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Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies

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Mitigation scenarios that achieve the ambitious targets included in the Paris Agreement typically rely on greenhouse gas emission reductions combined with net carbon dioxide removal (CDR) from the atmosphere, mostly accomplished through large-scale application of bioenergy with carbon capture and storage, and afforestation. However, CDR strategies face several difficulties such as reliance on underground CO_2 storage and competition for land with food production and biodiversity protection. The question arises whether alternative deep mitigation pathways exist. Here, using an integrated assessment model, we explore the impact of alternative pathways that include lifestyle change, additional reduction of non-CO_2 greenhouse gases and more rapid electrification of energy demand based on renewable energy. Although these alternatives also face specific difficulties, they are found to significantly reduce the need for CDR, but not fully eliminate it. The alternatives offer a means to diversify transition pathways to meet the Paris Agreement targets, while simultaneously benefiting other sustainability goals.

The Paris Agreement on climate change aims at 'holding the increase in the global average temperature to well below 2 °C', and 'to pursue efforts to limit the temperature increase to 1.5 °C'[1]. However, the knowledge of how to achieve these 'Paris goals' is still limited. The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report examined a considerable amount of literature on scenarios leading to a radiative forcing at around 2.6 W m^{-2} above pre-industrial levels by 2100, corresponding to a likely change (that is, >66%) of not exceeding the 2 °C goal[2]. The IPCC report hardly discussed the question of how to keep warming below 1.5 °C (corresponding to a forcing level of around 1.9–2.0 W m^{-2}) due to lack of existing literature (with some exceptions[3,4]). New scenarios for this goal are currently being developed in response to the policy interest, and the IPCC will publish a special report on this topic[5].

Mitigation scenarios developed using integrated assessment models (IAMs) can provide insight into strategies that drastically reduce greenhouse gas (GHG) emissions[2,6,7]. This is typically achieved by finding a cost-optimal combination of technologies, given model rules on system behaviour and a set of technology and policy assumptions (for example, delay in participation)[2,8]. Scenarios consistent with the Paris goals reduce GHG emissions by switching to zero- and low-carbon energy options, increasing energy efficiency, using carbon capture and storage (CCS), reducing non-CO_2 GHG emissions, eliminating emissions related to land-use change and stimulating afforestation[2,7]. Cost-optimal scenarios, without delays or constraints in technology deployment, project GHG emissions to peak around 2020, followed by rapid emission reductions, carbon neutrality sometime in the second half of the century and eventually net CO_2 removal (CDR) from the atmosphere[2,7,9]. This can be referred to as the default strategy. Of the 114 scenarios assessed by the IPCC leading to forcing values of around 2.6 W m^{-2} (likely probability for 2 °C), 104 show net CDR in the second half of the century, mostly achieved by bioenergy with CCS (BECCS), sometimes complemented by reforestation[2]. The total CDR in these scenarios is substantial—that is, typically around 10 GtCO$_2$ per year in 2100 or 200–400 GtCO$_2$ over the course of the century[10,11]. Moreover, the same literature suggests considerable cost increases, or even infeasibilities, if CDR is not available[2]. The relatively few 1.5 °C scenarios published to date show pathways similar to the 2 °C scenarios, but with deeper reductions occurring earlier in time[3].

Several publications question whether it is possible to achieve the IAM-based scenarios and, especially, the proposed scale of CDR[11,12]. Their concerns relate to the possible impacts of land-use-based CDR options, such as bioenergy and reforestation, on food production, biodiversity, GHG emissions and albedo[11]. Moreover, while geological storage capacity estimates exceed several thousand gigatonnes of CO_2, questions remain about whether the full capacity is available[13,14]. Finally, CCS has currently little societal support as demonstrated by the difficulty in implementing real-world experiments[13,15]. As several key CDR options share these concerns, they cannot readily substitute one another if future performance is poorer or more difficult than projected. Since it will soon be impossible to achieve ambitious climate goals without implementing CDR to compensate overshoot of the carbon budget (that is, cumulative CO_2 emissions corresponding to a climate target)[2], an assessment of their use or alternative options will have to be made now, even if the situation of net CDR will not occur before 2050[16].

As IAMs select technologies on the basis of relative costs, they normally concentrate on reduction measures for which reasonable estimates of future performance and costs can be made. This implies that some possible response strategies receive less attention, as their future performance is more speculative or their introduction would be based on drivers other than cost, such as lifestyle change or more rapid electrification[17,18]. Moreover, existing studies hardly look into more aggressive implementation of options such as rapid implementation of the best available technologies or deep reduction of non-CO_2 GHGs (with some exceptions, for example,

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Table 1 | Scenario framework

Scenario	Short name	Description and key assumptions
Baseline	SSP2	SSP2 implementation[19].
Default 2.6	DEF_2.6	Climate policy is implemented by introducing a uniform carbon tax in all regions and sectors from 2020 onwards; the radiative forcing level is 2.6 W m^{-2} in 2100[19].
Default 1.9	DEF_1.9	Climate policy is implemented by a uniform carbon tax in all regions and sectors from 2020 onwards; the radiative forcing level is 1.9 W m^{-2} in 2100[23].
Efficiency	Eff	Rapid application of the best available technologies for energy and material efficiency in all relevant sectors in all regions.
Renewable electricity	RenElec	Higher electrification rates in all end-use sectors, in combination with optimistic assumptions on the integration of variable renewables and on costs of transmission, distribution and storage.
Agricultural intensification	AgInt	High agricultural yields and application of intensified animal husbandry globally.
Low non-CO_2	LoNCO2	Implementation of the best available technologies for reducing non-CO_2 emissions and full adoption of cultured meat in 2050.
Lifestyle change	LiStCh	Consumers change their habits towards a lifestyle that leads to lower GHG emissions. This includes a less meat-intensive diet (conforming to health recommendations), less CO_2-intensive transport modes (following the current modal split in Japan), less intensive use of heating and cooling (change of 1 °C in heating and cooling reference levels) and a reduction in the use of several domestic appliances.
Low Population	LowPop	Scenario based on SSP1, projecting low population growth.[29]
All	TOT	The combination of all the options described above.

Note: The affixes _2.6 and _1.9 refer to scenarios that assume climate policies are enacted aiming to reach 2.6 and 1.9 W m^{-2} forcing targets by the end of the century, respectively.

ref. [19]). Technology development could also be more rapid than typically assumed in IAM model runs (for example, the costs of batteries in recent years[20]). The lack of focus on such alternative scenarios implies that insight into their consequences is lacking. This paper explores a set of what-if scenarios that explore these alternative assumptions, and analyses the extent to which they reduce the need for CDR. The evaluated measures (Table 1) have been mentioned in scientific literature and could possibly limit CDR use. While the options considered could be feasible (see Supplementary Information), actual implementation will certainly not be effortless. The rate and level with which the measures are introduced are meant to reflect ambitious, but not unrealistic implementation. There is, however, not a clear metric to compare the ambition level. This means that the results need to be interpreted relative to the what-if description. However, selection based on marginal costs (that is, cost-optimal scenarios) also does not guarantee a similar ease of implementation as often measures other than cost-optimal model outcomes have been implemented in the past[21]).

Integrated assessment of alternative pathways. In the analysis presented here, the IAM IMAGE[22] is used to explore alternative pathways leading to a radiative forcing level of 1.9 W m^{-2} in 2100. The scenarios are all based on the IMAGE implementation of the Shared Socioeconomic Pathway 2 (SSP2) scenario[19] (see Supplementary Information). The SSP2 scenario describes a future with median assumptions for input parameters, making it a relevant starting point for the analysis. The deep mitigation scenarios based on the standard set-up of the model (that is, DEF_2.6 and DEF_1.9 in Table 1) are implemented via the introduction of a uniform global carbon price to meet the radiative forcing target[19], resulting in a strategy similar to the default strategy in the literature. The 1.9 W m^{-2} scenario also follows this strategy, but earlier and more forcefully[23]. The alternative scenarios are developed by implementing narrative-based changes to the input assumptions, mostly in the 2020–2050 period (Table 1 and Supplementary Information). The results take possible feedbacks included in IMAGE into account. Several assumptions are based on the 'sustainable development' SSP1 scenario[19].

First, we evaluate the 'pure' impact of the measures under baseline conditions. Subsequently, their impact on the use of energy-based CDR in deep mitigation scenarios is examined. This is achieved by developing a mitigation scenario with the same carbon price trajectory as used as in the default 1.9 W m^{-2} scenario (DEF_1.9) but applying a 'cost premium' on BECCS to reduce its use to a level consistent with the 1.9 W m^{-2} target (see Supplementary Information). Finally, we combine the different options to explore the question of what would be needed to totally avoid the use of BECCS in IMAGE. Since it is nearly impossible to put a price tag on most of these measures, none of the scenarios has been evaluated in terms of costs.

In the efficiency scenario (Eff), current investment barriers to efficiency are assumed to be overcome and efficient technologies are adopted in transport, industrial production, buildings and use of materials. For example, only the most efficient transport vehicles are sold, while more efficient material use leads to less use of steel and clinker, leading to an energy efficiency improvement of 25% compared to SSP2. In the renewable electricity scenario (RenElec), rapid electrification takes place driven by technological breakthroughs in storage and load management, increasing the share of electricity from 21% now to 46% in 2050 (compared to 31% in SSP2). This development is combined with a steady expansion of solar and wind technologies, building on the rapid progress in the last few years. The agricultural intensification scenario (AGInt) assumes strategies to further intensify agriculture, leading to higher crop yields and more land-efficient livestock farming (similar to SSP1). In the low non-CO_2 scenario (LoNCO2), mitigation is driven by stringent enforcement of measures to reduce end-of-pipe emissions and by introduction of in vitro (cultured) meat, produced on the basis of stem-cell technology, and input of energy and proteins (mostly based on soya). The viability of this last strategy depends on further development of technology[24], but also on social acceptance[25]. The lifestyle change scenario (LiStCh) assumes a radical value shift towards more environmentally friendly behaviour, including a healthy, low-meat diet, changes in transport habits and a reduction of heating and cooling levels at homes. Such a shift could be motivated by both environmental and health concerns[26–28]. The low population scenario (LowPop), finally, assumes a decrease in fertility rates in most regions, which could be achieved by stronger education policies[29]. Here, we used the SSP1 population scenario that follows the low end of projections for global population.

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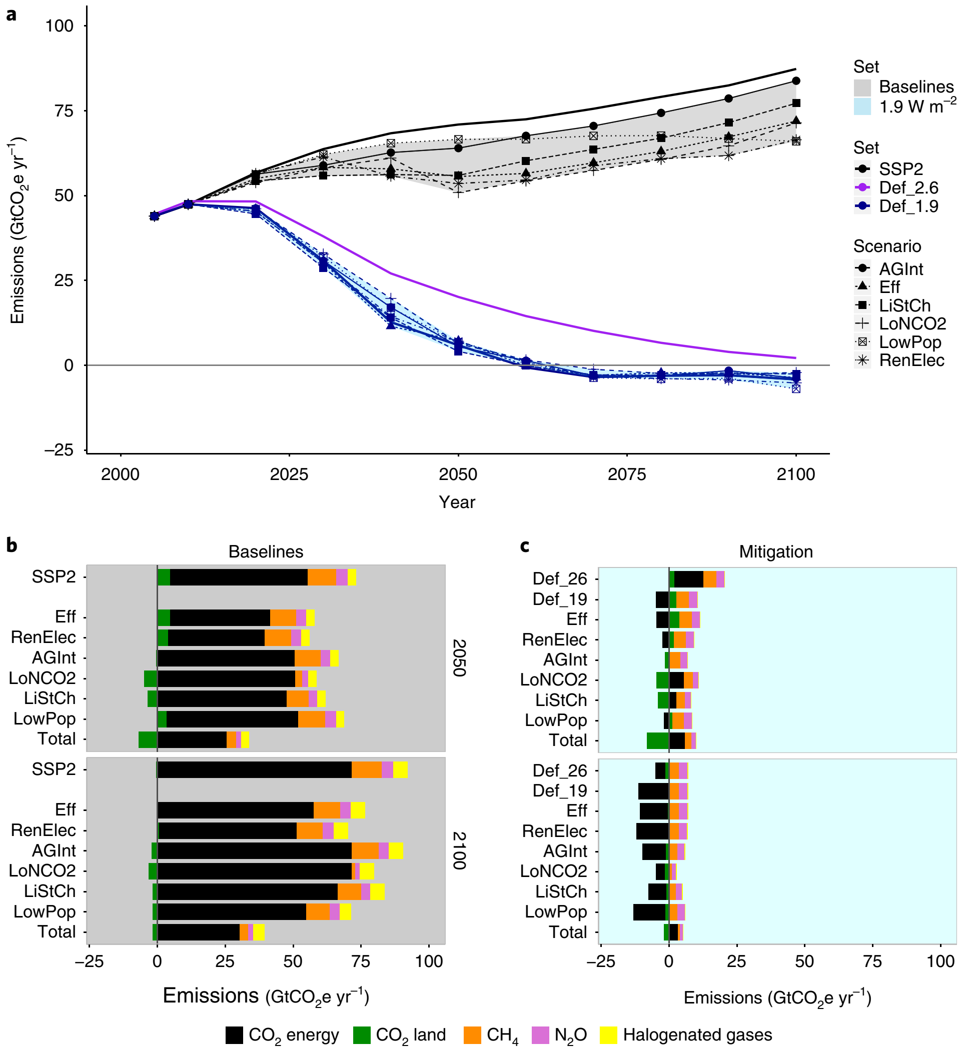

Fig. 1 | GHG emission for the baseline and mitigation scenarios. **a**, Total emissions. **b**,**c**, Emissions for each emission category for the baseline (**b**) and mitigation scenarios (**c**). Emission categories include CO_2 emissions from energy (black) and from land-use change (green), CH_4 emissions (orange), N_2O emissions (purple) and halogenated gases (yellow). The background shading in **b** and **c** refers to the colour of the scenario category in **a** (baseline, 2.6 and 1.9 W m^{-2}).

Impact on emissions. In the IMAGE SSP2 baseline, annual emissions increase from 50 GtCO_2e in 2015 to around 70 GtCO_2e in 2050 and 80 GtCO_2e in 2100. Deep reductions are needed to reach emission pathways consistent with a 2.6 and 1.9 W m^{-2} radiative forcing target (Fig. 1a). Looking first at the alternative scenarios without further climate policy, Fig. 1b shows that 2050 emissions reductions range from 10% in the low population scenario to 30% in the renewable electrification scenario compared to SSP2, partly reflecting the speed at which these changes can be introduced (demographic changes occur more slowly). While the lifestyle change, low non-CO_2 and agricultural intensification scenarios mostly impact non-CO_2 and land-related CO_2 emissions, the efficiency, renewable electrification and low population scenarios are more effective in reducing fossil-fuel-related CO_2 emissions. By 2100, the strongest reductions are found in the renewable electrification and low population scenarios (25%).

Obviously, none of the alternative pathways leads by itself to emission reductions large enough to implement the Paris Agreement (Fig. 1a). Therefore, they are complemented by climate policy simulated by a uniform carbon tax to induce further emission reductions (Fig. 1c). In the default 1.9 W m^{-2} scenario, strong emission reductions are achieved for CO_2 and non-CO_2 gases compared to the baseline. For CH_4 and N_2O, the emission reduction is around 50% compared to the baseline. For CO_2, emission reductions are deeper and already negative in 2050. The net negative CO_2 emission flux is the sum of positive and negative fluxes in the energy and land-use systems (Fig. 2a). The rapidly declining energy-related emissions result from reductions in fossil-fuel emissions (black) and an increase in the use of BECCS. The use of BECCS in a situation with or without net CDR has different implications. If overall CO_2 emissions are net positive, BECCS can still be replaced by zero-emission technologies. However, if emissions are net negative, BECCS can be substituted only by other CDR options to achieve a similar emission pathway. Therefore, Fig. 2 also shows the share contributing to net negative emissions. The results show that BECCS can be competitive even decades before a net CDR situation occurs, offsetting emissions from sectors where reduction is more difficult to achieve (for example, air traffic and freight transport). In the default scenario, in fact, part of the fossil-fuel-related emissions remains until the end of the century. While CO_2 removal by BECCS is reported as energy-related emissions, CO_2 emissions from the related land conversion are accounted for under land use. The expansion of bioenergy crop area leads to increased land-use emissions, while at the same time the

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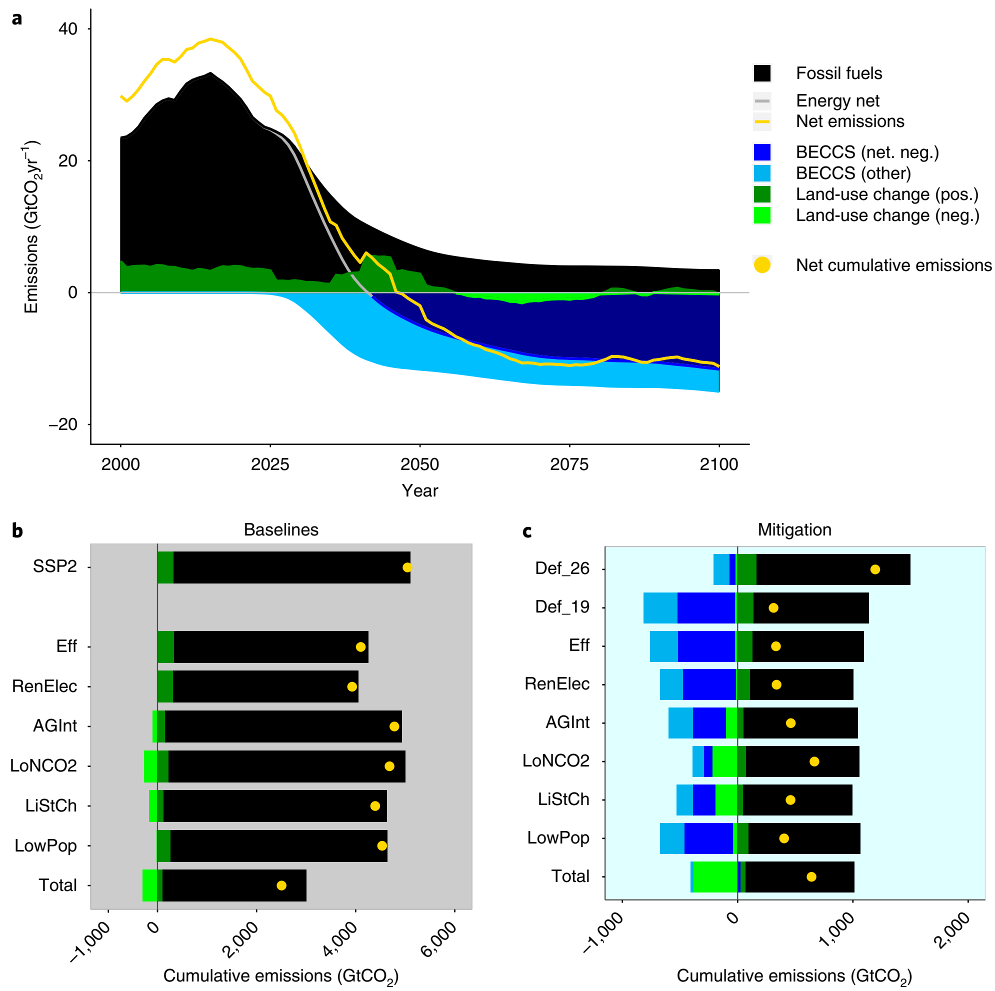

Fig. 2 | CO_2 emissions for the baseline and mitigation scenarios. a, CO_2 fluxes for the default 1.9 W m^{-2} scenario. The plot shows the sum of all categories (yellow line), positive fossil fuel emissions (black), negative emissions from BECCS (dark blue for net negative emissions, light blue for other BECCS) and land-use-change emissions (dark green for positive emissions, light green for negative emissions). **b**,**c**, The same flows in terms of the cumulative emissions for the 2010–2100 period, for baseline cases (**b**) and mitigation scenarios (**c**). The yellow marker represents the net emissions. The shading in **b** and **c** refers to the colour of the scenario category in Fig. 1a (baseline, 2.6 and 1.9 W m^{-2}).

afforestation policies lead to less emissions. In the default 1.9 W m^{-2} scenario, as a result, land-use CO_2 emissions remain close to zero from 2050 onwards.

The cumulative CO_2 fluxes are shown in Fig. 2b,c retaining the colour scheme of Fig. 2a. The baseline impacts (Fig. 2b) show again the individual impact of the options. Focusing on the impacts for the 1.9 W m^{-2} scenarios (Fig. 2c), the impact on the total 2010–2100 CO_2 budget is shown by the yellow marker (thus indicating the net result of the energy and land-use flows). In the default strategy, the cumulative CDR amounts to 750 $GtCO_2$ (of which 500 $GtCO_2$ is net CDR) to partly offset a positive emission budget of greater than 1,100 $GtCO_2$, leading to a net total emission ('carbon budget') of 350 $GtCO_2$ (in line with the range reported by the IPCC[30]). The deep reductions in non-CO_2 GHG in the low non-CO_2 scenario (and lifestyle change and agriculture intensification, in which reduced cattle stocks play an important role) allow for a higher amount of total cumulative CO_2 emissions and less need for CDR. A significant reduction in the energy-related CDR can also be achieved in scenarios reducing agricultural area, leading to an uptake of CO_2 through regrowth of natural vegetation, as illustrated for the lifestyle and low non-CO_2 scenarios. Finally, also reducing CO_2 emissions rapidly can contribute to less CDR need (all other scenarios).

A rapid transformation in energy consumption and land use is needed in all scenarios. All mitigation scenarios show a rapid transformation of the energy and land-use systems (Fig. 3). In the energy system, the uptake of low-carbon energy sources increases rapidly in all scenarios from 15% to about 80% in 2050 for the 1.9 W m^{-2} scenarios worldwide. This concerns mostly bioenergy, CCS and solar, wind and nuclear power (see Fig. 3c,d). Energy efficiency also contributes to emission reduction as illustrated by the reduction of the bars (Fig. 3c). Figure 3 reflects the key characteristics in each scenario such as a high penetration of wind and solar power in the Renewable Electrification case and low energy consumption in the low population scenario. Projections of modern bioenergy consumption by 2050 (with and without CCS) vary between less than 100 EJ in the low non-CO_2, lifestyle change and renewable electrification scenarios, and 200 EJ in the default mitigation scenario (Fig. 3 and Fig. 4a for BECCS) with agriculture and forestry residues accounting for 80 EJ yr^{-1}. IPCC assessed the sustainable potential supply of bioenergy in 2050 to be most likely be at least 100 EJ yr^{-1} and possibly 300 EJ yr^{-1}.

The bioenergy demand is reflected in the required production area (Fig. 3a,b). In the default mitigation scenario (DEF_1.9), more than 600 Mha is required for bioenergy (for comparison, the current crop and pasture area are 1,600 and 3,300 Mha, respectively).

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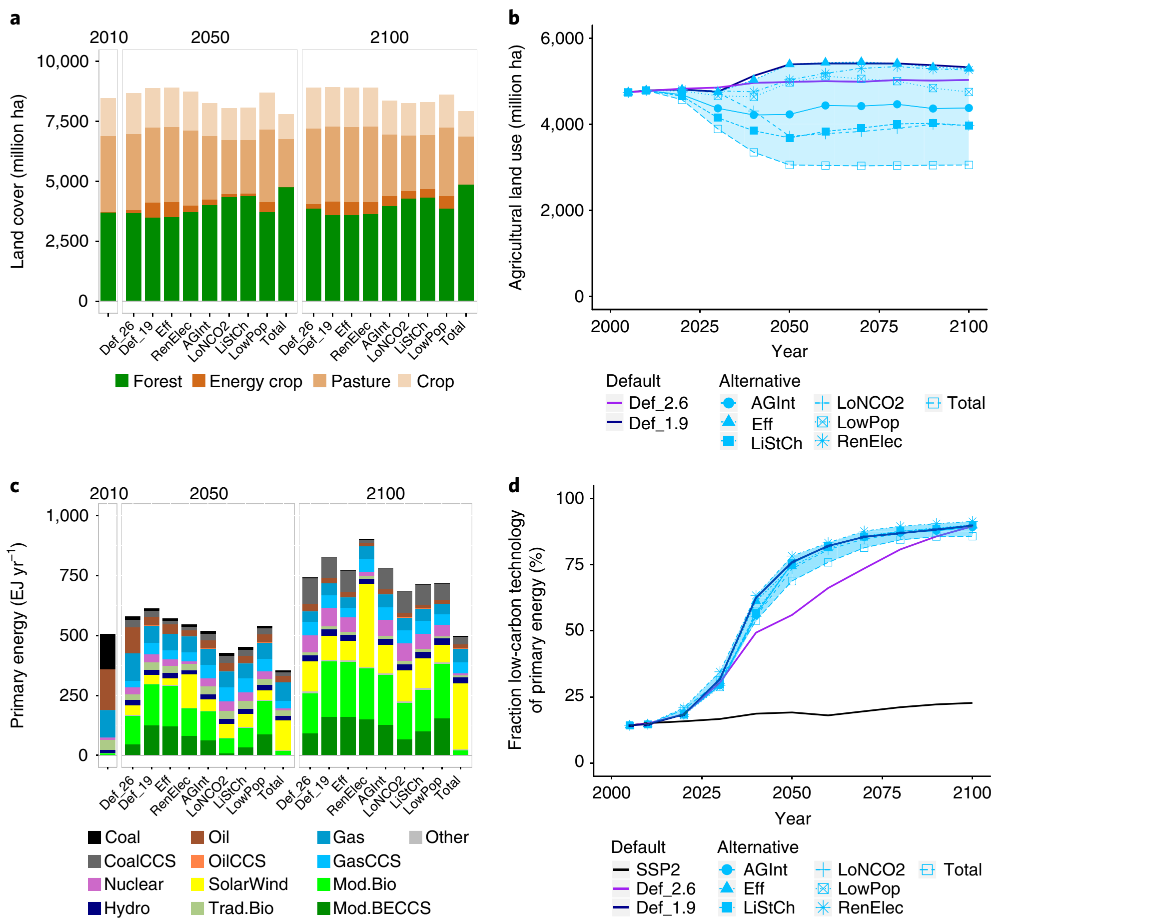

Fig. 3 | Transformations in land use/cover and energy use. a,**b**, Land cover for agriculture crops, pasture, energy crops and total forest area (natural and managed) by category (**a**) (remaining natural land cover types are not included) and the evolution of agricultural land use (the sum of crop, pasture and bioenergy area in **a**) over time (**b**). **c**,**d**, Primary energy use per energy carrier (**c**) and the share of low-carbon technology in total primary energy (**d**). Low-carbon technology is defined as solar, wind, nuclear power, bioenergy (traditional and modern), hydropower and fossil fuels (coal, oil, natural gas) with CCS.

As a result, total agricultural area (pasture, crop land and land for bioenergy) expands considerably. Most alternative mitigation scenarios lead to considerably lower land use, reducing the area for food production or bioenergy, or both. In the low non-CO_2 and lifestyle change scenarios, the amount of pasture and cropland to produce animal feed is reduced by 20–25%, resulting from reduced animal meat consumption. This allows for an increase in forest area, critical for terrestrial carbon storage. In the agricultural intensification scenario, a similar result is obtained, but due to increasing efficiency in agriculture and livestock farming.

Different transition pathways. The analysis show that alternative pathways exist allowing for more moderate use and postponement of BECCS (Figs. 3 and 4a). This allows more time to further develop CDR and implies less reliance on bioenergy in the next decades. A stabilizing or even declining global population after 2050 (as often projected) could reduce the pressure from competing land claims, allowing for more bioenergy production or reforestation[31]. To date, the IAM literature has mostly concentrated on the default mitigation strategy, and typically did not consider aggressive replacement strategies as considered here. This established the clear relationship between forcing target and net CDR from energy (Fig. 4b)[9,10]. The range in net CDR BECCS use in the literature is caused by differences between models and their assumptions, including baseline emissions, the possible rate of change and existing differences among models regarding alternatives to BECCS (for example, non-CO_2 reductions and afforestation). For instance, the authors of a previous study[32] emphasized that BECCS reliance could be reduced in their scenarios if efficiency would be more forcefully implemented. To reduce BECCS use to zero in IMAGE, all options would have to be combined (Fig. 4b, total marker).

The volume of CDR or BECCS can thus be limited by a range of societal and technological factors and choices. Given the possible disadvantages of BECCS, it is important to seriously discuss and appraise such alternative pathways. This could focus on issues such as feasibility, social acceptance, associated costs and benefits, requiring input from other scientific disciplines to complement the model-based scenarios. Clearly, the alternative pathways will not emerge without introducing large changes in current energy and land-use systems; this will require support and action by a range of actors (for example, consumers changing behaviour in the lifestyle change scenario). This could clearly be associated with barriers to implementation given the (perceived) interests of different actors (for example, opposition to lifestyle changes) and/or require technological breakthroughs (for example, to achieve high penetration rates of intermittent renewables). However, most alternative pathways are also associated with important co-benefits. As evidence suggests that rapid transitions are much more likely if they lead to perceived welfare improvement, this can be important[33,34]. For instance, pathways based on reduced consumption of animal products (via dietary change) not only reduce land-use and non-CO_2 emissions, but also improve human health[25]. Secondly, efficiency measures and

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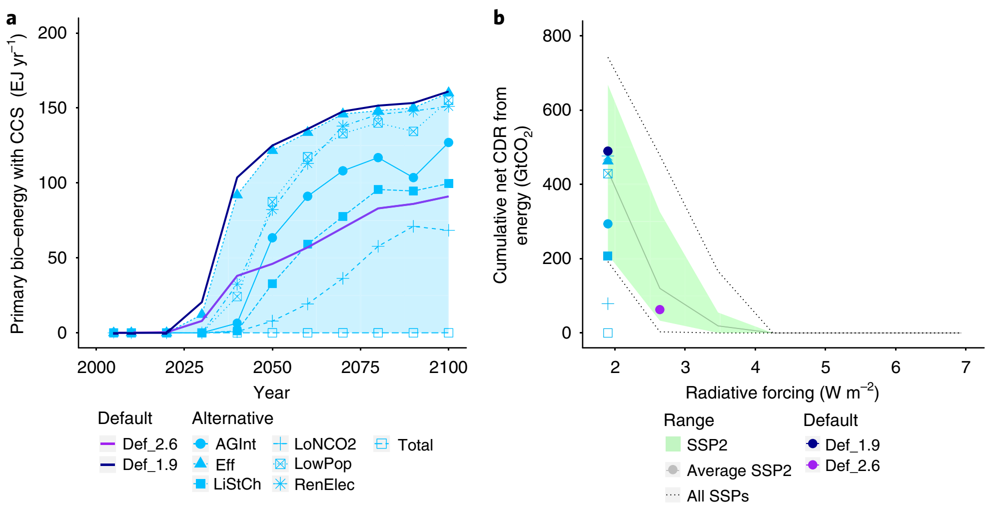

Fig. 4 | The use of BECCS in mitigation scenarios. a, The use of BECCS over time (that is, the bottom category of the energy bar chart in Fig. 3). **b**, The cumulative net CDR from energy (BECCS) as a function of radiative forcing target. Shown are the scenarios described in this paper (dots), and also the literature range (green area: 10–90th percentile for SSP2; grey line: average; dotted lines: range for all SSP scenarios). The dark lines in **a** and the black dots in **b** refer to the default 2.6 and 1.9 W m^{-2} scenarios.

transition to renewables may not only reduce GHG emissions, but also reduce air pollutant emissions and improve energy security[35]. The low population pathway would reduce overall resource consumption and could be combined with an investment in education[28]. Finally, reforestation (especially in the lifestyle, agricultural intensification and low population pathways) can be combined with biodiversity strategies if natural vegetation is allowed to grow back[36].

Exploring the feasibility of these pathways requires not only insights from IAMs, but also in-depth knowledge of social transitions[18]. As such, subsequent research may focus on the technological and social feasibility of the presented transition pathways, including heightened attention to regional differences. There are also other options that might have similar effects, including increases in waste recycling, rapid forced closure of fossil-fuelled power plants, enhancement of soil carbon in agricultural land and direct air capture technology.

Finally, while this study shows that alternative options can greatly reduce the volume of CDR to achieve the 1.5 °C goal, nearly all scenarios still rely on BECCS and/or reforestation (even the hypothetical combination of all alternative options still captured 400 $GtCO_2$ by reforestation). Therefore, investment in the development of CDR options remains an important strategy if the international community intends to implement the Paris target. In that light, the set of alternative scenarios leads to a diversification of possible transition pathways, including more explicitly the option of changing consumption patterns. Given the uncertainties related to the default strategy, a more diverse portfolio of options and an open debate concerning their contribution could provide more flexibility to ensure that the goals are reached.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available at https://doi.org/10.1038/s41558-018-0119-8.

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Author contributions

D.P.v.V. supervised the work and developed the original idea. All authors were involved in the design of the experiments, the model analysis and contributed to the writing of the article.

Competing interests

The authors declare no competing interests.

Additional information

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Methods

Overall description. In the analysis presented here, the integrated assessment model IMAGE[22] is used to explore alternative pathways leading mostly to a radiative forcing level of 1.9 W m^{-2} in 2100. The scenarios are based on different assumptions that could minimize the use of CO_2 removal (CDR). The scenarios are all derived from the IMAGE implementation of the SSP2 scenario[19]. The SSP2 scenario describes a future with middle-of-the-road assumptions for input parameters, making it a relevant starting point for the analysis. Two default mitigation scenarios are based on the standard set-up of the model, and implemented via the introduction of a uniform global carbon price to meet the radiative forcing target[19]. The alternative scenarios are developed by implementing narrative-based changes to the input assumptions, mostly in the 2020–2050 period (see Table 1 and Supplementary Information). We evaluate first the 'pure' impact of the measures under baseline conditions. Subsequently, their impact on the use of energy-based CDR in deep mitigation scenarios is examined. This is achieved by developing a mitigation scenario with the same carbon price trajectory as used as in the default 1.9 W m^{-2} scenario (DEF_1.9) but applying a 'cost premium' on BECCS to reduce its use to a level consistent with the 1.9 W m^{-2} target. Since it is nearly impossible to put a price tag on most of these measures, none of the scenarios has been evaluated in terms of costs. We finally combine the different options to explore the question of what would be needed to totally avoid the use of BECCS in IMAGE. Below we describe the IMAGE model and the scenario implementation of the baseline, the alternative assumptions and the reduced CDR scenarios.

IMAGE-3 model. IMAGE-3 is an integrated assessment model describing possible future changes in the human and Earth system and their interaction[22]. The IMAGE model is documented in detail on a dedicated website and in print[22]. IMAGE is a simulation model, which means that changes in model variables are calculated on the basis of the information from the previous time step. In terms of structure, IMAGE is a model framework, with some components linked directly to each other via model code while others are connected through soft links (this means that models are run independently with information exchange via data files). Key linkages between the human and Earth system are emissions, land use, climate feedbacks and policy responses. Socio-economic parameters are described for 26 regions. The Earth system describes changes in key natural environment systems such as the carbon and hydrological cycle and climate. Most environmental parameters are calculated at a geographical grid of 30 by 30 min or 5 by 5 min (the difference scales depend on the submodel[22]).

The development of driving forces such as population, economic development, lifestyle, policies and technology change are major assumptions used in the energy and agricultural economy models of IMAGE[22]. The energy model consists of a system-dynamics simulation model. In the energy system model, future energy systems are described in terms of changes in energy demand, energy conversion and supply. Energy demand is calculated for five key sectors (that is, industry, transport, residential energy use, service sector and other energy use) on the basis of an assessment of energy service demand changes (mobility, production of materials, heating and so on). Subsequently, this demand can be met by different energy carriers, with market shares determined by changes in costs and preferences. The demand for final energy is supplied by primary energy carriers using a detailed representation of the electricity system and supply models for the various energy carriers. Again, the competition between the energy carriers is mostly based on relative costs and preferences. The agro-economy model MAGNET is a computable general equilibrium model[37] that is connected via a soft link to the core model of IMAGE. MAGNET uses information from IMAGE on land availability and suitability and on changes in crop yields due to climate change and agricultural expansion into heterogeneous land areas. The results from MAGNET on production and endogenous yield (management factor) are used in IMAGE to calculate spatially explicit land-use change, and the environmental impacts on carbon, nutrient and water cycles, biodiversity and climate.

Changes in energy, food and biofuel production are used in the Earth system to induce land-use changes and emissions of carbon dioxide and other greenhouse gases. A key component of the Earth system is the LPJmL model[38,39]. LPJmL describes the terrestrial carbon cycle and vegetation dynamics and is used to determine the productivity of natural and cultivated ecosystems for each grid cell on the basis of so-called plant and crop functional types. Based on the regional production levels, a set of allocation rules in IMAGE determine the actual land cover. The rules allocate agricultural production to cells with high yield, close to existing agriculture area and close to water. The emissions projections based on the energy and agriculture projections are used to derive changes in concentrations of greenhouse gases, ozone precursors and species involved in aerosol formation on a global scale. Climate change is calculated as global mean temperature change using a slightly adapted version of the MAGICC 6.0 climate model[40]. The model accounts for several feedback mechanisms between climate change and dynamics in the energy, land and vegetation systems. For the purpose of the SSP scenarios, climate impacts have been switched off, with the exception of the impact of climate change and rising CO_2 concentration on natural vegetation.

Description of key scenario assumptions. *SSP2-baseline scenario.* The analysis has been performed on the basis of the SSP2 scenario as implemented in IMAGE[9,22,19]. In the SSP2 scenario, which forms part of the overall SSP set, middle-of-the-road assumptions have been made for all key model assumptions. This includes demographic assumptions (global population increases to around 9 billion people in 2050 and stabilizes after that), economic growth, technology change and lifestyle. The changes in agriculture and the energy system in the short term are similar to projections by the Food and Agriculture Organization of the United Nations and the International Energy Agency[19,41,42]. The IMAGE implementation of the SSP2 scenario leads to trends that are similar to those of the SSP2 marker for overall energy production, land use and radiative forcing, but represents particular characteristics of the IMAGE model[19]. The default response scenario described in this paper leading to the 2.6 W m^{-2} target is very similar to the climate policy scenarios described elsewhere (except for small updates in emission factors)[19].

Default mitigation approach. In the default scenarios, climate policy is introduced via a global price on greenhouse gas emissions. This induces a set of responses throughout the system. Emissions from the energy system are reduced as a result of a reduction of fossil fuel use (substituted by low-greenhouse gas-emitting technologies—renewables, carbon capture and storage, nuclear power and bioenergy—and efficiency[6]). Similarly, non-CO_2 emissions from agriculture and energy system activities are reduced by changes in emission factors representing mostly so-called end-of-pipe technologies[43]. Finally, afforestation and reduced deforestation measures are implemented consistent with the greenhouse gas price[42].

Alternative scenarios. Table 1 (see Supplementary Information) provides an overview of the most important assumptions made for each alternative scenario. The assumptions are further discussed below. The scenarios explored here are what-if scenarios, and results should be assessed against the description of the key assumptions. As the measures are very different in nature, it is simply not possible to directly compare them (for example, impact of the low population scenario versus lifestyle change). Assumptions on the rate of introduction and the extent of the changes made have been based on available literature: options were implemented in a way that was considered ambitious yet not unrealistic. The feasibility of implementation might not be so different from that for normal 'cost-optimal' scenarios, as empirical research has shown that successful transitions are not necessarily cost-optimal[17,18,21]. Since it is nearly impossible to assign costs to these measures, we do not evaluate the scenarios in terms of costs.

We use the following experiment to test how the impact of the alternative measures could lead to less BECCS use. First, for each alternative option, the assumptions in Table 1 (see Supplementary Information) were implemented without making any other change (baseline conditions). This allowed us to evaluate the direct impact of each option on emissions, energy and land use. Several measures lead to abandonment of agricultural land. If not used for other purposes, this land will be used in IMAGE for regrowth of natural vegetation, as described by LPJml using the settings of the natural vegetation. This means that while carbon is sequestered, the same area can also serve other ecological functions. Next, the scenarios were combined with the carbon price trajectory of the default 1.9 W m^{-2} scenario. Using the same carbon price means that the same level of policy effort is assumed except for: the introduced measures; and BECCS (see below). The additional reduction measured (see Supplementary Information, Table 1) means that the alternative scenarios originally overachieved the 1.9 W m^{-2} target; however, an additional 'BECCS price' was introduced to explore how the overachievement could be used to reduce the use of BECCS. The 'BECCS price' was implemented in 2020 and held constant throughout the rest of the century. The BECCS price was at the point where the 2100 forcing of the scenario was equal to 1.9 W m^2 (see Supplementary Fig. 1).

The scenarios were evaluated for their climate outcomes using the MAGICC-6 model included in the IMAGE framework[40]. The cumulative CO_2 emissions ('CO_2 budget') presented are therefore a result of the calculations and are not prescribed as a target. The budgets found for the default scenarios are consistent with those determined by comparable methods in the Fifth Assessment Report of the IPCC[29,44]. Several of the alternative scenarios are obviously characterized by relatively high cumulative CO_2 emissions, as they reduce non-CO_2 gases more than most scenarios in the literature. The budgets reported here are less than those reported by a recent study[45] that re-estimated the so-called threshold exceedance budgets on the basis of estimates of observed increase in global mean temperature and lower non-CO_2 emissions. However, correcting for the methodological differences (for example, the type of carbon budget) is likely to reduce these differences. Moreover, the general finding of the paper that it is possible to reduce CDR needs for stringent climate targets remains true.

Lifestyle change. The lifestyle scenario explores the possibility that environmentally friendly and resource-efficient lifestyles are adopted by a majority of the population worldwide. The scenario includes dietary change, food waste reduction and changes in transportation and residential energy use. For dietary change, we assume a quick transition to a healthier diet (the so-called Wilett diet) between 2020 and 2050, with low levels of meat consumption: 10.4 kcalories per capita per day of cattle, 16.0 of pork, 32.3 of eggs, 33.2 of poultry and 13.0 of fish and

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seafood[27]. The reduced consumption of meat proteins is compensated by increasing pulses/oilcrops (mostly soy) and adjusting staples/luxuries to keep the total calories as in the default scenario. Earlier implementations of this scenario have been described in detail[26,46]. Food waste as a fraction of total demand is reduced in households (10% less avoidable waste per year starting in 2011, reaching 98% reduction in 2050), and in storage and distribution systems (5% less waste per year starting in 2011, reaching 86% in 2050) (for details, see ref. [46]). For transport, changes are made to reduce transport volume and the use of energy-intensive modes. The new parameterization leads to less private vehicle use through increased car sharing and more mass transit options and non-motorized options (walking, cycling). Secondly, it leads to reducing air travel demand (for details, see refs [26,47]). For residential energy use, changes are made in heating and cooling demand, and appliance ownership and use. For heating and cooling, the base temperature has been adapted by 1 °C downward and 1 °C upward, respectively[27]. Water heating demand is reduced by assuming reduced shower time of 25%. Household electricity demand is curtailed by reducing the ownership of appliances to a maximum of two per household. This does not affect appliance ownership in households that have not yet satiated basic energy function demands. Tumble dryers, however, are assumed to be completely phased out. We also assume environmentally conscious behaviour in domestic appliance use (reducing standby and smarter use of appliances). The demand for plastics and chemicals is reduced to historically observed rates (for details, see ref. [27]).

Agriculture intensification. In the agricultural intensification scenarios (AGI_BL and AGI_19), optimistic assumptions are made for the development of crop yields and the efficiency of livestock production systems. Maximum crop yields per region are derived from SSP1 and SSP5[42] (these yields are implemented by 70% in 2050 and by 100% in 2100). Livestock systems are assumed to globally converge to the most efficient systems for up to 80% in 2100. The efficiency gains are mostly possible due to large-scale technological improvements such as improved feed digestibility and animal health, as well as higher animal productivity from genetic improvement and reduced age at slaughter[48]. As traditional livestock systems are assumed to continue to exist, no full convergence is assumed[49].

Low non-CO_2. This scenario explores the impact of further reducing non-CO_2 greenhouse gases (methane, nitrous oxide, fluorinated gases and black carbon) using the best available technologies and additional technological progress. To a large extent, this is realized by end-of-pipe measures (for example, in the fossil fuel industry, chemical industry and in agriculture). These measures are assumed to increase towards the maximum abatement in the year 2050 and to remain at this level up to 2100. In 2030, half of the maximum reduction is achieved, going beyond the standard settings in IMAGE. It is estimated that with current techniques, relative emission reductions in the oil and gas industry can reach up to 95%[50,51]. A 100% reduction would require additional efforts to develop new techniques. Emissions from underground coal mining can, in principle, be fully mitigated with (often uneconomical) removal of ventilation air methane[52,53]. Emissions from surface coal mining are much lower, but to a large degree also impossible to mitigate, leading to an estimated maximum reduction potential of 90%. Based on these sources, the maximum reductions were set at: methane from: gas/oil production 100%, coal production 90%. Emission reduction potentials in the agricultural sector have recently been assessed on the basis of a literature review[54]. Successful complete global deployment of all available reduction measures is estimated to lead to reductions of slightly less than assumed in this study. Some emissions are expected to remain partly unavoidable (CH_4 from enteric fermentation in ruminants, N_2O emissions from nitrogen release from fertilizers and uncollected manure). Based on the literature, maximum CH_4 reductions are set to: enteric fermentation in ruminants 73%, sewage 95%, landfills 100%, animal waste/manure 100%. N_2O emissions reductions are set at: fertilizer use 80%, animal waste/manure 75%. For fluorinated gases, we assume the maximum reduction to be 97%, while for black carbon, emission factors are assumed to be minimized, based on the maximum feasible reduction levels from the GAINS database[55].

In addition, this scenario assumes a technological breakthrough and mainstream acceptance of cultured meat, starting in 2035. Scientists working on cultured meat indicated that large-scale production could start in 2030[24]. We assume that by 2050, 80% of meat and eggs (but not fish and seafood) are replaced by cultivated meat, which is grown directly from corn and small amounts of soy. The inputs are based on earlier scenario analyses—that is, 1.197 kg of corn and 0.008 kg of soybeans per kilogram of meat (or 2.4 kcal corn and 0.02 kcal soy per kilocalorie of meat)[56].

Electrification and rapid penetration of renewables. The electrification scenario (REN_BL and REN_1.9) assumes rapid electrification in the demand sectors, combined with low integration challenges for renewable energy due to optimistic assumptions about flexibility provision, grid expansion and storage. Electrification of demand sectors is achieved by either stimulating the use of electricity by changing the preference factors for electricity (industry) or disallowing the use of non-electric technologies (transport and residential sector). Globally, the electricity shares in end-use increase to 48% for residential, 33% for transport and 47% for industry. For freight and air travel in the long term also hydrogen- or electricity-based modes become available. At the moment, aircraft manufacturers are already considering the introduction of electric planes around 2030[57]. In this study, hydrogen-based technologies have been assumed, given the higher feasibility of transporting this energy carrier over large distances with relatively low costs[58]. The penetration of wind and solar in supply is increased by reducing the integration constraints following a different setting in the default data set[59]. In addition, conditions for early retirement of fossil power capacity are relaxed and power sector foresight on carbon price development is increased.

Population. The SSP2 population pathway is a middle-of-the-road scenario following the medium variant of the IIASA-VID-Oxford projections[29]. This leads globally to a population size in 2050 of 9.2 billion people and in 2100 of 9 billion people. Although controversial, limiting population growth can be effective in reducing environmental pressure (see also ref. [60]). Here, we have replaced the population of SSP2 by the one of SSP1, leading to a population of 8.4 billion in 2050 and 6.9 billion in 2100. These differences are caused mainly be a faster reduction of fertility rates. Educational attainment of younger adult women can be a critical factor to achieve this[29]. The lower population level leads to less consumption of energy and food.

Efficiency. In the high-efficiency scenario, we assume a quick transition to the best available technologies in terms of energy use and material use for 2025 onwards. In the power sector, new plants are all efficient and distribution losses are minimized. In the transport sector, new cars and airplanes need to be efficient from 2025 (cars less than 1.2 $MJ\,km^{-1}$) and for other transport modes also efficient technologies are implemented based on the assumed best practices for 2050[61,62]. In cement production, only efficient dry kilns are built with preheater and precalcination (2.9 MJ per tonne of clinker)[63], while demand is set lower and the cement to clinker ratio is assumed to improve to 60–70% (2025) and 55% (2050). This is considerably lower than current assumptions in most regions; China's clinker to cement ratio is currently 58%[64,65]. The whole steel production sector moves to world best practice (15.6 GJ per tonne of steel)[66] and the recycling rate of metal available to use as obsolete scrap improves to 80%[67] (was 70%)[68]. In the residential sector, only appliances with the lowest energy consumption are allowed, including a complete shift to light-emitting diode lighting. Highly efficient building shells are assumed (in line with the best current practices) that reduce heating and cooling demand intensity (that is, per unit floor space). The fraction of plastics produced from recycling of post-consumer waste is increased. Finally, in services and other industry higher energy-efficiency improvement rates are assumed.

Data availability. The data that support the findings of this study are available from the corresponding author upon request.

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