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Residual fossil CO_2 emissions in 1.5–2 °C pathways

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The Paris Agreement—which is aimed at holding global warming well below 2 °C while pursuing efforts to limit it below 1.5 °C—has initiated a bottom-up process of iteratively updating nationally determined contributions to reach these long-term goals. Achieving these goals implies a tight limit on cumulative net CO_2 emissions, of which residual CO_2 emissions from fossil fuels are the greatest impediment. Here, using an ensemble of seven integrated assessment models (IAMs), we explore the determinants of these residual emissions, focusing on sector-level contributions. Even when strengthened pre-2030 mitigation action is combined with very stringent long-term policies, cumulative residual CO_2 emissions from fossil fuels remain at 850–1,150 $GtCO_2$ during 2016–2100, despite carbon prices of US$130–420 per tCO_2 by 2030. Thus, 640–950 $GtCO_2$ removal is required for a likely chance of limiting end-of-century warming to 1.5 °C. In the absence of strengthened pre-2030 pledges, long-term CO_2 commitments are increased by 160–330 $GtCO_2$, further jeopardizing achievement of the 1.5 °C goal and increasing dependence on CO_2 removal.

A central insight of geophysical climate research is the quasi-linear relationship between cumulative CO_2 emissions and temperature increase[1], implying a finite but uncertain limit on admissible emissions for any long-term temperature stabilization goal[2,3]. Crucially, cumulative CO_2 emissions budgets for the 1.5 °C limit are estimated to be much lower than those for 2 °C (refs [4,5]).

The tight cumulative emissions budget for 1.5 °C, in combination with the inadequacy of current emissions reductions efforts[6] and the nationally determined contributions (NDCs)[7–10], give rise to concerns about the world's increasing reliance on future carbon dioxide removal (CDR). Due to the large land requirements for combining bioenergy with carbon capture and storage (BECCS) or afforestation, which are the most prominently discussed CDR options, there are substantial sustainability concerns about large-scale CDR deployment[11]. Given a budget on anthropogenic net CO_2 emissions, the scale of CDR required depends directly on the scale of cumulative residual gross CO_2 emissions from fossil fuels and industry (Res-FFI-CO_2). We here define the Res-FFI-CO_2 of a mitigation scenario as the amount of CO_2 emissions from fossil fuels and industry (excluding negative emissions from CDR) whose abatement remains uneconomical or technically infeasible under the assumptions of the respective model and scenario.

This study examines the drivers of Res-FFI-CO_2 in very low stabilization scenarios, with the goal of identifying crucial decarbonization bottlenecks towards 1.5–2 °C stabilization on the basis of the cross-sectoral perspective of seven technology-rich IAM frameworks. Understanding from which sectors and activities major Res-FFI-CO_2 originate is of crucial value for decisionmakers to prioritize climate policy interventions and technological innovation. Previous IAM studies have focused on net anthropogenic CO_2 emissions (for example, refs [4,12,13]), but have not disentangled positive and negative components of the CO_2 budget[14]. Our approach, by contrast, characterizes the sectoral composition of deep decarbonization pathways in terms of both their residual (gross) fossil fuel emissions and their CDR requirements. Past studies have also mostly focused on the 2 °C limit[4,12,15,16], whereas to date, only a few recent studies have explored pathways limiting end-of-century warming to 1.5 °C (refs [5,17]).

In light of the Paris Agreement, this study also contrasts scenarios of early strengthening of policy ambition in line with the 1.5–2 °C goals with scenarios assuming no strengthening of NDCs before 2030. We can thus explore to what extent delayed strengthening increases cumulative Res-FFI-CO_2, both due to increased near-term emissions and to further carbon lock-in[18], and consequently increases long-term CDR requirements or renders climate goals unattainable.

Decarbonization scenarios for 1.5–2 °C stabilization

We use seven global IAMs—AIM/CGE (Asia-Pacific Integrated Model/Computable General Equilibrium), IMAGE (Integrated Model to Assess the Global Environment), GCAM (Global Change Assessment Model), MESSAGE-GLOBIOM (Model for Energy

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Supply Strategy Alternatives and their General Environmental Impact–GLObal BIOsphere Management), POLES (Prospective Outlook on Long-term Energy System), REMIND (REgionalized Model of INvestments and Development) and WITCH (World Induced Technical Change Hybrid Model)—each of which implemented three different constraints on net cumulative 2016–2100 CO_2 of around 200 $GtCO_2$, 800 $GtCO_2$ and 1,400 $GtCO_2$ to differentiate alternative climate target stringencies (see Methods and Supplementary Table 1). Using a probabilistic version of the reduced-form carbon-cycle and climate model MAGICC (Model for the Assessment of Greenhouse gas-Induced Climate Change)[3,19,20], these three scenario groups are characterized as likely to be below the temperature, T, of 1.5 °C by 2100 ('B200|1.5C-T_{2100}| > 67%' in the remainder of this article; abbreviated 'B200' in the figures, where 'B' stands for budget), likely to avoid 2 °C over the twenty-first century ('B800|2C-T_{max}| > 67%'; 'B800' in figures) or more likely than not (>50% chance) to avoid 2 °C ('B1400|2C-T_{max}| > 50%'; 'B1400' in figures), respectively (Table 1 and Supplementary Fig. 1). The relation between cumulative CO_2 emissions and warming illustrates the tight emissions space for mitigation in line with the objectives of the Paris Agreement. The 200 $GtCO_2$ and 800 $GtCO_2$ emission budgets for the 1.5 °C and well-below 2 °C limits compare with current annual CO_2 emissions of around 41 $GtCO_2$ (ref. [21]), and cumulative 2016–2100 CO_2 emissions of around 4,000 $GtCO_2$ that would occur if the Paris Agreement were not implemented ('Reference' policies scenarios; see Methods for details).

Importantly, the size of the remaining CO_2 budget for 1.5 °C is highly uncertain, depending on assumptions on present-day warming, non-CO_2 emissions and abatement, climate sensitivity and the exact target specification. For instance, a recent study[22] found a greater remaining carbon budget for 1.5 °C, but assumed a lower 2015 temperature than our study. Moreover, they considered the CO_2 budget at the time of 1.5 °C exceedance, which is greater than the budget for avoiding 1.5 °C warming in 2100 (see Supplementary Text 1 for a detailed discussion).

Residual fossil CO_2 emissions

To provide a more detailed perspective on the mitigation challenges associated with the 1.5–2 °C targets, Fig. 1a,b disaggregates cumulative CO_2 emissions into remaining Res-FFI-CO_2 and negative emissions components from BECCS and land use.

We find that in the very stringent B200|1.5C-T_{2100}| > 67% scenarios, under the assumption of early strengthening of mitigation action, 2016–2100 cumulative gross Res-FFI-CO_2 amounts to 1,020 [850–1,150] $GtCO_2$ (median across models, with ranges referring to the 68% confidence intervals throughout the paper; see Methods). This exceeds by far most estimates of the remaining net anthropogenic CO_2 budget for a likely chance of limiting end-of-century warming to 1.5 °C (Table 1 and Supplementary Fig. 1). Consequently, these B200|1.5C-T_{2100}| > 67% scenarios feature cumulative CDR from BECCS and land use of 790 [640–950] $GtCO_2$ to offset the exceedance. The variations in sectoral Res-FFI-CO_2 and CDR can be attributed to model-specific structures and assumptions (see Supplementary Table 3).

Cumulative Res-FFI-CO_2 remain at this level despite an immediate phase-in of globally harmonized CO_2 prices, which reach US$250 [130–420] per tCO_2 (all prices are expressed in US$$_{2010}$) by 2030 in the B200|1.5C-T_{2100}| > 67% scenarios (Fig. 1c), more than double the level required for B800|2C-T_{max}| > 67%. Diagnostic experiments with even higher CO_2 prices show that abatement costs as a function of cumulated Res-FFI-CO_2 are highly convex in the neighbourhood of 1.5 °C budgets. While it is not possible to establish an absolute lower limit of Res-FFI-CO_2, the results indicate that there is limited scope to reach Res-FFI-CO_2 emission reductions beyond those realized in the B200|1.5C-T_{2100}| > 67% pathways (see Supplementary Text 3 and Supplementary Fig. 18).

Energy supply

Energy supply accounts for about 45% of present-day energy-related CO_2 emissions[23] and a major share of cumulative emissions in the Reference scenarios. The bulk of these emissions originate from the power sector. Other energy-supply emissions come from centralized heat supply and refineries. Since these non-electric fossil fuel emissions are reduced broadly in line with the decarbonization of the other sectors, and because of their relatively small share in total CO_2 emissions (see Fig. 1b and Supplementary Figs. 3 and 6), they are not the focus of the analysis in this section.

Previous studies have pointed out that electricity supply offers large and low-cost emission reduction potentials[4,13,24], and considerable flexibility[4,25], resulting in substantial variation in technology choice across models (Supplementary Text 2, Supplementary Table 3). In the B200|1.5C-T_{2100}| > 67% scenarios, it is virtually carbon free by 2050, with a fossil carbon emissions intensity of electricity of around 4 [2–17] $gCO_2\,kWh^{-1}$, compared with current levels of around 530 $gCO_2\,kWh^{-1}$ (ref. [26]) (Fig. 2), and only slightly greater at 19 [12–28] $gCO_2\,kWh^{-1}$ in B800|2C-T_{max}| > 67%. The remaining cumulative 2016–2100 emissions from the power sector are 210 [140–220] $GtCO_2$ in the B200|1.5C-T_{2100}| > 67% scenarios, and 240 [200–310] $GtCO_2$ for the B800|2C-T_{max}| > 67% scenarios. As the power sector turns essentially carbon free in the second half of the century, its cumulative Res-FFI-CO_2 depends mostly on the pace at which emissions decline before mid-century. The additional emission reductions in the B200|1.5C-T_{2100}| > 67% scenarios are largely achieved by a faster phase-out of conventional coal-fired power, and quicker ramp-up of carbon-free electricity (Fig. 2 and Supplementary Figs. 11 and 12).

Demand-side transformation

Stabilizing warming in the 1.5–2 °C range also requires substantial reductions of direct demand-side CO_2 emissions, defined here as the emissions from the combustion of fossil fuels in the industry, buildings and transport sectors, excluding upstream emissions from energy conversion processes. Demand-side emission reductions are generally less deep than those achieved in power generation: for instance, while 2050 emissions from power supply have decreased by ~90% relative to 2010 in the B800|2C-T_{max}| > 67% scenarios, reductions of direct Res-FFI-CO_2 from industry, buildings and transportation are only 50%, 40% and 5%, respectively (Fig. 1d). Hence, most of the additional Res-FFI-CO_2 reductions required for 1.5 °C relative to 2 °C stabilization need to come from the energy demand sectors.

Demand-side emissions reduction efforts can be broadly categorized into energy demand savings, replacing combustible fuels by electricity as a final energy and decarbonization of fuels (Fig. 3 and Supplementary Figs. 14–16). Even under Reference policy trends without further climate policy efforts, the final energy intensity, that is, the ratio between final energy demand and global economic output, is projected to decrease by 1.3[1.0–1.7]% per year between 2010 and 2050, in line with historically observed trends. Our B200|1.5C-T_{2100}| > 67% scenarios estimate additional final energy demand savings of 36[2–40]% in 2050, equivalent to an annual efficiency increase of 2.1[1.8–2.9]% per year over 2010–2050. These policy-induced energy demand reductions are around 50% greater than those observed in our B800|2C-T_{max}| > 67% scenarios, but not outside the range observed in 2 °C pathways of the pre-existing scenario literature[4,27] or sector-specific studies of efficiency potentials[26,28–31]. They encompass both reductions in consumers' demands for energy services and energy-intensive materials (for example, via reduced travelling or increased reuse and recycling of products) and increases in technical efficiency (for example, via better insulation of buildings, increased vehicle efficiencies or increased efficiency in industrial processes). Similar demand reductions are realized in industry and buildings (Fig. 3a,b), while those achieved in transportation (Fig. 3c) are

Table 1 | Characterization of deep decarbonization pathways

		B200|1.5C-T_{2100}| > 67%	B800|2C-T_{max}| > 67%	B1400|2C-T_{max}| > 50%
		Likely chance of warming below 1.5 °C in 2100	**Warming limited below 2 °C in twenty-first century with >67% chance, but not likely below 1.5 °C in 2100**	**Medium likelihood (>50%) of limiting warming in twenty-first century to below 2 °C**
Cumulative 2016–2100 net CO_2 total (exogenous) ($GtCO_2$)	**Median**	**210**	**810**	**1,420**
	16th–84th percentiles	190–240	790–860	1,390–1,450
	(minimum–maximum)	(182–250)	(760–880)	(1,330–1,490)
Cumulative 2016–2100 greenhouse gases total ($GtCO_2e$)	**Median**	**880**	**1,600**	**2,240**
	16th–84th percentiles	690–990	1,402–1,639	2,030–2,340
	(minimum–maximum)	(670–1,090)	(1,320–1,700)	(2,000–2,400)
Cumulative 2016–2100 gross fossil fuels and industry ($GtCO_2$)	**Median**	**1,020**	**1,450**	**1,940**
	16th–84th percentiles	850–1,150	1,260–1,660	1,670–2,140
	(minimum–maximum)	(820–1,310)	(1,140–1,700)	(1,630–2,180)
Cumulative 2016–2100 CO_2 removal from BECCS ($GtCO_2$)	**Median**	**−730**	**−510**	**−340**
	16th–84th percentiles	−830 to −450	−720 to −380	−630 to −340
	(minimum–maximum)	(−840 to −420)	(−770 to −360)	(−670 to −310)
Cumulative 2016–2100 CO_2 from land use ($GtCO_2$)	**Median**	**−150**	**−90**	**−50**
	16th–84th percentiles	−190 to −40	−150 to −40	−130 to 10
	(minimum–maximum)	(−230 to 40)	(−160 to 90)	(−140 to 160)
Global warming (maximum twenty-first century) (MAGICC median) (°C)	**Median**	**1.54**	**1.69**	**1.92**
	16th–84th percentiles	1.51–1.57	1.62–1.71	1.87–1.94
	(minimum–maximum)	(1.49–1.65)	(1.58–1.77)	(1.74–1.96)
Global warming (2100) (MAGICC median) (°C)	**Median**	**1.29**	**1.56**	**1.88**
	16th–84th percentiles	1.20–1.31	1.53–1.60	1.86–1.92
	(minimum–maximum)	(1.16–1.33)	(1.44–1.63)	(1.74–1.93)
Likelihood of avoidance of 2 °C in twenty-first century (%)	**Median**	**0.88**	**0.79**	**0.57**
	16th–84th percentiles	0.88–0.91	0.77–0.83	0.56–0.60
	(minimum–maximum)	(0.84–0.93)	(0.72–0.87)	(0.54–0.71)
Likelihood of avoidance of 1.5 °C (2100) (%)	**Median**	**0.71**	**0.43**	**0.16**
	16th–84th percentiles	0.70–0.81	0.36–0.46	0.15–0.17
	(minimum–maximum)	(0.67–0.83)	(0.35–0.56)	(0.13–0.25)
Carbon price in 2030 (US$$_{2010}$ per tCO_2)	**Median**	**250**	**70**	**40**
	16th–84th percentiles	130–420	60–200	30–110
	(minimum–maximum)	(110–590)	(48–200)	(20–200)

All pathways are with early strengthening and are characterized by total net cumulative CO_2 (exogenously chosen scenario assumption) and greenhouse gas emissions, positive and negative CO_2 budget components, as well as likelihood of avoiding exceedance of 2 °C in twenty-first century and 1.5 °C in 2100, and carbon price levels in 2030. Ranges are given as 68% confidence intervals (16th–84th percentiles; see Methods), with full minimum to maximum spreads in parentheses. BECCS emissions are reported as sequestered CO_2 from BECCS, while land-use-change emissions induced by biomass are accounted for in land use. Emissions and carbon prices are rounded to the nearest 10 $GtCO_2$ and $ per tCO_2, respectively.

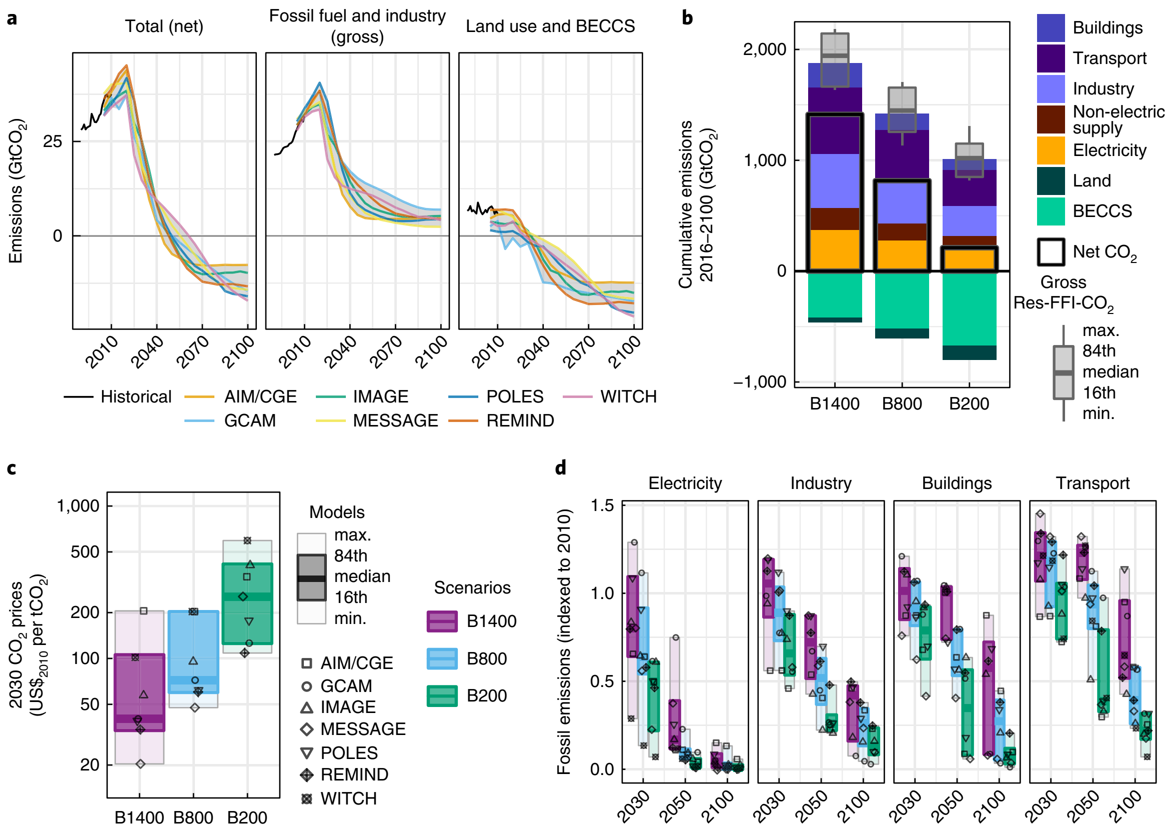

Fig. 1 | Overview of global and sectoral emissions. a, Total net CO_2 emissions and their breakdown into fossil fuel and industry CO_2 (Res-FFI-CO_2), as well as mostly negative emission contributions from BECCS and land use in B200|1.5C-T_{2100}| > 67% scenarios. **b**, Breakdown of cumulative 2016–2100 CO_2 emissions into sectoral Res-FFI-CO_2 and negative CDR components. Net CO_2 emissions are represented by the black boxes. Grey box plots indicate the median and 16th–84th percentile range; whiskers indicate full spread. **c**, Carbon prices in 2030 in three main scenarios (B200|1.5C-T_{2100}| > 67%, B800|2C-T_{max}| > 67% and B1400|2C-T_{max}| > 50%). **d**, Decarbonization of sectoral emission. The industry sector includes process emissions, for example from cement production. Bold boxes in **c** and **d** indicate the median and 16th–84th percentile range; light boxes indicate full spread. A model-by-model and time-resolved representation of sectoral Res-FFI-CO_2 is shown in Supplementary Fig. 3.

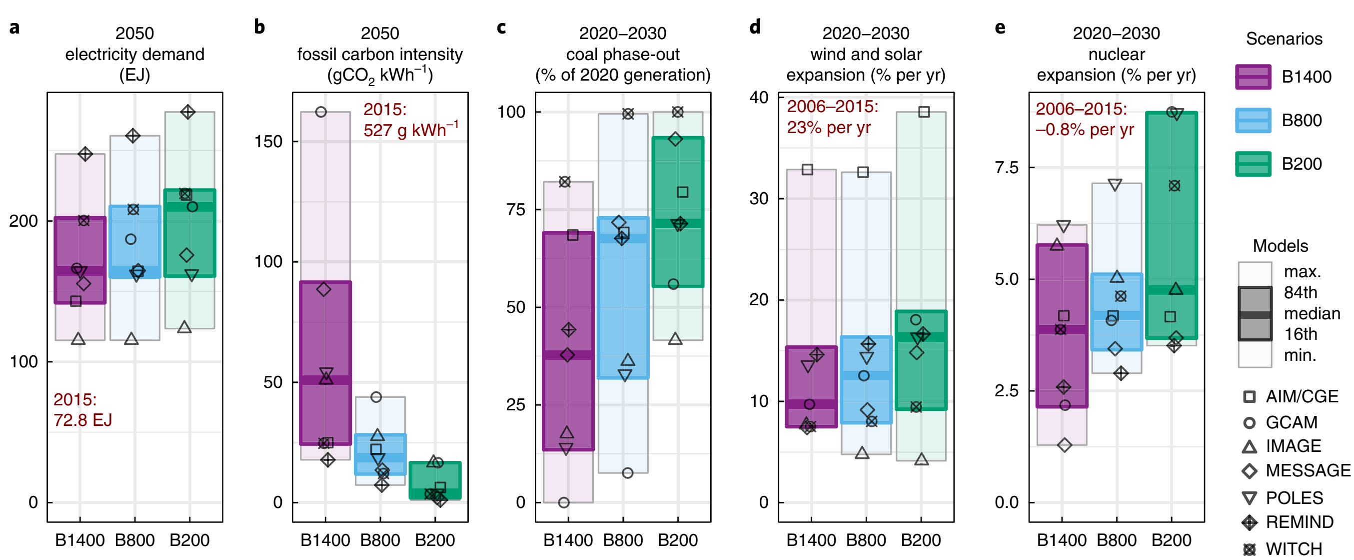

Fig. 2 | Indicators of power-sector decarbonization. a, 2050 electricity demand. **b**, Fossil CO_2 emissions per kWh supplied (not accounting for possible negative emissions from BECCS) for 2050. **c**, Retirement of conventional coal power between 2020 and 2030. **d**, Average compounded growth rate of wind and solar. **e**, Average compounded growth rate of nuclear electricity generation for 2020–2030 period. Bold boxes indicate the median and 16th–84th percentile range; light boxes provide full spread.

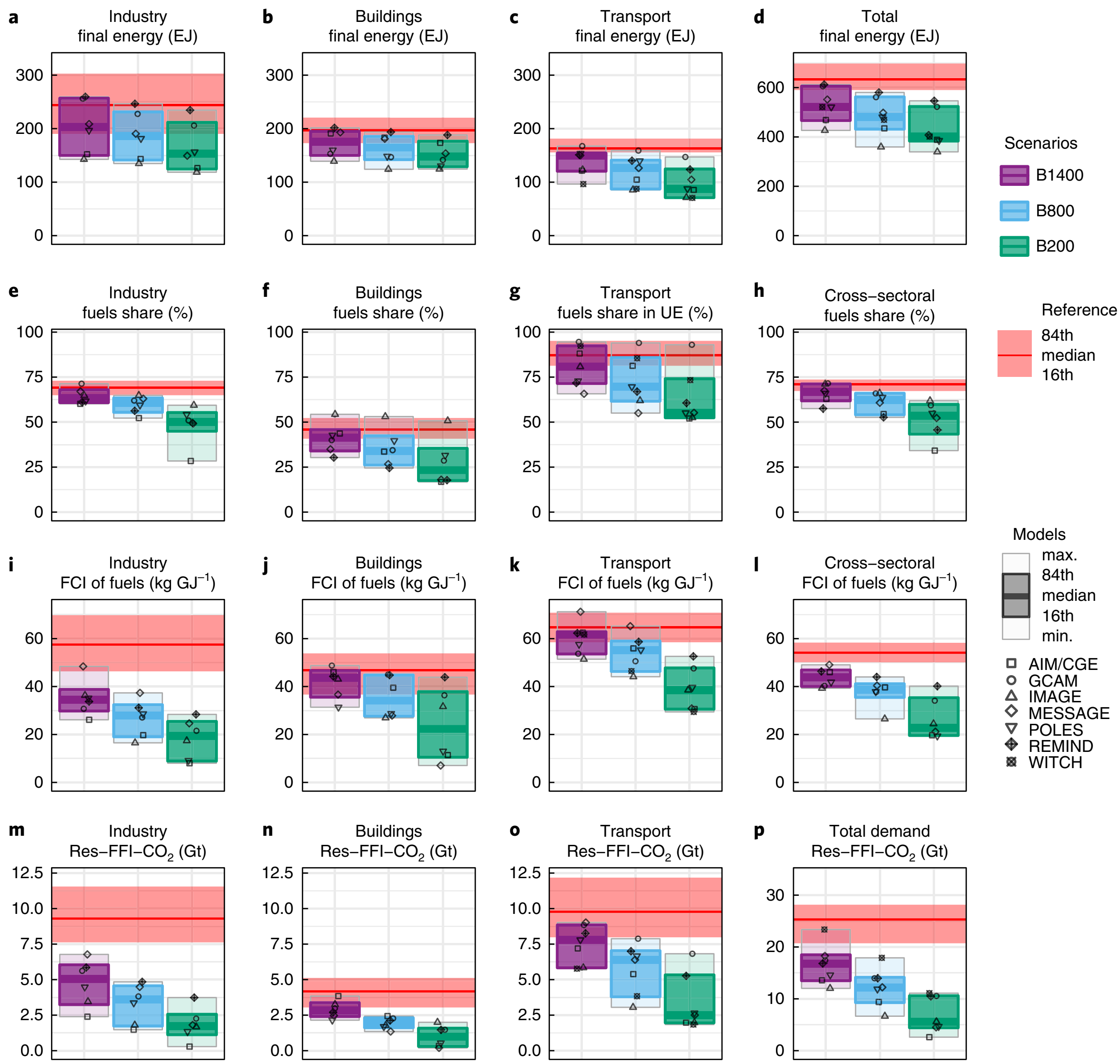

Fig. 3 | Mitigation indicators of demand-side transformation in 2050 for the industry, buildings and transport sectors, as well as the cross-sectoral totals. a–d, Final energy consumption, indicating the scope for demand reductions. **e–h**, Share of combustible fuels in final energy (buildings, industry, total) and useful energy (UE) (transportation) as an inverse indicator to electrification. **i–l**, Fossil carbon intensity (FCI) of combustible fuels, indicating the potential for supply-side decarbonization of fuels, most importantly by switching to bioenergy or hydrogen. **m–p**, Res-FFI-CO_2 emissions. Bold boxes indicate the median and 16th–84th percentile range; light boxes provide full spread. The red areas show 16th–84th percentile range values in the Reference scenarios.

greater because electric motors are substantially more efficient than internal combustion engines.

Given the rapid decarbonization of power supply, an accelerated electrification of end-uses becomes an increasingly powerful mitigation option[12,32]. In consequence, the share of combustible fuels decreases relative to today and relative to the Reference scenarios (Fig. 3e–h). Electrification potentials differ widely across sectors and thus are an important driver of sectoral differences in Res-FFI-CO_2 reduction potentials.

In the buildings sector, already under current policies, the share of combustible fuels in energy consumption decreases to 45[41–52]% by 2050, as the demand for appliances and cooling increases, while heating becomes increasingly efficient, and cooking with traditional biomass gets phased out. In the most stringent B200|1.5C-T_{2100}|>67% decarbonization scenarios, a further reduction of the share of combustible fuels in buildings-sector final energy to 23[18–35]% is achieved predominantly by supplying low-temperature heat from electrical heat pumps.

Reaching high electrification shares in transportation requires a more fundamental transformation than in the other sectors[30]. In 2014, electricity accounted for less than 1% of transportation energy demand (mostly electric rail)[26]. Electric vehicles can contribute substantially to future transport-sector emissions abatement[28,33,34]. However, the share of combustible fuels in useful energy for transportation remains at 55[52–74]% in 2050 in the B200|1.5C-T_{2100}|>67% scenarios, as electrification is substantially more challenging for freight, aviation and shipping[35].

Industry encompasses a wide variety of subsectors. Bulk materials industries, including ferrous and non-ferrous metals, cement, chemicals, pulp and paper, as well as mining and extraction, are the most energy-intensive industry sectors, accounting for around 60% of industrial energy demand[26] and an even higher share of direct CO_2 emissions[36]. The bulk of energy end-uses in industry are related to process heating and steam generation[37]. Whereas the other end-uses, mostly mechanical work and cooling, as well as low-temperature heat generation, can be readily electrified, high-temperature

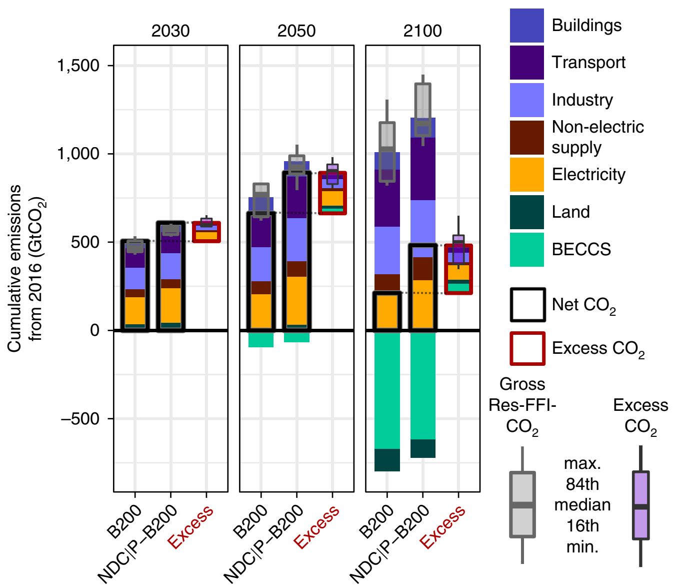

Fig. 4 | Sectoral cumulative emissions under early versus delayed strengthening of climate policy ambition. Comparison of sectoral cumulative CO_2 emissions in early strengthening scenarios ratcheting up mitigation action after 2020 ('B200'), and scenarios following the NDCs until 2030 before adopting carbon prices as in the B200|1.5C-T_{2100}| > 67% scenarios ('NDC|P-B200'). Net CO_2 emissions are represented by the black boxes. The red boxes and purple box plots represent excess emissions due to delayed strengthening, that is, the difference between NDC|P-B200 and B200|1.5C-T_{2100}| > 67% (as indicated by dashed horizontal lines). Bars and boxes show multi-model means, grey and purple box plots represent 16th–84th percentile ranges and whiskers represent full spread.

heat cannot be generated with heat pumps and is therefore more costly to supply from electricity. In the B200|1.5C-T_{2100}| > 67% scenarios, the share of fuels declines to 50[45–55]% by 2050, around 10 percentage points lower than in the B800|2C-T_{max}| > 67% scenarios, and much lower than the 68[65–73]% in the Reference scenarios.

Further Res-FFI-CO_2 reductions require a decline of the fossil carbon content of combustible fuels (Fig. 3i–l). By 2050, the greatest reduction of fossil carbon intensity of fuels, defined here as the ratio between sectoral direct Res-FFI-CO_2 and combustible fuel use, is achieved in industry. By contrast, transport carbon intensity remains comparatively higher, achieving a less than 50% reduction compared with the Reference scenarios even in the stringent B200|1.5C-T_{2100}| > 67% scenarios. The main driver of the reduction of fuel carbon intensity is biomass, and differences in the representation of biomass feedstocks and conversion technologies result in variations across models (see Supplementary Table 3). Bioenergy is, however, subject to considerable sustainability concerns, and its overall potential is constrained by the competition for food production and other land uses[38,39]. By 2050, biomass accounts for 86[66–100]% of solid final energy for the industry and buildings sectors in the B200|1.5C-T_{2100}| > 67% scenarios, while 28[20–35]% of liquids, mostly for transportation, are biofuels (Supplementary Fig. 7). In contrast to biofuels, hydrogen can be produced from different energy carriers, including electricity, but it is more difficult to handle and requires separate new infrastructure and new demand-side technologies. Hydrogen plays a modest role in the deep decarbonization scenarios assessed here, accounting for <6% of total final energy supply in the B200|1.5C-T_{2100}| > 67% scenarios in 2050 (Supplementary Fig. 8).

An important characteristic of industry in comparison with other demand sectors is the option of capture and geological storage of energy- and process-based CO_2 emissions. The large-scale installations of the steel, cement and petrochemical subsectors are particularly suitable for such industry carbon capture and storage applications. However, there is substantial uncertainty about industry carbon capture and storage deployment, which amounts to 0.69–2.7 $GtCO_2$ per year in 2050 for the B200|1.5C-T_{2100}| > 67% scenarios, corresponding to a captured share of 24–48% of CO_2 generated in the sector (Supplementary Fig. 9).

The impact of not strengthening before 2030

The mitigation scenarios discussed in the previous section assumed a ratcheting up of mitigation efforts after 2020, with 2030 emission levels in line with least-cost pathways towards the long-term goal[2,3]. Although the Paris Agreement is widely considered a historic milestone for ambitious international climate policy, NDCs fall short of the emission reductions implied by these least-cost pathways holding global warming to below 2 °C (refs [7–10]). The emissions gap is even greater for the 1.5 °C limit: in our scenario set, NDC pathways result in globally aggregate 2030 CO_2 emissions that exceed those of the B200|1.5C-T_{2100}| > 67% scenarios (Fig. 1a) by 19 [15–22] $GtCO_2$ per year.

Earlier studies have explored the implications of delayed or weak near-term action on the achievability of the 2 °C target[4,15,16,40–43]. They consistently found that delaying the peaking of global emissions until 2030 drastically increases mitigation challenges, in terms of technology upscaling requirements, stranded assets and medium to long-term mitigation costs for climate stabilization. A delay of climate policy strengthening has an even more severe impact on the achievability of the 1.5 °C limit. For four (AIM/CGE, IMAGE, MESSAGE-GLOBIOM, WITCH) out of the seven models participating in this study, the cumulative emission constraint of the B200|1.5C-T_{2100}| > 67% scenarios could not be met if no mitigation actions beyond the NDCs are implemented before 2030 (Supplementary Text 3), since greater Res-FFI-CO_2 emissions cannot be compensated by additional CDR.

To further study the consequences of not ratcheting up pre-2030 mitigation action in the context of the 1.5 °C limit, we calculated 'NDC|P-B200' scenarios, in which NDCs are assumed not to be strengthened until 2030 but, thereafter, climate action of the same stringency as in the B200|1.5C-T_{2100}| > 67% scenarios is implemented. Crucially, models assumed that the strengthening of mitigation ambition is not anticipated until 2030. After 2030, a carbon price is introduced that equals the post-2030 carbon price observed in the corresponding B200|1.5C-T_{2100}| > 67% scenarios of the same model.

These NDC|P-B200 scenarios show that a failure to strengthen NDCs leads to additional CO_2 emissions of 290 [160–330] $GtCO_2$ until 2100. Although the climate policy differs only in the time period 2020–2030, these ten years of less ambitious climate policy not only result in excess emissions relative to the cost-optimal mitigation pathway until 2030, but also, and more importantly, reduce the post-2030 mitigation potential by exacerbating carbon lock-ins (investments into fossil-based infrastructure from 2020 to 2030 are not sufficiently disincentivized) and insufficient investments into upscaling of innovative low-carbon technologies. Cumulative post-2030 excess emissions of the NDC|P-B200 scenarios relative to the B200|1.5C-T_{2100}| > 67% scenarios amount to 200 $GtCO_2$, in addition to the direct excess emission of around 90 $GtCO_2$ before 2030 (Fig. 4). Most of these excess emissions come from electricity supply and the industry sectors, where delay of the transformation has particularly severe implications because of the longevity of the relevant capital stocks. Notably, models also show that not strengthening the NDCs might decrease the long-term BECCS potential considerably, suggesting that early investments and upscaling are crucial for enabling future large-scale deployment.

Conclusions and policy implications

The substantial magnitude of residual fossil fuel emissions has important implications for climate policy and the feasibility of very low temperature targets. We find that even under Herculean efforts[44] by all countries, including early and substantial strengthening of the NDCs, the residual fossil carbon emissions over 2016–2100 remain as high as 1,020 [890–1,150] $GtCO_2$. Much of the residual emissions are already locked into the system due to existing infrastructure and path dependencies. In the B200|1.5C-T_{2100}| > 67% scenarios, despite early strengthening of NDCs, around half of the Res-FFI-CO_2 accrues within the next 15 years, and three-quarters until 2050.

This is in stark contrast to the tight net cumulative CO_2 emissions budget for 2016–2100 required to return warming to below 1.5 °C, which here was chosen at around 200 $GtCO_2$ for the B200|1.5C-T_{2100}| > 67% scenarios to ensure a likely chance of achieving the target. In these scenarios, Res-FFI-CO_2 emissions are offset by cumulative CDR of 800 [640–950] $GtCO_2$. While land use and CDR contributions already reach 9.5 [6.0–13.1] $GtCO_2$ per year by 2050, 90% of cumulated CDR occurs after 2050. Scholars have brought forward fundamental concerns about the biophysical, technological and institutional viability of large-scale CDR[14,45–47]. Our results also show that CDR is no longer a choice but rather a necessary requirement for the 1.5 °C goal: none of the seven participating models was able to achieve the B200|1.5C-T_{2100}| > 67% budget if BECCS was assumed to be unavailable (Supplementary Text 3). The scenarios already assume stringent abatement of non-CO_2 emissions. If this is not realized, CO_2 budgets would be smaller and imply even greater CDR requirements. The CDR dependence can be substantially reduced only for a more lenient interpretation of the Paris goals, as realized in the B800|2C-T_{max}| > 67% and B1400|2C-T_{max}| > 50% scenarios or in the case of a weaker climate response to emissions.

In view of the fundamental concerns about large-scale CDR, minimizing Res-FFI-CO_2 needs to be the central climate policy priority. We find that Res-FFI-CO_2 abatement is crucially limited by system inertia in all sectors and the extent to which end-uses in industry and transport can substitute fossil-based fuels. At the same time, there is substantial uncertainty precisely about the pace of socio-technical transitions, as well as technological innovations that determine abatement potentials in the long term. For instance, Res-FFI-CO_2 would be higher in the case of a slower pace of power-sector decarbonization. More limited bioenergy availability would not only reduce CDR potential, but also reduce biofuel availability as a substitute for fossil-based fuels[48], thus further increasing Res-FFI-CO_2. Conversely, Res-FFI-CO_2 could be reduced if innovative technologies such as catenary electric truck systems[49], carbon capture and storage for industry[50] or the production of electricity-based synthetic fuels[51] can be brought to market readiness swiftly. Many of these technological approaches are not explicitly represented in state-of-the-art IAMs, but become increasingly relevant for mitigation targets in the 1.5 °C range. Ultimately, not only technology solutions but also behavioural factors such as lifestyle changes towards less energy- and material-intensive consumption will play an important role in the mitigation efforts. Advanced modelling of aspects such as heterogeneity, distributional implications and interconnected innovation systems could enable a more explicit representation of the socio-technical transformation towards near-zero economies[52].

Importantly, our results also show that near-term policy stringency is an important driver of cumulative Res-FFI-CO_2 in climate change mitigation scenarios. If strengthening of NDCs fails, Res-FFI-CO_2 will be even higher, not only because of additional near-term emissions, but also due to a decrease of economic mitigation potentials in the longer term caused by further carbon lock-in. Delaying the strengthening of mitigation action will increase the world's dependence on CDR for holding warming to well below 2 °C, and is likely to push the 1.5 °C target out of reach for this century.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available at https://doi.org/10.1038/s41558-018-0198-6.

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Author contributions

G.L., Z.V., V.K., E.K., K.R., B.S. and D.P.V.V. designed the research and scenarios; C.B., O.Y.E., R.C.P., H.S.D.B., L.D., J.E., O.F., S.F., P.H., G.I., A.K., K.K. and M.P. performed scenario modelling work; J.R. performed climate analysis; G.L. performed scenario data analysis in collaboration with C.B. and M.P.; G.L. created the figures and wrote the paper with inputs and feedback from all authors.

Competing interests

The authors declare no competing interests.

Additional information

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Methods

Study design. Seven IAMs participated in this study. These IAMs provide an integrated representation of the energy–economy–land-use system. The study was conducted in the context of the ADVANCE (Advanced Model Development and Validation for the Improved Analysis of Costs and Impacts of Mitigation Policies) project[53], as part of which modelling teams also collaborated to improve crucial aspects of their models, such as transportation[28], mitigation in industry[29], variability and integration challenges of wind and solar power[54,55], or the representation of near-term climate action planned by individual countries. Short descriptions as well as further references on the individual models are provided below.

Supplementary Table 1 lists the scenarios considered in this study. We distinguish between fragmented policy scenarios, scenarios with early strengthening towards the 1.5–2 °C limits and delayed strengthening scenarios. The two fragmented scenarios do not have a long-term climate constraint and allow us to put the 1.5–2 °C scenarios into the perspective of currently discussed mitigation actions. The Reference policy scenario accounts for national mitigation pledges to the Copenhagen Accord for 2020 only, and does not consider the more recent national mitigation commitments made in the context of the COP21 (21st Conference of the Parties) climate conference held in Paris in December 2015. The NDC policy scenario, in addition, accounts for the effect of the intended NDCs that were submitted by the vast majority of parties to the UNFCCC (United Nations Framework Convention on Climate Change) ahead of the COP21 and converted to NDCs thereafter[56]. Most of the NDCs refer to 2030 as a target year. For countries that submitted both conditional and unconditional NDCs, we assumed that the conditional NDCs are realized. The Reference and NDC scenarios do not pursue specific global long-term climate targets; rather, national mitigation efforts are extrapolated beyond 2020/2030 on the basis of the respective near-term ambition levels.

Most of the analysis shown in this study focuses on the early strengthening scenarios. In these scenarios, indicative constraints on total cumulative 2011–2100 CO_2 emissions of 1,600 $GtCO_2$, 1,000 $GtCO_2$ and 400 $GtCO_2$ (translating to around 1,400 $GtCO_2$, 800 $GtCO_2$ and 200 $GtCO_2$ for 2016–2100, respectively) were implemented as a surrogate for explicit temperature targets, thus ensuring comparability of CO_2 mitigation efforts across models by eliminating the uncertainties related to the climate system response and mitigation potentials of non-CO_2 greenhouse gases (see Supplementary Fig. 2). This results in a spread of about 0.15 °C in the 2100 median temperature response if evaluated with a harmonized version of the reduced-form climate model MAGICC[20] (Supplementary Text 1 and Supplementary Fig. 1), mostly attributable to differences in non-CO_2 greenhouse gas emissions. Regarding near-term policy ambition, the early action scenarios assume that mitigation efforts are strengthened after 2020, with a harmonized carbon price in line with the long-term emissions constraint implemented across all sectors and world regions.

The delayed strengthening scenarios fulfil the national mitigation pledges made under the NDCs, while assuming neither strengthening before 2030 nor anticipation of the stringent emissions reductions required afterwards. After 2030, the 'NDC|B200' and 'NDC|B800' scenarios assume that the same carbon budgets as in B200|1.5C-T_{2100}| > 67% and B800|2C-T_{max}| > 67%, respectively, apply such that excess emissions between 2020 and 2030 need to be compensated by additional emission reductions after 2030. Only three out of the seven models found the NDC|B200 case to be feasible (Supplementary Table 2). The 'NDC|P-B200' and 'NDC|P-B800' cases, by contrast, assume that the same post-2030 carbon prices as in B200|1.5C-T_{2100}| > 67% and B800|2C-T_{max}| > 67%, respectively, are applied without compensating for excess 2020–2030 emissions. This thus results in higher cumulative 2016–2100 carbon budgets compared with the corresponding early strengthening cases.

There are two additional diagnostic scenarios. The 'B200|NoBECCS' scenario explores the feasibility of the B200|1.5C-T_{2100}| > 67% CO_2 budget constraint if BECCS is assumed to be unavailable. However, none of the participating models was able to find a feasible solution for this case. The 'CO_2price|3×B200' scenarios explore the low end of Res-FFI-CO_2 emission by assuming the threefold CO_2 price levels from the B200|1.5C-T_{2100}| > 67%.

Throughout the paper, the uncertainty ranges given represent 16th–84th percentile ranges. This 68% confidence interval encompasses the central five out of seven data points from the model ensemble, and corresponds to the 1-σ interval of a Gaussian normal distribution. All numbers given are rounded to two significant digits unless stated otherwise.

Descriptions of participating models. We employed seven state-of-the-art energy–economy–climate modelling systems for this study. They are briefly described in the following. For AIM/CGE, IMAGE, MESSAGE-GLOBIOM, POLES, REMIND and WITCH, detailed harmonized model documentations are available at the Common IAM documentation, http://themasites.pbl.nl/models/advance/index.php/ADVANCE_wiki. Detailed information about the GCAM model is available from the GCAM website and at GitHub http://jgcri.github.io/gcam-doc/toc.html.

AIM/CGE. AIM/CGE is a one-year-step recursive-type dynamic general equilibrium model that covers all regions of the world[57–59]. The AIM/CGE model includes 17 regions and 42 industrial classifications. For appropriate assessment of bioenergy and land-use competition, agricultural sectors are also highly disaggregated[57]. Details of the model structure and mathematical formulae are described by Fujimori et al.[58]. The production sectors are assumed to maximize profits under multi-nested constant elasticity of substitution functions and each input price. For energy transformation sectors, input energy and value added are fixed coefficients of output. They are treated in this manner to deal with energy conversion efficiency appropriately in the energy transformation sectors. Power generation values from several energy sources are combined with a logit function. This functional form was used to ensure energy balance because the constant elasticity of substitution function does not guarantee an energy balance. Household expenditures on each commodity are described by a linear expenditure system function. The parameters adopted in the linear expenditure system function are recursively updated in accordance with income elasticity assumptions. In addition to energy-related CO_2, CO_2 from other sources, CH_4, N_2O and fluorinated gases are treated as greenhouse gases in the model. Energy-related emissions are associated with fossil fuel feedstock use. The non-energy-related CO_2 emissions consist of land-use change and industrial processes. Land-use-change emissions are derived from the forest area change relative to the previous year multiplied by the carbon stock density, which is differentiated by global agro-ecological zones. Non-energy-related emissions other than land-use-change emissions are assumed to be in proportion to the level of each activity (such as output). CH_4 has a range of sources, mainly the rice production, livestock, fossil fuel mining and waste management sectors. N_2O is emitted as a result of fertilizer application and livestock manure management, and by the chemical industry. Fluorinated gases are emitted mainly from refrigerants used in air conditioners and cooling devices in industry. Air pollutants (CO, NH_3, non-methane volatile organic compounds, NO_x, SO_2, black carbon, organic carbon) are also associated with fuel combustion and activity levels. Essentially, emissions factors change over time with the implementation of air pollutant removal technologies and relevant legislation.

GCAM. GCAM is an open-source model primarily developed and maintained at the Pacific Northwest National Laboratory's Joint Global Change Research Institute. The full documentation of the model is available online, and the model can be downloaded along with the source code. The full documentation of the model is available at the GCAM documentation page (http://jgcri.github.io/gcam-doc/), and the description in this section is a summary of the online documentation and based on refs [60–62].

GCAM is a dynamic-recursive model, combining representations of the global energy, economy, agriculture and land-use systems[63–66]. Outcomes of GCAM are driven by assumptions about population growth, labour participation rates and labour productivity in 32 geopolitical regions, along with representations of resources, technologies and policy. GCAM operates in five-year time steps from 2010 (calibration year) to 2100 by solving for the equilibrium prices and quantities of various energy, agricultural and greenhouse gas markets in each time period and in each region. GCAM tracks emissions of 24 substances, including greenhouse gases, short-lived species and ozone precursors, endogenously on the basis of the resulting energy, agriculture and land-use systems.

The energy system formulation in GCAM comprises detailed representations of extractions of depletable primary resources such as coal, natural gas, oil and uranium (at global levels), along with renewable sources such as bioenergy, hydro, solar and wind (at regional levels). GCAM also includes representations of the processes that transform these resources to secondary energy carriers, which are ultimately consumed in the buildings (divided into the residential and commercial), transportation and industrial sectors. Secondary energy carriers include refined liquids, refined gas, coal, commercial bioenergy, hydrogen and electricity.

GCAM is a technology-rich model—it contains detailed representations of technology options in all of the economic components of the system. Individual technologies in each sector compete for market share on the basis of their technological characteristics (conversion efficiency in the production of products from inputs), and cost of inputs and price of outputs.

The agriculture and land-use component represents the competition for land among food crops, commercial biomass, forests, pasture, grassland and shrubs in 283 agro-economic zones within the 32 regions. The energy system and the agriculture and land-use systems are hard linked (coupled in code) through bioenergy and fertilizer. Demand for commercial biomass originates in the energy system, while supply is determined by the agriculture and land-use component. Fertilizer is produced in the energy–economy system, while fertilizer demand originates in the agriculture and land-use system.

IMAGE 3.0. IMAGE 3.0 is a comprehensive integrated assessment framework, modelling interacting human and natural systems[67]. The IMAGE framework is suited for assessing interactions between human development and the natural environment, including a range of sectors, ecosystems and indicators. The impacts of human activities on the natural systems and natural resources are assessed and how such impacts hamper the provision of ecosystem services to sustain human development. The model framework is suited to a large geographical (usually global) and temporal scale (up to the year 2100).

The IMAGE framework identifies socio-economic pathways, and projects the consequences for energy, land, water and other natural resources, subject to resource availability and quality. Impacts such as air, water and soil emissions, climatic change and depletion and degradation of remaining stocks (fossil fuels, forests) are calculated and taken into account in future projections. Within the IAM group, different types of models exist, and IMAGE is characterized by relatively detailed biophysical processes and a wide range of environmental indicators.

The TIMER (Targets IMage Energy Regional) model has been developed to explore scenarios for the energy system in the broader context of the IMAGE framework. Similar to other IMAGE components, TIMER is a simulation model. The results obtained depend on a single set of deterministic algorithms, according to which the system state in any future year is derived entirely from previous system states. TIMER includes 12 primary energy carriers in 26 world regions and is used to simulate long-term trends in energy use, issues related to depletion, energy-related greenhouse gas and other air polluting emissions, together with land-use demand for energy crops. The focus is on dynamic relationships in the energy system, such as inertia and learning-by-doing in capital stocks, depletion of the resource base and trade between regions.

MESSAGE-GLOBIOM 1.0. MESSAGE-GLOBIOM 1.0 integrates the energy engineering model MESSAGE with the land-use model GLOBIOM via soft-linkage into a global IAM framework[68,69].

MESSAGE is a linear programming energy engineering model with global coverage[70–72]. As a systems engineering optimization model, MESSAGE is primarily used for medium- to long-term energy system planning, energy policy analysis and scenario development. The model provides a framework for representing an energy system with all its interdependencies, from resource extraction, imports and exports, conversion, transport and distribution, to the provision of energy end-use services such as light, space conditioning, industrial production processes and transportation. To assess economic implications and to capture economic feedbacks of climate and energy policies, MESSAGE is linked to the aggregated macroeconomic model MACRO[73].

Land-use dynamics are modelled with the GLOBIOM model, which is a partial-equilibrium model[74,75]. GLOBIOM represents the competition between different land-use-based activities. It includes a detailed representation of the agricultural, forestry and bioenergy sector, which allows for the inclusion of detailed grid-cell information on biophysical constraints and technological costs, as well as a rich set of environmental parameters, including comprehensive agriculture, forestry and other land-use greenhouse gas emission accounts and irrigation water use. For spatially explicit projections of the change in afforestation, deforestation, forest management and their related CO_2 emissions, GLOBIOM is coupled with the G4M (Global FORest Model)[76,77]. As outputs, G4M provides estimates of forest area change, carbon uptake and release by forests, and supply of biomass for bioenergy and timber.

MESSAGE-GLOBIOM covers all greenhouse gas-emitting sectors, including energy, industrial processes as well as agriculture and forestry. The emissions of the full basket of greenhouse gases, including CO_2, CH_4, N_2O and fluorinated gases (CF_4, C_2F_6, HFC-125, HFC-134a, HFC-143a, HFC-227ea, HFC-245ca and SF_6), as well as other radiatively active substances such as NO_x, volatile organic compounds, CO, SO_2 and black carbon / organic carbon, are represented in the model. Air pollution implications of the energy system are accounted for in MESSAGE by applying technology-specific air pollution coefficients from the GAINS (Greenhouse gas–Air pollution INteractions and Synergies) model[78,79]. MESSAGE-GLOBIOM is used in conjunction with MAGICC version 6.8 (ref. [20]) for calculating atmospheric concentrations, radiative forcing and annual-mean global surface air temperature increase.

POLES. POLES is a global partial-equilibrium simulation model of the energy sector with an annual step, covering 29 regions worldwide (the G20 (Group of Twenty), the OECD (Organisation for Economic Co-operation and Development), principal energy consumers) plus the European Union. The model covers 15 fuel supply branches, 30 technologies in power production, 6 in transformation, 15 final demand sectors and corresponding greenhouse gas emissions. GDP (gross domestic product) is an exogenous input into the model, while endogenous resource prices, endogenous global technological progress in electricity generation technologies and price-induced lagged adjustments of energy supply and demand are important features of the model. Mitigation policies are implemented by introducing carbon prices up to the level where emission reduction targets are met: carbon prices affect the average energy prices, inducing energy efficiency responses on the demand side, and the relative prices of different fuels and technologies, leading to adjustments on both the demand side (for example, fuel switch) and the supply side (for example, investments in renewables). Non-CO_2 emissions in energy and industry are endogenously modelled with potentials derived from literature[80] (marginal abatement cost curves). Agriculture and land-use-change emissions projections are derived from the GLOBIOM model[74] (dynamic look-up of emissions depending on climate policy and biomass energy use), starting from historical emissions (from the UNFCCC, the FAO (Food and Agriculture Organization of the United Nations) and EDGAR (Emissions Database for Global Atmospheric Research)). A full documentation of POLES is available at http://ec.europa.eu/jrc/poles.

For this study, the POLES-ADVANCE model version that was used integrated an enhanced representation of energy demand (energy demand per end-use in the residential sector; electricity demand-side flexibility) as well as of electricity supply (intermittent renewables with representative production curves and updated resources with supply curves; representation of electricity storage options).

REMIND. REMIND models the global energy–economy–climate system for 11 world regions and for the time horizon until 2100. For the present study, REMIND in its version 1.7 was used. REMIND represents five individual countries (China, India, Japan, the United States and Russia) and six aggregated regions formed by the remaining countries (the European Union, Latin America, sub-Saharan Africa without South Africa, the Middle East / North Africa / Central Asia, other Asia, the rest of the world). For each region, intertemporal welfare is optimized on the basis of a Ramsey-type macroeconomic growth model. The model explicitly represents trade in final goods, primary energy carriers and, in the case of climate policy, emission allowances, and computes simultaneous and intertemporal market equilibria on the basis of an iterative procedure. Macroeconomic production factors are capital, labour and final energy. REMIND uses economic output for investments in the macroeconomic capital stock as well as consumption, trade and energy system expenditures.

By coupling a macroeconomic equilibrium model with a technology-detailed energy model, REMIND combines the major strengths of bottom-up and top-down models. The macroeconomic core and the energy system module are hard linked via the final energy demand and costs incurred by the energy system. A production function with constant elasticity of substitution (nested constant elasticity of substitution production function) determines the final energy demand. For the baseline scenario, final energy demand pathways are calibrated to regressions of historic demand patterns. More than 50 technologies are available for the conversion of primary energy into secondary energy carriers as well as for the distribution of secondary energy carriers into final energy.

REMIND uses reduced-form emulators derived from the detailed land-use and agricultural model MAgPIE (Model of Agricultural Production and its Impact on the Environment)[81,82] to represent land-use and agricultural emissions as well as bioenergy supply and other land-based mitigation options. Beyond CO_2, REMIND also represents emissions and mitigation options of major non-CO_2 greenhouse gases[80,83].

WITCH. WITCH is an IAM designed to assess climate change mitigation and adaptation policies. It was developed and is maintained at the *Fondazione Eni Enrico Mattei* (Eni Enrico Mattei Foundation) and the *Centro Euro-Mediterraneo sui Cambiamenti Climatici* (Euro-Mediterranean Centre on Climate Change). WITCH is a global dynamic model that integrates into a unified framework the most important drivers of climate change. An intertemporal optimal growth model captures the long-term economic growth dynamics. A compact representation of the energy sector is fully integrated (hard linked) with the rest of the economy so that energy investments and resources are chosen optimally, together with the other macroeconomic variables. Land-use mitigation options are available through a linkage with a land use and forestry model.

WITCH represents the world in a set of a varying number of macro regions: for the present study, the version with 13 representative native regions has been used; for each, it generates the optimal mitigation strategy for the long term (from 2005 to 2100) as a response to external constraints on emissions. A modelling mechanism aggregates the national policies on emission reduction or the energy mix into the WITCH regions (the United States, China, Europe, South Korea / Australia, Canada/Japan, transition economies, the Middle East / North Africa, sub-Saharan Africa, South Asia, East Asia, Latin America, India, Indonesia). Finally, a distinguishing feature of WITCH is the endogenous representation of research and development diffusion and innovation processes that allows a description of how research and development investments in energy efficiency and carbon-free technologies integrate the mitigation options currently available.

For this study, WITCH 2016 has been used; key publications describing the model are refs [84,85]. A full documentation is available at http://doc.witchmodel.org/.

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