of standardised and systematic reporting between the different models makes some results difficult to compare and therefore difficult to use for a precise benchmark definition. Some benchmarks are therefore presented as broad ranges.
- With exceptions, **indicator values cannot be differentiated in terms of weak vs strong dependency on negative emissions technologies** deployment of negative emissions technologies is evident in all currently available data sources that relate to the Paris Agreement and to its well-below 2°C/1.5°C limit. Available data is too limited to make a useful distinction.
- **Projections based on current policies and developments are relatively short term** and do not reflect the required level of ambition to meet the Paris agreement. Projections are therefore difficult to use to challenge model results for some indicators

The suggested benchmarks are the results of the pilot phase including expert inputs for the collection of the data sources. To date the results have not yet been shared with the broader climate community. This process will be owned and organised by ClimateWorks Foundation, the European Climate Foundation and the We Mean Business Coalition. Collecting feedback on the results is a very important step before defining the next phase of the project. Key considerations for the stakeholders' consultation process include:

- **Benchmarks values should be drawn from the more "ambitious" end of the range of each particular indicator in discussion with stakeholders**, to avoid the need for other benchmarks to over-deliver and perhaps even to hedge against the risk that other benchmarks may under-deliver.
- **The overall aim of the project is to push all sectors to the limit. This is not a negotiation between sectors on who does more.** However, benchmarks results in the context of global Paris-Agreement goals represent trade-offs between efforts required in different sectors. When sectoral experts have different views on the suggested benchmarks levels based on their interpretation of the challenges and the potential lying in their particular sector, it may be beneficial to have the discussion on required actions levels across the different sectors and confront sector "representatives" with the challenges faced in other sectors.

5.2 Recommendations for Phase 2

Based on the outcomes of the current analysis, we recommend the second phase to focus on the following objectives, with stakeholders' consultation playing an important role in further data collection:

1. Deepen the current analysis to close the data gaps and reinforce the robustness of our suggested benchmark with **additional data collection and analytical work:**
    a. The current data sources should be complemented by collection of new integrated assessment model results that will become available soon, providing more basis for benchmarks and to reconcile e.g. 100% RES back-casting model results with IAMs, as they roughly seem to be converging.
    b. The current approach should also be continued and complemented with additional and updated alternative data gathering, in particular for indicators that have limited availability of Paris consistent model results (e.g. EV sales share).
    c. The current approach should be complemented by modelling and analytical work, in particular for indicators with good availability of Paris consistent model results that requires further harmonisation to derive robust country level results (incl. beyond just the largest emitters). To do so, we propose to pursue and deepen the downscaling of results to country and sector levels (beyond largest countries; electricity sector), based on GDP per capita country projections for each scenario of each model, or based on more sophisticated downscaling approaches at energy system level, followed by adjusting the associated representation of the national energy system to reflect recent developments at country level. Such additional work would enable to include additional constraints on national-scale modelling work and analysis, derived from national-specific circumstances (including related to recent national policies on both supply and demand side, updated technology portfolios and costs, etc.).
    d. Ultimately, it should be a joint decision-making process by a larger group of users to determine the benchmarks to translate the global goals of the Paris Agreement into sector goals.

    Collecting additional data in terms of spatial resolution (countries) and indicators, analysing these data, downscaling and subsequent adjusting national energy-system model representations to national circumstances, will require substantial time and effort. Current work being performed by the CAT team (e.g. Raising Ambition project or work performed on Japan) is closely related to such development and should be considered when developing a more precise approach for the next phase. Data from step b is essential to feed into this work.
2. Organise a **consultation process** with key stakeholders, to refine the approach and collect additional data and decisions on the benchmarks. To stress the need for all sectors to be pushed to the highest feasible level of ambition, we recommend organising consultations with stakeholders from different sectors at the same time and encourage them to take a holistic view to the challenges.
3. **Extend the scope** of Phase 1 to develop
    a. more insights and more actionable results based on existing benchmarks, including by adding related, more granular, sector-specific indicators (e.g. "energy related CO_2", "total emissions from agriculture", "year of last coal power capacity new-build" or "year for RES only power capacity new-build")
    b. a broader range of benchmarks, covering at least a larger group of countries for existing indicators and potentially some additional indicators

    Develop the approach further and put emphasis on how to **communicate and put the benchmarks into practice**. An important dimension of Phase 2 will be the involvement of stakeholders and the definition of a collaborative process to collect new data, make results accessible and review the proposed shared benchmarks.

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7 Appendices

7.1 Project approach

7.1.1 Overall project approach

The project is structured into two distinct phases:

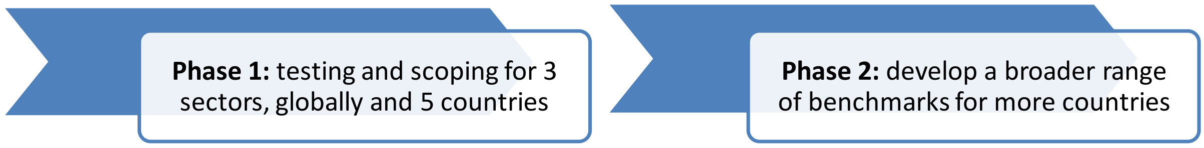

Figure 10: Overview of the proposed shared benchmarks

1. **Phase 1** is a test and scoping phase with the project group, to arrive at a mutual understanding of possible shared benchmarks, and a way to present the results and the underlying analysis and data, including existing data gaps.

   The approach to define shared benchmarks was based on three steps:
   - Collect data on Paris compatible scenarios for each indicator and country from most recognised models (Integrated Assessment Models and IEA ETP model)
   - Identify the limitations and gaps of the models and collect alternative sources where relevant to complement or challenge results (e.g. NGO or industry projections and forecasts, but also considerations of existing and planned policies)
   - Iteratively develop shared benchmarks building on the previous steps and estimate if more ambitious action becomes possible and acceptable.

2. **Phase 2** will extend this work in a collaborative process to making existing and new data accessible through regular aggregation and streamlining to achieve a broader range of benchmarks for more countries, building on the lessons learned from Phase 1.

7.1.2 Data sources description

7.1.2.1 Integrated Assessment Models (IAMs)

Integrated Assessment Models of Climate Change (IAMs) that operate in a cost-effectiveness mode are the analytical mainstay of most analyses undertaken to learn about long-term transformational pathways that achieve a predetermined climate target, e.g. the Paris Agreement long-term temperature goal. These models explicitly take into account economic trade-offs associated with the required massive transformation of the energy system and resulting effects on the economy over long time periods. Another class of IAMs are those constructed to give information in terms of an economic cost-benefit analysis; these models, not considered here, must also attempt to explicitly monetise damages due to a changing climate, adding a level of significant uncertainty and controversy, and these models generally have much worse resolution in terms of mitigation technology portfolios and technological development.

The more suitable IAMs, however, also have clear drawbacks, in particular when it comes to short-term projections of a decade or so, since the models generally lag somewhat in updating on recent policy, technology and market developments, and have limited resolution both in time—usually delivering projections for every 5–10 years—and space. The latter arises because the models consider 10–20 global regions comprising either single large countries (USA, China) or continent/sub-continent-scale regions aggregating scores of distinct countries (Sub-Saharan Africa being the most prominent example).

Due to their complexity and focus on providing a broad, long-term perspective rather than being policy prescriptive, IAMs can often lag behind in terms of representing the most recent development in relevant technological fields. An important example is the investment cost of renewables. Figure 11 depicts how most IAMs model the decrease in cost of renewables as additional installed capacity increases, due to "*learning-by-doing*", i.e. cost savings along the whole value chain from production to installation.

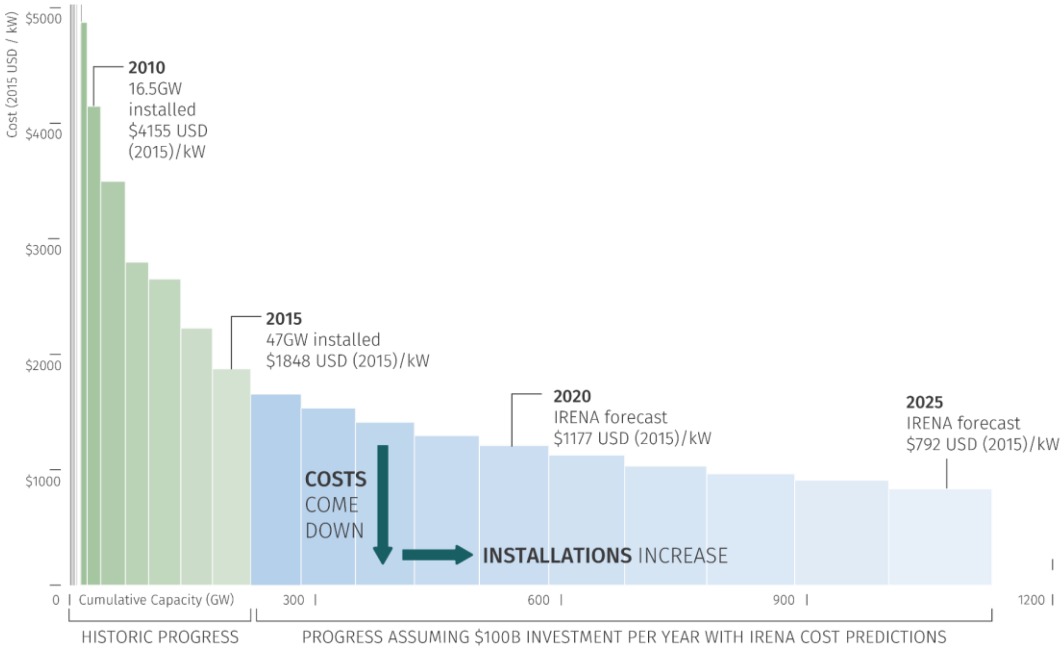

Figure 11: Relation between cost and installed capacity for photovoltaics. Historical progress in green and potential installations based on IRENA price predictions and USD $100B investment per year. Source: (Climate Analytics & UNDP, 2016)

Such cost savings can, of course, not continue forever and therefore, one important parameter is the assumed floor cost, i.e. the minimal cost one will have to pay at some point in the future, which is mainly governed by factors such as resource availability and other physical, rather than economic constraints. Other important assumptions are the initial value at which capital costs start out in such a model and the rate, usually measured in percent cost reduction per doubling of capacity, at which costs move towards the floor cost. Historical data show that solar photovoltaic costs decrease by about 20% for each doubling of cumulative installed capacity.

Figure 12 depicts how a large set of IAM scenarios that are also part of the scenario database used by the IPCC in its Fifth Assessment Report (AR5) performs in comparison to recent historical data on solar PV investment cost (solid squares in Figure 12). Real-world costs are already well below what was expected for much later in the century by most of the IAMs and the 2015 cost levels are already below the floor cost levels of several models. **A clear conclusion from this is that these IAM scenarios underestimate the competitiveness of solar PV. Similar developments can be observed for other renewable energy technologies like wind power.**

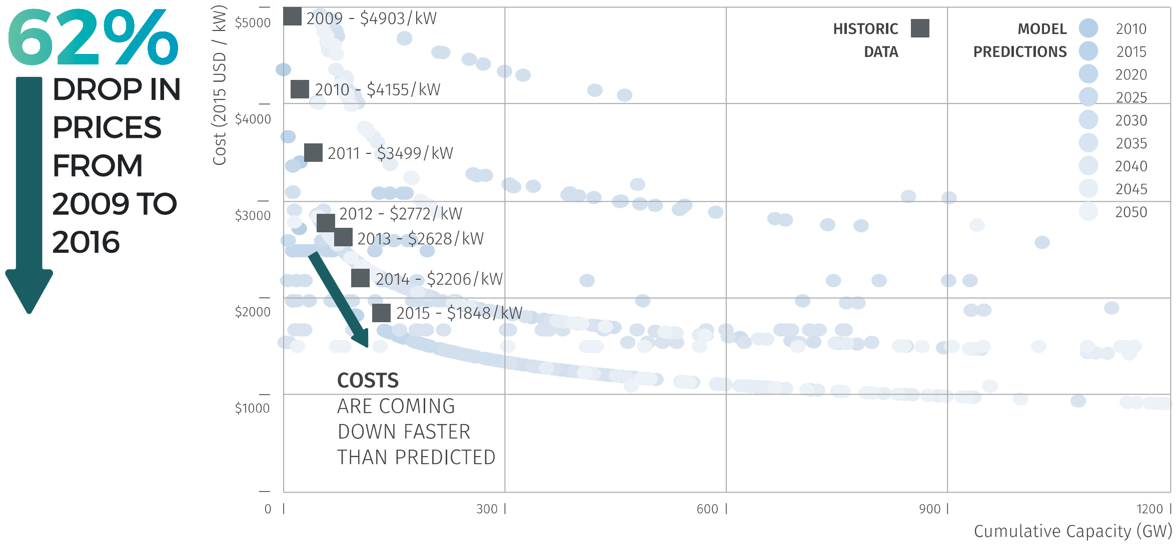

Figure 12: Solar PV cost vs installed capacity: 2009-2015 data and cost projections from energy-system models (2005-2100). Various symbols indicated different models. Source: (Climate Analytics & UNDP, 2016)

IAM modellers are of course very aware of such limitations (Creutzig et al., 2017) and regularly update the respective assumptions. An example where this is relatively well documented is the REMIND[7] model from the Potsdam Institute for Climate Impact Research in Germany. Over consecutive model versions, the PV investment cost assumptions were updated (Table 38).

REMIND's modelling horizon starts in 2005 and it then calculates output in 5-year time-steps. To account for more recent data, the model is usually "fixed" to historic data if such is available for the historic time steps. By comparing Figure 12 and Table 38 one can see that the 2015 value of REMIND 1.7 is well in line with recent data from IRENA. Also, the floor cost assumptions were adjusted downward, reflecting recent research on that topic.

Table 38: Solar PV investment cost assumptions in different versions of PIK's REMIND IAM. Sources: (*"ADVANCE wiki - Reference card - REMIND," n.d.; Luderer et al., 2013, 2015*)

Model version	Investment cost ($/kW)		Cost decrease (% per doubling of capacity)	Floor cost ($/kW)
	2005	2015		
1.5 (2013)	5300			600
1.6 (2015)	4900			500
1.7 (present)	5900	1750	20%	450

REMIND model version 1.5 was also used for the scenarios underlying the AR5 database, 1.6 is the version used for the SSP-IAM database[8]. The most recent version 1.7 was used for the

[7] *Regionalized Model of Investments and Development*, more information can be found at https://www.pik-potsdam.de/research/sustainable-solutions/models/remind.

[8] Recent IAM scenario database with models achieving a series of pre-defined geophysical limits (radiative balance by end of century, so-called Representative Concentration Pathways, or RCPs) under various combinations of socio-economic development (population, GDP and various other indicators related to sustainability and economic considerations) – see public data portal https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about

ADVANCE project[9], which also delivers new scenarios in line with the Paris Agreement (see section 7.2.1). The ADVANCE scenarios were meant to become publicly available over the course of 2017, but this was delayed.

Similar considerations regarding the update of assumptions apply to several other models. This is happening in preparation for publishing the IPCC's Special Report on 1.5°C[10] which is due for publication in autumn 2018. With it, many 1.5°C and accompanying baseline and 2°C scenarios will become available, which will improve the data situation considerably.

For now, a simple methodology for deriving part of the information for 1.5°C compatible benchmark values from the existing scenario base was derived, which is described here briefly for the case of global GHG emissions. Figure 13 shows the total GHG emissions for 2020 (red), 2030 (green) and 2050 (blue) as a function of the respective level of warming in 2100. While there is hardly a difference in 2020 levels, the difference is clearly pronounced for 2050. To derive 1.5°C compatible benchmarks, we use a least-squares fit[11] to project the 1.5°C warming compatible value. With fewer scenarios available closer to a temperature limit of 1.5°C, this method allows us to supplement direct information on the output of 1.5°C scenarios with information contained in the published non-1.5°C scenarios to gain insights into how these models may behave if they were run with the aim of providing a scenario consistent with 1.5°C.

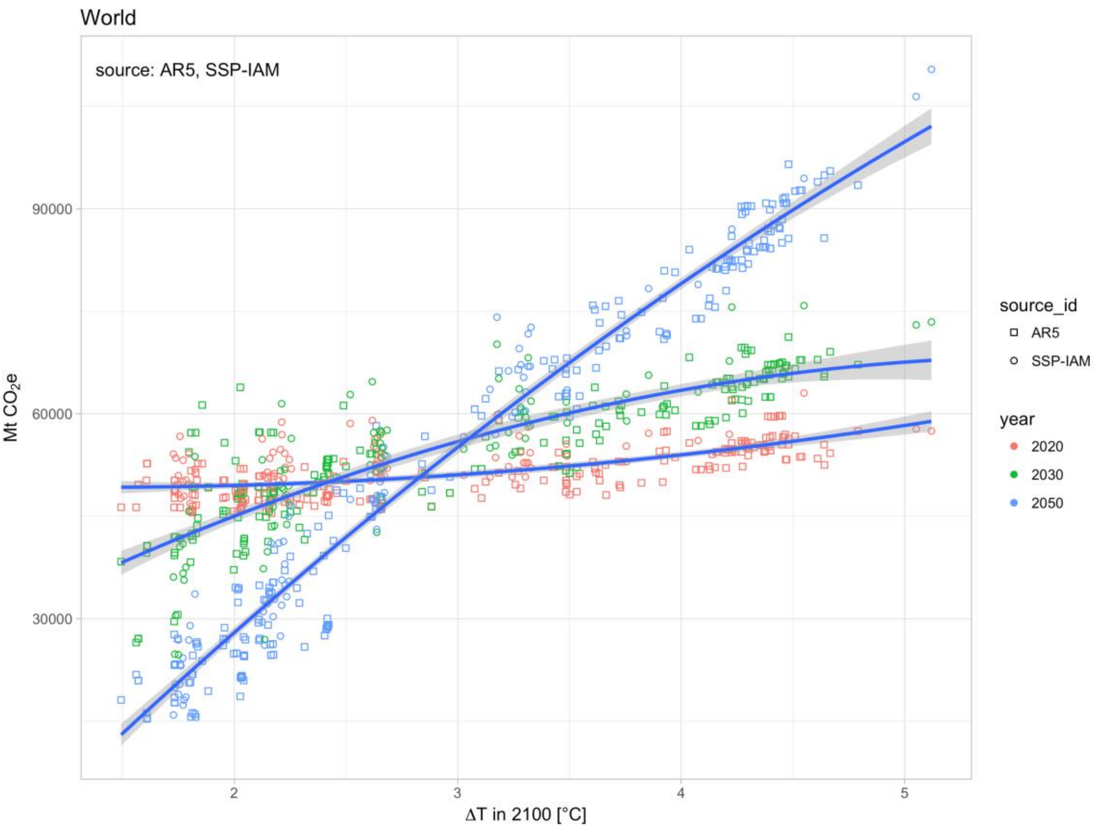

Figure 13: GHG emissions for 2020, 2030 and 2050 from AR5 and SSP-databases over 2100 global warming levels.

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[9] http://fp7-advance.eu/ At the time of writing this, the website was undergoing maintenance—possibly the data could be publicly available soon.

[10] https://ipcc.ch/report/sr15/

[11] in this case a quadratic fit with the grey areas describing the 95% confidence intervals

7.1.2.2 Broader / alternative literature sources

To further compensate IAMs' limitations in terms of being up-to-date and providing only partial coverage of indicators, we have also included a broader range of literature sources, such as bottom-up models, hybrid models, industry projections/forecasts and back-casting models.

By including results that take into account consumer preferences and short-term policy, technology and market developments, these alternative sources of information can help to estimate if ambitious actions are possible and acceptable. However, as most of these sources are not necessarily tied to a specific emissions/temperature outcome, nor to trade-offs (in space and time), they should only be used in conjunction with IAM results to define truly Paris compatible benchmarks.

Mixed approach

The main models using a mixed approach are the IEA Energy Technology Perspectives 2017 (IEA ETP 2017) and the IEA Mobility Model 2017 (as used for World EV Outlook 2017) that applies a combination of back-casting and forecasting over three scenarios from now to 2060. The analytical approach used in the ETP model[12] is described as aiming at identifying a cost-effective way for society to reach the desired outcome. They reflect constraints such as political preferences, feasible ramp-up rates and public acceptance that are not always in line with a least-cost ideal. An important caveat to the analysis is that it does not account for secondary effects resulting from climate change, such as adaptation costs.

The Beyond 2 Degrees Scenario (B2DS) used in our analysis looks at how far known clean energy technologies could go if pushed to their practical limits, in line with countries' more ambitious aspirations in the Paris Agreement.

Back-casting models

The second approach, back-casting, while perhaps taking into account short-term trends as part of its input data, concentrates more on the end goal, and then sets up a model to understand how technological and socioeconomic development can allow the goal to be achieved. Given the large range of possibilities available to, in principle, reach any goal, a criterion such as cost optimisation (minimisation) can be used as a constraint in solving the problem set out by the model, while also making assumptions about economic growth, population growth, and the rates of improvement of technology (including costs). These models tend to focus on the medium-term (a few decades ahead), recognising that the underlying components of the socio- and techno-economic systems become more difficult to reliably project longer-term developments.

The main back-casting models used in the analysis are:

- Greenpeace, The Energy [R]evolution, 2015
- Deep Decarbonization Pathways, Country Reports, 2015

Projections based on current developments

The formally least sophisticated approach is to project future developments based on current and recent trends. Robustness can come from expert opinions, through data from governmental policies or from industrial players that are directly involved in the changes being investigated. For example, if the automobile sector is already making plans over the next several years that imply a growth rate in electric vehicles sales by 25% per year, then this assumption can be carried forward as an input to modelling vehicle stocks over the next decade. Typically, these

[12] For the description of the analytical approach, refer to https://www.iea.org/etp/etpmodel/

projections will tend to look at isolated parts of the entire energy-economy-climate system, without considering interactions. Projections based on current policies and developments usually have shorter time horizons, during which they possibly represent the most realistic approach, and are updated frequently. Over time, these forecasts can converge with projections from back-casting models.

The main projections sources used in the analysis are:

- Climate Action Tracker, Decarb Portal, 2017
- Carbon Transparency Initiative, 2016
- BP Energy Outlook 2018
- Navigant Research, Internal Solar Forecast, 2017
- Navigant Research, EV Market Forecast, 2017
- BNEF, New Energy Outlook, 2017
- BNEF, EV Outlook, 2017
- UBS Evidence Lab 2017
- BofA Merril Lynch EV Report 2017
- Energy Innovation Research Note 2017

7.2 Explanation of key assumptions

7.2.1 Mitigation benchmarks and the Paris Agreement long-term temperature goal

7.2.1.1 The new paradigm for emissions pathways under the Paris Agreement

Article 2 of the Paris Agreement defines its long-term temperature goal (LTTG) as holding *"… the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels …"*. Defining mitigation benchmarks compatible with the Agreement requires one to first understand specifics of the LTTG.

While the 1.5°C limit in the LTTG is clear, one needs to establish which level of warming is implied by "well below 2°C", to derive practical implications for mitigation benchmarks.

The "well below 2°C" formulation in the Paris Agreement LTTG goes beyond the former "below 2°C" goal agreed in Copenhagen and Cancun. In the scientific literature, the latter has been commonly quantified using global emissions pathways that keep warming below 2°C with a probability of at least 66%[13], with the issue of probabilities related to remaining scientific uncertainties in the climate system and carbon cycle.

Compared to the goal agreed in Cancun and Copenhagen, the explicit strengthening of the goal in the Paris Agreement to "well below" 2°C and to 1.5°C implies[14] that emissions benchmarks consistent with the Paris Agreement would need to be derived from mitigation pathways that:

- Either achieve a probability to stay below 2°C that is substantially higher than the 66% level that was characteristic of the pathways previously associated with the former "below 2°C" goal
- OR such pathways need to achieve the same 66% probability below a limit substantially lower than 2°C
- AND such pathways need to be consistent with achieving the 1.5°C limit

[13] See for example UNEP "The Emissions Gap Report 2015. A UNEP Synthesis Report", United Nations Environment Programme, Nairobi, Kenya, November 2015.

[14] See Schleussner, C.-F., Lissner, T. K., Rogelj, J., Fischer, E. M., Knutti, R., Licker, R., Levermann, A., Frieler, K., Schaeffer, M. and Hare, W. (2016) "Science and policy characteristics of the Paris Agreement temperature goal", Nature Climate Change **6**, 827–835, doi:10.1038/nclimate3096.

In addition, while *holding* the temperature increase well below 2°C clearly implies not allowing for an overshoot of the 2°C limit, the only currently published energy-economic pathways that relate to the 1.5°C limit show a temporary overshoot of that limit, subsequently dropping back below 1.5°C before, or by 2100 (with at least 50% probability). This requires carbon dioxide removal, which is achieved in these particular scenarios by a combination of afforestation, reforestation and bioenergy with carbon capture and storage. These temporary overshoot pathways can for now be used as a proxy for deriving mitigation benchmarks consistent with the Paris Agreement 1.5°C limit. In the course of 2018 a large number of new pathways is expected to be published—and will be included in the IPCC Special Report on 1.5°C—with higher probabilities to drop back below 1.5°C by 2100, as well as pathways that hold warming below 1.5°C with at least 50% probability throughout the 21st century, without overshoot. Note that overshoot scenarios require carbon-dioxide removal by land-based options like afforestation and deforestation, biomass with carbon capture and storage, and/or other methods, as mentioned further below in this report.

7.2.1.2 Reconciling 1.5°C and well below 2°C for the purpose of this work

Mitigation pathways derived from energy-economic models are commonly tested for their ability to limit warming below 2°C and 1.5°C using climate/carbon-cycle models. All of the pathways assessed in IPCC AR5 are shown as dots in Figure 14, indicating the probability to stay below 1.75°C (left panel) and 2°C (right panel) throughout the 21st century (horizontal axes), and limit below 1.5°C by 2100 (vertical axis).

For the purposes of deriving mitigation benchmarks, these figures show that emission pathways generally achieve a range of probability and temperature limits simultaneously. Of particular importance in the context of the Paris Agreement LTTG is then the simultaneous achievement of a probability of:

1) About 85% to hold warming below 2°C throughout the 21st century
2) About 70% to hold warming below 1.75°C throughout the 21st century
3) About 50% to limit warming to 1.5°C by 2100

Note that while this general guidance is useful for deriving practical implications from the Paris Agreement LTTG, substantial differences remain between the pathways in terms of variations over time in warming throughout the century: While two pathways could reach the same peak warming in the 2060s, with equal probability to stay below 1.75°C, they could very well develop differently after the peak in warming, with different probabilities of dropping below 1.5°C by 2100. Indeed, the figure shows that pathways (represented by dots) that achieve probabilities of, for example, 70% to hold warming below 1.75°C (vertical dashed line in left panel) and 85% below 2°C (vertical dashed line in right panel) throughout the century, can still be associated with a range of warming levels by 2100, shown by the vertical spread in dots in both graphs and representing the probability levels around 50% to limit warming below 1.5°C by that time (horizontal dashed line in both panels), but ranging between about 40 and 60%. In addition, as mentioned above, a broader set of 1.5°C scenarios is expected to be published in the course of 2018, which could modify this picture somewhat.

Despite these caveats, and for practical purposes, the simultaneous achievement of the temperature limits and (three) probability levels above can for now be seen as compatible with the Paris Agreement LTTG.

We show later that for benchmarks at high sectoral detail (e.g. EV sales), data and other uncertainties are more determining, such as most recent developments, reductions in other sectors, or limited data availability. This may make the agreement on a benchmark easier in cases where stakeholders have diverging views on the Paris Agreement temperature goal, i.e. precise interpretation of the Paris temperature goal is not always necessary.

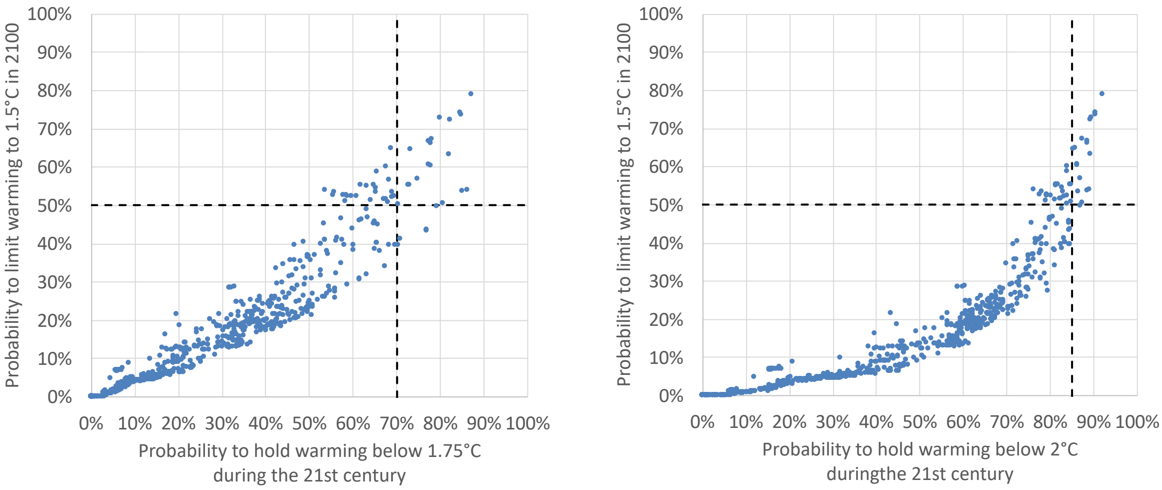

Figure 14: Relation of achieving the PA LTTG over probabilities of staying below 1.75°C (left panel) and 2°C (right panel) throughout the century. A 50% probability to be below 1.5°C in 2100 (horizontal dashed lines) correlates with about 70% probability to stay below 1.75°C and 80-85% probability of below 2°C (vertical dashed lines). Source: AR5 scenario database, Rogelj et al 2015, own calculations

7.2.2 Approach to negative emissions, fuel and Carbon Capture and Storage (CCS) and biomass

7.2.2.1 Negative emissions

The goal of reducing greenhouse gas (GHG) emissions towards zero by the end of the century is confounded by the fact that some sectors of the economy present particularly large challenges for decarbonisation. Examples of these sectors include agriculture, particularly important for methane and nitrous oxide emissions play a leading role; cement production, where a large share of associated CO_2 results from chemical reactions involved, as well as the air transportation and shipping sectors. Therefore, even if building, industrial and transportation end-uses were fully electrified, and the electricity sector completely decarbonised, significant GHG emissions would remain. Achieving a goal of globally aggregate zero emissions, will require Carbon Dioxide Removal (CDR—see below) as compensation.

Clearly, as the stringency of temperature targets increases, the budget for greenhouse gas emissions decreases, and the likelihood that CDR will be necessary increases. CDR, or negative anthropogenic emissions, can be achieved through reforestation and afforestation, or through build-up of carbon stored in soil. Although potentially significant contributions, these processes are unlikely to result in the necessary multi-gigatonne scale removal of carbon dioxide required to offset residual emissions. Therefore, additional technologies are needed to capture and remove carbon dioxide, either during energy generation or directly from the air.

Direct air capture (DAC) is a very new technology in which chemical reactions with ambient air allow CO_2 to be removed and sequestered. For the most part, being untested at scale, DAC is not included in IAMs, although this could change in a next generation of models. **Capturing carbon from power plants** that burn coal or natural gas represents one way to reduce emissions, but the limit in this case would be low emissions, not negative emissions. **Bioenergy with Carbon Capture and Storage** (BECCS) extends the concept of capturing and sequestering carbon dioxide at a power plant to generation that uses biomass as the input fuel and can result in negative emissions. Growing biomass leads to the absorption of CO_2 during photosynthesis; combustion of that biomass in a thermal electric power plant would re-release the same CO_2; capturing the emitted CO_2 at the power plant and storing it underground permanently is the key step to reaching negative emissions, assuming life-cycle emissions of the biomass feedstock is lower than uptake during growth.

BECCS technology is, in principle, a well-understood approach to reducing emissions and is thus relatively easy to incorporate in IAMs. To date, however, there are no BECCS projects at large-enough scale from which definite conclusions about the technology may be drawn. On the other hand, until there are financial incentives for construction and operation of BECCS plants, for example a price on carbon emissions, growth in the implementation of the technology may be slow. The implication of the Paris Agreement, with NDCs as the driving factors, is that there will be increasing incentive for climate mitigation efforts in general, and BECCS in particular.

(IPCC, 2014) estimates CDR in the range of 10-15 Gt CO_2/a by 2050 for 2°C scenarios. A recent paper, for which underlying data of the 13 scenarios might become available eventually, estimates typical CDR in 1.5°C scenarios of 10-15 Gt CO_2/a as well in the period 2050-2100. However, one out of six models (the GCAM model) reaches values of around 30-50 Gt CO_2/a by 2050, split roughly equally between land-restoration efforts, such as afforestation and reforestation, and technological options, such as BECCS (Rogelj et al., 2018) and Supplementary Information). Results depend strongly on the underlying socioeconomic scenario (population and GDP per capita).

Figure 15 compares the level of cumulative BECCS deployment (measured in its primary energy content) with the mean temperature increase in 2100 above preindustrial levels for the scenarios in the AR5 and more recent SSP databases, differentiated by model. Current (2016) global primary energy demand is about 580 EJ (IEA, 2017c), which would approach 50,000 EJ cumulative until 2100 at hypothetical fixed present-day levels. The CO_2 actually captured by BECCS is not reported separately in publicly available IAM data underlying results shown here. Assuming a constant carbon uptake per energy unit, above numbers could be associated with CO_2 captured. IPCC (2006) reports emissions intensities of between 84.7-117 Mt CO_2/EJ with an average of 100 Mt CO_2/EJ for “other primary solid biomass”, which should be the most appropriate category. Actual values used in the models depend on the specific crops assumed for biomass energy and their share in bioenergy supply, information which is not public. Also, the capture and storage technology is not perfect, so that only a share of the CO_2 emitted during combustion is actually captured and subsequently stored underground. Typical capture efficiencies are around 90% (D. P. van Vuuren et al., 2013). Another unknown are the emissions associated with growing the biomass, e.g. from fertilizer use or land-use change.

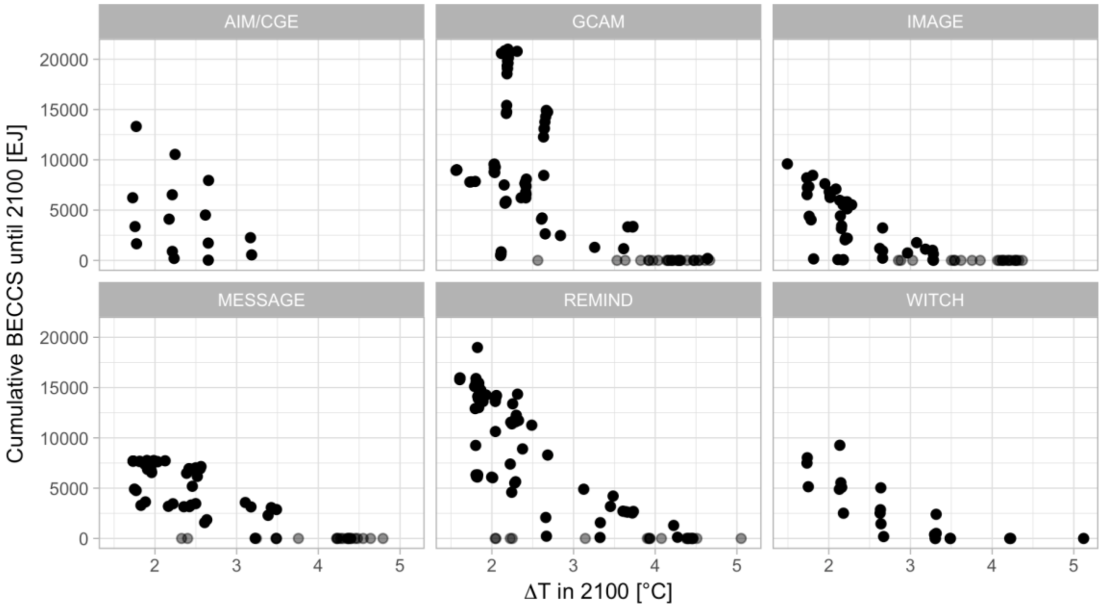

Figure 15: Cumulative Bio-Energy with Carbon Capture and Storage (BECCS) deployment over 2100 mean temperature. Source: AR5 & SSP-IAM databases

Figure 16Figure 16 shows the maximum deployment rate of BECCS in the AR5 and SSP-IAM databases. Solid symbols depuct a peak in 2100, semi-transparent symbols indicate a peaking before 2100.

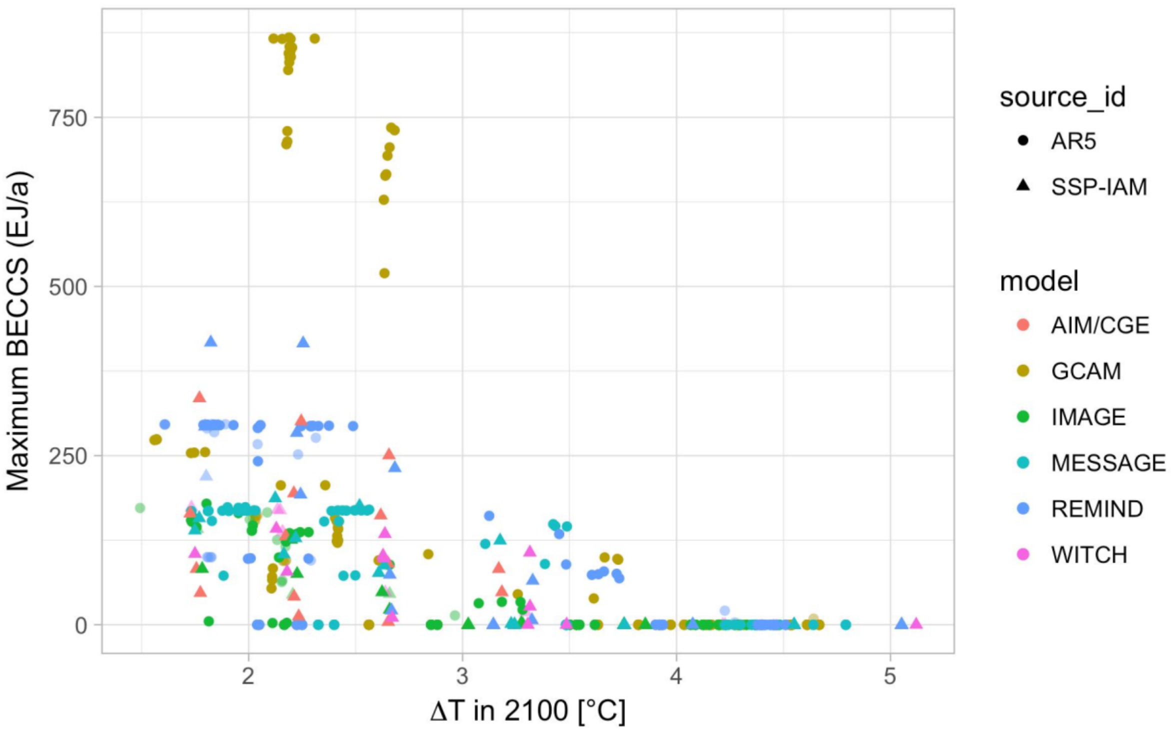

Figure 16: Maximum BECCS deployment in IAM models. Semi-transparent symbols depict a peaking year before 2100. Sources: AR5 and SSP-IAM databases, own calculations

Most scenarios stay below 15,000 EJ of cumulative BECCS deployment and MESSAGE, IMAGE and WITCH scenarios show less than 10,000 EJ. More ambitious scenarios in terms of climate change mitigation are usually associated with the same level of BECCS deployment in terms of energy output/CO_2 captured per year, but this deployment happens about 5–10 years earlier, driving up cumulative deployment over the century.

Regarding the maximum deployment rate, most scenarios stay below about 300 EJ/a, there are only a few outlier scenarios from GCAM in the AR5-database, that reach values above 500 EJ/a and up to 800 EJ/a.

While most models in Figure 16 show the highest deployment of BECCS for the most ambitious climate change mitigation targets, i.e. the lowest temperature increase in 2100, this is not the case for a group of scenarios from the GCAM model that show the highest deployment between 2°C and 3°C temperature difference, we therefore chose to exclude these scenarios from further analysis – these are the same as those that show the most extreme deployment ratios.

Some scenarios—even those considered here as alternative or bottom-up sources—seem to depict a transformation process towards achieving the Paris LTTG without deploying much negative emissions. This is, however, often due to limiting the respective models' sectoral, temporal or spatial horizon—just looking at the energy sector or only looking ahead a few decades or limiting the analysis to certain countries or regions—something that is, by definition, not possible in IAMs. To visualise how a limited time horizon, e.g. just through to 2050, can suggest negative emissions may be (largely) avoided, Figure 17 compares cumulative deployment of BECCS in the first and the second half of the century, showing that even in scenarios with very ambitious climate change mitigation, BECCS deployment happens mostly after 2050.

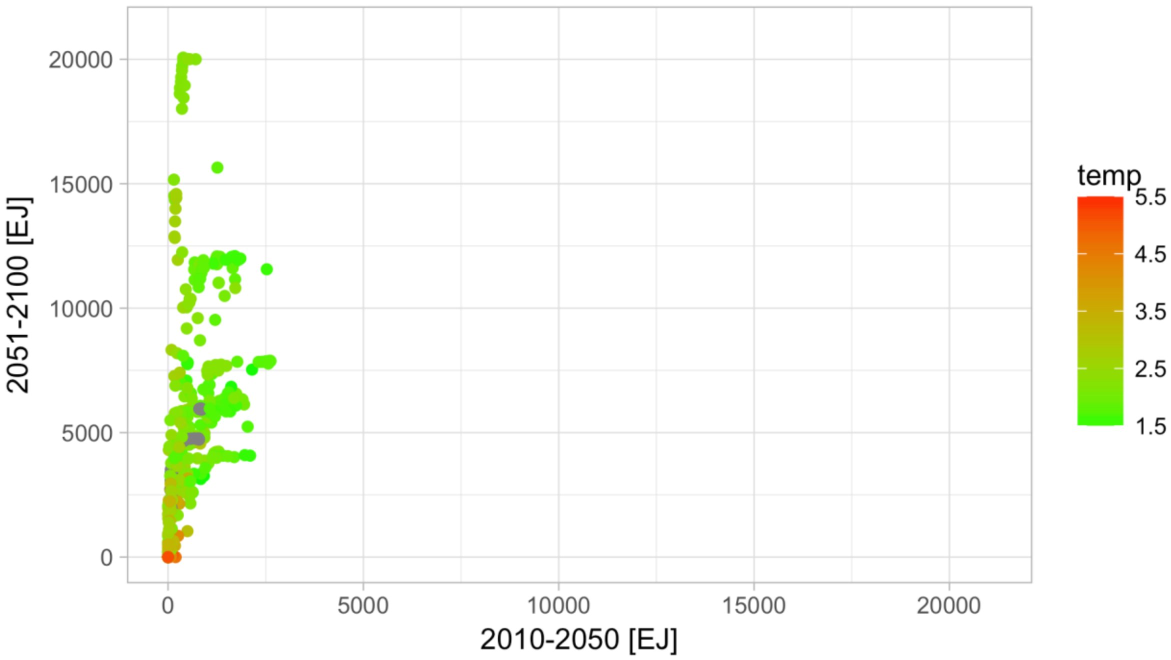

Figure 17: Comparison of cumulative BECCS deployment in the first (x-axis) vs the second half (y-axis) of the century. Colour depicts median 2100 temperature outcome. Sources: AR5 & SSP-IAM databases

IEA models also include some important assumptions on negative emissions. In both the 2DS and B2DS scenarios defined by IEA, BECCS is deployed at a large scale, delivering 36 GtCO2 of cumulative negative emissions in the 2DS and 72 GtCO2 in the B2DS in the period to 2060 and assumed to continue through to 2100 to reach substantially higher cumulative amounts. Negative emissions would likely need to be greater in the case of a 1.5°C trajectory.

With exceptions, **indicator values cannot be differentiated in terms of weak vs strong dependency on negative emissions technologies**. Although deployment of negative emissions technologies is evident in all currently available data sources that relate to the Paris Agreement and to its well-below 2°C/1.5°C limit, available data is too limited to make a useful distinction