Reducing sectoral hard to abate emissions to limit reliance of Carbon Dioxide Removal in 1.5°C scenarios

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Abstract

Achieving net-zero greenhouse gas targets is often achieved by compensating residual greenhouse gas emissions in the hard to abate (HtA) sectors, with carbon dioxide removal (CDR) options. However, large-scale application of CDR may lead to environmental, technical and social concerns. The extent to which residual emissions can be reduced in the industry, agriculture, buildings and transport sector is analysed based on integrated assessment of scenarios with ambitious measures in the HtA sectors. Two scenarios that explore demand and technology-focused approaches show that by reducing residual emissions, the CDR ceiling can be significantly lowered (23-30%) compared to reference in the net-zero year. The agriculture sector plays a critical role in this given the large share of residual emissions. The additional measures allow to create a 1.5°C scenario in which crop-based bioenergy use is limited to 40 EJ/yr, therefore within sustainable limits, and afforestation can be limited to abandoned cropland and grassland.

Introduction

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[1]. To accomplish this, CO_2 emissions need to reach net zero (i.e. a balance between anthropogenic emission sources and sinks). For the 1.5^{o}C target, in fact, this goal would need to be accomplished around 2050[2]. Over the past few years, 149 countries, 252 cities with a population of half a million or more, and more than 900 of the 2000 largest companies in the world have set net-zero emission targets[3]. These targets often encompass all greenhouse gasses (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].

Scenario studies show that it is often more economical to maintain a level of residual emissions in some sectors balanced by sinks in other sectors than aiming for complete decarbonisation in each sector individually[7]. In fact, the scenarios assessed by IPCC in AR6 that reach net zero do so by allowing, on average, 11 Gt CO_2 residual emissions, compensated through CDR measures elsewhere. Only 5% of the scenarios report residual emissions of less than 5 Gt CO_2, equal to more than 10% of current CO_2 emissions, in the net-zero year. The residual greenhouse gas emissions largely consist CO_2 emissions from energy-intensive industries (mainly defined by the steel, cement and chemical industries), international transport (mainly air and shipping) and non-CO_2 emissions from agriculture (mainly from rearing livestock, 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 homogenous sector like the power sector[8,9]. Also in the residential sector achieving net-zero emissions can be difficult due to the granularity of the sector with many actors involved, site-specific conditions and the slow capital turnover[10–12]. These four sectors are in this study referred to as hard-to-abate (HtA) sectors.

Residual emissions need to be compensated by CDR measures if net zero emissions is to be achieved. However, CDR measures involve environmental, social or 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 [13–18]. Moreover, future existence of forest is difficult to assure leading to a risk of non-permanence[19]. Also, direct air carbon capture and storage (DACCS) is still costly and requires large amount of energy capacity[20]. While none of the CDR measures have been proven at scale and their potential is limited, particularly uncertain is the geological storage capacity and logistics required for large-scale application of CCS as part of the DACCS and bioenergy and CCS (BECCS) strategy[21].

Therefore, it can be attractive to reduce emissions in the HtA sectors further than usually assumed in default net-zero emission scenarios in order to limit the reliance on CDR technologies. However, as shown also by the latest IPCC report, limited scenarios are available that target residual emissions in the hard-to-abate sectors. In this paper, we explore the available demand and technological options for achieving this. We do so by first discussing why it is so difficult to strongly reduce emissions in the HtA sectors and what possible additional demand- and technology-oriented measures and policies could help overcome these difficulties. We then develop a set of scenarios using the IMAGE integrated assessment framework (see methods) that include these additional measures to identify the impact on sectoral emissions[22,23]. We show that with these measures, crop-based bioenergy use and afforestation can be limited to sustainable levels.

This study demonstrates that, while the HtA sectors face significant challenges, they can attain lower, sometimes near-zero in the case of buildings and industry, emission levels by implementing drastic demand and technological interventions reducing reliance on CDR. Agriculture plays a critical role, as non-CO_2 greenhouse gases in this sector remain substantial, despite sizeable reductions of 1-2 $GtCO_2$ eq. compared to the reference 1.5°C scenario. This also indirectly results in more afforestation potential on the abandoned land otherwise used for grazing and feed. Stronger emission reductions in the HtA sectors reduces the dependency on CDR, which may increase the technical feasibility and limit adverse side effects of policies aimed towards climate change mitigation.

Results

Emissions in HtA sectors

The four HtA sectors (i.e. heavy industry, international transport, agriculture and buildings) face specific challenges in terms of climate change mitigation. These include relatively fast service growth, limited availability of readily available technological emission reduction options and lack of public support. The industry and international transport sector face additional hurdles given the international competitive markets large upfront costs and the long lifetime of infrastructure. In the buildings and agriculture sector, in contrast, the diversity of actors, limited financial means combined with site-specific conditions from obstacles for transformation[24–30] (see Supplementary Materials). In the agriculture sector in addition the availability of reduction measures is limited and substantial growth of agricultural activity is expected. Consequently, the pace of emission reductions in most 1.5°C scenarios is relatively slow, while rapid emissions reductions are achieved in electricity generation, transport on land and land use. This is illustrated by Figure 1, showing a typical 1.5°C scenario of the Integrated Assessment Model IMAGE. The scenario is based on the IMAGE implementation of the Shared Socioeconomic Pathway 2 (SSP2), describing a future world following current socio-economic trends while, though the introduction of a uniform global carbon price, the radiative forcing target of 1.9 W/m^2 is met.

The right hand panel of the figure shows the speed and extent of emission reduction achieved in the different sectors. The transport sector initially grows compared to 2020 levels but after 2035 steadily reduces emissions, reaching 59% reduction by 2060. Compared to 2020 the agricultural sector shows a slow decline, with 11% reduction by 2060. Note however that in a reference scenario without climate policy this sector rapidly grows in emissions, therefore this slow decline of emissions is a substantial decrease compared to baseline. The figure shows that to meet net-zero emissions in 2060 BECCS and afforestation, shown by the negative energy supply and land use emissions, is strongly applied. Compared to the IPCC assessed scenarios the IMAGE reference 1.5°C scenario shows a deeper reduction of emissions. This can be explained by 1) the IPCC C1 category assuming no temperature overshoot, 2) the IPCC set includes all scenarios that have more than 50% chance of reaching 1.5°C, while the IMAGE 1.5°C is set at more than 67% chance of reaching the climate target.

Several measures and policies are proposed in the literature to address the challenges that the HtA sectors face. This includes technological advancements associated with sustainable fuels, electrification and efficiency-improving techniques are recommended, followed by procedural advancements regarding operations, circularity and waste, tackling the long lifetimes and slow technological advancement[31]. In the agriculture, buildings and transport, effective measures are found on the demand side in the form of lifestyle changes, such as diet shifts[32,33]. Common aspects of policy include pricing, taxation of high-emission services and products and subsidies on low-emission alternatives, either regarding the end product for consumers (e.g. airline tickets or meat) or earlier in the supply chain (e.g. sustainable transport fuel and process emissions). Direct investments in R&D and training can break the deadlock of investments being commercially non-viable or risky in competitive markets in industry, transport and agriculture. Finally, for some products and services, it may be effective to enforce standards and verification mechanisms by means of legislation — for example, building-related energy efficiency standards. Table1-4 (See Supplementary Materials) provide an overview per sector of the challenges to mitigate emissions, and the connected measures and policy instruments to overcome these challenges.

To assess the impacts of changes in demand and technology on HtA sectors emissions, we explore the impact of two new scenarios focussing on additional, ambitious measures in either of these categories (*Demand* and *Technology)*, based on the literature review (See Supplementary Materials). Demand-side changes are defined as those in the consumption of services, compared to the *Reference* scenario, while, on the technology side, changes concern additional technology deployment in the provision of services, and relate to innovation, operation and technology diffusion. The scenarios allow to examine the additional mitigation potential of the identified policies and measures that go beyond what is typically considered in mitigation scenarios, and the required effort of reaching lower emission levels in these HtA sectors. To all three scenarios (*Reference, Demand and Technology*) a uniform carbon tax is applied to reach a radiative forcing of 1.9 W/m^2 by 2100 (equivalent limiting warming below 1.5°C). Table 1 presents an overview of the measures applied in the *Demand* and *Technology* scenario per sector.

Table 1
The specific assumptions made in the Demand (1.) and Technology (2.) scenarios, for the four HtA sectors.

Demand

Transport	Buildings	Industry	Agriculture
Increased teleworking and alternative tourism, result in a 25% reduction in activity compared to Reference. Airline ticket tax of USD 4 per flight; Money spend on travelling with increasing income reduces; Faster saturation of freight demand-industrial value added elasticities. Transition from short-distance aviation to high speed rail between 2025 and 2035;	Reduction in Cooling Degree Days/Heating Degree Days; Reduced ownership of household appliances; Reduced heating, cooling, appliances and lighting waste via e.g. occupancy sensors, avoiding stand-by mode; 25% reduction in hot water demand (e.g. shorter showers). Converge regional per-capita floorspace to 45 m^2; Increase in household occupancy rate by 20% in more affluent regions, reducing the per-capita ownership of certain appliances.	Steel, paper and pulp, cement, non-energy and other industry reduce material demand according to the LED scenario in the IRP RECC report[34], leading to an average 43.5% decrease in material demand by 2060 compared to 2016. After this period standard default assumptions on material demand development are applied.	Transition towards healthy diets[35] (incl. reduction of meat and dairy products); 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 (consistent with 50% waste reduction in Willet et al. 2019[35]); Lower cost of non CO_2 measures.

2. Technology

Transport	Buildings	Industry	Agriculture
More fuel-efficient aircraft on the market; Light weight and retrofitted airplanes; Drop in Bio-jet fuel can replace kerosine 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 (e.g. use of air-coolers and heat pumps); Use net-metering, promoting the use of residential PV; Increased use of architectural designs that have lower heating demand and require less floorspace.	Steel: Foreclosure of unabated (blast furnace) technologies from 2021 onwards and phase-out of metallurgical coal use towards 2030; Only electric arc furnace, hydrogen reduced iron (from 2030 onwards) and electrowinning (from 2040 onwards) in steel making; Cement: Foreclosure of unabated technologies from 2021 onwards; Incentive stimulating electricity use; Paper and Pulp: Incentive for the use of biomass, electricity and hydrogen. For fuel types having a CHP (combined heat and power) option available, only the CHP 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[36]: implemented as a 60% substitution by 2050 and an 80% substitution by 2100; Lower cost of non CO_2 measures; Increased maximum reduction potential by 2100 for CH_4 and N_2O: Rice production: 80% Enteric fermentation: 60% Fertilizer use N_2O: 70% Animal waste/manure CH_4: 80%, N_2O: 70%

Emission reductions per sector

The measures implemented under the *Demand* and *Technology* scenarios lead to notable additional emission reductions, reducing global residual emissions from the HtA sectors to 6.3 and 7.0 $GtCO_2$-eq respectively by 2060 (see Figure 2), compared to 9.8 $GtCO_2$-eq in the *Reference 1.5°C* scenario. Under the *Technology* scenario, the electrification of space and water heating in the built environment leads to very low residual emission levels (this includes the phase-out of traditional biomass use by urban households). In the agricultural sector, both scenarios show a substantial decrease in non-CO_2 emissions through decreased meat and dairy consumption, through 1) substitution, cultivated meat or 2) other plant-based alternatives respectively. Still, residual agricultural emissions of respectively 4.2 and 5.0 $GtCO_2$-eq remain in both *Demand* and *Technology* scenarios. The responses in the aviation and shipping sectors differ between the scenarios. In the *Demand* scenario, there is a stronger short-term response from the implementation of the airline ticket tax and the shift to high speed train and local tourism. In the *Technology* scenario, increased development and availability of fuel and technology alternatives lead to a longer-term impact.

The stringent industrial measures assumed can effective reduce emissions in both the *Technology* and *Demand* scenarios. Compared to the *Reference 1.5°C* scenario, the alternative pathways are particularly effective to switch the course of the steel sector. Going completely to net zero-emission in the industry is, however, ambitious and depends on CDR in cement and pulp and paper, higher conversion rates for material and energy uses (e.g. material retention, recycling), and the extensive availability of zero-carbon energy for other industrial sectors[37,38]. In both the *Technology* and the *Demand* scenario, the lower residual industrial emissions and application of BECCS result in net-zero industrial emissions by 2060 (see Figure 3).

In the aviation, shipping and agricultural sectors, the largest changes can be seen in the *Demand* scenarios (see Figure 3). The reduction in short-distance air travel and the decrease in longer distance flights reduce emissions by 43%. Likewise, in the agriculture sector, the switch to healthy diets for 80% of the global population and a 40% reduction in food waste (*Demand* scenario), results in strongly reduced non-CO_2 emissions and in a strong indirect effect on land-use change (less agricultural land is needed leading to afforestation). The latter dominates the impact on emissions. A similar effect occurs in the *Technology* scenario, where meat is largely replaced by artificial meat, and novel techniques significantly reduce non-CO_2 agricultural greenhouse emissions (e.g. from rice cultivation), resulting in less agricultural land required for food production.

Impact of the HtA measures on CDR

The additional mitigation options implemented in HtA sectors unlocks additional potential in the *Demand* and *Technology* scenarios helping to achieve the 1.5°C target. It also means that less reliance is needed on the use of CDR measures to compensate for residual emissions[13]. Moreover, the additional mitigation potential can be used to replace other high-costs mitigation options. The scenarios illustrate what the impact of the additional measures in the hard-to-abate sectors may look like.

The lower CDR requirement in the *Demand* and *Technology* scenarios allows to limit annual crop-based bioenergy use and additional afforestation. In the *Demand* scenario, only afforestation on abandoned croplands and grasslands is permitted, to avoid competition with food supply and biodiversity, while in the *Technology* scenario*,* some additional afforestation was still allowed to achieve the temperature target, however, still the amount was reduced to half of the default potential (about 500 Mha instead of about 1000 Mha). Note that there is considerable reforestation in both scenarios anyway, as a result of the lower meat demand. The additional options also lead to a new, lower, carbon price for the *Demand* and *Technology* scenarios.

In the *Reference 1.5°C* scenario, net-zero greenhouse gas emissions are achieved partly by offsetting positive emissions from HtA sectors with CDR (see also Figure 4). Figure 4 provides a time slice for the net-zero year for all three scenarios, demonstrating that the additional HtA options looked at in this paper can reduce CDR need by 23-30 %. Moreover, the net-zero year is achieved earlier (resp. 2050 and 2051 for the *Demand* and *Technology* scenario) leading to reduced exceedance of the carbon budget and a decrease in temperature overshoot, see cumulative CO_2 emissions displayed in right hand panel.

In both the *Demand* and the *Technology* scenario*,* annual crop-based bioenergy will stay below 40 EJ/yr (see Figure 5), which is lower than the sustainable level of 60 EJ/yr, as identified by Fuss et al. (2018)[39] throughout the century due to i) less demand for bioenergy from transport due to lower total transport activity, and ii) the reduced use of BECCS (given the lower residual emissions). Under the *Technology* scenario, crop-based bioenergy use will however peak earlier, namely in 2060 (Figure 5), due to its use in aviation. It should be noted that the higher BECCS numbers still present in the *Demand* and *Technology* scenarios are based on residue use (not requiring additional land, but with a somewhat uncertain supply)[39,40]. For the *Technology* scenario, total bioenergy use is reduced – but the use of residues is slightly increased.

The reduction of meat consumption in both alternative scenarios increased the land available for reforestation. Still, for the full century, the total CO_2 uptake as a result of afforestation is higher in the *Reference* scenario as a result of the fact that in both the *Demand* and *Technology* scenarios we restricted additional afforestation (to benefit from the lower CDR needs). Cumulatively, from 2020 onwards, CO_2 uptake via land use is 227 $GtCO_2$ under the *Demand scenario* and 151 $GtCO_2$ under the *Technology scenario,* compared to 305 $GtCO_2$ under the *Reference scenario,* see also Figure 5.

As shown in Figure 5, lower residual emissions in the first half of the century reduce the extent to which CDR measures need to be implemented in the second half of the century, in order to remain within *1.5°C* warming. The deeper reductions achieved earlier on, particularly under the *Demand* scenario, reduce the scale at which CDR measures are implemented at the end of the century. This can be seen in both the amount of BECCS (bottom right) and the level of afforestation (top right) at the end of the century. The scenarios also show that despite ambitious emissions reduction level in the hard to abate sectors, they still rely on the use of CDR techniques. However, the CDR ceiling is significantly reduced, which is critical for the adverse consequences such as biodiversity and food risks.

Discussion

The *Demand* scenario assumes that additional demand-side measures can be implemented on the short-term leading to an immediate impact emissions (Fig. 3). While this illustrates the potential of demand-side measures, it should be noted that social change also requires time depending on social acceptance. As some new technologies are not yet available, some of the changes under the *Technology* scenario take effect only after 2040 (Fig. 3). In this scenario, the pace increases when novel technologies are adopted on a large scale. This result, however, is sector dependent (e.g. in buildings the challenge is not to implement innovative technologies, but existing technologies such as heat pumps, allowing for a more rapid implementation).

Agriculture plays a crucial role in achieving net-zero emissions, given its role in non-CO_2 emissions and the possible land for reforestation. Therefore, measures targeting the remaining emissions from this sector may have a strong direct impact, notably those on reduced or cultured meat consumption as well as healthier levels of food intake that lower emissions from enteric fermentation and manure. In addition, these measures reduce the amount of land used for grazing and feed and, therefore, indirectly, allow for more afforestation.

While this study explores technology- and demand-oriented measures separately, their potential can be greatly increased if combined. Moreover, many demand-side options can be supported by technology, and vice versa. For instance, replacing short-distance flights by high-speed rail will only be possible if the required rail infrastructure is in place. In the case of industry, more effective recycling can reduce the demand for primary inputs and support a transition towards carbon-neutral production technologies. In the end, however, none of the measures proposed in this study will be easy to implement as they all come with specific challenges and costs. The challenge of achieving net-zero emissions within a few decades is simply enormous and will require difficult and sometimes costly measures.

Despite the obstacles that the HtA sectors face in reaching net-zero emissions this study shows that, with drastic demand and technology measures, HtA sectors can reach lower, near-zero emission levels within a shorter amount of time. This means that hard-to-abate does not equate them being impossible to mitigate. This understanding offers policymakers a choice to focus on targeted HtA sector policies to avoid dependency on large scale CDR application.

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Methods

Literature study

The literature study first provides an overview of the characteristics of each hard-to-abate sector and discusses what makes it difficult to achieve net-zero targets in these sectors. The second part of the review focuses on the possible policies and measures to address these obstacles. The review serves 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 context to the model analysis, by using the identified policies and measures in developing the scenarios and in the interpretation of the model projections. The results are presented in the Appendix.

Sectoral analysis

IMAGE modelling framework

To understand the role of the development in hard-to-abate sectors in trying to limit global warming to 1.5 °C, the IMAGE model was used. IMAGE is an integrated assessment modelling framework that simulates the interaction between human activity and economic development, on the one hand, and the environment on the other. The model has been frequently used to explore comprehensive scenarios on global climate change mitigation, such as used for IPCC's Sixth Assessment Report[2] and the UNEP Emissions Gap Report[41]

IMAGE is a process-oriented integrated assessment model (IAM), providing an intermediate complexity representation of human and earth systems[23]. The key components of the human system that largely contribute to greenhouse gas emissions are the energy system and the agricultural and land systems. The energy and industry system are represented by the TIMER model (ref), agricultural demand, production and trade by the MAGNET model (Woltjer et al. 2014). 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 LPJmL model (Carbon, crops, vegetation, water) (Schaphoff et al., 2018; Müller et al. 2016). The human and earth systems are interconnected by emissions and land use. The socio-economic 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 5x5 minute grid for land use and land-use changes and on a 30x30 minute grid for plant growth and the carbon and water cycles. IMAGE operates in annual time steps and, as such, is suitable for long-term climate mitigation assessments up to 2100.

IMAGE describes, in detail, the development of all five hard-to-abate sectors considered in this study. Based on historical trends, the demand for travel, housing, specific materials and agricultural products 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, depending on resource availability, technology development, operation and availability, amongst other things. Passenger transport modes include buses, bicycles, motorcycles, walking, trains, passenger vehicles and aircraft, and which mode people choose may depend on personal preferences, 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. 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. Demand for agricultural products is determined by food demand driven by increases in population and income. 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. The industry distinguishes between the iron and steel sector, clinker and cement, paper and pulp, food processing, non-energy and other industry. Non-energy industry includes olefins, methanol, ammonia and other refinery products, and other industry consists of the non-ferrous metals, non-metallic minerals, petrochemical sector (excl. feedstock), transport equipment, machinery, mining and quarrying, construction, textile and leather and other non-specified industries.

Table 1

Overview of modelling of hard-to-abate sectors in the IMAGE model framework

Sector	Drivers	Service provided	Technology detail
Aviation and shipping	Income, fuel price, technology development	Passenger kilometer travel, tonne kilometer transported	Aviation: 16 technologies with varying levels of efficiency, depending on production year, using bio-jet fuel or conventional jet fuel, electric aircraft and hydrogen-fuelled aircraft; Shipping: 8 technologies with varying levels of efficiency, using fuel oil, biofuel or hydrogen.
Industry and Materials	Income, population, fuel price, feedstock availability, (simplified) technology development	Material produced (e.g. in tonnes of steel, cement, paper and pulp)	Iron and steel: 13 combinations for iron ore reduction and steel production, including primary and secondary production routes; Clinker and cement: 4 different lime kiln configurations; Paper and pulp: 16 combinations for heat production across 6 heating technologies, including primary and secondary production routes; Food processing: 12 combinations for heat production across 5 heating technologies and two temperature grades (> and < 100 °C); Non-energy industry, olefins include 6 different primary feedstock production routes with 2 simplified steam cracker types and 3 secondary feedstock production routes; Other industry: simplified representations of improved energy efficiency, electrification and CCS that are correlated with the carbon price.
Buildings	Income, temperature, fuel price, technology development, electrification. Income influences floorspace and household size, which act as secondary drivers	Cooking, heating (space and water), cooling, appliances	Fossil (solid, liquid and gaseous), biomass (modern and traditional) and electricity technologies compete for market shares for space heating, water heating and cooking. For traditional biomass, we assume that 60% can be considered to be fully renewable. For the remaining 40%, the carbon content (26kg-C/GJ) is assumed to contribute to emissions. Space heating can also be provided from district heating, and electric heating is further disaggregated to resistance heating and heat pumps. Three cooling technologies (fan, air cooling, air conditioning), nine household appliance groups, and lighting increase electricity demand.
Agriculture and non-CO_2	Income, food preferences, food prices, land availability	Food	16 food crops, 5 animal products and 5 bio-energy crops; Rainfed and irrigated agriculture.

Default climate scenarios (SSPs)

The framework of Shared Socio-Economic Pathways (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. 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. The SSP4 scenario indicates a world of substantial inequality. Finally, the SSP5 scenario describes a conventional development pathway, where rapid growth is achieved based on fossil fuel expansion. The most recent IMAGE SSPs scenarios follow the SSPs narratives and include the impacts of the COVID-19 pandemic[42]. In this paper, the reference scenario is the IMAGE middle-of-the-road SSP2 scenario.

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 hard-to-abate sectors, various scenarios are developed and compared. This includes a reference scenario without climate policy, 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 hard-to-abate sectors are implemented. The developed scenarios build on the literature review described in the appendix.

Demand scenario

Under the *Demand scenario,* the demand for services is reduced, compared to under the *Reference* scenario. The hard-to-abate sectors are characterised 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 changes in demand include changes that do not require fundamental changes in how sectors operate but do push them to their limits within current operation modes (non-structural) and changes that require fundamental adjustments their operating methods, resulting in a strong reduction in demand (structural). In the buildings sector, the demand for energy is reduced in various ways, such as by people lowering the thermostat setting, taking shorter showers, and using occupancy sensors to minimise 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. High cost penalties on non-CO_2 mitigation measures that result in higher food prices are removed, which gives more priority to the implementation of low cost non-CO_2 emissions than is the case under the *Reference* scenario. In addition, food waste throughout the supply chain is significantly reduced. In the transport sector, there is a lower increase in the money spent on transportation 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) (Hertwich et al., 2020). The 43.5% reduction in material by 2060, compared to 2016 levels, as is seen under the LED scenario, 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 will allow for more adoption 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 faster development and adoption of efficient aircraft. 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 the short-to-medium distances. The transition towards these alternative propulsion techniques is accelerated due to early retirement of traditionally fuelled equipment. In the agricultural sector, artificial meat becomes the dominant market player, resulting in 60% reduction in meat by 2050, and 80% by the end of the century, decreasing the demand for livestock. The assumption being that the feedstock of artificial meat is maize, which has a 42% caloric conversion efficiency[36]. 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. In the steel sector, only electric arc furnace (EAF), 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

The final part of the analysis is aimed at better understanding how the additional policies and measures in the hard-to-abate sectors affect economy-wide 1.5 ℃ mitigation strategies. Specifically, to understand whether, with these additional measures, global warming can be limited to 1.5 ℃ while keeping BECCS and afforestation at sustainable levels. For this set of scenarios, a global emission pathway that limits global warming to 1.5 ℃ is determined by minimising cumulative discounted mitigation costs, and, as such, following a cost-effective carbon price pathway.

For this, we focus on three 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 is lower than the carbon prices applied in Chapter 5, reaching USD 800 per tonne of carbon by 2035 and about USD 1000 per tonne of carbon by 2050, compared to USD 1750 per tonne of carbon by 2035 and USD 4000 per tonne of carbon;

- *Demand 1.5 °C*: This scenario uses the same carbon price trajectory as *Reference 1.5 °C* and additional measures in the *hard-to-abate* sectors following the *Demand* scenario assumptions depicted in Table 1. Afforestation and bioenergy are restricted (see below).
- *Technology 1.5 °C*: This scenario uses the same carbon price trajectory as *Reference 1.5 °C* and additional measures in the *hard-to-abate* sectors according to the *Technology* scenario assumptions depicted in Table 1. Afforestation and bioenergy are restricted (see below).

Bioenergy deployment

A maximum limit of 60 EJ/yr was set for the deployment of bioenergy from energy crops, based on maximum levels of what can be sustainably harvested[39]. As such, the mitigation challenges in the hard-to-abate sectors can be evaluated while enforcing a sustainable use of biomass. The limit on bioenergy was not applied to agriculture and forestry residues and municipal solid waste.

Afforestation

In the Demand and Technology carbon-price driven afforestation was limited as much as possible to avoid competition with food supply and biodiversity[43]. Note that there is considerable forest expansion in both scenarios anyway, as a result of the lower meat demand. In the *Demand* scenario as a result only afforestation on abandoned croplands and grasslands is permitted; In the *Technology* scenario*,* some carbon-price driven afforestation was still allowed to achieve the temperature target, however, the amount was reduced to half of the default potential which is about 500 Mha instead of about 1000 Mha.