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2020 emissions levels required to limit warming to below 2 °C

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This paper presents a systematic scenario analysis of how different levels of short-term 2020 emissions would impact the technological and economic feasibility of achieving the 2 °C target in the long term. We find that although a relatively wide range of emissions in 2020—from 41 to 55 billion tons of carbon dioxide equivalent (Gt CO_2e yr^{-1})—may preserve the option of meeting a 2 °C target, the size of this 'feasibility window' strongly depends on the prospects of key energy technologies, and in particular on the effectiveness of efficiency measures to limit the growth of energy demand. A shortfall of critical technologies—either for technological or socio-political reasons—would narrow the feasibility window, if not close it entirely. Targeting lower 2020 emissions levels of 41–47 Gt CO_2e yr^{-1} would allow the 2 °C target to be achieved under a wide range of assumptions, and thus help to hedge against the risks of long-term uncertainties.

A large body of scientific literature shows that stabilizing global temperatures requires a limit on the cumulative amount of long-lived greenhouse gases (GHGs) emitted to the atmosphere[1–4]. International climate agreements[5] contain aspirational global temperature targets but do not explicitly contain such a long-term global GHG limit. Instead, pledges are made to reduce emissions in the short term, for example, by 2020. In this paper we provide an explicit quantification of the relationship between such short-term policy decisions and the feasibility of long-term mitigation within a single, fully consistent integrated assessment modelling (IAM) framework capable of exploring uncertainty across a range of underlying assumptions.

Previous studies have analysed an array of IAM scenarios found in the literature and examined whether they achieve the 2 °C target[1,6–8]. On the basis of this information, these studies have defined a desirable range of 2020 emissions levels that are consistent with the 2 °C warming limit and compared this range with the pledges[6,9]. Their verdict is that a gap exists between 2020 emission levels implied by the present country pledges and by IAM scenarios consistent with 2 °C. However, because most scenarios in the present literature represent cost-optimal emissions pathways, they cannot definitively say that such 2 °C-consistent levels are required.

To determine a range of required emissions, we conduct a large-scale experiment and sensitivity analysis to identify the feasibility frontier for global emissions in 2020, illustrating the emissions levels at which reaching the 2 °C target would become infeasible. We use a combination of two well-established modelling frameworks: Model for Energy Supply Strategy Alternatives and their General Environmental Impact[10,11] (MESSAGE), a technology-rich IAM with a detailed representation of the global energy system; and Model for the Assessment of Greenhouse-gas Induced Climate Change[12,13] (MAGICC), a probabilistic climate model (see Methods). We explicitly investigate how high emissions could be in 2020 before a 'point of no return' is reached in our model that would foreclose reaching 2 °C with a high probability. Figure 1 provides a conceptual overview of our analysis, which is further explained in the Methods.

Exploring feasibility

Feasibility of emission reductions is a subjective concept and depends entirely on what is deemed possible or plausible in the real world[14]. It encompasses multiple aspects, be they technological, economic, societal or political in nature. Given the substantial inertia of the energy system[15], there is a limit to how deeply GHG emissions can be reduced by 2020. At the same time, in the absence of ambitious short-term actions, it may ultimately become infeasible to limit warming to below 2 °C in the long term. A range of emission levels in 2020 may thus exist that, on the lower end, could still feasibly be reached over the next decade and that, on the upper end, would retain the possibility of holding global temperature increase to below 2 °C throughout the twenty-first century. We refer to this emission range as the 2020 feasibility window and further develop this concept throughout the paper.

We use four main criteria to define the feasibility of a scenario: issues attributed to short-term technological transitions, which arise when the model cannot find sufficient mitigation options to reduce emissions by 2020; issues attributed to long-term technological transitions, which arise when the model is unable to find long-term mitigation options to reduce emissions from their 2020 levels down to levels that are consistent with the global temperature goal; the other two criteria are attributed to strong or very strong economic penalties, indicating whether mitigation cost increases are especially large and fast. Economic penalties arise when a large mismatch exists between the level of GHG mitigation achieved by 2020 and the level required afterwards. Of these four criteria, strong economic penalties are flagged as an issue in the results, but are not considered infeasible *per se*; very strong economic penalties, on the other hand, signify an infeasible scenario in our analysis.

We define very strong economic penalties as a jump in carbon price between 2020 and 2030 of at least US$1,000 per t CO_2e. Strong economic penalties are flagged when this increase is between 500 and US$1,000 per t CO_2e. These ranges are comparable to an increase in the price of crude oil over a 10-year period of about US$135–270 per barrel (strong penalty) or more (very strong

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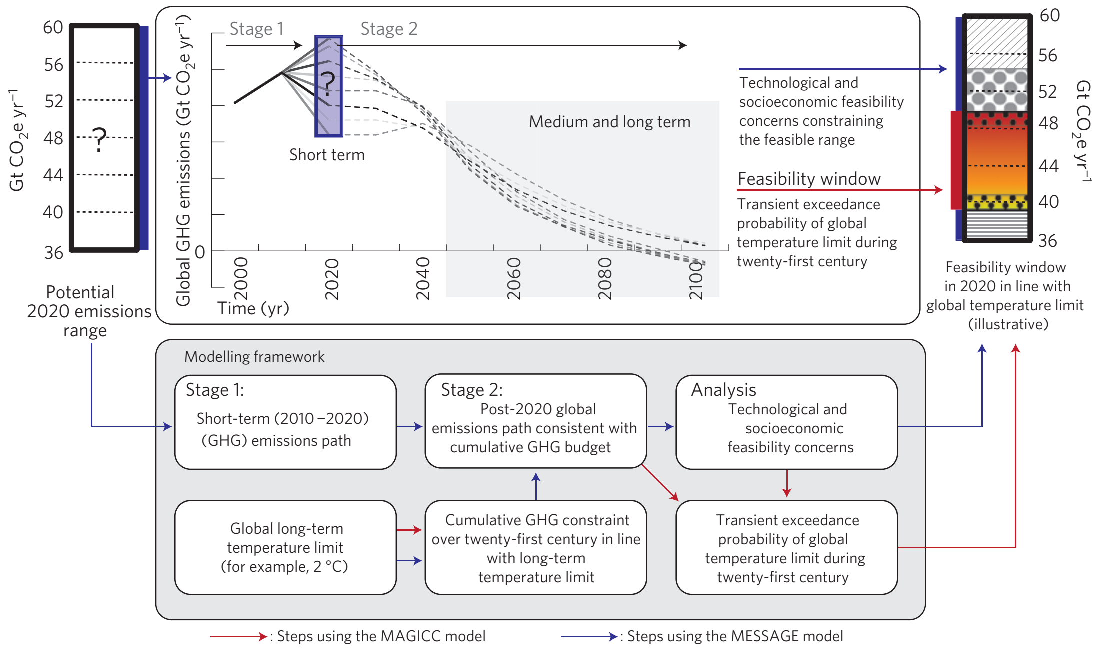

Figure 1 | Schematic representation of the two-stage model set-up to quantify the feasible 2020 emission windows to stay below 2 °C. After having simulated the transition from 2010 to a given GHG emission level in 2020 (Stage 1), MESSAGE optimizes the energy system configuration, for the rest of the century, given a cumulative GHG constraint that limits global temperature increase to below 2 °C relative to pre-industrial levels (Stage 2). Each scenario is analysed in terms of technological and socioeconomic feasibility concerns. With the MAGICC model, the risk of overshooting the 2 °C limit during the twenty-first century is computed for each feasible scenario. The final feasibility window is colour-shaded according to the overshooting risk. A detailed legend for the feasibility window at the right-hand side is provided in Fig. 2.

penalty), relative to the 2011–2012 level of US$100–120 per barrel. For comparison, crude oil prices increased by about US$100 per barrel between 2000 and 2008 from a relatively low US$25 per barrel in January 2000. Our strong economic penalty would thus clearly be a cause for concern, and our very strong penalty could substantially hamper future economic development.

Whether a particular mitigation goal is infeasible in our study depends on a number of factors, including the availability of low-carbon technologies, the levels of energy demand, and various political and social factors affecting how policies are implemented. We therefore carry out this analysis for a reference case and a number of different sensitivity cases (based on ref. 16), each defining a unique collection of assumptions and constraints on technologies, demands and policies. Our cases are summarized in Table 1, and a more detailed description is provided in the Supplementary Information. The cases span a range of possible futures, but they should not be considered exhaustive of all potential outcomes. The intent is to use the cases to provide core insights. For each case, an ensemble of scenarios is run with different 2020 emission levels.

In our reference case (intermediate demand), energy demand follows historical trends (that is, energy intensity improvements are only slightly faster than historical trends), and the scale-up of all low-carbon energy-supply technologies is assumed to be successful and pervasive worldwide. On the policy side, all countries are assumed to fully participate in a global climate agreement that aims at achieving the 2 °C target; whether by 2020, if climate policies are assumed to be in place by that time, or immediately thereafter. The sensitivity cases vary these core assumptions one-by-one to assess the resulting changes in the feasibility windows (Table 1 and Supplementary Information).

Quantified feasibility windows

We find that in the reference case, GHG emissions must stay below 55 Gt CO_2e yr^{-1} in the short term (2020) if global temperature increase is to be limited to less than 2 °C above pre-industrial levels in the long term. If emissions are higher than this level, our model indicates that it will be either technologically or economically infeasible (or both) to reduce GHGs fast or far enough after 2020 to meet the 2 °C target. The feasible lower limit to short-term mitigation in our reference case is 41 Gt CO_2e yr^{-1}. Therefore, we estimate the 2 °C-consistent feasibility window for 2020 to be 41–55 Gt CO_2e yr^{-1} (Fig. 2)—larger than estimates based on cost-optimal scenarios found in the present literature[7].

An important caveat is that the feasibility windows we estimate are based on the results of a single IAM. Previous model inter-comparison studies[17] have shown that the spread across models can be quite significant, owing to key structural differences and varied assumptions. This suggests that if similar analyses were conducted with other IAMs, the emission ranges would probably differ from those shown here. Our emission pathways are at the high end of the literature range of 2 °C-consistent scenarios[7] (Fig. 3a). This is because our analysis explicitly explores the maximum range of emissions in 2020, rather than exploring cost-optimal pathways.

By comparison, if the unconditional emissions reduction pledges in the Cancun Agreement are ultimately met, then 2020 emissions are estimated[9] to be 55 Gt CO_2e yr^{-1} (median; 51–60 Gt CO_2e yr^{-1} minimum–maximum range). This range lies directly on the upper frontier of the feasibility window of our reference case. To put our feasibility window results further in context, the lower end of our range is about 20% below global emissions levels in 2010, and the upper end is about 10% above 2010 emissions, representing a reduction from (unmitigated, no climate policy) baseline emissions of about 7.5%. Our baseline sees emissions growing to 59 Gt CO_2e yr^{-1} in 2020; this is at the high end of the range from the Special Report on Emissions (SRES) Scenarios marker scenarios[18] (47–60 Gt CO_2e yr^{-1}). In all of our scenarios, global emissions peak in 2020 at the latest. If emissions were to peak at a later date, the upper end of the feasibility window would close further.

When specific mitigation technologies are excluded, the 2020 feasibility window becomes compressed (Fig. 2). The no new nu-

Table 1 | Description of all cases.

CASE	Description	Influence rel. to reference
Demand cases		
Intermediate demand	Demand and energy efficiency improvements follow development paths that are only slightly faster than historical trends. The full portfolio of low-carbon energy-supply technologies are successful worldwide. All countries join in global mitigation efforts from now until 2020 (if required) and onwards.	Reference case
Low demand	As the reference case, however, substantial improvements in energy intensity in all end-use sectors (buildings, industry, transport), made possible through stringent efficiency measures and lower-energy lifestyles (includes advanced transportation, see below).	Window-opening
Supply cases		
Technology-limiting cases		
No new nuclear	No new investments into nuclear power from 2020 onwards; existing plants are fully phased out by 2060.	Window-closing
Limited land-based measures	Limitations are set to the mitigation potential from biomass, land use and forestry. The maximal total global biomass potential is further limited compared with the reference case (from 145 (220) EJ yr^{-1} to 80 (125) EJ yr^{-1} in 2050 (2100); based on ref. 46), and afforestation is not allowed explicitly for climate mitigation.	Window-closing
No CCS	The technology to capture and geologically store carbon dioxide (CCS) never becomes available. This impacts both the potential to implement lower emission options with fossil fuels and the possibility to generate negative emissions when combined with bio-energy.	Window-closing
Technology breakthrough cases		
Advanced transportation	Greater than expected progress with electric vehicle technologies, allowing them to meet a far greater share of mobility demands worldwide.	Window-opening
Advanced non-CO_2 mitigation	Continuous improvements in the mitigation potential of non-CO_2 GHGs, from agricultural CH_4 and N_2O sources, beyond best practice of technologies available at present.	Window-opening
Policy framework cases		
Delayed participation	The global 'South' delays its participation in global mitigation efforts until after 2030; emissions in these countries rise unconstrained until that time. The South in this sensitivity case consists of all countries outside Europe, North America, the former Soviet Union, Australia, Japan and New Zealand. It includes the emerging economies such as Brazil, India and China (see Supplementary Table S5 and Fig. S8 for details).	Window-closing
1.5 °C GHG budget	The cumulative global GHG emission budget for the twenty-first century is further reduced so that temperature increase relative to pre-industrial levels returns to below 1.5 °C by 2100 with a 50% probability; overshoot of the target is allowed before 2100.	Window-closing

Further details for each case can be found in the Supplementary Information. Note that Technology-limiting cases are independent from each other. For example, although the No new nuclear case implements a phase-out of nuclear power, the no CCS case again allows for the continued use of nuclear power.

clear case, for example, narrows the 2020 window by 5 Gt CO_2e yr^{-1}, reducing the upper end to 50 Gt CO_2e yr^{-1}. More strikingly, both the cases of limited land-based measures and no CCS (no carbon capture and storage) close the window entirely. This means that, assuming an intermediate level of future energy demand, no feasible transformation paths for 2 °C could be found by the model in these cases. A principal reason for this is the reduced or entirely eliminated potential for negative emissions[19]. Negative emissions are typically assumed to be achieved through a combination of biomass energy and capture and geological storage of the emitted carbon dioxide[20]. In our reference case, negative emissions scale up from around 0.6 Gt CO_2 yr^{-1} in 2030 to 12 Gt CO_2 yr^{-1} in 2100, well below the maximum of 30 Gt CO_2 yr^{-1} in 2100 found in the literature (1–13 Gt CO_2 yr^{-1} interquartile range, computed from scenarios with CCS from biomass energy from ref. 21).

In contrast, when further, more optimistic assumptions on mitigation options are made than in the reference case, the 2020 feasibility window widens. Figure 2 shows, in fact, that in both the full portfolio advanced transportation and advanced non-CO_2 mitigation cases, it becomes feasible to reach the 2 °C target without any GHG mitigation before 2020. Note, however, that any future technological advancement or breakthrough hinges on investments in research and development that begin immediately. Even if the 'no new nuclear' assumption is added to these cases, little or no mitigation by 2020 is required to keep the 2 °C target feasible. Assuming that these breakthroughs take place but that land-based measures are limited has a stronger effect, bringing the 2020 emissions limit down to 50–51 Gt CO_2e yr^{-1}. Finally, if CCS is assumed to be unavailable, the 2 °C target remains infeasible (the window closes entirely) despite the technological breakthroughs.

If future energy demand is substantially limited (the 'low demand' cases, Table 1 and Supplementary Information), baseline emissions in 2020 reach only 53 Gt CO_2e yr^{-1}, compared with 59 Gt CO_2e yr^{-1} in the reference case (Fig. 2). This is the result of non-climate-related energy efficiency and other demand reduction policies, which are assumed to be already in place by 2020. Under these conditions, no further short-term mitigation (beyond important efficiency improvements) is required to keep the long-term 2 °C target feasible, a robust finding that holds even if

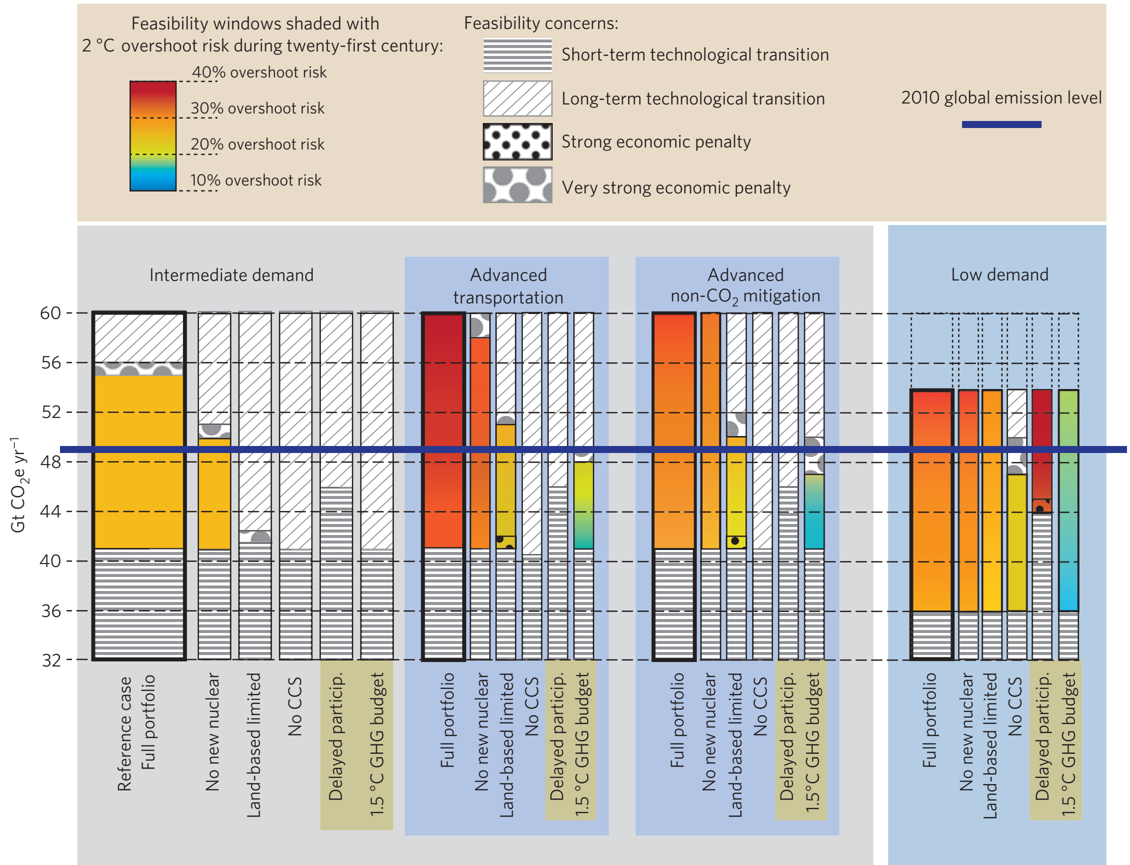

Figure 2 | Feasibility windows for global GHG emissions in 2020 required to limit global temperature increase to below 2 °C relative to pre-industrial levels. Twenty-four unique cases are shown. Feasibility windows (see also Fig. 1) in line with the 2 °C target for each case are represented by the colour-shaded inner parts of each bar, respectively. The 2 °C overshoot risk is the probability of exceeding the 2 °C temperature limit at any time during the twenty-first century (and equals 1 minus the probability to stay below 2 °C). For each case, areas with hatching represent ranges where no feasible scenarios were found owing to the lack of short-term (horizontal) or long-term (diagonal) technological mitigation options. Dotted areas represent economic feasibility concerns.

further constraints on nuclear or land-based mitigation measures are assumed. Furthermore, in contrast to all other cases, the 'low demand' case is the only one that retains the feasibility of achieving the 2 °C target when CCS is assumed to be unavailable; however, this case does require limiting emissions in 2020 to just 47 Gt CO_2e yr^{-1}. As a result of demand reduction measures, the low end of the feasibility window (36 Gt CO_2e yr^{-1}) is also lower than in the reference (intermediate demand) case.

Under a fragmented international policy framework, in which there is late accession of the global South (including emerging economies such as Brazil, India and China; see definition in Table 1 and Supplementary Information) into a global climate regime, it becomes considerably more difficult to reach the long-term 2 °C target. In fact, for the delayed participation cases, in which the South does not join the global mitigation effort until after 2030, we find no feasible solutions as long as future energy demand remains at the intermediate level. Interestingly, this picture does not change even in the more technologically optimistic advanced transportation and advanced non-CO_2 cases. Only if there is a global shift towards more energy-efficient modes of living does the feasibility window begin to open again (44–53 Gt CO_2e yr^{-1}, Fig. 2). Previous model inter-comparison studies[17] have also shown the infeasibility of limiting CO_2 concentrations to low levels when there is delayed participation among certain major international players.

Finally, we consider a situation in which Parties of the United Nations Framework Convention on Climate Change decide to switch to a lower long-term temperature target of 1.5 °C (see ref. 5). We find that the 1.5 °C target cannot be reached from our reference case and would require either breakthrough mitigation technologies or a slowing of energy demand growth. In the advanced transportation and advanced non-CO_2 mitigation cases, for instance, the feasibility window remains open: 41–48 Gt CO_2e yr^{-1} and 41–47 Gt CO_2e yr^{-1}, respectively. On the other hand, if the world were to follow an ambitious high-efficiency and low-demand path, the 2020 emissions window for reaching 1.5 °C would open significantly—much beyond what earlier assessments have found using simpler methods[6,9,22].

Pathway characteristics, costs and risks

The transformation towards a low-carbon energy system will inevitably require major changes in how energy is produced and consumed. For example, traditional coal-fired power plants (without CCS) will be some of the first technologies to be abandoned, given that coal has the highest carbon intensity of all conventional fossil fuels. As coal plants typically have very long lifetimes (approximately 50 years), early retirement of existing coal power infrastructure is a real possibility. We find that although the timing of this premature retirement differs depending on which 2020 GHG emission level is achieved, the total amount of premature-shutdown capacity by the end of the 2020s does not differ markedly (Fig. 3d). The total global installed coal-fired power capacity in 2010 in our model is about 1,400 GW. We find that either about 65% of existing coal plants are retired by 2020 and almost none afterwards, or only 5% of the fleet

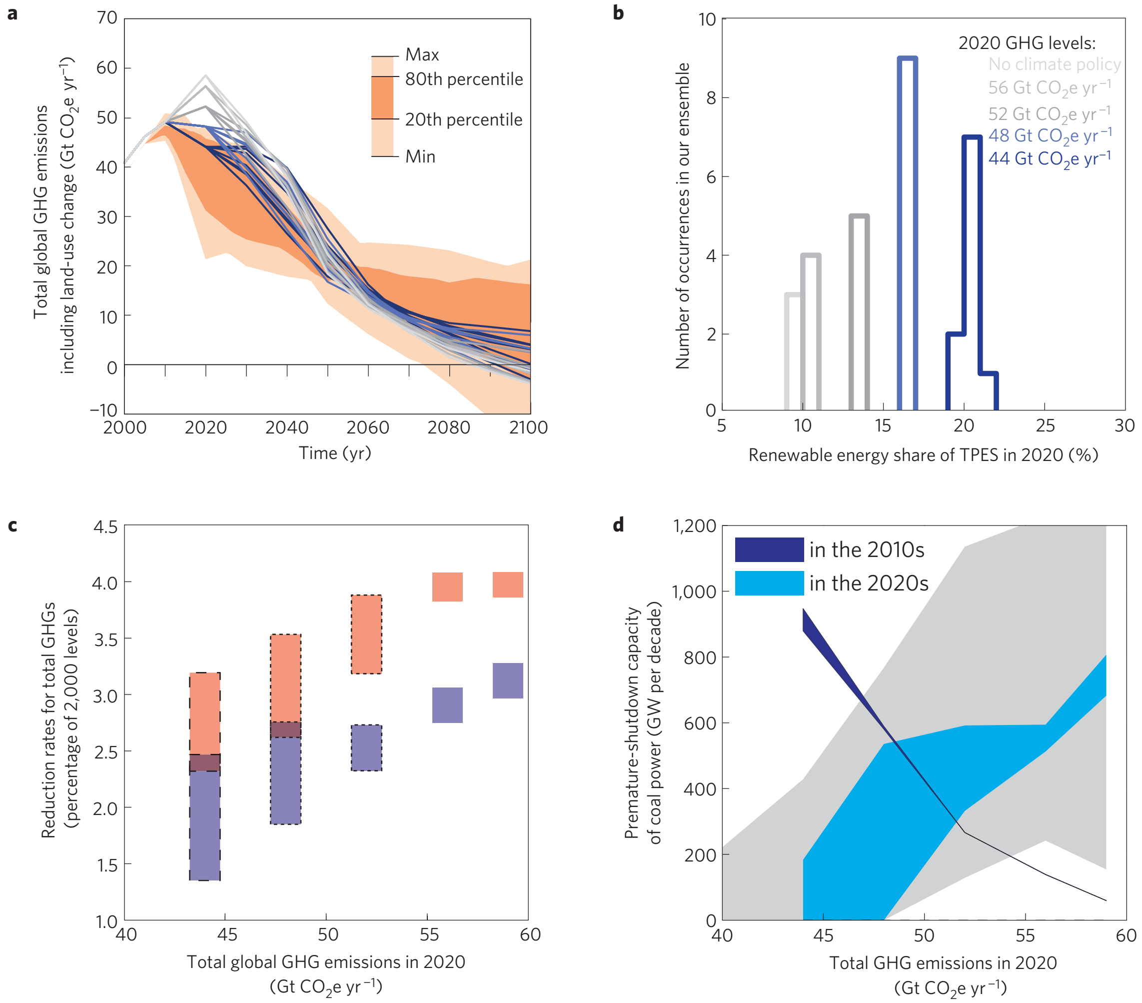

Figure 3 | Characteristics of all feasible 2 °C scenarios with intermediate energy demand. **a**, Total global GHG emissions (purple lines) compared to the range of scenarios in the literature (orange) with >66% probability to stay below 2 °C from ref. 7. **b**, Share of renewables in global TPES (direct equivalence method) as a function of total GHG emissions in 2020. **c**, Post-2020 reduction rates for total GHGs (minimum–maximum ranges), for both the maximum decadal (orange) and average (purple) reduction rates from 2020 to 2050. Edges summarize the proportion of scenarios considered feasible at that particular emission level: 50–75% (dashed edges), 25–50% (dotted edges), <25% (no edges). **d**, Premature shutdown of coal-fired power capacity. Both prematurely shutdown capacity in the 2010s (between 2010 and 2020, dark blue area) and in the 2020s (light blue area) are shown. Grey shaded areas indicate infeasible scenarios.

is retired by 2020 but 55% in the following decade. In the low demand case, 30–50% less infrastructure is retired prematurely (Supplementary Fig. S1).

A second anticipated element of any major energy system transition will likely be a pronounced shift towards renewable energy sources. In our baseline intermediate demand cases, for example, in the absence of climate policy by 2020, the global share of renewable energy in total primary energy supply (TPES, direct-equivalence method) is about 10% in 2020 (Fig. 3b). Under more stringent climate policy regimes, the share of renewables increases significantly: reducing emissions to 44 Gt CO_2e yr^{-1} by 2020 would necessitate a doubling of the renewables share (to approximately 20%) relative to the baseline case. In the low-demand case (Supplementary Fig. S2), a doubling of the renewable share (relative to no climate policy) would help to reduce global emissions in 2020 to 40 Gt CO_2e yr^{-1}. Note that the literature shows a 2 °C-consistent range[9] of renewable shares of 11–38% (2020 emissions: 39–49 Gt CO_2e yr^{-1}).

In addition, we find that both short- and long-term mitigation costs depend strongly on the emission reductions that have been achieved by 2020 (Table 2 and Supplementary Fig. S3). The more stringent the 2020 target, the higher the required mitigation costs and associated carbon prices by 2020 to achieve it—but the lower are the long-term mitigation costs (and also carbon prices in 2030) because less rapid reductions are required after 2020 to meet the 2 °C target. Lowering 2020 emissions implies thus greater mitigation costs in the short term, but generally reduced costs in the longer term. However, there is a 2020 emission level at which longer-term costs (2020–2050) become minimal. Letting emissions rise until 2020 above the least-cost level (around 44 Gt CO_2e yr^{-1} for the reference case) implies consistently and significantly higher costs (up to 30% by 2050, up to 50% by 2100; Table 2 and Supplementary Information S1) for staying below 2 °C in the long term. The stringency of emissions abatement by 2020 thus critically determines carbon prices and abatement costs post-2020.

Another important insight from Table 2 is that lower emissions by 2020 keep more options open and hence reduce the risk that limiting global temperature increase to below 2 °C becomes infeasible in the long term. In other words, low 2020 emissions hedge against the risk of undesirable technology ‘surprises’. For instance, in the case of the failure or limitation of specific key technologies (for example, the no new nuclear and limited land-based measures cases), pathways with lower

Table 2 | Overview of costs as a function of emissions in 2020 for our 2 °C technology cases.

Intermediate future energy demand														
Cumulative discounted energy system costs in scenario without climate policies (2005 US$ billion)														
	Until 2020:						**14,347**	**From 2020 until 2050:**						**38,450**
Mitigation costs (Percentage relative to scenario without climate policies)														
2020 total GHG level ($Gt\ CO_2e\ yr^{-1}$)	NoCP	56	52	48	44	40	36	NoCP	56	52	48	44	40	36
	Until 2020:							**From 2020 until 2050:**						
Reference case														
Full portfolio	INF	INF	3%	9%	17%	INF	INF	INF	INF	66%	61%	56%	INF	INF
No new nuclear	INF	INF	INF	9%	17%	INF	INF	INF	INF	INF	73%	66%	INF	INF
Land-based limited	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF
No CCS	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF
Advanced transportation														
Full portfolio	0%	1%	3%	9%	17%	INF	INF	47%	43%	41%	37%	36%	INF	INF
No new nuclear	INF	1%	3%	9%	17%	INF	INF	INF	54%	53%	47%	44%	INF	INF
Land-based limited	INF	INF	INF	9%	17%	INF	INF	INF	INF	INF	72%	68%	INF	INF
No CCS	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF
Advanced non-CO_2 mitigation														
Full portfolio	0%	1%	3%	9%	17%	INF	INF	50%	45%	44%	40%	38%	INF	INF
No new nuclear	0%	1%	3%	9%	17%	INF	INF	61%	53%	52%	48%	45%	INF	INF
Land-based limited	INF	INF	INF	9%	17%	INF	INF	INF	INF	INF	82%	77%	INF	INF
No CCS	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF
Low future energy demand														
Cumulative discounted energy system costs in scenario without climate policies (2005 US$ billion)														
	Until 2020:						**13,279**	**From 2020 until 2050:**						**30,003**
Mitigation costs (Percentage relative to scenario without climate policies)														
2020 total GHG level ($Gt\ CO_2e\ yr^{-1}$)	NoCP	52	48	44	40	36	32	NoCP	52	48	44	40	36	32
	Until 2020:							**From 2020 until 2050:**						
Full portfolio	0%	0%	2%	7%	14%	26%	INF	24%	22%	21%	20%	23%	30%	INF
No new nuclear	0%	0%	2%	7%	14%	27%	INF	26%	24%	22%	21%	24%	32%	INF
Land-based limited	0%	0%	2%	7%	15%	29%	INF	44%	39%	37%	34%	32%	39%	INF
No CCS	INF	INF	INF	7%	15%	29%	INF	INF	INF	INF	65%	52%	53%	INF

Costs for a scenario without climate policy (baseline; NoCP, no climate policy) are presented in terms of cumulative discounted energy system costs until 2020, and from 2020 until 2050. Mitigation costs are provided relative to the baseline and are given for all cases and feasible scenarios, respectively. The colouring shifts from turquoise, over green to orange as a function of increasing mitigation costs. Infeasible scenarios are marked with INF and in red. Costs are discounted to the beginning of each period, respectively.

2020 emissions still achieve the 2 °C target in the long term, albeit at higher costs.

In addition to cost metrics, annual global emission reduction rates are often used in mitigation analyses as a proxy for whether an emission pathway could be feasible or not[14,23,24]. On this point, our analysis corroborates previous findings in the literature[25,26]: between 2020 and 2050, none of our scenarios shows average GHG reduction rates exceeding 3.3% yr^{-1} relative to emissions in the year 2000 (Fig. 3c), and the maximum post-2020 CO_2 emission reduction rates in our scenario set never exceed 5.7% yr^{-1} relative to 2000 emissions (Supplementary Fig. S4a). Most of the reduction rates that we find over longer time periods and for all GHGs are thus significantly lower than the maximum rates of reduction of CO_2 alone.

Finally, although we use a cumulative emission budget as a proxy for staying below 2 °C when constructing our scenarios (see Methods), the risk of overshooting this target (colour-shaded feasibility windows in Fig. 2) varies depending on the trajectory[1,2,27] and mix of gases[1,27]. This risk is higher when short-term emissions in 2020 are higher, larger contributions of negative emission technologies are allowed in the long term, non-CO_2 gases (in particular methane) have a relatively larger share in the cumulative budget (and especially a higher emission rate at the time of the temperature peak[27]), or a combination of these is true. By the time negative emissions technologies (primarily from fuel and electricity production from biomass combined with CCS) are sufficiently scaled up in our scenarios—which occurs at some point during the middle part of the century—the cumulative GHG budget has already been exceeded. Only later in the century do emissions return to within the allowable budget. Following a path in which the potential of and dependence on negative emissions is limited or eliminated (as in the limited land-based mitigation or no CCS cases) significantly reduces the overshoot risk. The opposite is true if technologies for very rapid and deep reductions become available during the century (for example, advanced non-CO_2 mitigation and advanced transportation). Furthermore, some pathways have relatively lower methane emissions than other pathways, either because the methane mitigation potential is larger (advanced non-CO_2 mitigation) or because the CO_2 mitigation potential is smaller (limited land-based mitigation and no CCS). This contributes to the relatively lower transient overshooting risk in these pathways. In the advanced transportation and low demand pathways, where CO_2 emissions can be reduced rapidly, methane emissions are the highest.

Discussion

With our sensitivity cases, we can assess the relative importance of measures in achieving the 2 °C target. First and foremost, improving the efficiency of energy systems is key (see refs 16,28). Substantially limiting energy demand has the largest impact on our feasibility window, in that it significantly relaxes the necessary emission reductions that must be achieved by 2020. Second, consistent with earlier studies[17,29], the availability of CCS and the immediate participation of all regions in global mitigation efforts also seem to be very important factors. It is infeasible to achieve 2 °C in our framework if these two critical assumptions are not realized, unless demand is low. Third, the full potential of land-based mitigation measures seems to be required in our scenarios to achieve the 2 °C target (see ref. 30), unless breakthrough mitigation technologies (advanced transport and non-CO_2 mitigation) are available. Finally, although the availability of nuclear power as a mitigation option opens the 2020 feasibility window to some extent, nuclear power does not seem to be a required mitigation option (unless 2020 emissions exceed 49 Gt CO_2e yr^{-1}; consistent with refs 16,31).

Taking into account all aspects of our analysis, limiting global GHG emissions in 2020 to the window of 41–47 Gt CO_2e yr^{-1} would keep the widest array of options open to achieve the 2 °C target. This range is similar to the multi-model emissions range consistent with 2 °C (with >66% chance) based on least-cost scenarios from the literature[7], as well as to global 2020 emission benchmarks based on simpler scenario methods (see ref. 32 and references therein). However, the range presented here contains much richer information. Staying within this window in 2020 hedges against the risks of potential technological failures and the uncertainty of future socio-political developments; yet even outside this window, feasible, yet more risky, pathways are found to exist. In our model, the 47 Gt CO_2e yr^{-1} emission limit would thus maintain the feasibility of the 2 °C target in the event that the contribution of nuclear, land-based mitigation measures or CCS is either restricted or completely unavailable. However, the feasibility of such transformations will critically depend on the level of future energy demand.

Finally, if the long-term climate goal would be strengthened in 2015 to 1.5 °C, the 41–47 Gt CO_2e yr^{-1} window for 2020 might still preserve the option of achieving this goal, contingent on major technological breakthroughs in transportation or non-CO_2 mitigation options or on a low-energy-demand future. Present emissions are slightly above 50 Gt CO_2e yr^{-1} (ref. 33). Global emissions would therefore have to peak and decline before the end of this decade to land in the 41–47 Gt CO_2e yr^{-1} window in 2020. In contrast, present unconditional emission reduction pledges would lead to global emissions in 2020 of 55 Gt CO_2e yr^{-1} (central estimate[9]) and thus do not constitute a robust path for limiting global temperature increase to below 2 °C.

Methods

We employ the MESSAGE IAM to project and analyse possible future evolutions of global GHG emissions in combination with the reduced complexity climate and carbon-cycle model MAGICC (refs 12,34), version 6. An elaborated description of the MESSAGE model is given in the Supplementary Information and earlier literature[10,16,35]. MAGICC is set up to probabilistically[1] span the uncertainties in carbon-cycle[36], climate system[37] and climate sensitivity[13] of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), is constrained by historical observations of hemispheric land/ocean temperatures[38] and historical estimates for ocean heat-uptake[39], and is used to compute the transient exceedance probabilities for each scenario. Temperature increase relative to pre-industrial values is computed relative to the average temperature between 1850 and 1875.

In this analysis we run MESSAGE in a two-stage set-up[35] (Fig. 1). In the first stage, the model simulates a possible range of GHG emission outcomes to 2020. It has no knowledge of the future beyond 2030 (referred to as 'myopic') and therefore makes no attempt to optimize the energy system towards an eventual long-term climate target. We represent climate policies by 2020 with global carbon caps of varying stringency, ranging from the level likely to be realized in the absence of climate policy (about 59 Gt CO_2e yr^{-1} in the reference case) down to the level at which it becomes technologically infeasible within our modelling framework to realize further short-term emission reductions (about 40 Gt CO_2e yr^{-1} in the reference case). Subsequently, the state of the global energy system to 2020 is frozen, and at that time the model immediately and unexpectedly learns about a global GHG emission budget constraint for the remainder of the century. In this second stage, the model optimizes the energy system evolution over the twenty-first century such that cumulative GHG emissions stay within this constraint.

Owing to climate policies, fossil-fuel technologies will be substituted with renewables that emit low or zero levels of short-lived climate forcers such as black carbon or sulphur oxides. Therefore, emissions of short-lived climate forcers will probably decrease across the board as well[40–42]. No further measures are assumed on these species. The emission budget we specify equals 2,500 Gt CO_2e over the twenty-first century, which has been iteratively estimated from standard, cost-optimal (one-stage, full-century) MESSAGE runs so that it limits global temperature increase to below 2 °C with >66% probability given an IPCC AR4-consistent set-up of MAGICC (ref. 13). This budget includes emissions of all GHGs of the so-called 'Kyoto basket of gases', which contains carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorinated compounds and sulphur hexafluoride, and is expressed in terms of CO_2e emissions computed with 100-year global warming potentials reported by the IPCC (ref. 43).

Each combination of short-term emission level and long-term budget, within the given scenario family (that is, technology or policy framework case), represents a unique scenario. Every scenario is assessed to determine whether possible feasibility concerns arise. In this study, a scenario is considered infeasible if supply- and demand-side technologies cannot match useful energy demands (across all regions and time periods) at reasonable costs[16,44]. Failure to do so could be the result of, for example, limits to the rate of technological diffusion, constraints on the scale of technologies due to intermittency and variability concerns, and limits to the size of the available resource base. Our model can also employ so-called backstop technologies to meet energy demand. Backstops represent technologies whose characteristics are not yet known today but that are assumed to be able to supply low-carbon energy at a very high cost in the future. In practice, no feasible scenario in our set contained backstops. Consistent with earlier literature[17], we assume pathways are infeasible that have discounted carbon prices exceeding US$1,000 per t CO_2e in 2012.

We span the entire possible range of GHG emission levels in 2020 with 4 Gt CO_2e increments. The upper and lower borders of each emission window are subsequently sampled at 1 Gt CO_2e increments. For the analysis of the various additional aspects of the 2020 feasibility window (for example, costs, shares of renewable energy and so on) only data at the coarse 4 Gt CO_2e increment resolution are taken. Owing to the uncertainty in historical emission inventories[32,45], we indicate the historical 2010 emission level used by the MESSAGE model in Fig. 2 as a point of comparison for the 2020 emission windows. This value (49 Gt CO_2e yr^{-1}) is closely in line with recent estimates[33].

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Author contributions

All authors were involved in designing the research; J.R. performed the research in close collaboration with D.L.M.; all authors contributed to writing the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to J.R.

Competing financial interests

The authors declare no competing financial interests.