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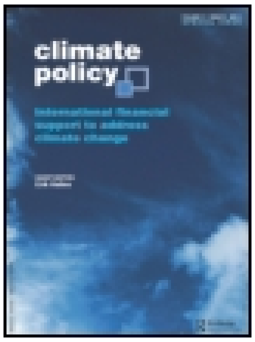

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RESEARCH ARTICLE

Ten key short-term sectoral benchmarks to limit warming to 1.5°C

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ABSTRACT
This article identifies and quantifies the 10 most important benchmarks for climate action to be taken by 2020–2025 to keep the window open for a 1.5°C-consistent GHG emission pathway. We conducted a comprehensive review of existing emissions scenarios, scanned all sectors and the respective necessary transitions, and distilled the most important short-term benchmarks for action in line with the long-term perspective of the required global low-carbon transition. Owing to the limited carbon budget, combined with the inertia of existing systems, global energy economic models find only limited pathways to stay on track for a 1.5°C world consistent with the long-term temperature goal of the Paris Agreement.

The identified benchmarks include:

- Sustain the current growth rate of renewables and other zero and low-carbon power generation until 2025 to reach 100% share by 2050;
- No new coal power plants, reduce emissions from existing coal fleet by 30% by 2025;
- Last fossil fuel passenger car sold by 2035–2050;
- Develop and agree on a 1.5°C-consistent vision for aviation and shipping;
- All new buildings fossil-free and near-zero energy by 2020;
- Increase building renovation rates from less than 1% in 2015 to 5% by 2020;
- All new installations in emissions-intensive sectors low-carbon after 2020, maximize material efficiency;
- Reduce emissions from forestry and other land use to 95% below 2010 levels by 2030, stop net deforestation by 2025;
- Keep agriculture emissions at or below current levels, establish and disseminate regional best practice, ramp up research;
- Accelerate research and planning for negative emission technology deployment.

Key policy insights

- These benchmarks can be used when designing policy options that are 1.5°C, Paris Agreement consistent.
- They require technology diffusion and sector transformations at a large scale and high speed, in many cases immediate introduction of zero-carbon technologies, not marginal efficiency improvements.
- For most benchmarks we show that there are signs that the identified needed transitions are possible: in some specific cases it is already happening.

KEYWORDS
Benchmarking; COP21; mitigation scenarios; Paris Agreement; technological change; transition; UNFCCC; 1.5°C

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1. Introduction

The Paris Agreement, adopted in December 2015 under the United Nations Framework Convention on Climate Change (UNFCCC), set a long-term temperature goal (LTTG) of 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels' and pursuing 'efforts to limit the temperature increase to 1.5°C' (UNFCCC, 2015, Article 2). To meet the LTTG, countries are to act together so as to achieve 'a balance between anthropogenic emissions by sources and removals by sinks' of GHGs in the second half of the twenty-first century (UNFCCC, 2015, Article 4.1), with the timing and pathway to achieving this set according to the best available science. To meet the Paris Agreement's LTTG, GHG emissions urgently need to peak, begin declining and reach zero globally by around 2060, with CO_2 emissions from fossil fuels reaching zero globally by around 2050 (Luderer et al., 2013; Rogelj, McCollum, Reisinger, Meinshausen, & Riahi, 2013; Schleussner et al., 2016).

Governments have submitted their post-2020 climate action plans for the Paris Agreement, known as Nationally Determined Contributions (NDCs), but the aggregate impact of NDCs is far from sufficient to limit temperatures to 1.5°C (or even 2°C). Even if NDCs are fully implemented global GHG emissions are expected to continue to increase towards 2030 and the median increase of global average temperature from preindustrial levels is projected to be 2.6–3.1°C by 2100 (Rogelj et al., 2016). Current policies would lead to emissions substantially above globally aggregated NDC levels, implying substantially higher warming. Urgent action is needed to keep the door open for achieving 1.5°C, consistent with the Paris Agreement's LTTG, without waiting for formal review processes under the UNFCCC to be established (Höhne et al., 2017).

A large body of literature describes long-term emission scenarios that are consistent with limiting warming to 2°C (Clarke et al., 2014). An as yet smaller number of scenarios in the literature holds warming below 2°C and returns warming to 1.5°C by 2100 (Rogelj et al., 2015) and were reviewed in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). Under development are scenarios that may be more consistent with the Paris Agreement goal of holding warming well below 2°C and limiting twenty-first century warming to around 1.5°C, providing a more comprehensive picture. Rockström et al. (2017), for example, illustrate the required global transition, providing a storyline of essential developments that are needed during subsequent decadal periods between now and 2050 to keep emissions to a level consistent with a 50% chance of limiting warming below 1.5°C by 2100.

There are, however, only few studies that describe the *short-term* actions and transitions that need to occur at sector level around 2020–2025 to meet the 1.5°C limit, consistent with the LTTG of the Paris Agreement, either by achieving an early peak and decline of emissions, or as a near-term precondition for the longer-term transformation required to meet the 1.5°C limit. It is fundamental to the implementation of the Paris Agreement that clear and understandable guidance is given to policy makers so that they can implement the short-term actions that pave the way to meeting the LTTG. Such guidance needs to strike the balance between being scientifically rigorous (including as many uncertainties and caveats as possible) and being simple, understandable and therefore actionable.

Against this backdrop, this article lays out ten key actionable benchmarks to be achieved by 2020–2025 to limit warming to 1.5°C, based on existing emissions scenarios, studies on mitigation potential and other sources, in order to provide guidance to policy makers on what needs to happen in each sector. We zoom in on the period until 2025 and provide actual numerical requirements of interventions in all sectors. These benchmarks are intended as guidance to help policy makers set up policies and policy targets that are consistent with the Paris Agreement, and not necessarily as the minimum targets that must be achieved in all countries to limit warming to 1.5°C.

This article largely builds on previous work undertaken as part of the Climate Action Tracker (Kuramochi et al., 2016).

2. Data and methods

The sectors assessed in this article – power, transport, buildings, industry and LULUCF – cover more than 85% of total GHG emissions of 49.5 billion metric tonnes of annual CO_2-equivalent emissions ($GtCO_2e$/yr) in 2010 (Victor et al., 2014). Assuming the effort to achieve net zero GHG emissions in the second half of the twenty-first century and limit warming to 1.5°C is ultimately distributed in a cost-effective manner among sectors and geographic regions, a transition needs to be triggered in *all sectors* and by *all actors*.

The analysis presented in this article was conducted in three phases, starting with a broad assessment of mitigation potentials and scenarios, mostly focused on the 2°C warming limit, subsequently tightened and constrained by the available literature on 1.5°C. Detailed steps for benchmark quantification differed across sectors and are described in the Supporting Information (SI).

Such analysis would ideally be based on a wide span of 1.5°C scenarios with sufficient sectoral granularity, from which median values, uncertainty ranges and the ten most important sector-level benchmarks can be directly derived. In the absence of such information, the second best approach is to take information from the vast scenario literature available on 2°C scenarios, and modify it on the basis of comparatively limited information available for 1.5°C scenarios to derive the required ten benchmarks. This is the approach this article has used.

First, the deployment levels of key mitigation technologies and options under '2°C-consistent' scenarios up to 2050 were assessed for each sector. The assessment was based on a range of recent peer-reviewed studies, including the IPCC AR5 (IPCC, 2014) and the IEA Energy Technology Perspectives (ETP) 2016 (IEA, 2016a) for energy supply and end-use sectors. Ranging across sectors, the ten benchmarks were identified based on their importance to limit warming to 1.5°C. Therefore, they do not necessarily represent sectors or areas with the largest mitigation potential in the short term. In this regard this study differs from a 'wedge' analysis as performed by Pacala and Socolow (2004), which identified 15 technological options that are together sufficient for a 500 ppm CO_2 stabilization. In our study, the criteria for the selection of key mitigation technologies and options include: the scale of (sub)sector GHG emissions, potential cumulative emissions reductions through to the end of the twenty-first century, as well as the status of policy and/or technology development in respective (sub)-sectors (e.g. near-term urgency for research to realize essential long-term mitigation potential).

Hence, as a second step, 1.5°C scenarios from our reference literature were compared with 2°C scenarios from a range of literature at the sectoral level to quantify if the emissions reduction and/or technology deployment benchmarks need to be achieved sooner under 1.5°C scenarios, and by how much. The quantification was conducted on the basis of single future year emissions (2020 or 2025, depending on data availability).

The assessment of 1.5°C-consistent emission trajectories for energy supply and end-use sectors were based on median values in Rogelj et al. (2015) derived from about thirty-five 1.5°C-consistent scenarios of the MESSAGE and REMIND integrated assessment models (IAMs). Here we have defined 1.5°C-consistent scenarios as those with greater than 50% chance of keeping warming below 1.5°C relative to pre-industrial levels by 2100 (Rogelj et al., 2015). It is to be noted, however, that while this approach allows us to use existing scenario literature, it should not be perceived as an interpretation of the Paris Agreement LTTG. Scenarios are in preparation that appear more consistent with the Paris Agreement LTTG in that they limit warming to 1.5°C in the twenty-first century. MESSAGE and REMIND are IAMs that are highly responsive to climate policy signals because they represent a large variety of low-carbon technology options (Kriegler et al., 2015). In Rogelj et al. (2015), 1.5°C-consistent scenarios reach global zero CO_2 emissions 10–20 years earlier than 2°C scenarios (>66% chance) by mid-century. Under these 1.5°C scenarios, median global total GHG emissions peak before 2020 at around 56 $GtCO_2e$/yr and reduce to roughly 2010 levels in 2025 (47 $GtCO_2e$/yr). The use of median values for setting sector benchmarks aims to keep the aggregate of these benchmarks within the 1.5°C-consistent emissions range, while maintaining the benchmarks sufficiently communicable for policymakers.

Emissions pathway and mitigation potential assessments for other sectors were based on Luderer et al. (2013), Rogelj, McCollum, O'Neill, and Riahi (2012), Rogelj et al. (2013), personal communication with Joeri Rogelj (November 2016) for the LULUCF sector and Wollenberg et al. (2016) for non-CO_2 emissions from the agriculture sector.

Third, synthesizing the information from the previous two phases, 1.5°C-consistent actionable benchmarks for 2020–2025 were derived for the technologies and options reviewed in the first phase. For example, if a scenario with a more than 50% chance of staying below 2°C in the literature projects an *x*% of technology *y*'s market share in sector *z* in 2040, and Rogelj et al. (2015) show that the emission level of sector *z* in 2040 in the 'medium 2°C' (>50% chance) scenario is achieved 15 years earlier in the 1.5°C scenario, then we assumed that technology *y*'s market share would reach *x*% in 2025 in a 1.5°C-consistent scenario.

For each element, we discuss actions required to meet the benchmarks, provide examples of recent developments that are already in line with these benchmarks, and highlight the main challenges in meeting the benchmarks worldwide.

3. Results by sector

Of the five sectors analysed, we identified multiple benchmarks in three sectors, where our literature review showed some sub-sectors require earlier transition (e.g. coal-fired electricity generation separate from power sector overall) and/or involve different actors and policies (e.g. road transport vs aviation; existing vs new building stock; forestry vs commercial agriculture). Finally, we identified a tenth overarching benchmark that assesses the need for negative emission technologies.

The ten benchmarks identified in this study and recent developments toward the benchmarks are summarized in Table 1. Our findings are presented in the following sections per sector. Further details of our findings and discussions can be found in the SI. All values for 1.5°C-consistent scenarios presented are from Rogelj et al. (2015), unless otherwise noted.

3.1. Power sector

3.1.1. Sustain the growth rate of renewables and other zero and low-carbon power generation until 2025 to reach 100% share by 2050

Under the median outcome of 1.5°C scenarios, CO_2 emissions from electricity generation need to be reduced from around 12 $GtCO_2$/yr in 2010 to around 6–11 $GtCO_2$/yr in 2020, around 2–5 $GtCO_2$/yr in 2030 and zero to −2.5 $GtCO_2$/yr in 2050. Full decarbonization of power by 2050 implies a rapid transition to renewables and other zero-carbon (primarily nuclear) and low-carbon (primarily carbon capture and storage-equipped fossil energy) sources. In 2012, 33% of electricity was generated from these sources globally (IEA, 2016c) and the share has slightly decreased since 1990 (see SI, Figure S-1). Under the median trajectory of 1.5°C scenarios, this share will need to reach around 35–60% by 2020, 60–80% by 2030, and approach 100% by 2050.

In absolute terms, solar and wind power generation has been increasing by 25–30% year-on-year over the last decade and hydropower is reporting growth of 2–4% per year (IEA, 2016c). If growth in solar and wind power generation were to continue for another five to ten years at similar levels to those seen over the last decade, and then gradually relax to around 4–5% per year from 2025 until 2050, this would be sufficient to completely decarbonize the power sector, despite the projected increase in demand (see Figure 1). This leads to our benchmark: *sustain the growth rate of renewables and other zero and low-carbon power until 2025 to reach 100% share by 2050*.

To facilitate this power sector transition, policies are needed to transform technical systems, market design and financing structures (see SI, Figure S-2 for an overview). Flexible electricity networks are needed to enable high shares of renewable power sources, and many different options are currently under development. Markets need to support the transformation by facilitating access for renewables, and promoting grid development to enable flexibility. Finally, direct financial support through production subsidies provides investors with assurance

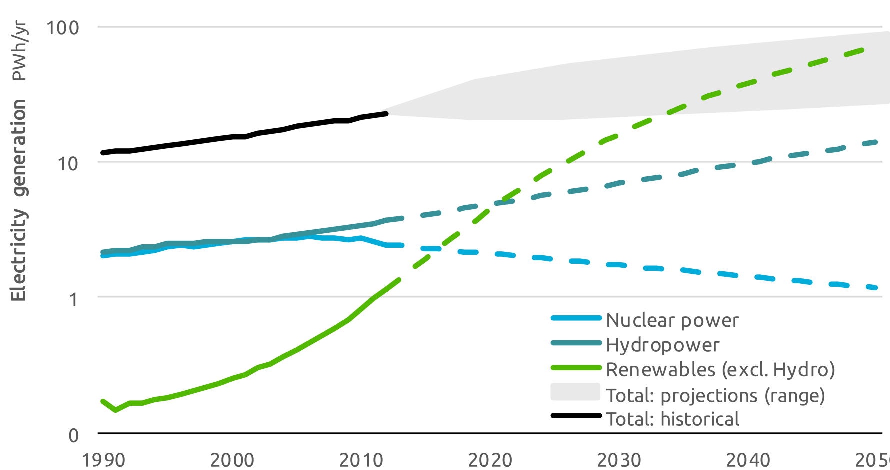

Figure 1. Annual power generation from low-carbon sources and median projections from 2°C pathways. Source: Adapted from IIASA (2015).

that a certain return on investment will be received, whereas indirect financial support can be provided through policies such as carbon pricing, which internalize the external cost of conventional electricity generation (Held, Ragwitz, Gephart, Klessmann, & de Visser, 2014; Klessmann, 2012; Leonardo Energy, 2016; Noothoot et al., 2016).

There are a number of recent global developments that are compatible with this benchmark. Renewables are becoming competitive in comparison to fossil fuel-fired generation in many regions (IRENA, 2014). Between 2010 and 2014 the levelized cost of electricity (LCOE) for solar photovoltaics decreased by half (IRENA, 2014). The decreasing trend in costs is expected to continue due to increasing economies of scale, more competitive supply chains and technological improvements. Global weighted average LCOE from wind and solar energy can further reduce by 26–59% between 2015 and 2025 with the right regulatory and policy frameworks (IRENA, 2016b). In addition, the number of jurisdictions with policy support for renewable energy is substantial: IRENA (2016a) reports that 110 have feed-in policies, 100 have renewable portfolio standard or quota policies and 64 have tendering/public competitive bidding for renewable energy.

An important challenge is to integrate high shares of weather-dependent renewables in the electric power system. Energy markets need to modernize to redefine how they value system services and flexibility to provide incentives for the transition. This change in energy grids and markets may be particularly challenging in developed countries where they mean a departure from the long-established status quo (IRENA, 2017).

3.1.2. No new coal power plants, reduce emissions from existing coal fleet by 30% by 2025

To limit warming to 1.5°C, the global power sector needs to decarbonize ten years earlier than under a 2°C pathway. 1.5°C scenarios assessed by the IPCC indicate this sector needs to reach zero carbon dioxide emissions globally around 2050 (Rogelj et al., 2015). Emissions from coal-fired power stations must therefore be phased out globally before 2050. Power generation from the current coal-fired power plant fleet should be reduced by 30% by 2025 and 65% by 2030, for example through early retirement or reducing the running time of existing power plants (Figure 2). It is highly uncertain whether the retrofit of carbon capture and storage (CCS) could be deployed at large scale due to costs and space availability as well as the availability of storage sites.

This phase-out needs to happen at different times in different regions, and stands in stark contrast to current and planned coal capacity worldwide (Global Coal Plant Tracker, 2016). To close the gap between current ambition and what is needed for 1.5°C, while simultaneously limiting stranded assets, not one new coal-fired power plant can be built. This leads us to our benchmark: *no new coal power plants, reduce emissions from existing coal fleet by 30% by 2025*.

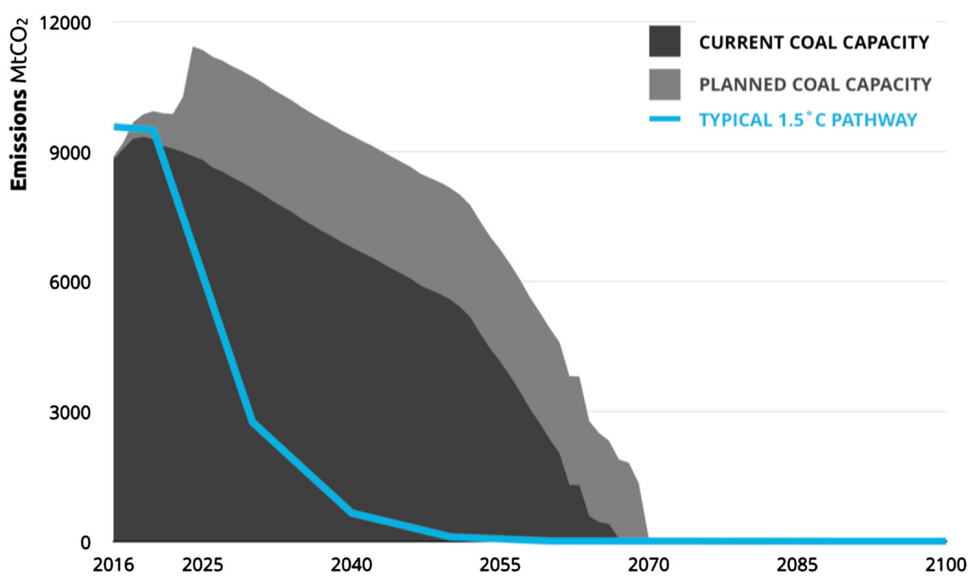

Figure 2. Potential annual CO_2 emissions from existing and planned coal capacity compared to a typical 1.5°C pathway (Global Coal Plant Tracker, 2016; Rogelj et al., 2012, 2015).

As of February 2017 the global coal fleet reached around 1964 GW, and there were additional 273 GW of coal-fired capacity in construction and 570 GW in pre-construction globally (Shearer, Ghio, Myllyvirta, Yu, & Nace, 2017), with most of the planned capacity being concentrated in fast growing economies. Under current plans and without additional policy interventions the global coal fleet would likely continue to increase as opposed to what is needed to limit warming to 1.5°C.

The literature shows the negative role of fossil subsidies in any form (post-tax consumer, pre-tax consumer or production subsidies) in hindering clean energy investment by making fossil fuels artificially cheaper (IEA, 2014), in hampering economic growth by imposing large fiscal costs (Coady, Parry, Sears, & Shang, 2015) or in increasing the vulnerability of countries to volatile international energy prices (Coady et al., 2015). Scrapping these subsidies would thus also be an important step towards limiting warming to 1.5°C and an integral part of any global coal phase-out. In addition, if the subsidies were to be redirected to 'investments in basic infrastructures over the next 15 years, substantial strides could be made in reducing poverty' (Edenhofer, 2015).

Examples of individual actions are already in line with or close to this benchmark. National and subnational efforts to phase out coal are observable across the globe. In its thirteenth Five Year Plan China set a cap on coal (Central Committee of the Communist Party of China, 2016). The new draft electricity plan of India issued in December 2016 suggests that no new coal power capacity is needed after 2022, apart from the 50 GW that is currently under construction and likely to be ready by 2022 (Central Electricity Authority, 2016). In the EU, many countries have already announced their intention to phase out coal in the electricity sector in the next decades (Climate Analytics, 2017).

A major challenge will be how to address existing coal-fired power plants before the end of their economic lifetime. Roughly half of the expected emissions from existing plants need to be cut (Climate Analytics, 2016). This will require significant transformations in regions that are currently dependent on coal extraction and use. Premature retirement of existing coal-fired power plants is still a major challenge in many countries because it is generally expensive (Bruckner et al., 2014) and can be politically difficult (Caldecott, Sartor, & Spencer, 2017). An additional challenge is to redirect investments from new coal-fired power plants to alternatives. Without further policies, coal will likely remain attractive in many countries due to its technological maturity and wide availability, as well as its relatively low price and low capital intensity compared to renewable energy sources (Steckel, Edenhofer, & Jakob, 2015). For more on the coal sector transition, see Spencer et al. (2017).

3.2. Transport sector

Decarbonization of the transport sector in line with the Paris Agreement requires shifts towards zero-carbon fuels. The transport sector comprises a diverse amount of vehicle types, including cars and smaller vehicles such as motorcycles (together known as 'light duty vehicles' (LDVs)), buses, trucks, trains, airplanes and ships.

In this section, we focus on light-duty vehicles in road transport and on aviation as case studies, which leaves out heavy-duty vehicles, transport by rail, and maritime shipping (although we do touch on this latter mode in Section 3.2.2 on aviation). For these transport modes we make the following observations:

- In heavy-duty road transport, similar technological shifts are required as those currently happening for light-duty vehicles but technology is currently not advanced enough for similar trends to emerge.
- For rail transport, a continued drive towards electrification would be the most obvious way to decarbonize this sub-sector, as long as the necessary actions for decarbonizing the power sector are taken at the same time.
- The situation for maritime shipping is comparable to that in aviation (see also Section 3.2.2 on aviation below).

3.2.1. Passenger transport: last fossil fuel car sold by 2035–2050

The requirement that zero-emission vehicles should become the dominant mode of light transport is supported by many studies (Deng, Blok, & van der Leun, 2012; IEA, 2016b; Sims et al., 2014; Sterl et al., 2016).

According to the IEA ETP2016 scenario consistent with a 50% chance of limiting global warming to 2°C (IEA, 2016a), a roughly 70% decrease of specific emissions (well-to-wheel, measured in gCO_2 per passenger-kilometre (pkm) in light road traffic by 2050 below current levels is necessary in the absence of deep demand reductions. A 50% chance of limiting global warming to 2°C, however, is far removed from the goal of the Paris Agreement.

A gradual tightening of emission standards, barring unreasonably large improvements in energy efficiency of conventional cars, will not be sufficient for the 1.5°C limit (Sterl et al., 2016). This means that the rapid introduction of zero emission vehicles is the key for decarbonization of passenger transport. To achieve car fleets consisting of 100% zero-emission cars by 2050–2065 (median 2055), the last fossil-fuel powered car would have to be sold roughly before 2035–2050, assuming an average lifetime of 15 years. For the benchmark, we chose the lower end of the range, because (1) more model results are at the lower end (skewed distribution) and (2) electric vehicle (EV) market development may happen faster than that of low-carbon options in other sectors for which the same timeline holds, since the EV market has grown much faster than expected in recent years even as, for instance, the buildings sector has lagged behind (Cronin et al., 2015; Sterl et al., 2017). This leads to our benchmark: *last fossil fuel car sold by 2035–2050*.

Of the options for zero-emission vehicles, the EV currently appears to be the most promising. While their energy efficiency typically already exceeds that of conventional cars, vehicles will be zero-emission vehicles only if the power sector decarbonizes (IEA, 2016b).

Assuming exponential growth of the EV market, the implication of the benchmark of having 100% EVs in new vehicle sales worldwide by 2035 is equivalent to a doubling of the market share of EVs in new vehicle sales roughly every 2.5 years from 2016 levels, based on a 2016 share of 0.6% of battery electric vehicles in new vehicle sales (EV-Volumes, 2016).

Some examples are already compatible with our benchmark. The market is growing rapidly, especially in China in recent years (see SI, Figure S-3). All car manufacturers sell electric models and plan on increasing shares of electric vehicles. A few countries have managed relatively high shares of (plug-in hybrid (PH)) EVs in new car registrations. Norway is the worldwide frontrunner, with (PH)EV registrations accounting for close to 30% of new cars followed by the Netherlands with 10% (EAFO, 2017). For Norway, a combination of financial incentives and behavioural incentives (e.g. allowing EV drivers onto bus lanes and giving them free public parking) have helped to boost EV sales (Figenbaum, Assum, & Kolbenstvedt, 2015). Compatible with the benchmark are the suggestion in Norway's National Transport Plan for new light-duty vehicles to be zero-emission after 2025 (Avinor, Norwegian National Rail Administration, Norwegian Coastal Administration, & Norwegian Public Roads Administration, 2016); the coalition agreement for the new cabinet in the Netherlands aims for all new vehicles to be zero emission by 2030 (VVD, CDA, D66, & ChristenUnie, 2017); France and the UK announced they were ending the sale of conventional petrol and diesel cars by 2040 (DEFRA & DfT, 2017; Ewing, 2017). China and India are also considering setting deadlines for phasing out petrol and diesel vehicles (see the SI for further information on recent policy developments). Volvo is the first conventional car producer to announce that it will sell only cars with an electric motor as of 2019 (Volvo, 2017).

The largest challenges that the electric car industry currently faces are: pricing, range anxiety and charging infrastructure (Erich & Witteveen, 2017; IEA, 2016b; Nijland, Geilenkirchen, van Meerkerk, 't Hoen, & Hilbers, 2016). In addition, resistance from the conventional car industry and the car component industry against a transformation towards a market in which EVs dominate may be considerable. Lastly, it remains to be seen whether it is physically feasible that the industrial infrastructure needed to supply the growing vehicle market can be established (Mission, 2020, 2017; Sterl et al., 2017). However, consumer expectations on price, range and charging infrastructure may be exceeded in the EU in the period 2020–2030, based on current developments, such that EVs may become the dominant technology by 2035 as far as consumer demand is concerned (Erich & Witteveen, 2017).

3.2.2. Aviation and shipping: develop and agree on a 1.5°C-consistent vision

Reducing emissions in the aviation sector requires action in three broad areas: aircraft efficiency, carbon content of fuels or energy source and modal shifts in demand.

In the timeframe until mid-century, 2°C pathways suggest that the emissions from air transport would have to decrease by 56% (IEA, 2016a), even though air travel demand (measured in pkm) may increase by almost 140%

by 2050 above 2013 levels. This corresponds to an 82% decrease in specific emissions per pkm. This 2°C pathway assumes substantial increases in energy efficiency of airplanes, an increase in the use of low-carbon fuels (55% of the fuel demand by 2050), and to a certain extent a shift in travel demand from aviation to other transport modes, such as high-speed rail.

The implications of the above are that energy efficiency of aircrafts will have to increase substantially in the next decade, as will the aviation sector's use of low-carbon fuels. Together, this would have to reduce emissions per pkm travelled by 23% by 2025 below 2013 levels and the share of low-carbon fuels would need to increase to roughly 14% by 2025 (IEA, 2016a).

For a 1.5°C-consistent pathway, an even earlier and more stringent decrease of aviation emissions may be necessary. Even if detailed studies on 1.5°C-consistent aviation scenarios are not yet available, it is clear that aviation emissions need to decline eventually to zero, to avoid larger dependence on negative emission technologies (see Section 3.7).

The lack of ambitious targets on how the aviation and shipping sectors should be decarbonized shows that the potential measures outlined here are mainly options on paper (Bows-Larkin, 2015). Encouraging examples, however, include the EU (responsible for 35% of global aviation emissions), which has attempted to include aviation into its Emissions Trading System, or China, which is building many high-speed train lines (Sims et al., 2014).

The immediate pathway towards decarbonization for the aviation and shipping sector should consist of three points: (1) implementing and scaling up options for mitigation, and standardizing best-practice; (2) agreeing on a long-term vision for the aviation sector in the context of decarbonization, including the development of 1.5°C-consistent scenarios; and (3) intensifying research activities to identify and realize the technology roadmaps needed for such scenarios. This leads us to our benchmark: *Develop and agree on a 1.5°C-consistent vision*.

The recent establishment by International Civil Aviation Organisation (ICAO) of market-based measures for offsetting emissions from aviation under the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) scheme are a step in the right direction in terms of getting such an international vision on action (ICCT, 2017); see also e.g. Huang (2017). However, as detailed in the SI, the currently envisioned actions and targets of ICAO's offsetting schemes are insufficient for achieving the deep reductions in emissions needed.

The debate on maritime emissions is generally in an earlier stage than that on aviation, with a principal barrier being the maritime principle of 'no more favourable treatment', which is in apparent contradiction with the 'common but differentiated responsibility' principle of the UNFCCC. Technical mitigation options for shipping appear, however, more promising than for aviation.

3.3. Buildings: all new buildings fossil-free and near zero energy by 2020, and increase renovation rates from less than 1% in 2015 to 5% by 2020

Scenarios with a likely – or very likely – chance of limiting warming to less than 2°C require a 20–30% reduction of direct emissions from the building sector by 2020 from 2010 levels, 50–60% by 2030 and 70–80% by 2050 (Rogelj et al., 2015). For 1.5°C-consistent scenarios, the emissions need to be reduced by 20–35% by 2020, 60–70% by 2030 and 80–90% by 2050. Indirect emissions, primarily from electricity, also require full decarbonization by mid-century (see Section 3.1).

Figure 3 shows two broad global emissions pathways: The 'immediate action' pathway requires

- 100% of new buildings to be zero emissions (i.e. fossil-free and near-zero energy) by 2020 in Organisation for Economic Co-operation and Development (OECD) (2025 in non-OECD) regions;
- Annual retrofit rates of existing stock to increase from less than 1% to about 5% in OECD regions (about 3% in non-OECD) regions by 2020, with about 90% direct emissions reduction per retrofit (Boermans, Bettgenhäuser, Offermann, & Schimschar, 2012).

This leads us to our benchmark: *all new buildings fossil-free and near zero energy by 2020 and increase building renovation rates from less than 1% in 2015 to 5% by 2020*.

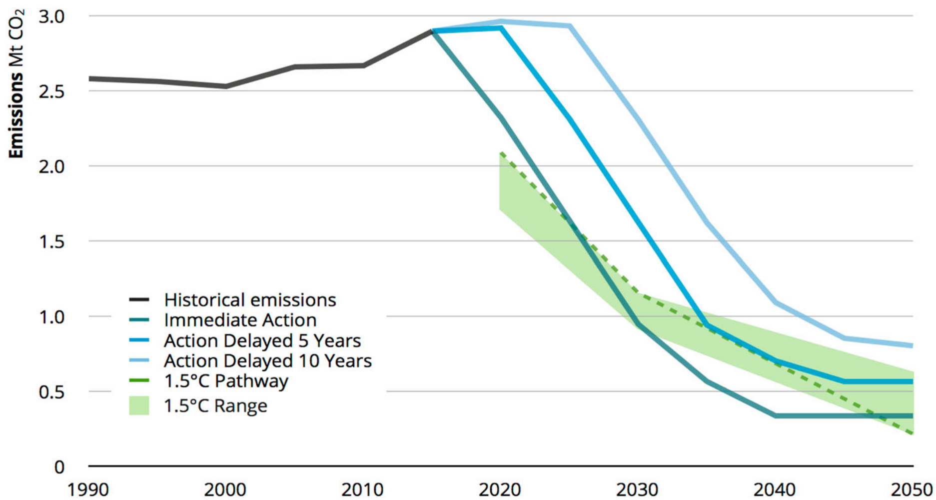

Figure 3. Annual direct emissions from buildings in three different scenarios shown in comparison with the range dictated by 1.5°C scenarios in Rogelj et al. (2015).

The 2050 emissions level of 80–90% below 2010 can still be achieved if action is delayed by up to five years, but this would require additional reductions in transport, industry or land use, land-use change and forestry (LULUCF), or additional negative emissions to compensate for higher emissions from buildings in the years to 2050.

Action needs to be taken in all regions for both new and existing stock. However, action on the existing stock should play an even larger role in developed economies, whereas the abatement potential from new buildings is primarily found in developing economies (see SI, Figure S-4).

There are a few national policy 'frontrunners' emerging, both on retrofitting and new building standards (see the SI for details). An example for developments in line with the benchmark is the EU's Energy Performance of Buildings Directive (EPBD), which specifies new buildings to be nearly zero energy by the end of 2020. The envisaged retrofit rate in the EPBD is 3% instead of the required 5% estimated in our immediate action scenario, and applicable to centrally owned government buildings only, but it is a step in the right direction. With a combination of best available technologies and policies that provide the right incentives, it is possible to achieve emissions reductions that are in line with a 2°C or 1.5°C-pathway (IEA, 2013). Key instruments include loans with preferential rates, required minimum building performance standards and direct subsidies for additional investment costs (other examples of existing policies are provided in the SI, Box S-1).

The main challenges that inhibit fast roll-out of technologies for zero-energy housing through both renovation and new builds include the non-uniformity of the global building sector, long payback periods for investments in energy efficiency in buildings, split incentives between tenant and investor and a lack of awareness among building owners of direct and indirect benefits of investments in energy-efficient measures (Sterl et al., 2017; Wouters et al., 2016).

3.4. Industry: all new installations in emissions-intensive sectors are low-carbon after 2020, maximize material efficiency

The industry sector accounted for about 14GtCO_2e/yr or 29% of global total GHG emissions in 2010 (Fischedick et al., 2014). We estimate that these emissions would need to reduce by roughly 10% by 2020 and 20% by 2030 from 2010 levels to be consistent with 1.5°C (authors' own calculations based on: Fischedick et al., 2014; Rogelj et al., 2015) (see the SI for details). Emission levels in 2030 and 2050 under scenarios with greater than 50% chance of staying below 2°C will need to be reached roughly 10 years and 20 years earlier, respectively, under 1.5°C-consistent scenarios.

This section hereafter focuses on the iron and steel subsector for illustrative purposes for the following reasons: (i) it is one of the most CO_2-intensive subsectors, (ii) few technological alternatives are available for low-carbon industrial production, (iii) few lower-carbon substitute products are available in the market and (iv) it requires long-term investment decisions, due to the long lifetime and the large scale of facilities. The assessment described below is largely applicable also to the cement and chemical subsectors, which are two other major emitting industrial subsectors.

On emissions intensity, the IEA ETP 2016s 2°C (>50% chance) scenario shows that CO_2 emissions per tonne of crude steel halves by 2035 from 2013 levels (IEA, 2016a). This milestone would have to be achieved even earlier to be consistent with a 1.5°C pathway, and policymakers need to go well beyond energy efficiency improvements. Large-scale deployment of low-carbon steelmaking technologies, including CCS, would need to take place immediately (Milford, Pauliuk, Allwood, & Mu, 2013; van Ruijven et al., 2016). Another key area is material efficiency; few policies around the world have specifically pursued material or product service efficiency to date (Fischedick et al., 2014; Scott, Roelich, Owen, & Barrett, 2017), but the potential is large. Material efficiency improvements that reduce total crude steel production by about 20% from business-as-usual projections in 2025 are essential for reducing total subsector CO_2 emissions by 50% by 2050 from 2010 levels (roughly consistent with 1.5°C), alongside the need for the last conventional blast furnace without CCS to be built before 2020 (Milford et al., 2013).

This brings us to our benchmark: *all new installations in emissions-intensive sectors are low-carbon after 2020, maximize material efficiency*. Owing to the complex nature of the industry sector, this benchmark is less specific on material efficiency compared to the benchmarks in other sectors.

Having no new conventional carbon-intensive installations, such as blast furnaces without CCS, after 2020 is ambitious, but it is technically and economically feasible. First, not only is steel scrap recovery expected to increase considerably in the next few decades (Oda, Akimoto, & Tomoda, 2013; Pauliuk, Milford, Müller, & Allwood, 2013), there is significant potential for reducing liquid steel lost as process scrap (Milford, Allwood, & Cullen, 2011). Second, innovative low-carbon technologies equipped with CCS may become available from 2025 (IEA, 2015). Third, the on-going international efforts to resolve the current excess capacity problem for blast furnaces in China (OECD, 2016), which produce more than 60% of steel from blast furnaces today (World Steel Association, 2016), can minimize new installations globally during the next ten-year period. Construction of new blast furnaces over that period needs to be avoided, and after that period new construction must be fitted with CCS technology, possibly commercially available by then. The excess capacity problem is also serious in the global cement subsector, including for the largest producer, again China (Global Cement, 2017a, 2017b).

One major challenge, common for other CO_2-intensive subsectors, is the slow progress in CCS technology development. The governments of countries with large industrial CO_2 emissions need to significantly scale up their support for research, development, demonstration and deployment of this technology. Another major challenge for governments is to identify and implement stringent mitigation measures that can also enhance market competitiveness of certain carbon-intensive industrial subsectors in the short term. This is particularly challenging when options for technological alternatives are limited (e.g. cement) and when the subsector is competing in the international market (e.g. iron and steel) (Denis-Ryan, Bataille, & Jotzo, 2016).

3.5. Forestry: reduce emissions from forestry and other land use to 95% below 2010 by 2030, stop net deforestation by 2025

Forest and land-use change emissions in scenarios underlying the conclusions on 1.5°C in the IPCC's AR5 and Synthesis Reports, supplemented by the most recent modelling of 1.5°C scenarios (Luderer et al., 2013; Rogelj et al., 2012, 2013; Rogelj, pers. comm.), contain a considerable degree of uncertainty. Nevertheless, all show significantly lower emission levels than at present: 0.2 (range −1.2 to 4.4) $GtCO_2$/yr in 2030 (average over the 2025–2035 period), compared to 4.6 (range 2.6 to 7.2) $GtCO_2$/yr in 2010 (average 2005–2015). This implies emission levels reduce on average across the scenarios by 95% (range 40–145%) below 2010 by 2030. An essential element in achieving these reductions is that, by 2025, net global deforestation stops, or reverses (where global forest area starts to increase again). We take this as our benchmark: *reduce emissions* *from forestry and other land use to 95% below 2010 by 2030, stop net deforestation by the 2025.* Afforestation is discussed as an option for negative emissions in Section 3.7.

Reducing emissions from this sector must not be an alternative to reducing fossil fuel CO_2 emissions – action in this area is best seen as an essential protection of the natural storage reservoirs of carbon, as the ability of forests to act as on-going carbon sinks is limited, especially compared to the scale of fossil fuel emissions (see the SI for further discussion).

At least three mechanisms must be operationalized for financial support to eliminate deforestation and forest degradation. First, the reducing emissions from deforestation and forest degradation+ initiative needs to become operational at a large scale. Second, non-market mechanisms must be developed further and supported financially through the Green Climate Fund (GCF) and other channels, as market mechanisms are not suitable for all contexts and not all recipient countries support the use of market-based mechanisms. Third, the root causes of deforestation can be addressed via policies not directly related to forest-land management, focusing on some of the drivers of deforestation (see the SI for details).

Reducing deforestation has been a global goal for many years, and recent developments give signs of hope that actions have finally been successful and can even be enhanced. For example, as a result of effective policies implemented over the last decade to fight deforestation, Brazil has – in absolute terms – reduced its annual deforested area by 79% between 2005 and 2015 (Ministry of Science Technology and Innovation of Brazil, 2016).

At the international level, the Bonn Challenge, an alliance of companies, governments and civil society launched in 2011, initiated practical means of realizing existing international commitments with the 'aspiration' to restore 150 million hectares of the world's deforested and degraded lands by 2020 and 350 million hectares by 2030 (GPFLR, 2013). Likewise, in 2014, such an alliance endorsed a timeline to end natural forest loss by 2030 (New York Declaration on Forests, 2014).

Despite the significant progress, major obstacles need to be overcome, in particular in the three major contributors to deforestation emissions, namely, Brazil, Indonesia and Democratic Republic of the Congo (DRC). In Brazil the deforestation emissions turned to an increase again in 2016 with 30% more emissions compared to 2015 (Observatório do Clima, 2017). Although it remains to be seen whether this signifies a reversal of the trend over the last decades, it shows the risks of losing again the benefits of successful policies. DRC has not reduced its LULUCF GHG emissions between 1990 and 2010 (FAO, 2014) and these are projected to steadily increase under both business and usual scenarios and its NDC up to 2030 (Forsell et al., 2016). In Indonesia, emissions have also been increasing between 2010 and 2016 despite its temporary prohibition of primary forest clearing and peat land conversion (Climate Action Tracker, 2016).

Information on forest cover over time and geographical location is essential to be able to monitor and manage deforestation, yet there are relatively few comparable studies, and the cost of collecting such information can be vast (Hansen et al., 2013; Ostrom & Nagendra, 2007). Transaction, monitoring and enforcement costs of global programmes also need to be considered as part of programme design and implementation to ensure their effectiveness (Alston & Andersson, 2011).

3.6. Agriculture: keep emissions in 2020 at or below current levels, establish and disseminate regional best practice, ramp up research

To limit warming to 2°C, an emissions abatement effort of around 1 $GtCO_2e$/yr by 2030 is required in the agricultural sector against baseline projections of 7.5–9.0 $GtCO_2e$/yr (Wollenberg et al., 2016). This would still allow an increase in these emissions from today (around 5 $GtCO_2e$/yr in 2014).

Further mitigation effort is required to meet the more ambitious target of limiting warming to 1.5°C. Frank et al. (2017) found that by 2050, emissions in the agriculture, forestry and other land use (AFOLU) sector need to be reduced by 7.9 $GtCO_2e$/yr compared to a baseline scenario, to reach around 0.6 $GtCO_2e$/yr (Frank et al., 2017). The share of emissions reductions from the agriculture sector in this total amounted to about 2.7–3.5 $GtCO_2e$/yr in 2050, which was about 0.8 $GtCO_2e$/yr larger than the emissions reductions required in the 2°C scenario in the same study.

We distinguish between mitigation measures on the *food production (supply)* versus the *food consumption (demand)* side: On the *supply side*, a variety of ongoing technological and breeding developments offer promising ways to reduce emissions, such as the use of methane inhibitors for dairy cows, cattle breeds that produce less methane, cereal varieties that inhibit nitrous oxide emissions and high-tech soil management practices that sustain soil organic matter (Wollenberg et al., 2016). However, most of these options are still under development and/or remain unaffordable without further financial support and coordinated research development (Wollenberg et al., 2016). It is unlikely that these supply side options could on their own reduce emissions by a large enough amount to meet the Paris Agreement's goals, notwithstanding the uncertainty inherent in this sector. For reference, Gerber et al. (2013) estimated an abatement potential for the current system of livestock rearing of 0.8–1.3 $GtCO_2e$/yr versus a total of 5.2 $GtCO_2e$/yr through adoption of best practices in a given system, region and climate.

Additional low-cost global emission reductions are possible through soil storage options but also through *demand side* measures, such as reducing food loss, food waste and changing dietary habits. This could result in emissions abatement of around 2.3–4.6 $GtCO_2e$/yr below baseline by 2030 (Wollenberg et al., 2016), thus contributing substantially to achieving a 1.5°C pathway. The demand side options are especially promising: Although drivers include a growing world population and increasing wealth in the developing world, a shift to lower-carbon food sources will have significant co-benefits in terms of human health and land use (Bajželj et al., 2014; Erb et al., 2016; Hedenus, Wirsenius, & Johansson, 2014; Perignon, Vieux, Soler, Masset, & Darmon, 2017; e.g. Springmann, Charles, Godfray, Rayner, & Scarborough, 2016).

We therefore formulate the benchmark as: *keep emissions in 2020 at or below current levels, establish and disseminate regional best practice, ramp up research*.

Currently, there are not many policy instruments to reduce emissions in agriculture and most of them are still under development. There is also a large uncertainty around the economic affordability of these instruments which could pose challenges to their implementation (Herrero et al., 2016). It is important that the policies reflect the cost-effectiveness of measures, account for displacement effects and are tailored to the needs of producers and consumers (Macleod, Eory, Gruere, & Lankoski, 2015). Policies that reduce emissions could endanger food security if regional differences are not carefully considered (Frank et al., 2017). Through soil organic carbon sequestration, and options on the demand side, such as diet shifts and food waste reduction, ambitious emission reductions can be achieved while ensuring food security (Frank et al., 2017).

There are a few programmes that are noteworthy in terms of promotion of best practices and reducing GHG emissions in the sector. Examples include elements of the EU's Common Agriculture Policy such as the Rural Development Programme and the green direct payments scheme, the EU's Nitrate Directive, the Conservation Reserve Programme in the US and Farming for a Better Climate in Scotland (see the SI for details). The EU is also investing considerable funds into 'climate-smart agriculture' (CSA) (Michalopoulos, 2016), a concept which typically combines mitigation, adaptation and food security. This is a relatively new approach and there are diverse perspectives as to what CSA is; further research is needed to fully understand its potential impacts (Chandra, McNamara, & Dargusch, 2017).

Using regulations and statutory instruments to prohibit activities harmful to the climate can be effective but monitoring and validation of compliance can be an issue due to the inherent nature of the sector, including the non-permanence of enhanced carbon stocks in agricultural soils, human and natural interaction with cropland management, as well as displacement of emissions to other regions when trying to improve land use management locally (Smith et al., 2008).

Further research is needed to devise effective policy options to reduce emissions in the agriculture sector. However, the international community is increasingly giving more importance to introducing sustainable practices as well as reducing emissions in the agriculture sector.

3.7. CO_2 removal: accelerate research and planning for negative emission technology deployment

In large part due to insufficient emissions reductions realized to date, negative CO_2 emissions will unfortunately be necessary at scale from mid-century to limit warming to 2°C, and even more so for 1.5°C (Clarke et al., 2014; Rogelj et al., 2015). Through negative emissions technologies, CO_2 is extracted from the atmosphere and stored for long geological timescales.

We consider it unhelpful to lump negative emissions technologies together with geoengineering options such as solar radiation management, because of fundamentally different risk profiles and associated policy development (Williamson, 2016). Bioenergy combined with carbon capture and storage (BECCS) and afforestation/reforestation cannot reasonably be categorized as geoengineering, because their primary purpose is not to compensate for GHG warming, but to remove the causes of it, as a desirable co-benefit while providing energy and other services. BECCS is an integral part of energy systems, providing energy services with the benefit of removing CO_2 from the atmosphere. Likewise, afforestation provides benefits, or 'ecosystem services' such as water management, biodiversity, etc., in addition to removing CO_2 from the atmosphere. This section does not address afforestation and reforestation, which are covered under the forestry benchmark above. Instead, we focus here on BECCS, as a cost-effective mid- to long-term option most commonly included in 1.5 and 2°C scenarios. For a discussion of solar radiation management, see Nicholson et al. (2017).

More than 500 $GtCO_2$ would need to be extracted from the atmosphere through negative emission technologies (such as BECCS) up to 2100, even when mitigation actions up to 2030 are substantially strengthened, in order to limit warming below 1.5°C (Rocha et al., 2016; Rogelj et al., 2015). This is about 80–100 $GtCO_2$ larger than under 2°C-consistent emission pathways (Rogelj et al., 2015).

Early and rapid action now – as explained in all other sections of this report – is needed to minimize the need for negative CO_2 emissions, with such action required across the full range of mitigation options and to protect and enhance natural ecosystems so that they can retain and store more carbon. The corollary is that failure to meet benchmarks in any sector discussed above would either have to be compensated for by higher pressure on other sectors, or further increase the future dependency on negative emissions, or both.

Political decisions are needed to trigger a broader investigation of the different options, as well as their wider implications. The technical, engineering and sustainability challenges require substantial research and development. From a national legislative and legal perspective, liability issues associated with the transport and storage of CO_2 need be resolved (Schaeffer et al., 2015).

Irrespective of whether any BECCS technology is ever deployed, measures are needed to deal with the existing deployment of bioenergy, as well as its projected further growing role in global energy supply. Measures should include the strengthening of integrated land management and stimulating nature conservation alongside second- and third-generation bioenergy. This is needed to minimize competition with food crops for land and water resources, typical of first-generation biomass (see e.g. IPCC AR5 WGIII chapters 6 and 11 (Clarke et al., 2014; Smith et al., 2014), Schaeffer et al., 2015).

Hence we formulate the benchmark as: *accelerate research on and planning for negative emission technology deployment*.

Current developments are not on track with this benchmark. The biggest challenges lie in the very rapid upscaling of this technology that would be required in both 1.5°C and 2°C pathways in the 2030–2050 period. Elements of this technology are, in principle, available, and demonstration plants are already functional, but the feasibility of such large-scale deployment of this technology is not yet established and needs further research in the near term to understand the issues that will arise.

4. Discussion

Our methodology for identifying the benchmarks in this article depends on mitigation potentials and requirements, based on a broad literature review and expert judgment, subsequently synthesized with additional constraints from 1.5°C-consistent energy-economic scenarios. These additional 1.5°C constraints are based on about 35 scenarios developed by only two IAMs (Rogelj et al., 2015). These constraints represent therefore a limited reflection of uncertainties, and is more a snapshot of our current understanding than a definite outcome. Model uncertainty expresses itself in emissions pathways, among others, as different balances between mitigation efforts in sectors, regions and GHGs. We anticipate a broader range of 1.5°C scenarios to become available soon, and it seems justified to require a re-evaluation of the benchmarks. However, since the benchmarks are based on a wide range of literature and different analyses across different sectors, including bottom up studies and likely below 2°C scenarios, and because the two models with 1.5°C-consistent energy-economic scenarios generally produce results typical of the range of IAMs (e.g. Kriegler et al., 2013) and are understandable with reference to further developments from 2°C scenarios, we believe the identified benchmarks in this article will prove robust.

This article identified short-term technical benchmarks, and the technical and to some extent economic and political feasibility of achieving them. As mentioned, our analysis is based partly on IAM scenarios that assume globally uniform carbon pricing, producing what is called in the literature globally 'least-cost' solutions. On the one hand, IAMs could be overly optimistic on the mitigation potential in some sectors because they do not fully reflect the difficult political realities of climate policy implementation (Peters, 2016). On the other hand, published scenarios from IAMs are at present overly pessimistic about the costs and rate of roll out of renewable energy technology in large economies, with cost reductions observed in the market decades ahead of when they are seen in the generation of IAM models underlying published scenarios. In some non-energy sectors IAM models do not yet fully reflect all available options nor include resource efficiency as mitigation options. Current IAMs 'ignore material cycles and recycling, incoherently describe the life-cycle impacts of technology and miss linkages regarding buildings and infrastructure' (Pauliuk, Arvesen, Stadler, & Hertwich, 2017). Future research could investigate mitigation options further in the context of, e.g. circular economy.

The stringency of the Paris Agreement LTTG and its 1.5°C limit significantly constrains the levels of freedom to spread emission reductions across sectors, countries and over time. As a result of the limited carbon budget, combined with the inertia of energy, transport and industrial technologies and systems, as well as the particular difficulty of reducing emissions in some sectors, global energy models find only a limited set of pathways. If a sector does less, in particular the energy, industry and transport sectors, it would leave a high-emissions legacy for many decades, and would mean a failure to set in motion the system changes needed to achieve the required long-term transformation.

It should be noted that the achievement of the identified benchmarks does not ensure limiting warming to 1.5°C, consistent with the long-term temperature goal of the Paris Agreement. Global mitigation efforts must continue long after 2025 to reach the 1.5°C limit, and the long-term continuation of the stringent global mitigation effort could prove much more difficult than achieving the short-term benchmarks.

With regard to areas for future research, firstly the sector coverage should be expanded beyond the 85% coverage of emissions as conducted in this article because transformation must be triggered in all sectors, and by all actors, to meet the 1.5°C goal. Additional research should also focus on other dimensions of feasibility, beyond the technological and economic realm. The overall balance of policy and development priorities will differ across regions. While there is a limit to the flexibility for each of these benchmarks in terms of delays, there would clearly be an optimal balance of interventions and near-term policies for individual countries. At least three areas of research could inform the decisions at country level. First, a better understanding of the social and political feasibility of these benchmarks could be obtained through the detailed analysis and case studies of key countries' or regions' circumstances. Notably, it is crucial to test how flexible each of these benchmarks is in different parts of the world and what are the elements that are propelling or delaying change so that the transition can be achieved. Second, multi-dimensional policy decision frameworks could help to place the benchmarks identified in this article in a broader policy perspective, identifying co-benefits in other policy areas, such as clean air and employment opportunities, as well as broader resource efficiency, to bring down the overall costs and accelerate reaching the benchmarks, or even go beyond these. Third, equity considerations (Höhne, den Elzen, & Escalante, 2014) could be refined at the sectoral level to complement the primarily 'least-cost' perspective of this article.

5. Conclusions

This article has identified and quantified ten important benchmarks for action to be taken by 2020–2025 to peak emissions and begin the rapid decline that is crucial for limiting warming to 1.5°C; or that do not necessarily achieve near-term emissions reductions, but are essential pre-conditions for the longer-term transformation required to meet the 1.5°C limit. Based on a comprehensive analysis of the available literature on 1.5°C, and

Table 1. Ten benchmarks identified in this study and recent developments toward the benchmarks.

Benchmark	Recent developments toward the benchmark	Main challenges
Power: sustain the growth rate of renewables and other zero- and low-carbon power generation until 2025 to reach 100% share by 2050	Current growth rates are in line. Renewables already dominate new investments in new power generation, further reducing the costs	Progress must be made on the integration of high shares of weather-dependent renewables in the electric power system, technically and with regard to electricity markets
Power: no new coal plants, reduce emissions from existing coal fleet by 30% by 2025	China and India are already cancelling plans for, and construction of, coal-fired power plants. No new plants may be needed in India after 2022. Several EU countries have announced the phase out of coal in the electricity sector in the next decades	Roughly half of the expected emissions from existing plants need to be cut. Without further policies, coal will likely remain attractive in many countries
Passenger transport: last fossil fuel passenger car sold by 2035–2050	Norway and Netherlands have already significant shares of EVs sold today and are discussing 100% targets for 2025; India for 2030, France for 2040 All car makers have electric models and have e-mobility as part of their future strategy, with one committed to sell only cars with an electric motor as of 2019	Major current challenges include pricing, range anxiety and charging infrastructure as well as resistance from conventional car industry
Aviation and shipping: develop and agree on a 1.5°C-consistent vision	*(Current developments not in line with benchmark)*	Lack of common vision and consensus on mitigation options to reduce to zero
Buildings: all new buildings fossil-free and near zero energy by 2020	The EU already has a standard that all new buildings must be near zero energy as of 2020	The main challenges include the non-uniformity of the global building sector, long payback periods for investments in energy efficiency in buildings, the split incentive between tenant and investor and a lack of awareness among building owners of direct and indirect benefits of investments in energy-efficient measures
Buildings: increase renovation rates from less than 1% in 2015 to 5% by 2020	The EU has a target to increase renovation rate to 3% per year for some buildings	
Industry: all new installations in emissions-intensive sectors low-carbon after 2020, maximize material efficiency	For the iron and steel sector, international efforts to resolve the current excess capacity problem for blast furnaces in China could minimize new installations globally for the next ten years, by then CCS could become fully commercial	Progress in CCS technology development is slow Stringent mitigation measures need to be identified and implemented that can also enhance market competitiveness
Forestry: reduce emissions from forestry and other land use to 95% below 2010 levels by 2030, stop net deforestation by 2025	Brazil reduced its deforestation by 80% due to policy intervention Alliances of companies, governments and civil society formed to restore 350 million ha deforested/degraded lands and to end natural forest loss by 2030	Significant effective action still has to be incentivized, e.g. in Indonesia and DRC and successful action has to be sustained, e.g. in Brazil
Agriculture: keep emissions in 2020 at or below current levels, establish and disseminate regional best practice, ramp up research	*(Current developments not in line with benchmark)*	Food production: Mitigation opportunities are scattered and potential is limited Food consumption: A shift to lower-carbon food sources will likely be required for those parts of the world that are currently overconsuming
CO_2 removal: accelerate research and planning for negative emission technology deployment	*(Current developments not in line with benchmark)*	Elements of this technology are, in principle, available, but the feasibility of large-scale deployment is not yet established

by processing and constraining results available for 2°C when direct information on 1.5°C was not available, including with bottom up studies, we identified necessary sectoral near-term benchmarks supporting a low-carbon transition. These benchmarks provide a first basis for policy makers to design policy options and actions consistent with 1.5°C (see Table 1).

Some of the sectoral benchmarks identified require technology diffusion and sector transformations at an unprecedented scale and speed, in many cases immediate introduction of zero-carbon technologies, not efficiency improvements on the margin. While significant challenges remain (Table 1), for most benchmarks we show that there are signs that a transition of this magnitude is possible: in some specific cases it is already happening.

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References

Alston, L. J., & Andersson, K. (2011). Reducing greenhouse gas emissions by forest protection: The transaction cost of implementing REDD. *Climate Law*, *2*(2), 281–289. doi:10.3233/CL-2011-037

Avinor, Norwegian National Rail Administration, Norwegian Coastal Administration, & Norwegian Public Roads Administration. (2016). *Norwegian Government National Transport Plan 2018- 2029. English Summary*. Avinor, the Norwegian National Rail Administration, the Norwegian Coastal Administration and the Norwegian Public Roads Administration.

Bajželj, B., Richards, K. S., Allwood, J. M., Smith, P., Dennis, J. S., Curmi, E., & Gilligan, C. A. (2014). Importance of food-demand management for climate mitigation. *Nature Climate Change*, *4*, 924–929. doi:10.1038/NCLIMATE2353

Boermans, T., Bettgenhäuser, K., Offermann, M., & Schimschar, S. (2012). *Renovation tracks for Europe up to 2050. Report commissioned by Eurima - European insulation manufacturers association*. Cologne: Ecofys Germany.

Bows-Larkin, A. (2015). All adrift: Aviation, shipping, and climate change policy. *Climate Policy*, *15*(6), 681–702. doi:10.1080/14693062.2014.965125

Bruckner, T., Bashmakov, I. A., Mulugeta, Y., Chum, H., De la Vega Navarro, A., Edmonds, J., … Zhang, X. (2014). Energy systems. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, & J. C. Minx (Eds.), *Climate change 2014: Mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change* (pp. 511–597). Cambridge: Cambridge University Press.

Caldecott, B., Sartor, O., & Spencer, T. (2017). *Lessons from previous "coal transitions" high-level summary for decision-makers*. IDDRI and Climate Strategies.

Central Committee of the Communist Party of China. (2016). *The 13th Five-Year Plan for Economic and Social Development of the People's Republic of China*.

Central Electricity Authority. (2016). *Draft National Electricity Plan* (Vol. 1). Central Electricity Authority (CEA), Ministry of Power, Government of India.

Chandra, A., McNamara, K. E., & Dargusch, P. (2017). Climate-smart agriculture: Perspectives and framings. *Climate Policy*, 1–16. doi:10.1080/14693062.2017.1316968

Clarke, L., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., Fisher-Vanden, K., … Zwickel, T. (2014). Assessing transformation pathways. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, & J. C. Minx (Eds.), *Climate change 2014: Mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change* (pp. 413–510). Cambridge: Cambridge University Press.

Climate Action Tracker. (2016). *Indonesia*. Retrieved from http://climateactiontracker.org/countries/indonesia.html

Climate Analytics. (2016). *Implications of the Paris agreement for coal use in the power sector*. Berlin: Author.

Climate Analytics. (2017). *A stress test for coal in Europe under the Paris agreement*. Berlin: Author.

Coady, D., Parry, I., Sears, L., & Shang, B. (2015). *How large are global energy subsidies? IMF working paper WP/15/105. International Monetary Fund*. Washington, DC: International Monetary Fund.

Cronin, C., Menon, S., Monteith, S., Plechaty, D., Hagemann, M., Höhne, N., … Sferra, F. (2015). *Faster and cleaner – decarbonisation in the power and transport sectors is surpassing predictions and offering hope for limiting warming to 2°C*. San Francisco, CA: ClimateWorks Foundation, Climate Action Tracker.

DEFRA, & DfT. (2017). *UK plan for tackling roadside nitrogen dioxide concentrations. Detailed plan. July 2017*. London, UK: Department for Enviornment Food & Rural Affairs and Department for Transport.

Deng, Y. Y., Blok, K., & van der Leun, K. (2012). Transition to a fully sustainable global energy system. *Energy Strategy Reviews*, *1*(2), 109–121. doi:10.1016/j.esr.2012.07.003

Denis-Ryan, A., Bataille, C., & Jotzo, F. (2016). Managing carbon-intensive materials in a decarbonizing world without a global price on carbon. *Climate Policy*, *16*(June), S110–S128. doi:10.1080/14693062.2016.1176008

EAFO. (2017). Norway. Retrieved from http://www.eafo.eu/content/norway

Edenhofer, O. (2015). King coal and the queen of subsidies. *Science*, *349*(6254), 1286–1287. doi:10.1017/CBO9781107415324.004

Erb, K.-H., Lauk, C., Kastner, T., Mayer, A., Theurl, M. C., & Haberl, H. (2016). Exploring the biophysical option space for feeding the world without deforestation. *Nature Communications*, *7*, 11382. doi:10.1038/ncomms11382

Erich, M., & Witteveen, J. (2017, July). *Breakthrough of electric vehicle threatens European car industry*. ING Economics Department. ING Bank N.V.

EV-Volumes. (2016). *Global plug-in vehicle sales 2015*. Retrieved from http://www.ev-volumes.com/news/global-plug-in-vehicle-sales/

Ewing, J. (2017, July 6). *France plans to end sales of gas and diesel cars by 2040*. Retrieved from https://www.nytimes.com/2017/07/06/business/energy-environment/france-cars-ban-gas-diesel.html

FAO. (2014). *FAOSTAT emissions database*. Rome: Foos and Agriculture Organization of the United Nations.

Figenbaum, E., Assum, T., & Kolbenstvedt, M. (2015). Electromobility in Norway – experiences and opportunities with electric vehicles. *Research in Transportation Economics*, *50*, 29–38. doi:10.1016/j.retrec.2015.06.004

Fischedick, M., Roy, J., Abdel-Aziz, A., Acquaye, A., Allwood, J. M., Ceron, J.-P., … Tanaka, K. (2014). Industry. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, & J. C. Minx (Eds.), *Climate change 2014: Mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change* (pp. 739–810). Cambridge: Cambridge University Press.

Forsell, N., Turkovska, O., Gusti, M., Obersteiner, M., Elzen, M. d., & Havlik, P. (2016). Assessing the INDCs' land use, land use change, and forest emission projections. *Carbon Balance and Management*, *11*(1), 631. doi:10.1186/s13021-016-0068-3

Frank, S., Havlík, P., Soussana, J.-F., Levesque, A., Valin, H., Wollenberg, E., … Obersteiner, M. (2017). Reducing greenhouse gas emissions in agriculture without compromising food security? *Environmental Research Letters*, *12*(10), 105004. doi:10.1088/1748-9326/aa8c83

Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., … Tempio, G. (2013). *Tackling climate change through livestock - A global assessment of emissions and mitigation opportunities*. Rome: Food and Agriculture Organization of the United Nations (FAO).

Global Cement. (2017a, March 9). *Chinese planners consider 10% cut in cement production*. Retrieved from http://www.globalcement.com/news/item/5899-chinese-planners-consider-10-cut-in-cement-production

Global Cement. (2017b, June 12). *Indian cement producers continue to defend prices*. Retrieved from http://www.globalcement.com/news/item/6204-indian-cement-producers-continue-to-defend-prices

Global Coal Plant Tracker. (2016). *Global Coal Plant Tracker*. Retrieved from http://endcoal.org/global-coal-plant-tracker/

GPFLR. (2013). *The Bonn challenge and landscape restoration*. Washington, DC: Global Partnership on Forest Landscape Restoration.

Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., … Townshend, J. R. G. (2013). High-Resolution global maps of 21st-century forest cover change. *Science*, *342*(6160), 850–853. doi:10.1126/science.1244693

Hedenus, F., Wirsenius, S., & Johansson, D. J. A. (2014). The importance of reduced meat and dairy consumption for meeting stringent climate change targets. *Climatic Change*, *124*(1), 79–91. doi:10.1007/s10584-014-1104-5

Held, A., Ragwitz, M., Gephart, M., Klessmann, C., & de Visser, E. (2014). *D5.2: Best practice design features for RES-E support schemes and best practice methodologies to determine remuneration levels. DIA-CORE project report*. Fraunhofer ISI, Ecofys.

Herrero, M., Henderson, B., Havlik, P., Thornton, P. K., Conant, R. T., Smith, P., … Stehfest, E. (2016). Greenhouse gas mitigation potentials in the livestock sector. *Nature Climate Change*, *6*(5), 452–461.

Höhne, N., den Elzen, M., & Escalante, D. (2014). Regional GHG reduction targets based on effort sharing: A comparison of studies. *Climate Policy*, *14*(1), 122–147. doi:10.1080/14693062.2014.849452

Höhne, N., Kuramochi, T., Warnecke, C., Röser, F., Fekete, H., Hagemann, M., … Gonzales, S. (2017). The Paris agreement: Resolving the inconsistency between global goals and national contributions. *Climate Policy*, *17*(1), 16–32.

Huang, Y. (2017). The prospect of engaging China in the ICAO global MBM scheme. *Climate Policy*, *17*(4), 476–484. doi:10.1080/14693062.2016.1164656

ICCT. (2017). *Policy update: International civil aviation organization's carbon offset and reduction scheme for international aviation (Corsia)*. Washington, DC: International Council on Clean Transportation.

IEA. (2013). *Transition to sustainable buildings. Strategies and opportunities to 2050*. Paris: International Energy Agency.

IEA. (2014). *World energy outlook 2014*. Paris: International Energy Agency.

IEA. (2015). *Energy technology perspectives 2015*. Paris: International Energy Agency.

IEA. (2016a). *Energy technology perspectives 2016*. Paris: International Energy Agency.

IEA. (2016b). *Global EV outlook 2016: Beyond One million electric cars*. Paris: International Energy Agency.

IEA. (2016c). *World energy statistics and balances. 2016 edition*. Paris: International Energy Agency.

IIASA. (2015). *Scenario Database of the Fifth Assessment Report (AR5) of Working Group III of the Intergovernmental Panel on Climate Change (IPCC). Version 1.0.1*. Retrieved from https://secure.iiasa.ac.at/web-apps/ene/AR5DB/dsd?Action=htmlpage&page=about

IPCC. (2014). *Climate change 2014: Mitigation of climate change. Working group III contribution to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge: Cambridge University Press. doi:10.1017/CBO9781107415416

IRENA. (2014). *Renewable power generation costs in 2014*. Abu Dhabi: International Renewable Energy Agency.

IRENA. (2016a). *Renewables 2016 global status report*. Abu Dhabi: International Renewable Energy Agency.

IRENA. (2016b). *The power to change: Solar and wind cost reduction potential to 2025*. Abu Dhabi: International Renewable Energy Agency.

IRENA. (2017). *Adapting market design to high shares of variable renewable energy*. Abu Dhabi: International Renewable Energy Agency.

Klessmann, C. (2012). *Increasing the effectiveness and efficiency of renewable energy support policies in the European union* (PhD thesis). Utrecht University, Utrecht, The Netherlands.

Kriegler, E., Petermann, N., Krey, V., Schwanitz, V. J., Luderer, G., Ashina, S., … Van Vuuren, D. P. (2015). Diagnostic indicators for integrated assessment models of climate policy. *Technological Forecasting and Social Change*, *90*, 45–61. doi:10.1016/j.techfore.2013.09.020

Kriegler, E., Tavoni, M., Aboumahboub, T., Luderer, G., Calvin, K., Demaere, G., … van Vuuren, D. P. (2013). What does the 2°C target imply for a global climate agreement in 2020? The limits study on Durban platform scenarios. *Climate Change Economics*, *4*(4), 1340008. doi:10.1142/S2010007813400083

Kuramochi, T., Höhne, N., Hagemann, M., Sterl, S., El-Laboudy, T., Wouters, K., … Yanguas Parra, P. (2016). *The ten most important short-term steps to limit warming to 1.5°C*. Climate Action Tracker. Climate Analytics, Ecofys, NewClimate Institute.

Leonardo Energy. (2016). *Towards a flexibility tracker in electricity systems*. Retrieved from http://www.leonardo-energy.org/microsite/90/towards-a-flexibility-tracker-in-electricity-systems-57a1a4dc9d375

Luderer, G., Pietzcker, R. C., Bertram, C., Kriegler, E., Meinshausen, M., & Edenhofer, O. (2013). Economic mitigation challenges: How further delay closes the door for achieving climate targets. *Environmental Research Letters*, *8*(3), 034033. doi:10.1088/1748-9326/8/3/034033

Macleod, M., Eory, V., Gruere, G., & Lankoski, J. (2015). *Cost effectiveness of greenhouse Gas mitigation measures for agriculture: A literature review. OECD food, agriculture and fisheries, No. 89*. Paris: OECD.

Michalopoulos, S. (2016). *Commission promotes smart farming to mitigate climate change*. Retrieved from https://www.euractiv.com/section/agriculture-food/news/commission-promotes-smart-farming-to-mitigate-climate-change/

Milford, R. L., Allwood, J. M., & Cullen, J. M. (2011). Assessing the potential of yield improvements, through process scrap reduction, for energy and CO2 abatement in the steel and aluminium sectors. *Resources, Conservation and Recycling*, *55*(12), 1185–1195. doi:10.1016/j.resconrec.2011.05.021

Milford, R. L., Pauliuk, S., Allwood, J. M., & Mu, D. B. (2013). The roles of energy and material efficiency in meeting steel industry CO2 targets. *Environmental Science & Technology*, *47*, 3455–3462. doi:10.1021/es3031424

Ministry of Science Technology and Innovation of Brazil. (2016). *Executive summary - third national communication of Brazil to the UNFCCC*. Brasilia: Author.

Mission 2020. (2017). 2020 – *The Climate Turning Point*. Mission 2020.

New York Declaration on Forests. (2014). *Forests action statements and action plans*. New York, NY: United Nations.

Nicholson, S., Jinnah, S., & Gillespie, A. (2017). Solar radiation management: A proposal for immediate polycentric governance. *Climate Policy, 18*. Advance online publication. doi:10.1080/14693062.2017.1400944

Nijland, H., Geilenkirchen, G., van Meerkerk, J., 't Hoen, M., & Hilbers, H. (2016). *Quickscan doelmatigheid van aanschafsubsidie en laadtegoed voor elektrische auto's. Beleidsstudie*. Bilthoven: PBL Netherlands Environmental Assessment Agency.

Noothoot, P., de Jager, D., Tesniere, L., Sascha, v. R., Karypidis, N., Brückmann, R., … Gustav, R. (2016). *The impact of risks in renewable energy investments and the role of smart policies*.

Observatório do Clima. (2017). *Desmate no cerrado anula ganhos na Amazônia*. Retrieved from http://www.observatoriodoclima.eco.br/en/desmate-no-cerrado-anula-ganhos-na-amazonia/

Oda, J., Akimoto, K., & Tomoda, T. (2013). Long-term global availability of steel scrap. *Resources, Conservation and Recycling*, *81*, 81–91. doi:10.1016/j.resconrec.2013.10.002

OECD. (2016, April 18). *High-level meeting: Excess capacity and structural adjustment in the steel sector*. Palais d'Egmont, Brussels, Belgium. Organisation for Economic Co-operation and Development. Retrieved from www.oecd.org/sti/ind/steel-excess-capacity-structural-adjustment.htm

Ostrom, E., & Nagendra, H. (2007). Tenure alone is not sufficient: Monitoring is essential. *Environmental Economics & Policy Studies*, *8*(3), 175–199. doi:10.1007/s10018-007-0132-z

Pacala, S., & Socolow, R. (2004). Stabilization wedges: Solving the climate problem for the next 50 years with current technologies. *Science*, *305*(5686), 968–972. doi:10.1126/science.1100103

Pauliuk, S., Arvesen, A., Stadler, K., & Hertwich, E. G. (2017). Industrial ecology in integrated assessment models. *Nature Climate Change*, *7*(1), 13–20.

Pauliuk, S., Milford, R. L., Müller, D. B., & Allwood, J. M. (2013). The steel scrap Age. *Environmental Science & Technology*, *47*(7), 3448–3454.

Perignon, M., Vieux, F., Soler, L.-G., Masset, G., & Darmon, N. (2017). Improving diet sustainability through evolution of food choices: Review of epidemiological studies on the environmental impact of diets. *Nutrition Reviews*, *75*(1), 2–17. doi:10.1093/nutrit/nuw043

Peters, G. P. (2016). The "best available science" to inform 1.5°C policy choices. *Nature Climate Change*. doi:10.1038/nclimate3000

Rocha, M., Sferra, F., Schaeffer, M., Roming, N., Ancygier, A., Parra, P., … Hare, B. (2016). *What does the Paris climate agreement mean for Finland and the European Union?* Berlin: Climate Analytics.

Rockström, J., Gaffney, O., Rogelj, J., Meinshausen, M., Nakicenovic, N., & Schellnhuber, H. J. (2017). A roadmap for rapid decarbonization. *Science*, *355*(6331), 1269–1271. doi:10.1126/science.aah3443

Rogelj, J., den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., … Meinshausen, M. (2016). Paris agreement climate proposals need a boost to keep warming well below 2°C. *Nature*, *534*(7609), 631–639. doi:10.1038/nature18307

Rogelj, J., Luderer, G., Pietzcker, R. C., Kriegler, E., Schaeffer, M., Krey, V., & Riahi, K. (2015). Energy system transformations for limiting end-of-century warming to below 1.5°C. *Nature Climate Change*, *5*(6), 519–527. doi:10.1038/nclimate2572

Rogelj, J., McCollum, D. L., O'Neill, B. C., & Riahi, K. (2012). 2020 emissions levels required to limit warming to below 2 °C. *Nature Climate Change*, *3*(4), 405–412. doi:10.1038/nclimate1758

Rogelj, J., McCollum, D. L., Reisinger, A., Meinshausen, M., & Riahi, K. (2013). Probabilistic cost estimates for climate change mitigation. *Nature*, *493*(7430), 79–83. doi:10.1038/nature11787

Schaeffer, M., Rogelj, J., Roming, N., Sferra, F., Hare, B., & Serdeczny, O. (2015). *Feasability of limiting warming to 1.5 and 2°C. Update November 30, 2015*. Berlin: Climate Analytics.

Schleussner, C.-F., Rogelj, J., Schaeffer, M., Lissner, T., Licker, R., Fischer, E. M., … Hare, W. (2016). Science and policy characteristics of the Paris agreement temperature goal. *Nature Climate Change*, *6*(9), 827–835. doi:10.1038/nclimate3096

Scott, K., Roelich, K., Owen, A., & Barrett, J. (2017). Extending European energy efficiency standards to include material use: An analysis. *Climate Policy*, *38*, 1–15. doi:10.1080/14693062.2017.1333949

Shearer, C., Ghio, N., Myllyvirta, L., Yu, A., & Nace, T. (2017). *Boom and bust 2017. Tracking the global coal plant pipeline*. Coalswarm, Sierra Club, Greenpeace.

Sims, R., Schaeffer, R., Creutzig, F., Cruz-Núñez, X., D'Agosto, M., Dimitriu, D., … Kobayashi, S. (2014). Transport. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, & J. C. Minx (Eds.), *Climate change 2014: Mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovern- mental panel on climate change* (pp. 599–670). Cambridge: Cambridge University Press.

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E. A., … Tubiello, F. (2014). Agriculture, forestry and other land Use (AFOLU). In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, & J. C. Minx (Eds.), *Climate change 2014: Mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change* (pp. 811–922). Cambridge: Cambridge University Press.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., … Smith, J. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1492), 789–813. doi:10.1098/rstb.2007.2184

Spencer, T., Colombier, M., Sartor, O., Garg, A., Tiwari, V., Burton, J., … Wiseman, J. (2017). The 1.5°C target and coal sector transition: At the limits of societal feasibility. *Climate Policy, 18*. Advance online publication. doi:10.1080/14693062.2017.1386540

Springmann, M., Charles, H., Godfray, J., Rayner, M., & Scarborough, P. (2016). Analysis and valuation of the health and climate change cobenefits of dietary change. *Proceedings of the National Academy of Sciences*, *113*(15), 4146–4151. doi:10.1073/pnas.1523119113

Steckel, J. C., Edenhofer, O., & Jakob, M. (2015). Drivers for the renaissance of coal. *Proceedings of the National Academy of Sciences*, *112* (29), E3775–E3781. doi:10.1073/pnas.1422722112

Sterl, S., Hagemann, M., Fekete, H., Höhne, N., Cantzler, J., Ancygier, A., … Menon, S. (2017). *Faster and cleaner 2: Kick-starting global decarbonization*. Climate Action Tracker. Climate Analytics, Ecofys, NewClimate Institute, ClimateWorks Foundation.

Sterl, S., Kuramochi, T., Hagemann, M., Gonzales-Zuñiga, S., Wouters, K., Deng, Y., … Beer, M. (2016). *The road ahead - How do we move to cleaner Car fleets? CAT decarbonisation series*. Climate Action Tracker. Climate Analytics, Ecofys, NewClimate Institute.

UNFCCC. (2015). *Adoption of the Paris Agreement. Proposal by the President.* Draft decision -/CP.21. Conference of the Parties. Twentyfirst session, Paris, 30 November to 11 December 2015. FCCC/CP/2015/L.9. United Nations Framework Convention on Climate Change.

van Ruijven, B. J., van Vuuren, D. P., Boskaljon, W., Neelis, M. L., Saygin, D., & Patel, M. K. (2016). Long-term model-based projections of energy use and CO_2 emissions from the global steel and cement industries. *Resources, Conservation and Recycling*, *112*, 15–36. doi:10.1016/j.resconrec.2016.04.016

Victor, D. G., Zhou, D., Ahmed, E. H. M., Dadhich, P. K., Olivier, J. G. J., Rogner, H.-H., … Yamaguchi, M. (2014). Introductory chapter. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, & J. C. Minx (Eds.), *Climate change 2014: Mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change* (pp. 111–150). Cambridge: Cambridge University Press.

Volvo. (2017). Press release: Volvo Cars to go all electric. July 05, 2017. Retrieved from https://www.media.volvocars.com/global/en-gb/media/pressreleases/210058/volvo-cars-to-go-all-electric

VVD, CDA, D66, & ChristenUnie. (2017. October 10). *Vertrouwen in de toekomst – Regeerakkoord 2017–2021*. VVD, CDA, D66, ChristenUnie.

Williamson, P. (2016). Emissions reduction: Scrutinize CO2 removal methods. *Nature*, *530*(7589), 153–155. doi:10.1038/530153a

Wollenberg, E., Richards, M., Smith, P., Havlík, P., Obersteiner, M., Tubiello, F. N., … Campbell, B. M. (2016). Reducing emissions from agriculture to meet the 2°C target. *Global Change Biology*, doi;10.1111/gcb.13340

World Steel Association. (2016). *Steel statistical yearbook 2016*. Brussels: Author.

Wouters, K., El-Laboudy, T., Deng, Y. Y., Sterl, S., Kuramochi, T., Hagemann, M., … Beer, M. (2016). *Constructing the future: Will the building sector use its decarbonisation tools? CAT decarbonisation series*. Climate Action Tracker. Climate Analytics, Ecofys, NewClimate Institute.