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Reducing sectoral hard-to-abate emissions to limit reliance on carbon dioxide removal

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To reach net-zero greenhouse gas targets, carbon dioxide removal (CDR) technologies are required to compensate for residual emissions in the hard-to-abate sectors. However, dependencies on CDR technologies involve environmental, technical and social risks, particularly related to increased land requirements for afforestation and bioenergy crops. Here, using scenarios consistent with the 1.5 °C target, we show that demand and technological interventions can substantially lower emission levels in four hard-to-abate sectors (industry, agriculture, buildings and transport) and reduce reliance on the use of bioenergy with carbon capture and storage. Specifically, demand measures and technology-oriented measures could limit peak annual bioenergy with carbon capture and storage use to 0.5–2.2 $GtCO_2e$ per year and 1.9–7.0 $GtCO_2e$ per year, respectively, compared with 10.3 $GtCO_2e$ per year in the default 1.5 °C scenario. Dietary change plays a critical role in the demand measures given its large share in residual agricultural emissions.

With the adoption of the Paris Agreement, 196 parties agreed to hold the increase in global average temperature to well below 2 °C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5 °C (ref. 1). To accomplish this, CO_2 emissions need to reach net zero (that is, a balance between anthropogenic emission sources and sinks) around 2050 (5th to 95th percentile range from 2035 to 2070), while net-zero greenhouse gas (GHG) emissions is reached about 10 years later in most scenarios[2]. Over the past few years, 151 countries, 265 cities with a population of half a million or more and more than 1,000 of the 2,000 largest companies in the world have set net-zero emission targets[3]. These targets often encompass all GHGs but sometimes focus on only CO_2. The emergence of net-zero targets has led to a growing debate on how to attain net-zero targets[4–6] and on concerns about dependencies on carbon dioxide removal (CDR) technologies[6]. Here, consistent with most net-zero formulations, we focus on achieving net-zero GHG emissions.

Rather than aiming for complete decarbonization in each sector individually, scenario studies show that achieving net-zero emissions is more easily achieved by maintaining a level of residual emissions in some sectors, balanced by sinks in other sectors[7]. In fact, the scenarios assessed by the IPCC in AR6 that reach net-zero CO_2 do so by allowing, on average, 11 $GtCO_2$ residual emissions annually, compensated through CDR measures elsewhere. Only 5% of the scenarios report residual emissions of less than 5 $GtCO_2$, equal to more than 10% of current CO_2 emissions, in the net-zero year[8].

Residual GHG emissions largely consist of CO_2 emissions from energy-intensive industries (consisting mainly of the steel, cement and chemical industries), international transport (mainly air and shipping) and non-CO_2 emissions from agriculture (mainly from livestock,

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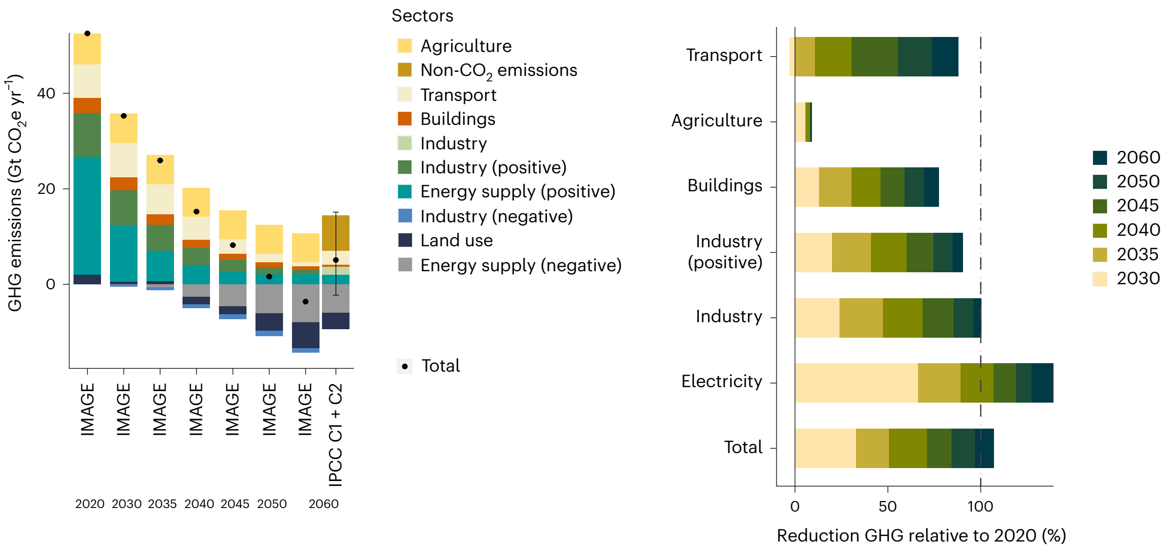

Fig. 1 | Projected global GHG emissions in the Reference 1.5 °C scenario (left) and reductions by sector in 2060 relative to 2020 (right). The reference scenario keeps global temperature below 1.5 °C with more than 67% probability by the end of the century. Emissions in 2060 are compared with the mean of the IPCC assessed scenarios in the category C1 and C2. The C1 and C2 category refers to all scenarios ($n = 230$) that limit warming to 1.5 °C (>50%) with no or limited overshoot (C1) and with overshoot (C2). The black dot indicates the median and the error bar the 25–75th percentile range (from −2.27 $GtCO_2e$ to 15.12 $GtCO_2e$). Non-CO_2 emissions are grouped in one category in the IPCC scenarios, while IMAGE allocates non-CO_2 emissions per sector. Industry includes cement process emissions and emissions from coke production and represents heavy industry and other industrial sectors. Transport includes international shipping and aviation and other transport sectors. Land use refers to land use, land-use change and forestry (LULUCF).

crop fertilization and paddy rice cultivation)[7]. Technical limitations in bringing emissions to zero, combined with more complex value chains, spatial and conditional specificities, long capital or in-use lifetimes and lack of societal support, makes transformations in these sectors more challenging than in a homogeneous sector such as the power sector[9,10]. In the buildings sector, achieving net-zero emissions can be difficult as well, due to the granularity of the sector with many actors involved, site-specific conditions and the slow capital turnover[11–13]. We therefore refer to these sectors as hard-to-abate (HtA) sectors.

The most important CDR measures applied in scenarios to compensate for these residual emissions are bioenergy with carbon capture and storage (BECCS), afforestation and reforestation, and in some scenarios, direct air carbon capture and storage. All of these measures involve environmental, social and economic risks. For example, bioenergy crops and afforestation require large amounts of land, with possible impacts on food security, water availability and biodiversity, which raises questions around feasibility and sustainability of their large-scale application[14–19]. Moreover, it is difficult to make sure that forests continue to remain in the future, leading to a risk of non-permanence[20]. Direct air carbon capture and storage requires almost no land, but is still very costly and requires large amounts of energy[21]. Particularly uncertain is the geological storage capacity and logistics required for large-scale application of carbon capture and storage (CCS)[22].

Owing to the challenges of large-scale CDR and especially BECCS, limiting the reliance on BECCS could enhance the feasibility of achieving net-zero emissions. This requires reducing emissions in the HtA sectors further than usually assumed in default net-zero scenarios. However, only a limited number of scenarios target residual emissions in the HtA sectors[2]. In this Article, we explore and assess demand and technological options for limiting residual emissions in the HtA sectors. We do so by first discussing the barriers to fully reduce emissions in the HtA sectors and the possible additional demand- and technology-oriented measures and policies that could help overcome these. This is done based on a comprehensive literature review (Supplementary Information). We then develop a set of new scenarios for the IMAGE integrated assessment framework (Methods) that include additional policies to support cost-effective measures to reduce emissions in the HtA sectors[23]. IMAGE is particularly suited for this analysis due to its relatively detailed representation of the HtA sectors, allowing to evaluate targeted measures and their impact on energy and land interactions, thereby capturing CDR implications. While previous studies have acknowledged the connection between HtA sectors and their impact on BECCS usage[9,10,24], this study dives deeper into assessing the feasibility of restricting BECCS by specifically targeting these challenging sectors.

Results

First, the results of the 'Reference 1.5 °C' scenario are discussed, followed by a short discussion of potential additional measures for reducing emissions in HtA sectors, and then the impact of these measures on emissions in HtA sectors and on the reduced reliance on CDR measures are presented and discussed.

Reference scenario

The four HtA sectors (that is, heavy industry, international transport, agriculture and buildings) face both common and specific challenges in terms of climate change mitigation. Common challenges include relatively fast service growth, limited availability of readily available technological emission reduction measures and lack of public support. The industry and international transport sector face additional specific hurdles, such as the international competitive markets, large upfront costs and the long lifetime of infrastructure. Specific challenges in the buildings and agriculture sector include a wide diversity of actors and limited financial means combined with site-specific conditions[25–31]. In the agriculture sector, limited availability of reduction measures is a very important challenge.

Due to these challenges, the pace of emission reductions in most 1.5 °C scenarios is relatively slow in these sectors and the extent to which emissions are reduced is limited compared with the reductions in electricity generation, transport on land and land use. This is illustrated by Fig. 1, left, showing a typical 1.5 °C scenario (Reference 1.5 °C) of the integrated assessment model IMAGE[32]. The scenario is based on the IMAGE implementation of the Shared Socioeconomic Pathway 2 (SSP2), describing a future world following current socioeconomic

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Table 1 | General interventions in the Demand 1.5 °C and Technology 1.5 °C scenarios

Transport	Buildings	Industry	Agriculture
Demand 1.5 °C			
Increased teleworking and alternative tourism. Airline ticket tax. Less money spend on travelling. Faster saturation of freight demand in relation to growth of industry value added. Transition from short-distance aviation to high-speed rail.	Reduction in cooling and heating. Avoid excess ownership of household appliances. Less energy waste from appliances and lighting. Reduction in hot water demand. Reduced floorspace. Increase in household occupancy rate.	Steel, paper and pulp, cement, non-energy and other industry reduce material demand according to the LED scenario in the IRP RECC report, leading to an average 43.5% (ref. 42) decrease in material demand by 2060 compared with 2016. After this period, standard default assumptions on material demand development are applied.	Transition towards healthy diets (including reduction of meat and dairy products)[43]. Transition implemented by 80% by 2050 and 100% by 2100. Reduction in food waste at farm, processing, retail and household levels by 40% by 2050 and 50% by 2100 (ref. 42).
Technology 1.5 °C			
More fuel-efficient aircraft on the market. Lightweight and retrofitted aeroplanes. Drop in bio-jet fuel can replace kerosene in existing aircraft. Electric aircraft for short-distance aviation. Hydrogen-fuelled aircraft for short- and medium-distance aviation. Faster market turnover.	No fossil fuels in space heating after 2050 and promote use of heat pumps. Accelerate transition away from traditional biomass in urban and rural households. Promoting refurbishment of heating technologies and appliances with newer/more efficient versions. Increase credit to households for adoption of efficient yet expensive technologies, including building envelope renovation. Increase efficiency of cooking, cooling and heating technologies (for example, the use of air coolers and heat pumps). Use net metering, promoting the use of residential photovoltaics. Increased use of architectural designs that have lower heating demand and require less floorspace.	Steel: no new investments into least efficient blast furnace steel plants from 2025 onwards. Only investments in electric arc furnace, hydrogen-reduced iron (from 2030 onwards) and electrowinning (from 2050 onwards). Cement: foreclosure of least efficient technologies from 2025 onwards. Incentive-stimulating electricity use. Paper and pulp: incentive for the use of biomass, electricity and hydrogen. For fuel types having a combined heat and power option available, only the combined heat and power option is active from 2025 onwards. Incentive stimulating electricity, biomass and hydrogen use.	Strong reduction in meat consumption due to a replacement by artificial meat[44]: implemented as a 60% substitution by 2050 and an 80% substitution by 2100. Note that implications on energy use are not considered. Higher non-CO_2 reduction potential: optimistic assumptions based on ref. 45, which include more speculative mitigation options in agriculture. Seaweed *Asparagopsis taxiformis* as a feed supplement to reduce enteric fermentation methane from ruminants and biochar to reduce nitrous oxide emissions from fertilizer.

trends, while, through the introduction of a uniform global carbon price, a radiative forcing target of 1.9 W m^{-2} is met.

Emissions from transport initially increase, but after 2035 they are below 2020 levels again, reaching 86% reduction by 2060 relative to 2020 (Fig. 1, right). The industry sector and the buildings sector reach, respectively, 90% and 78% reduction by 2060. The agricultural sector shows a slow decline, with a 7% reduction by 2060. Note, however, that without climate policy, emissions from this sector rapidly increase, so a slow decline of emissions relative to 2020 implies a substantial decrease compared with business as usual. BECCS and afforestation, shown by the negative energy supply, industry and land-use emissions, is strongly applied to meet net-zero GHG emissions. Compared with the leading set of scenarios published in the IPCC 6th assessment report, the Reference 1.5 °C scenario shows a deeper reduction of emissions in 2060. This is mainly due to the fact that the IPCC set includes all scenarios that have more than 50% chance of reaching 1.5 °C, while the Reference 1.5 °C scenario provides a more than 67% chance. Furthermore, the IMAGE scenario is more recent and includes latest emission and technological trends, resulting in higher reduction potential in transport and industry.

Additional mitigation measures

Several measures and policies are proposed in the literature to address the challenges that the HtA sectors face. These include promoting (1) the development of sustainable fuels, (2) electrification and efficiency-improving techniques and (3) procedural advancements regarding operations, circularity and waste[33]. In agriculture, buildings and transport, effective demand-oriented measures include promoting lifestyle changes such as diet shifts[34,35]. There is a wide range of policy instruments to promote both demand- and technology-oriented measures. The IPCC categorizes these into economic, regulatory and other instruments[36]. Examples of economic instruments that can be applied to reduce HtA emissions include subsidies and taxation, which can target either the end product for consumers (for example, taxing airline tickets) or earlier in the supply chain for producers (for example, subsidizing sustainable transport fuel or research and development or taxing process emissions). Regulatory instruments include energy efficiency standards, vehicle emission standards and renewable portfolio standards. Other instruments that are relevant for HtA sectors can consist of providing information or necessary infrastructure, voluntary agreements and technology transfer. In Supplementary Information, the literature review findings are presented, which includes an overview of the challenges to mitigate emissions in each HtA sector, potential measures and specific policy instruments to overcome these challenges (also see Extended Data Tables 1–5).

To assess the impacts of changes in demand and technology on emissions of HtA sectors, two new scenarios are constructed, focussing on additional, ambitious measures targeted either towards demand ('Demand 1.5 °C') or technology ('Technology 1.5 °C'). In addition, we analyse in a third scenario, the combined impact of both sets of measures ('Combined 1.5 °C'). These scenarios are developed under SSP1, SSP2 and SSP3 socioeconomic assumptions. Supplementary Information presents how the outcome of the literature review has been translated to the scenario implementation in the modelling framework. Demand-side measures refer to the consumption of services and technology measures to the provision of services, which relate to innovation, operation and technology diffusion. The additional emission reductions allows restricting the use of BECCS, while still reaching the set 1.5 °C target. Table 1 presents an overview of the set of HtA measures applied in the Demand 1.5 °C and Technology 1.5 °C scenarios per sector. Some measures are implemented at the level of policy intervention and some are implemented as changes in demand or technology, depending on the policy type (that is, economic incentives are implemented as such, while regulatory and other instruments are implemented as direct changes in demand or technologies; also see Discussion). The Combined 1.5 °C scenario combines both set of

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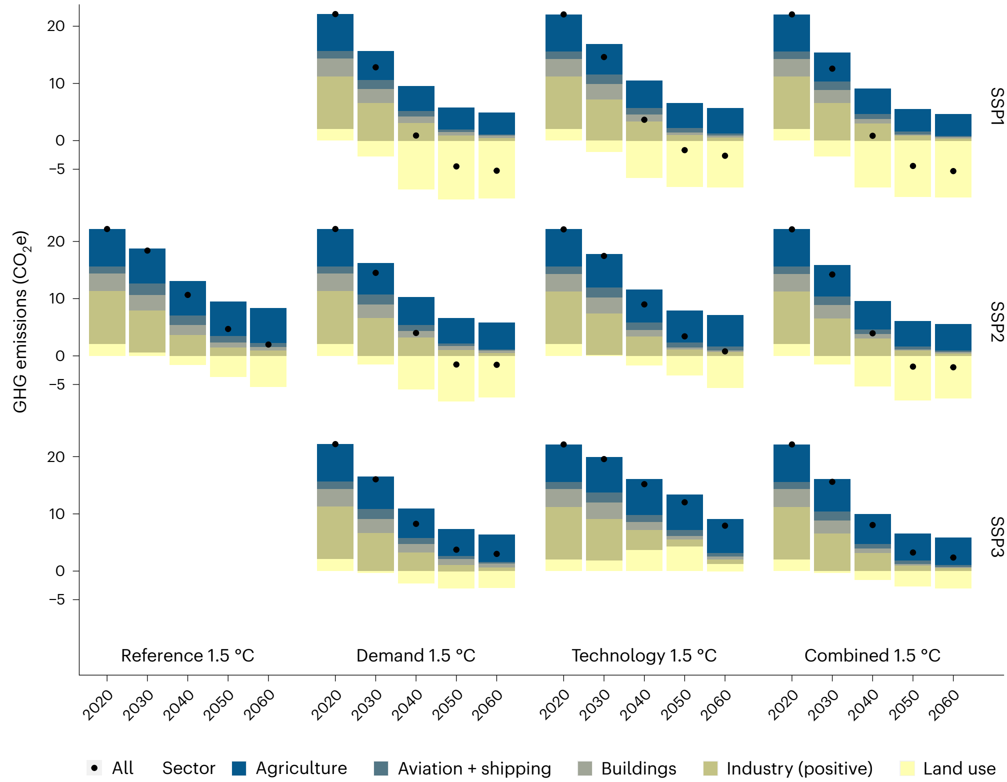

Fig. 2 | GHG emissions from the HtA sectors. For the Reference 1.5 °C scenario, only SSP2 is shown. For an equal comparison across the scenarios, the same carbon price trajectory is applied across all scenarios as in the SSP2 Reference 1.5 °C. Therefore, the SSP1 and SSP3 reference scenarios leads to different forcing targets. In the SSP3 scenarios, 1.9 W m^{-2} by 2100 is not met, reaching 2.07 W m^{-2} (Technology 1.5 °C), 2.23 W m^{-2} (Demand 1.5 °C) and 2.33 W m^{-2} (Combined 1.5 °C). Full details on forcing levels in 2100 are given in Supplementary Table 17.

measures, choosing the most effective measure when they overlap. In the agriculture sector, the diet change and replacement of meat by artificial meat overlap; therefore, the combined scenario only takes the diet change into account. The same measures are applied for the different SSPs.

Impact of additional measures on emissions

The measures implemented under the Demand 1.5 °C, Technology 1.5 °C and Combined 1.5 °C scenarios reduce global residual emissions from the HtA sectors to between 5.6 and 7.1 GtCO$_2$e by 2060 in an SSP2 world (with ranges of 4.7–5.6 GtCO$_2$e in SSP1 and 5.8–7.8 GtCO$_2$e in SSP3; Fig. 2), compared with 8.3 GtCO$_2$e in the Reference 1.5 °C.

The assumed stringent industrial measures can effectively reduce emissions in both the Technology 1.5 °C and Demand 1.5 °C scenarios. The Technology 1.5 °C scenario enforces immediate adoption of zero-carbon technologies via (in)direct electrification in the industrial sectors (for example, hydrogen-direct reduced iron in the steel sector), taking away leeway for transition technologies (CCS) to come on the market (Technology 1.5 °C). Substantially lowering demand reduces emissions in sectors with a lower transformational range (such as in clinker production) or gives space for a more diverse technological portfolio (for example, in iron reduction). In the clinker production sector, biofuel and CCS are used to compensate for remaining residual emissions[37,38]. In both the Technology 1.5 °C and the Demand 1.5 °C scenarios, residual positive industrial emissions are lowered (between 16–40% for Technology and 33–50% for Demand in 2060) (Fig. 3 for SSP2 and Extended Data Figs. 1 and 2 for SSP1 and SSP3).

In the aviation, shipping and agricultural sectors, the largest changes can be seen in the scenarios where the demand measures are applied (Fig. 3). Measures such as an airline ticket tax and the shift to high-speed train and local tourism reduce both short- and long-distance air travel, reducing transport emissions by 43–64% in 2060, depending on the SSP scenario. In the Technology 1.5 °C scenario, increased development and availability of fuel and technology alternatives lead to a faster reduction in emissions but not in higher reductions by 2060.

In the agricultural sector, the switch to healthy diets for 80% of the global population and a 40% reduction in food waste results in strongly reduced non-CO$_2$ emissions and in a strong indirect effect on land-use change as abandoned agricultural land is used for afforestation. The latter dominates the impact on emissions. A similar, but smaller, effect occurs in the Technology 1.5 °C scenario, where meat is partly replaced by artificial meat and novel techniques substantially reduce non-CO$_2$ agricultural greenhouse emissions (for example, from rice cultivation), resulting in less agricultural land required for food production. Still, agricultural emissions constitute the majority of remaining emissions, with 4.7 (3.8 for SSP1 and 4.8 for SSP3) and 5.4 GtCO$_2$e (4.4 for SSP1 and 5.9 for SSP3) remaining in, respectively, the Demand 1.5 °C and Technology 1.5 °C scenarios in 2060, compared with 6.0 GtCO$_2$e in the Reference 1.5 °C.

The impact of the Combined 1.5 °C scenario is much lower than the sum of the impact of the Demand 1.5 °C and Technology 1.5 °C scenarios due to system changes. For instance, in the residential sector, the Technology 1.5 °C scenario leads to massive improvements in energy use efficiency due to electrification and using efficient technologies such as heat pumps. In the Demand 1.5 °C scenario, reduced demand for (relatively inefficient) energy services leads to a sizeable decrease. In the Combined 1.5 °C scenario, since you have massive improvements in efficiency, reducing demand has a lower impact. For agriculture, diet change and replacement of meat by artificial meat largely overlap and therefore hardly any additional reductions are seen. For aviation and shipping, the technology measures only had a

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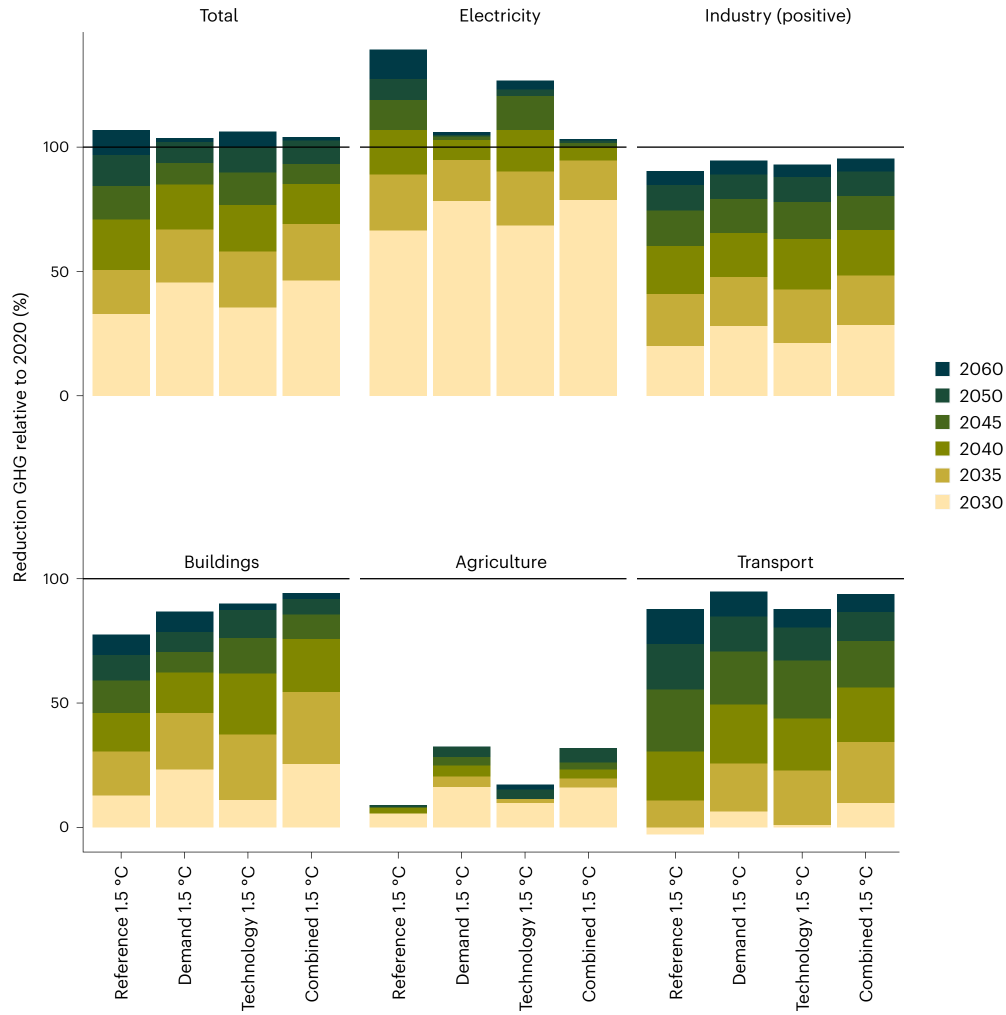

Fig. 3 | GHG emission reductions over time by sector for the SSP2-based scenarios. Agricultural emissions exclude land use. Extended Data Figs. 1 and 2 show the SSP1 and SSP3 results.

marginal impact on emissions and therefore combining aviation and shipping measures do not lead to additional reduction compared with the Demand 1.5 °C scenario.

Impact of the additional measures on BECCS

The mitigation options implemented in HtA sectors unlock additional potential in the Demand 1.5 °C, Technology 1.5 °C and Combined 1.5 °C scenarios and thereby help to achieve the 1.5 °C target with less reliance on BECCS. The additional emission reductions achieved in the HtA sectors, both directly and indirectly via land-use change, is translated to a restriction on annual BECCS use. Note that BECCS is not limited in the SSP3 scenarios given that the 1.5 °C target is not reached even with the additional measures.

In the net-zero year, BECCS is reduced strongly (by 20%, 74% and 94% under SSP3, SSP2 and SSP1, respectively; Fig. 4) in the Demand 1.5 °C scenario, as lower meat demand allows considerable forest expansion on land previously used for feed and pasture. BECCS use is only marginally reduced in the Technology 1.5 °C scenario under SSP2 (by 8%) because of (1) a faster assumed transition towards healthy diets in the Demand 1.5 °C scenario compared with the transition towards artificial meat in the Technology 1.5 °C scenario (Supplementary Tables 18 and 23) and (2) a stronger focus on bioenergy (for example, biofuels for aviation) in the Technology 1.5 °C scenario (Fig. 5). Owing to the latter, there is less land available for reforestation and CO_2 removal from land use is therefore limited. Under SSP1 assumptions, BECCS can be limited strongly in the Technology 1.5 °C scenario as well, as the lower population growth rate and dietary shifts frees up lots of land, which can be used for reforestation.

The maximum annual use of BECCS also differs strongly between the scenarios. In the Reference 1.5 °C scenario, annual BECCS use peaks during the 2070s at about 10 $GtCO_2e$ (Fig. 5). BECCS can be limited strongly to 2.2 $GtCO_2e\ yr^{-1}$ in the Demand 1.5 °C scenario (0.5 in SSP1; Extended Data Fig. 4), but also quite considerably in the Technology 1.5 °C scenario (7.0 $GtCO_2e\ yr^{-1}$ in SSP2 and 1.9 $GtCO_2e\ yr^{-1}$ in SSP1). The impact of the additional measures in the Technology 1.5 °C scenario on BECCS use is the strongest in the last decades of the century when more speculative non-CO_2 mitigation options and artificial meat really begin to have a strong impact. This is reflected in cumulative BECCS use, which is 22% lower in the Technology 1.5 °C scenario than in the Reference 1.5 °C scenario (Extended Data Fig. 3).

Discussion

Transforming the economy towards global net-zero emissions is very challenging. In our simplified representation, we have limited the challenge via physical adjustments to our production and consumption system, in terms of technological or social change, without describing the administrative, financial, infrastructural, spatial and organizational needs towards such a change. As also argued earlier[37,38], there are certain limitations to the extent by which global integrated assessment models can represent transformative change[39]. For example, in the scenario

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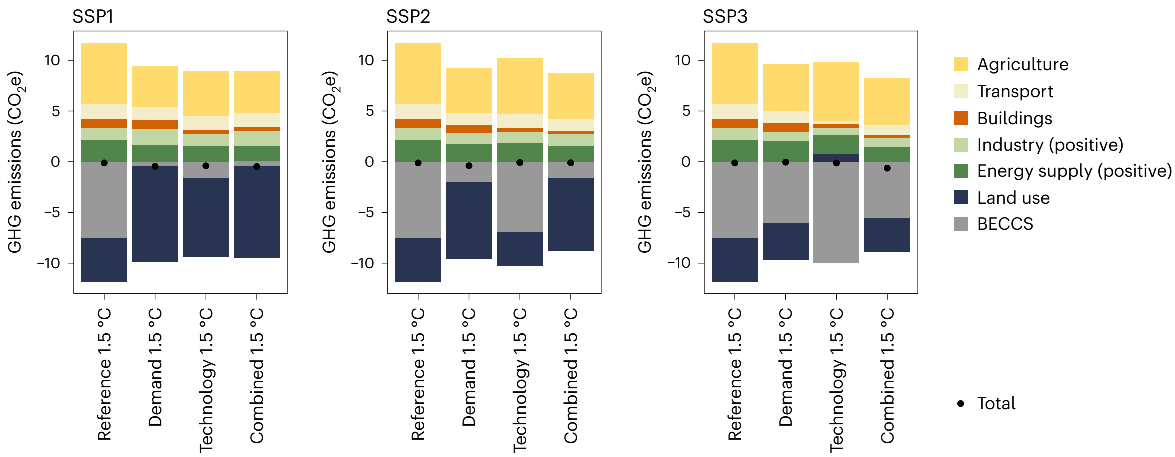

Fig. 4 | Global annual GHG emissions in the net-zero year. Net zero is achieved in 2052 for Reference 1.5 °C, 2046 for SSP1 Demand 1.5 °C, 2049 for SSP1 Technology 1.5 °C, 2046 for SSP1 Demand and Technology 1.5 °C, 2049 for SSP2 Demand 1.5 °C, 2050 for SSP2 Technology 1.5 °C, 2048 for SSP2 Demand and Technology 1.5 °C, 2052 for SSP3 Demand 1.5 °C, 2069 for SSP3 Technology 1.5 °C and 2051 for SSP3 Demand and Technology 1.5 °C.

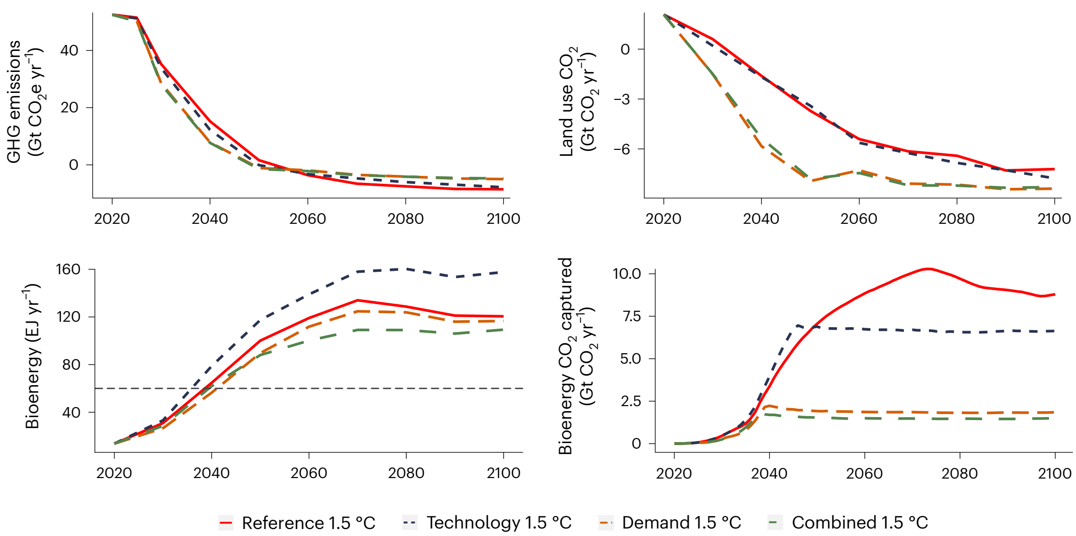

Fig. 5 | Global GHG emissions, land-use CO_2 emissions, bioenergy use and BECCS. The lines refer the SSP2-based scenarios; SSP1 is shown in the Extended Data Fig. 4. For SSP3, the 1.5 °C target is not reached in any of the scenarios and therefore not shown. In all scenarios, annual crop-based bioenergy stays below the sustainable level of 60 EJ yr^{-1}, as identified by Fuss et al.[38], based on ecological and biophysical concerns. However, total bioenergy use exceeds 60 EJ yr^{-1} as it includes residue use, which does not require additional land[46,47].

framework as presented in this study, we assume that additional demand-side measures, while considering a transition period, are fully effective. While this illustrates a theoretical potential of demand-side measures, our implementation does not account for social dynamics and individual preferences[40]. A lack of a solid evidence base for counterfactual developments complicates a thorough representation but, as we present here, still allows for drawing robust lessons on the critical relationship between HtA sectors and CDR. Compared with the IPCC scenario set, the IMAGE Reference 1.5 °C shows substantial reductions in HtA sectors. This suggest that the potential for reducing HtA emissions relative to other reference scenarios might be even larger.

This study demonstrates that, while the HtA sectors face important challenges, they can attain lower emission levels, sometimes near zero in the case of buildings and industry, by implementing drastic demand and technological interventions. This has considerable consequences for the peak annual use of BECCS, especially in scenarios with additional demand-oriented measures where peak use is limited to 0.5–2.2 $GtCO_2e\ yr^{-1}$ (depending on the socioeconomic pathway) compared with about 10 $GtCO_2e\ yr^{-1}$ in the Reference 1.5 °C scenario. In the pathway with additional technology-oriented measures, peak annual BECCS use is limited to 1.9–7.0 $GtCO_2e$. Our scenarios show that demand-side measures may increase the technical feasibility of achieving the 1.5 °C climate target and limit adverse side effects of climate change mitigation policies. Agriculture plays a critical role, as non-CO_2 GHGs in this sector remain substantial, despite sizeable reductions of 1–2 $GtCO_2e$ in the net-zero year compared with the Reference 1.5 °C scenario. Moreover, the reduced agricultural land used for grazing and feed as a result of the additional agricultural measures results in more afforestation potential, strongly reducing the need for BECCS.

While CDR is still considered crucial to achieve a net-zero economy, the extent and timing of CDR strongly depends on the representation of alternative solution options, as also argued by Wilson et al.[41]. However, none of the measures proposed in this study will be easy to implement as they all come with specific challenges and costs. However, the same can be argued for the measures in the Reference 1.5 °C scenario, for which, generally, cost effectiveness determines the implementation of mitigation measures. While cost effectiveness is one aspect of feasibility, it is definitely not the only one. The IPCC indicates that mitigation measures that are designed and conducted in the context of sustainable development and equity and rooted in the development aspirations will be more acceptable[36]. It is questionable whether a pathway that relies so strongly on CDR fulfils these criteria. This study provides alternative pathways to cost-effectiveness ones (Reference 1.5 °C) and while these might be less cost effective, they might not to be less feasible to achieve. However, in any case, the challenge of achieving net-zero emissions within a few decades is enormous and will require difficult and sometimes costly measures.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-024-02025-y.

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Methods

Literature study

The first step undertaken in this study was to assess, through a literature review, the characteristics of each HtA sector and the difficulties to achieve net-zero targets in these sectors. The second part of the review focused on the possible policies and measures to address these obstacles in each sector. The review served two purposes. It presents the state-of-the-art knowledge on the characteristics of the sectors relevant for climate change mitigation and possible future developments that could impact their mitigation potential. In addition, it provides the grounding of to the model analysis, by using the identified policies and measures in developing the scenarios. In the scenarios, the sectoral measures are represented, while results of the literature review presented in Supplementary Information provide an overview of the barriers to implement these measures and the possible policies to overcome them.

Sectoral analysis

IMAGE modelling framework. To understand the role of the development in HtA sectors in trying to limit global warming to 1.5 °C, the process-oriented integrated assessment model IMAGE model was used[23]. IMAGE is in particularly suitable given that the model describes, in detail, the development of all four HtA sectors considered in this study, allowing representation of specific mitigation measures in HtA sectors. The key components of the human system that largely contribute to GHG emissions are the energy system and the agricultural and land systems. The energy and industry system are represented by The Image Energy Regional Model (TIMER) model[48] and agricultural demand, production and trade by the Modular Applied GeNeral Equilibrium Tool (MAGNET) model[48,49]. The main drivers for the human system are demographic, economic and technological developments, as well as resource availability, lifestyle changes and policy. For the earth system, the modelling framework is used to describe land cover, crop growth, carbon and water cycles and climate, making also use of the internally coupled Lund-Potsdam-Jena model (LPJmL) model (carbon, crops, vegetation and water) and the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) climate model[50–52].

IMAGE is characterized by relatively detailed biophysical and land-based processes, a wide range of environmental and sustainability indicators and a detailed geographical scope. The socioeconomic processes and most of the human system parameters are described at the level of 26 world regions, while the earth system is modelled on a 5 × 5 min grid for land use and land-use changes and on a 30 × 30 min grid for plant growth and the carbon and water cycles. For both IMAGE and LPJmL, a geographic (or equirectangular) projection is applied, which is common for global raster datasets and earth system models. IMAGE operates in annual time steps and, as such, is suitable for long-term climate mitigation assessments up to 2100. The costs associated with the various components are tracked and relative costs of competing technologies and supply chains determine market share. Moreover, the model is particularly good in representing the physical world, including resource availability, energy and land flows and interactions, geological storage capacity, bioenergy production and trade of commodities across the global regions considered. This is critical to understand the implications of the changes in the HtA sectors to the rest of the system and in particular the use of CDR technologies. On the basis of historical trends, the demand for travel, housing, specific materials and agricultural products related to the HtA sectors are described and related to regional economic and price developments, cultural factors and demographic development. These services can be provided or produced in various ways; for instance, travel demand can be fulfilled by different transport modes and technologies. This depends on resource availability, technology development, operation and availability, historical preferences and climate policy, among others. Passenger transport modes include buses, bicycles, motorcycles, walking, trains, cars, high-speed trains and aeroplanes, and the distribution across the different modes depend on cultural preferences, mode speed and income levels as well as on costs. If, for example, air travel would become more expensive due to the implementation of air passenger tax, or conversely would become cheaper due to technological developments, the kilometres travelled by air may decrease or increase, respectively. Increased costs to travel by a certain transport mode can also lead to a shift towards a different cheaper mode. Each mode considers different vehicles types with varying levels of efficiency, cost and fuel types. This also accounts for the freight modes, which include trains, medium and heavy trucks, national and international ships and aeroplanes. The vehicle data for the aviation and shipping mode can be found in Supplementary Information.

The energy consumption in buildings follows the demand for cooking appliances, space heating and cooling, water heating and lighting. The model distinguishes between urban and rural housing and five income groups. The potential for insulation of houses depends on the construction cycles and housing stock dynamics[53]. Demand for agricultural products is determined by food demand, driven by increases in population and income. Among others, the model takes into account that, with increasing income, people are able to consume more expensive food types with more negative environmental footprints, such as meat. To fulfil demand, agricultural land use can be expanded or intensified, leading to the conversion of natural land, more water and fertilizer use, and increasing non-CO_2 emissions. Measures to reduce emissions include the protection of natural land, afforestation, technological measures to reduce non-CO_2 emissions or preference shifts in food consumption towards fewer animal-based products that have less environmental impact. In representing the industrial sectors, the IMAGE model distinguishes between five specific (basic) material industries that come with high energy and carbon intensity and aggregates other processing industries. The five distinct basic industry sectors are the iron and steel, clinker and cement, paper and pulp, food processing and (petro)chemical feedstock sector (also known as 'non-energy'), with the remainder categorized to 'other' industry (including non-ferrous metals, construction, machinery, transport equipment, mining and quarrying, wood and wood products, textile and leather and non-specified industry as identified by International Energy Agency World Energy Balances). In general, future consumption is deducted and extrapolated from statistical relationships between national income levels and reported historical national consumption. Energy consumption is specified through historical energy consumption levels as reported in the IEA World Energy Balances, specific energy consumption for production routes and technology developments over time with an implemented merit order based on cost factors (Supplementary Table 5)[38]. Total (in)direct carbon emissions are a result from this energy demand and specific accounted for process emissions if applicable.

Sector analysis through scenario framework. To analyse what the effect could be of the additional measures identified in the literature review on the emissions originating from HtA sectors, a set of scenarios are developed and compared. This includes a reference scenario climate policy represented by a carbon tax and a set of scenarios in which, besides the carbon price, specific measures directed towards the HtA sectors are implemented. The developed scenarios build on the literature review described in Supplementary Information. Full details of the scenario assumptions can also be found in Supplementary Information.

Demand scenario. Under the Demand scenario, the demand for services is reduced compared with under the Reference scenario. The HtA sectors are characterized by substantial growth in demand, if current trends continue, which is closely linked to economic growth and personal welfare, making it more difficult to mitigate emissions. The measures that are part of the demand scenario are a combination of incremental changes and structural changes. Incremental changes are defined as those that do not require fundamental changes in how sectors operate but do push them to their limits within current operation modes (non-structural), while the structural change require fundamental adjustments their operating methods, resulting in a strong reduction in demand. In the buildings sector, the demand for energy is reduced by lowering the thermostat setting, taking shorter showers and using occupancy sensors to minimize energy waste. Co-living will become common practice, increasing occupancy rates and reduced appliance ownership and floorspace used per capita. Over the course of the century, a full transition to a low-meat, healthy diet is expected to take place for 80% of the population, which will impact the agricultural sector. The proposed diet accounts for different diets in the Global South, especially in countries where malnourishment is prevalent. In those countries, the healthy diet in fact implies an increase in total caloric intake as well as an increase in consumption of animal-based products up to a healthy level.

High cost penalties on non-CO_2 mitigation measures that result in higher food prices are removed, which prioritizes implementation of low-cost non-CO_2 mitigation measures. In addition, food waste throughout the supply chain is substantially reduced. In the transport sector, there is a lower increase in transportation expenditure with increased income, leading to less transport growth in high-income countries. Furthermore, a global taxation on airline tickets is also implemented. Demand for aviation transport will decrease due to increases in teleworking and local rather than international tourism. Short-distance flights are replaced by high-speed rail in regions where such infrastructure is either available, under construction or planned. In the industrial sector, material demand decreases at the same rate as projected under the Low Energy Demand (LED) scenario, presented in the Resource Efficiency and Climate Change (RECC) report by the International Resource Panel (IRP)[42]. The LED scenario leads to a 43.5% reduction in material use by 2060 compared with 2016 levels, which is applied in the Demand scenario from 2023 onwards and can be considered a rather extreme reduction in the demand for material.

Technology scenario. Under the Technology scenario, fast diffusion of innovative low-carbon technologies takes place, assuming an optimistic outlook on technology development and adoption (non-structural) and technological changes require fundamental changes in the current mode of operation (structural). In buildings, fossil fuel space heating will be completely phased out after 2050, with increased use of heat pumps and faster technology turnovers. Increased access to loans and low interest rates, amplifying households credit, allows a higher adoption rate of efficient yet expensive technologies, including the renovation of building envelopes. New architectural designs lead to a lower demand for heating and promote alternative residential paradigms, resulting in more efficient use of space and facilities. Traditional biomass is being phased out for cooking for both urban and rural households. The aviation sector sees a faster development and adoption of efficient aircrafts. The aviation fuel infrastructure is adjusted so that bio-jet fuel can easily be blended with fossil fuels. Moreover, the state of the art in operational efficiency is implemented worldwide. Electric aircraft are available for short-distance travel and hydrogen or e-fuelled aircraft are used for short-to-medium distances. The transition towards these alternative propulsion techniques is accelerated due to the early retirement of traditionally fuelled equipment. In the agricultural sector, artificial meat becomes the dominant market player, resulting in a 60% reduction of meat consumption by 2050 and 80% by the end of the century, decreasing the demand for livestock. It is assumed that the feedstock of artificial meat is maize, which has a 42% caloric conversion efficiency[44]. Moreover, the maximum reduction potential for agricultural CH_4 and N_2O sources is increased. This is most impactful for enteric fermentation, where there is a widespread use of novel techniques, such as the seaweed *Asparagopsis taxiformis* as a feed additive. For industry, the technology parameters for iron, steel and clinker production have been adjusted to align with the latest insights in literature, resulting in less optimistic assumptions for CO_2 capture rates in blast furnace/basic oxygen furnace integrated steel mills and the availability of a monoethanolamine-based carbon sequestration option for lime kilns in the clinker production sector. Clinker ratios are now also responsive to high carbon tax values (but cannot drop below 65% clinker in cement mixes), implying an implicit shift to low-carbon alternative cementitious material use other than reported in Kermeli et al.[54]. Additionally, for the *Technology* scenario, only electric arc furnace, hydrogen steel making and electrowinning are available, resulting in rapid phase-out of fossil fuels. Also, for cement and paper and pulp, electrification is highly stimulated. In addition, for paper and pulp, only non-fossil energy inputs are available.

Achieving 1.5 °C. To better understand how the additional policies and measures in the HtA sectors affect economy-wide 1.5 °C mitigation strategies, two different strategies (Demand and Technology) are analysed, with sets of measures to reduce GHG emissions originating from the HtA sectors. In addition, a third strategy is analysed where both set of measures are combined (Combined). Specifically, the goal is to understand whether, with these additional measures, global warming can be limited to 1.5 °C while keeping BECCS and afforestation at sustainable levels. For this set of scenarios, a global emission pathway that limits global warming to 1.5 °C is determined by minimizing cumulative discounted mitigation costs and, as such, following a cost-effective carbon price pathway.

The analysis focuses on four core scenarios:

- Reference 1.5 °C: this scenario reaches a radiative forcing of 1.9 W m^{-2} by 2100 (corresponding to a 1.5 °C temperature target), using default SSP2 assumptions and by implementing a uniform carbon price. This carbon price trajectory reaches USD1,000 per tonne of carbon by 2035 and about USD1,700 per tonne of carbon by 2050.
- Demand 1.5 °C: this scenario uses the same carbon price trajectory as Reference 1.5 °C and additional measures in the HtA sectors following the Demand scenario assumptions described above and detailed in Supplementary Information. The use of BECCS is restricted (see below) based on the additional mitigation potential generated by the HtA measures.
- Technology 1.5 °C: this scenario uses the same carbon price trajectory as Reference 1.5 °C and additional measures in the HtA sectors according to the Technology scenario assumptions described above and detailed in Supplementary Information. The use of BECCS is restricted (see below) based on the additional mitigation potential generated by the HtA measures.
- Combined 1.5 °C: this scenario uses the same carbon price trajectory as Reference 1.5 °C and additional measures in the HtA sectors of both the Demand and Technology scenario assumptions. The use of BECCS is restricted (see below) based on the additional mitigation potential generated by the HtA measures.

In this paper, the Reference 1.5 °C scenario is based on the IMAGE middle-of-the-road SSP2 scenario. The most recent IMAGE SSP scenarios follow the SSP narratives and include the impacts of the coronavirus disease 2019 pandemic[48]. The framework of SSPs comprises five storylines for long-term global development, correlating with various challenges with respect to mitigation and/or adaptation within the context of climate change. The SSP1 scenario describes a pathway of sustainable development, with high economic growth, low population growth and high technological development. The SSP2 scenario is a middle-of-the-road pathway, with intermediate challenges. The SSP3 scenario depicts a fragmented world, with large challenges for economic growth and technology development. To understand the robustness of the scenario analysis, the three scenarios with varying measures to specifically target the HtA sector are also analysed within an SSP1 and an SSP3 world. For consistency, in these scenarios, the same carbon tax as in Reference 1.5 °C is used.

BECCS. The additional mitigation potential as a result of the HtA measures is applied to limit the use of BECCS while still complying with the 1.5 °C target. The scenario details are displayed in Supplementary Table 16. The table shows that in the SSP3-based scenarios, the HtA measures allow to come closer but do not reach the set climate target. As a result, no limit on BECCS has been set for the SSP3-based scenarios. For the other scenarios the limit has been set at a yearly permitted use, which in particular relieves the pressure on the land requirements to grow biomass. In all scenarios, the deployment of bioenergy from energy crops remained below 60 EJ yr^{-1}, which is considered a maximum levels of what can be sustainably harvested[47]. Note that beyond the use of bioenergy crops, residue bioenergy use from agricultural crops (stalks, branches, leaves, straw, waste from pruning and so on), forestry residues and municipal solid waste is also used in the scenarios.

Data availability
Data used to set up model simulations and major results data is available upon request. Figure source data are provided through figshare (https://doi.org/10.6084/m9.figshare.25272649)[32]. Source data are provided with this paper.

Code availability
PBL Netherlands Environmental Assessment Agency holds the proprietary rights to the IMAGE computer code; extensive documentation is provided (https://models.pbl.nl/image). The open source modules are published on: https://github.com/imagepbl.

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Author contributions
All authors conceived the study. O.Y.E., A.F.H., M.v.d.B., M.G.J.d.E. and D.P.v.V. conceived and designed the experiments. O.Y.E., H.S.d.B., H.-H.C., V.D., J.C.D., M.H., S.M., M.A.E.v.S., I.S.T. and W.-J.v.Z. performed the experiments. O.Y.E., A.F.H., H.S.d.B., H.-H.C., V.D., J.C.D., M.H., M.A.E.v.S., I.S.T. and W.-J.v.Z. analysed the data. O.Y.E., H.S.d.B., V.D., J.C.D. and M.H. contributed materials/analysis tools. O.Y.E., A.F.H., M.v.d.B., M.G.J.d.E., M.A.E.v.S., E.S. and D.P.v.V. wrote the paper.

Competing interests
The authors declare no competing interests.

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Extended Data Table 1 | Implementation of aviation HtA measures

Challenges		Opportunities	Implementation in model	Regional differences
Rapidly increasing demand; Carbon-intensive fuel, with no ‘off the shelf technology alternatives; Low fuel price elasticity due to fuel at a fraction of the cost price and limited alternatives; Long fleet lifetimes and slow infrastructure turnover; International sector is not included under the Paris Agreement	Demand	Alternative tourism, increased teleworking	Pkms of aviation are reduced by a factor based on the regional data considering the reduction in aviation activity during the covid pandemic. By 2040 this results in a 25% reduction in activity compared to Reference.	
		Airplane ticket-tax	Airline ticket tax of USD 25 per flight[55].	
		Improved alternative transportation infrastructure for alternative modes of transport such as high-speed rail	Short distance aviation is replaced by High speed rail between 2025 and 2035	Implemented only in in those regions where infrastructure is either available or planned to be build.
		Educational policies and policy acceptance.	The travel money budget reduces with increasing income resulting in less smaller share of income going to transport and therefore reduction in aviation passenger kilometers	This measure will impact in particular high income countries.
	Technology	Adapted aircraft design: efficient planes, light weighting, retrofit, operational efficiency	A comparison is made between the MAC curve described by[56] with cost in EUR/tCO_2 for several operational measures and the carbon price. If operational improvement reduce overall cost they are implemented	
		Long-term alternative fueling (for example hydrogen in aviation);	Electric aircraft is mandatory for short distance aviation and hydrogen fueled aircraft for short and medium distance trips from 2040	
		In the medium term, power-to-liquid fuel and biofuels	Each year a choice can be made between bio or oil based kerosine depending on their price. The result is a faster transition to drop-in biofuels.	
		Earlier retirement of conventional planes	Lifetime of airplanes are reduced which impacts the vehicle turnover	
		Carbon pricing (and including aviation in ETS), harmonisation of policy across countries (get ICAO on board)	In Reference 1.5C	

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Extended Data Table 2 | Implementation of shipping HtA measures

Challenges		Opportunities	Implementation in model	Regional differences
International character Market competitiveness and dependence on low fuel prices; Technological problems (difficulties in electrification, no near-term alternative fuels); Demand increases, linked with economic growth; Already highly efficient marine engines	Demand	Lifestyle change (for example, lower demand for industrialized products), increase in local production, regionalization of shipping	Service demand is projected with constant elasticity of the industry value added for each transport mode. This constant is set at 0.4 (default is 0.5)	
	Technology	Alternative fuels, energy efficiency, operational measures, efficient ship design	Reduced costs and increased energy efficiency (10% relative increase between 2020 and 2100) of alternative fueled vehicles according to the IMAGE SSP1 assumptions.	Energy efficiency is regionally differentiated based on historical differences.

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Extended Data Table 3 | Implementation of industry HtA measures

Challenges		Opportunities	Implementation in model
Complexity of the sector (product-wise and regionally) requires tailored policy; High competitiveness due to high energy intensity and capital costs; Intrinsic emissions in high-temperature and process industry; Demand inelastic and growing, due to linkages with other sectors, economic growth and infrastructure demand; Long lifetimes of products and factories in combination with high costs of change	Demand	Imposed switch to alternative building materials (implicit)	Implicitly implemented. Steel, paper and pulp, cement, non-energy and other industry reduce material demand according to the LED scenario in the IRP RECC report, leading to an average 43.5%[57] decrease in material demand by 2060 compared to 2016. After this period standard default assumptions on material demand development are applied.
		Lifetime extention	
		Higher recycling rate	
		Reduce demand for chemicals	
	Technology	Higher momentum for specific low-carbon technologies.	Steel: No new investments into least efficient blast furnace steel plants from 2025 onwards; Only investments in electric arc furnace, hydrogen reduced iron (from 2030 onwards) and electrowinning (from 2050 onwards). Cement: Foreclosure of least efficient technologies from 2025 onwards.
		Higher momentum for alternative fuels	Cement, paper and pulp: Preference factor for electricity, hydrogen and biomass (-5 USD/GJ)
		Promote the use of electric crackers	Replace all fossil energy use in steam cracking with electricity

Full details available in van Sluisveld et al.[58]. No regional differences are applied.

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Extended Data Table 4 | Implementation of buildings HtA measures

Challenges		Opportunities	Implementation in model	Regional differences
Heterogeneity across locations, building archetypes, local conditions; High costs of investments make profitability and affordability non-trivial; Conflicting motivations to take on investment costs across landlords and tenants; Household decisions dependent on private value judgments; Long lifetime and slow renovation pace, stock lock-in; Limited availability of unobstructed surface for PV systems in urban areas; High required electricity load for particular sub-sectorial buildings; Limited capacity for evaluation of compliance	Demand	Reduced waste via occupancy sensors	Occupancy factor reduces useful energy demand by approximately 10%	
		Behavioural change concerning appliance ownership and demand for energy services	Avoid excessive ownership (from baseline) of appliances with high energy consumption (refrigerators, other entertainment appliances); reduce set point temperatures of cooling and heating by 1 degree.	
		Communal spaces and shared energy services (for example cooking, appliances)	Use household size as a proxy for shared spaces. Increase by 20% above baseline	Applied only to households smaller than 3.8 persons per household.
		Lower floorspace per capita (for example smaller houses)	Limit per capita floorspace to 30m^2/cap and 35 m^2/cap for urban and rural households respectively	Limit applied globally, but regional floorspace per capita depends on local economic conditions
	Technology	Insulation and renovation	A 20% subsidy on the costs of high insulation levels; removal of high discount rates for poorer households.	Subsidy applied uniformly. Influence of reduced discount rates depends on regional households expenditures
		Local electricity and energy generation	Promote installation of rooftop PV	Measure applied uniformly but influence depends on local residential floorspace (proxy for roof area)
		Higher efficiency technologies	Promote electrification of heating and cooking; increase fraction of air-coolers to replace air conditioners (30%);10% increase in efficiency of cooking, heating, and cooling appliances; For appliances, we either assume a 10% increase in efficiency, or universal adoption of best available technologies, whichever leads to the greatest energy use reduction.	Measures applied uniformly. Impact on energy demand depends on regional climatic and household conditions. For example, the impact of air conditioning efficiency increases depends on the local requirement for cooling, and thus the overall demand for cooling. Furthermore, richer regions (which tend to use more energy), will see a greater impact of efficiency improvements.
		Energy-efficient architectural design	Increase 'functional' rooftop area for solar PV; reduce heating and cooling intensity; promote building types with lower heating/cooling intensity (avoid detached houses)	Depends on local house sizes and climatic conditions. For example, regions with high solar irradiation, larger building floorspace (and thus larger rooftops) will benefit more from this measure.
		Switch from traditional biomass for cooking to cleaner alternatives	Turn off availability of traditional cookstoves (force clean energy access)	

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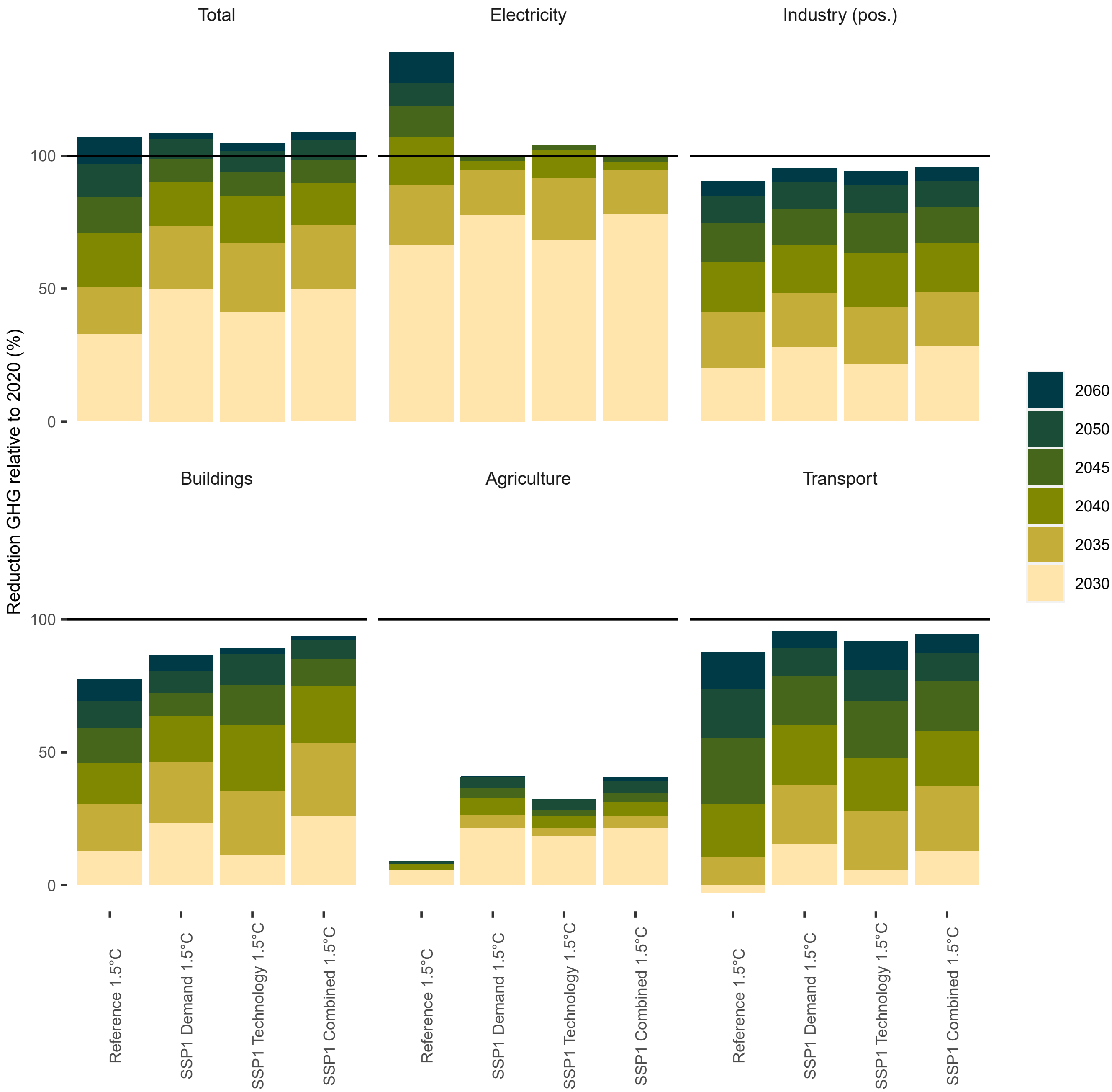
Extended Data Table 5 | Implementation of agriculture HtA measures

Challenges		Opportunities	Implementation in model	Regional differences
Continued increases in food demand and behavioural barriers to dietary change; Technological solutions overlap and are not enough to go to zero; In some cases, high up-front investments for farmers and lack of incentives; Competitive market; Majority of emissions are from smallholder farms; Non-financial barriers for farmers refer to knowledge and training.	Demand	Dietary changes	Transition towards healthy diets[43] (incl. reduction of meat and dairy products); transition implemented by 80% by 2050 and 100% by 2100	In regions with meat and dairy consumption below healthy levels, consumption is assumed to increase
		Decreases in food waste in farm processing, retail and households	Reduction in food waste at farm, processing, retail and household levels by 40% by 2050 and 50% by 2100 (consistent with 50% waste reduction in[43])	
	Technology	Technological solutions: more efficient livestock farming: genetic selection, feed additives	Higher non-CO_2 reduction potential: Optimistic assumptions based on[45], which include more speculative mitigation options in agriculture. Seaweed asparagopsis taxiformis as a feed supplement to reduce enteric fermentation methane from ruminants & biochar to reduce nitrous oxide emissions from fertilizer.	
		In rice production: reduced flooding techniques, reduced fertilizer and runoff: higher fertilizer efficiency, nitrification inhibitors		
		Land management techniques: higher water tables on peat soils, different agricultural management to increase soil carbon, increased tree cover in agricultural landscapes		
		Structural changes required to build knowledge, investment profitability, improved manure and livestock management systems		
		Alternative products (for example artificial meat)	Strong reduction in meat consumption due to a replacement by artificial meat[44]: implemented as a 60% substitution by 2050 and an 80% substitution by 2100	Only in high- and middle-income regions with average or above average levels of meat consumption.



Extended Data Fig. 1 | GHG emission reductions over time for the SSP1-based scenarios. Agricultural emissions exclude land use.

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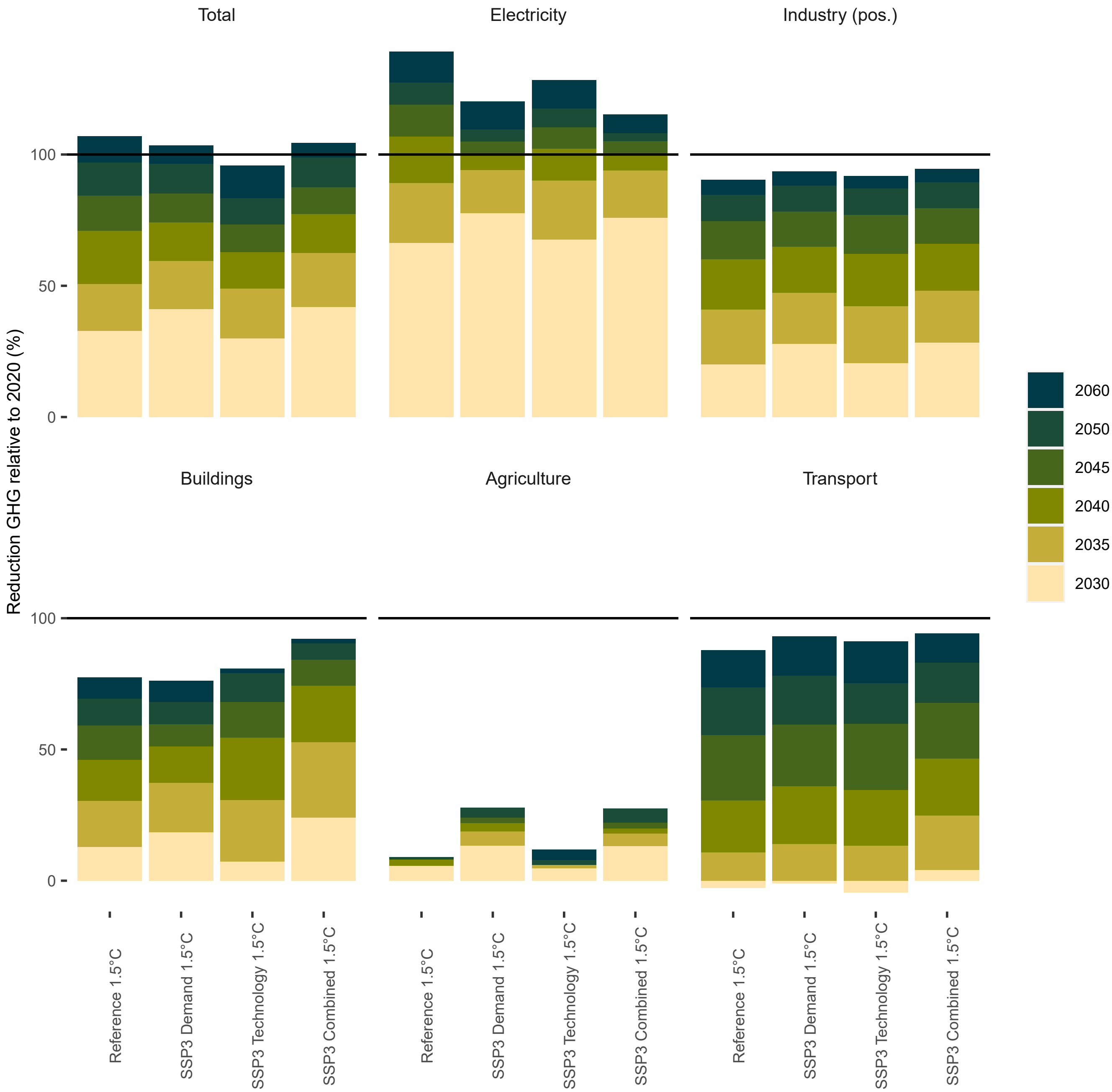
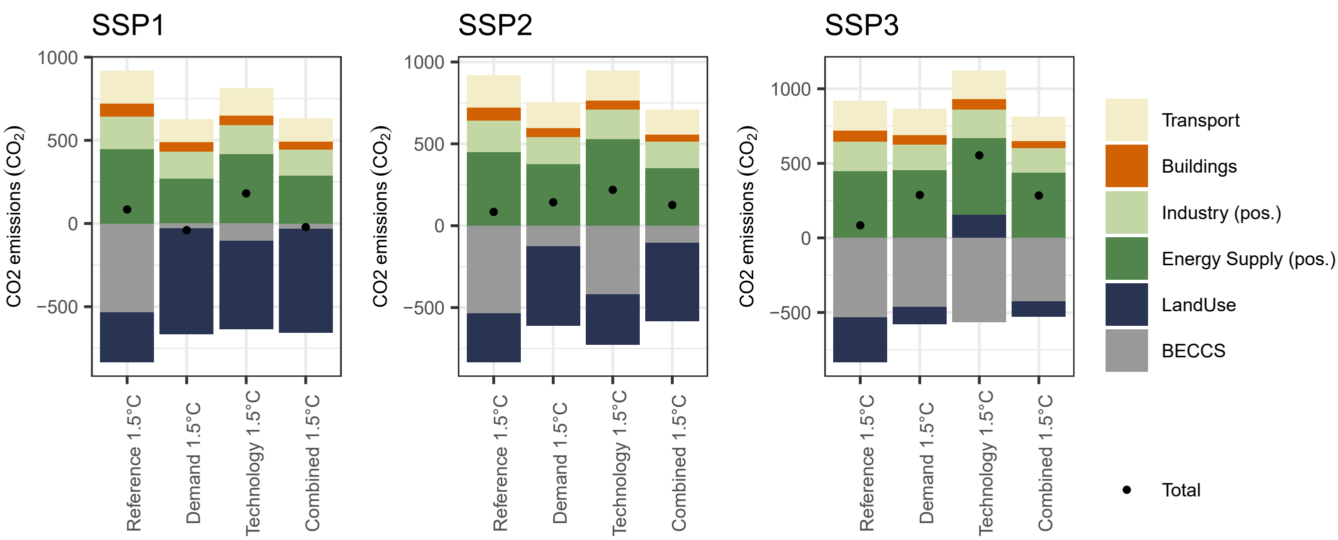
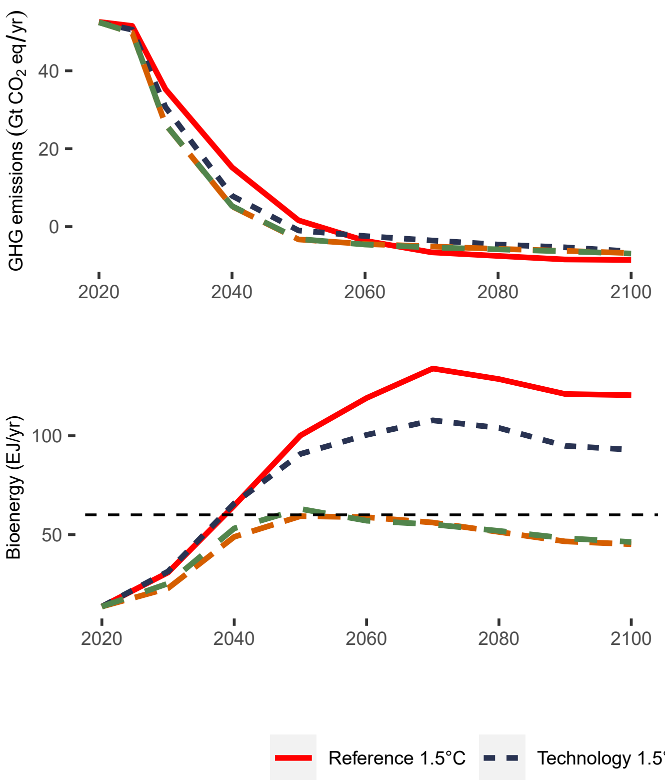


Extended Data Fig. 2 | GHG emission reductions over time for the SSP3-based scenarios. Agricultural emissions exclude land use.



Extended Data Fig. 3 | Cumulative CO2 emissions between 2020 and 2100. The radiative forcing target of 1.9 W/m^2 is achieved in all scenarios except for the SSP3-based scenarios.

 https://doi.org/10.1038/s41558-024-02025-y



Extended Data Fig. 4 | Global GHG emissions, land-use CO2 emissions, bioenergy use and BECCS in SSP1-based scenarios. In all scenarios, annual crop-based bioenergy stays below the sustainable level of 60 EJ/yr, as identified by Fuss et al.[38], based on ecological and biophysical concerns. However, total bioenergy use can exceed 60 EJ/yr as it includes residue use which does not require additional land[46,47].