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The transition in energy demand sectors to limit global warming to 1.5°C

Aurélie Méjean, Céline Guivarch, Julien Lefèvre, Meriem Hamdi-Cherif

Abstract

Achieving an emissions pathway that would be compatible with limiting the global temperature increase to 1.5°C compared to pre-industrial levels would require unprecedented changes in the economy and energy use and supply. This paper describes how such a transition may impact the dynamics of sectoral emissions. We compare contrasted global scenarios in terms of the date of emission peaks, energy efficiency, availability of low-carbon energy technologies and fossil fuels, using the global integrated assessment model IMACLIM-R. The results suggest that it is impossible to delay the peak of global emissions until 2030 while remaining on a path compatible with the 1.5°C objective. We show that stringent policies in energy-demand sectors - industry and transportation especially – are needed in the short run to trigger an immediate peak of global emissions and increase the probability to meet the 1.5°C objective. Such sector-specific policies would contribute to lowering energy demand, and would reduce the level of the carbon price required to reach the same temperature objective. Bringing forward the peak of global emissions does not lead to a homothetic adjustment of all sectoral emissions pathways: an early peak of global emissions implies the fast decarbonisation of the electricity sector and early emissions reductions in energy-demand sectors – mainly industry and transportation.

Keywords

Global integrated assessment model; dynamics of sectoral CO₂ emissions; energy demand patterns; peak of global emissions; scenario feasibility; 1.5°C

Highlights

- It may be impossible to delay the peak of global emissions until 2030 while remaining on a pathway compatible with a 1.5°C world, whatever the policies in place to lower energy demand across sectors.
- Stringent policies in energy-demand sectors - industry and transportation especially – are needed in the short run to trigger an immediate peak of global emissions and increase the probability to meet the 1.5°C objective
- Sector-specific policies reduce energy demand and reduce the level of the carbon price required to reach the same temperature objective by 25% to 50% in 2030.
- Bringing forward the peak of global emissions does not lead to a homothetic adjustment of all sectoral emissions pathways.
- An early peak of global emissions implies the fast decarbonisation of the electricity sector and early emissions reductions in energy-demand sectors – mainly industry and transportation.

1. Introduction

The aim of climate negotiations is to stabilize ‘greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system’ (Article 2 of the UNFCCC). In 2010, the Cancun Agreements recognized the objective of limiting the mean temperature increase of the atmosphere below 2°C above pre-industrial levels. However, a diverse range of actors, including scientists, have called for a more stringent climate objective (Hansen et al., 2008). Indeed, climate change impacts will affect different regions in very different ways. Some regions, for instance small island states and least-developed countries, will be particularly vulnerable to climate change (Hare et al., 2011), and may be unable to cope with the impacts associated with a 2°C world. Following the proposal of the Alliance of Small Island States, the Paris Agreement, adopted in 2015 by 196 countries, set the goal to limit the increase of global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels.

Achieving an emissions pathway that would be compatible with limiting the global temperature increase to 1.5°C compared to pre-industrial levels may require unprecedented changes in the economy and energy use and supply. In particular, limiting the increase to 1.5°C implies an early transition to net zero carbon emissions worldwide (Rogelj et al., 2015). However, given the uncertainty surrounding the possibility to achieve negative emissions at scale, the early decarbonisation of the economy may be warranted too. While previous studies have explored the implications of delayed mitigation action on the cost and feasibility of the 2°C objective (Luderer et al., 2013; Riahi et al., 2015), the question of bringing forward the peak in global emissions arises with the interest in the 1.5°C objective. The question of an early peak of global emissions is all the more relevant as (i) measured global CO₂ emissions have been stagnating for three years (Jackson et al., 2016; Le Quéré et al., 2016), which could indicate a peak if emissions would start decreasing immediately, and (ii) it has been shown that, for a given temperature target, an earlier peak alleviates the emissions reduction rates necessary after the peak, thus making them a bit less formidable than for a later peak (Guivarch and Hallegatte, 2013; Stocker, 2013; Figueres et al., 2017). If the question of the timing of the peak of global emissions has already been analysed thoroughly, the question of its impact on the pace of decarbonisation of sectoral emissions remains little explored. We thus address this question here, with an emphasis on end-uses (or energy-

demand) sectors, such as the industry, transportation and residential¹ sectors, and with a specific focus on how alternative energy-demand patterns affect the dynamics of sectoral emissions.

We compare contrasted global scenarios in terms of the date of emission peak, energy demand, availability of low-carbon energy technologies, and fossil fuel availability. The paper is organized as follows. Section 2 presents the analytical framework. We use the IMACLIM-R Global Integrated Assessment Model, which combines a Computable General Equilibrium Framework with bottom-up sectoral modules in a hybrid and recursive dynamic architecture (section 2.1). We examine the effect of bringing forward the peak of global emissions from 2030 to 2016, while reaching the same global emissions in 2050 (-65% compared to 1990), (see section 2.2). Our four families of scenarios correspond to four different dates for the peak of global emissions with four different cumulative emission levels by 2050 compatible with emission pathways based on the 1.5°C target (section 2.3). In the model, emission constraints are met by means of a uniform carbon price, and alternative emission peaks translate into different carbon price paths with consequences for the breakdown of emission reductions among sectors. Section 3 presents the results. We show that the pace of decarbonisation that would be required after the peak is impossible to reach if emissions peak late (in 2030), whatever the policies in place to improve energy efficiency and reduce energy demand. Also, without sector-specific policies aimed at lowering energy demand across sectors of the economy, achieving short to medium term emissions deemed compatible with the 1.5°C objective is likely to command levels of carbon prices that may be regarded as politically and socially unacceptable (section 3.1). We show that bringing forward in time the peak of global emissions relies on the fast decarbonisation of the electricity sector and on early emissions reductions in energy-demand sectors – mainly industry and transport (section 3.2). Section 4 concludes.

2. Analytical framework

This section presents the model used in the analysis (section 2.1), and describes the scenarios considered, in terms of emission trajectories and technological and socio-economic parameters (section 2.2). In particular, we compare our emission scenarios with the range of available 1.5°C scenarios in the literature.

¹ Note that the residential sector refers to private housing only, and is separate from the service (or composite) sector. We left the service sector out of the analysis as it represents less than 5% of total emissions in 2015 and as the representation of this sector is less detailed than other sectors in IMACLIM-R.

2.1 Model

IMACLIM-R (Waisman et al., 2012) is a global Integrated Assessment Model that represents the interlinked evolution of economic growth, energy demand and technical systems². This multi-region, multi-sector hybrid Computable General Equilibrium model represents changes in the macroeconomic and technological world both in money values and physical quantities in a consistent framework. It describes dynamic trajectories in yearly steps to 2050 or 2100 through the recursive succession of top-down static economic equilibria and bottom-up sectoral modules. The model explicitly represents limitations affecting the flexibility of technical systems and their interplay with macroeconomic trajectories by describing growth patterns in a world with market imperfections, partial use of production factors and imperfect expectations of economic agents for their investment decisions.

The model represents structural change, energy markets and induced technical change. In sectors where technologies are explicitly modelled (e.g. electricity production or personal vehicles), technology costs decrease through learning-by-doing. In sectors where explicit portfolios of technologies are not modelled (agriculture, industry, construction and services), endogenous energy efficiency improvements are induced by energy prices. Energy substitution is driven by energy prices and technology costs³ and may occur in all sectors. The inertia of economic sectors is captured by modelling the vintages of capital, as well as including constraints on the maximum speed of technology deployment. The residential and transportation sectors in particular have long-lived infrastructure, and replacing existing capital stock may take decades. In the transportation sector for instance, demand for mobility depends on the spatial organization at the urban level and on the existing network of roads, public transportation (metro, buses, railways) and airports, which are very inert. The model tracks the available transport capacity for various modes (road, bus & rail, air) in terms of passenger kilometers travelled per year. In each region, a representative household can switch between transportation modes to maximize its utility under constraints of income and time.

Final demand for goods and services, including energy services, results from solving a utility maximization program for each region. Energy commodities are not directly represented in the utility function, instead they are considered as production factors of mobility and housing services. The evolution of lifestyles and household preferences impact overall energy demand in end-use

² For a detailed description of the IMACLIM-R model, see:

http://themasites.pbl.nl/models/advance/index.php/Model_Documentation_-_IMACLIM

³ See Bibas et al. (2015) for a thorough description of the representation of technical change in IMACLIM-R.

sectors, through a number of non-price mechanisms. The mechanisms modelled include the possible saturation of the consumption volume of agricultural and industrial goods, the evolution of basic needs of mobility, the rate of increase of private car ownership and the rate of increase of residential floor area per capita.

IMACLIM-R belongs to the family of the Integrated Assessment Models (IAMs) that have a medium variety of low-carbon technologies and that can be defined as a “low response” model according to diagnostics of its response to carbon pricing. This latter point means that the carbon price needed to reach a given mitigation objective is higher than in other IAMs, thus implying higher mitigation costs (Kriegler et al., 2015). The relatively low responsiveness of the model to carbon prices is explained by the fact that the model represents real world features, such as market imperfections and the inertia of technical systems.

The model exclusively represents CO₂ emissions from energy, generated by the production and use of coal, oil and gas in final goods and transformation processes⁴. The climate constraint takes the form of a carbon emission trajectory that is exogenously prescribed over time. At each date, a carbon price is then endogenously calculated by the model so that the increase in the cost of fossil fuels triggers a decrease of their use consistent with the carbon constraint. In this study, we opt for an idealized implementation of the carbon price, i.e. a uniform carbon price across sectors, households and regions, similarly to the scenarios presented in (IPCC, 2014).

2.2 Scenarios

In order to study the impact of the date of the peak in global emissions on sectoral emissions, we compare contrasted global scenarios over the 2010-2050 period. This modelling horizon is chosen to focus the analysis on the short to medium term transition. We examine the effect of bringing forward the peak of global emissions from 2030 up to 2016 by considering four carbon emissions constraints (Figure 1) that differ in terms of date of their emission peak (2030, 2025, 2020 and 2016)⁵ and level of emissions at the date of the peak. The carbon emission trajectories are however set to reach the same level of emissions in 2050 (corresponding to a reduction of 65% with respect to 1990 levels). For all four emissions trajectories constraints, the emission levels are set to historical data over 2010-2016. Then, emissions growth decreases at a constant rate from 2016 to the peak date (it has a parabolic shape). After the peak date, the emission reductions increase for 5 years (at a constant

⁴ Non-CO₂ GHG gases and emissions from land-use change are not modeled explicitly in this version of the model.

⁵ Note that global emissions are imposed over that period, but not the sectoral shares of those emissions.

rate of increase, i.e. it also has a parabolic shape) and the rate of increase becomes then constant (the emissions reductions are linear) until 2050.

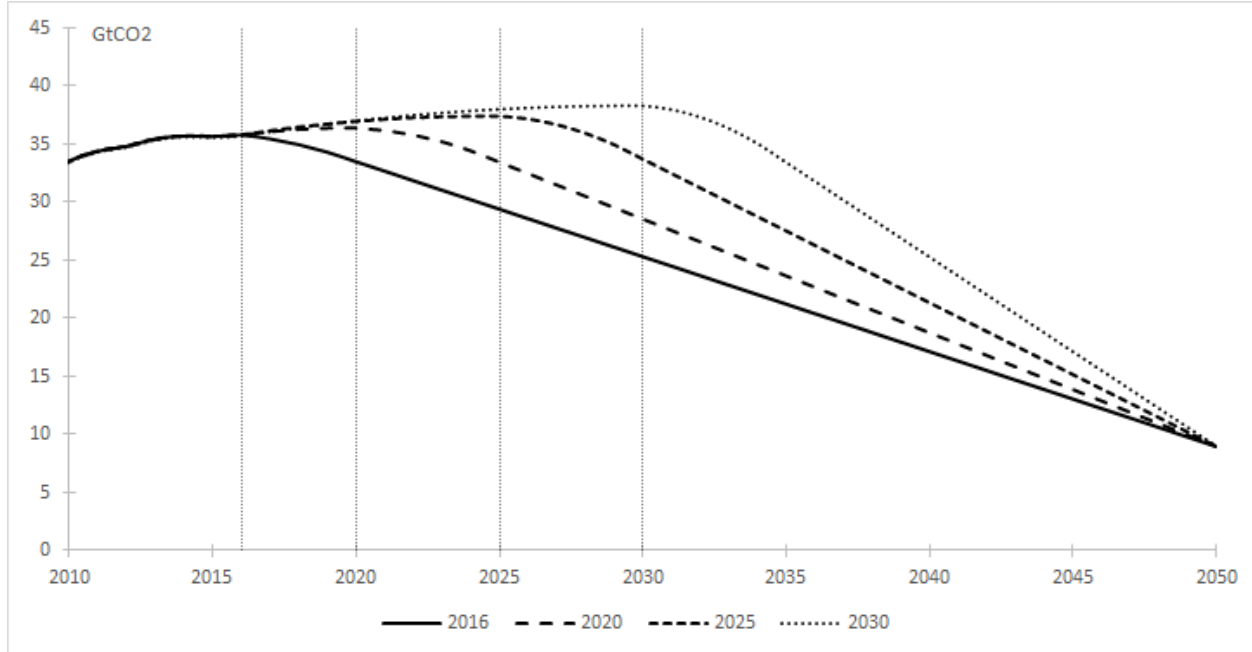


Figure 1: Emission constraint over time (GtCO₂). CO₂ emissions are set to peak at different dates (2016, 2020, 2025, 2030) according to the scenario considered and to reach the same level in 2050 in all scenarios.

We identify key uncertain parameters and group them into three major parameter sets, described below. When combining the different parameter options considered for this study (see Table 1) with the four emissions trajectories, we obtain a set of 32 scenarios.

Energy demand

This set includes parameters driving energy efficiency improvements in productive sectors (agriculture, industry, construction) and the development style of developing countries (motorization rate, evolution of floor space per capita, saturation of demand for industrial goods). Two variants are considered: an energy-intensive option (*high energy demand*) and a low-energy option (*low energy demand*).

The parameters influencing the level of energy demand in each sector and their values for each variant are detailed in the appendix. Switching from a high energy demand baseline scenario to a low energy demand baseline scenario requires increasing the level of stringency of existing mitigation

policies and implementing new demand-side policies specific to each sector, including regulatory instruments, economic instruments in addition to a carbon price, financial instruments and voluntary measures. The model parameters are therefore associated with a portfolio of policies that may be implemented in practice and that would trigger a switch from the high energy demand scenario to a low energy demand scenario. Some examples are given below.

In the case of the residential sector, emissions can be reduced through a mix of regulatory instruments such as standards and labels for buildings and appliances, (Zhou et al., 2011); economic instruments such as saving feed-in tariffs (Bertoldi et al., 2010; 2013); and financial instruments such as investment subsidies or low-interest loans to finance retrofits (Harmelink et al., 2008), (McGilligan et al., 2010). Households may be reluctant to adopt energy efficiency measures due to high upfront costs and delayed benefits (Kunreuther and Weber, 2014). Also, although households consume less electricity when prices increase, the magnitude of the impact of higher prices on demand depends on the availability of enabling technologies (e.g. smart thermostats) (Faruqui and Sergici, 2010). Policies designed to reduce energy consumption should therefore account for the fact that prices are not the only factor influencing behaviours. Energy efficiency interventions such as the provision of better information on energy use can contribute to encourage energy conservation. However, the mere provision of information does not necessarily lead to actual behaviour changes and energy savings (Abrahamse et al., 2005). Allcott and Mullainathan (2010) argue that interventions based on insights from behavioural science may help achieving energy savings. In particular, the way information is presented to energy consumers greatly influences the impact of that information on energy savings, for instance in the case of smart-meters (Bager and Mundaca, 2017) and for the choice of electricity providers (Pichert and Katsikopoulos, 2008). One of the parameters used to model energy efficiency in the residential sector is the income elasticity of the building stock growth, which is reduced when switching from a high energy demand scenario to a low energy demand scenario.

The transportation sector is characterised by strong inertia associated with existing transportation infrastructure (roads and public transportation networks) and urban sprawl, which constrains mobility and related emissions over long periods. As a result, the demand for transportation in terms of miles travelled and fuel consumption of vehicles is relatively inelastic to prices, at least in the short term (Goodwin et al., 2004; Creutzig et al., 2011). The transportation sector would thus require high and early carbon price signals to reach a high level of decarbonisation in the long term (Waisman et al., 2013), in particular when the sole policy instrument considered is a uniform carbon price. Emissions from transport can be reduced through technological and behavioral options (Chapman, 2007), (Schafer, 2012). One of the parameters used to model energy efficiency in this

sector is the growth of the motorization rate. A significant increase of motorized transport demand is expected in developing economies in the next decades (Grubler et al., 2012), particularly due to increasing GDP per capita and increasing urbanization (Sims et al., 2014). In the model, the growth of the motorization rate evolves as a function of GDP growth following the specification used in (IEA, 2008). The value of this parameter was set at 20% above the IEA value in the high energy demand scenario, and at 20% below the IEA value in the low energy demand scenario. Reducing the growth of the motorization could be achieved by policies aiming at changing the modal structure of mobility (e.g. through investments in public transports for passengers and shipping or inland waterways for freight) and by policies aimed at reducing the overall volume of mobility (e.g. through densifying urban spaces, promoting teleworking, reorganizing production and distribution processes).

In the case of the industry sector, the parameters used to model energy efficiency characterize an exogenous trend of energy efficiency improvements at constant energy prices. The energy efficiency of the leader region then evolves as a function of an energy price index (which is endogenous), and other regions catch up with the leader at a pace also parametrized in the model. Again, a number of policy options may allow the switch from a high energy demand scenario to a low energy demand scenario. The speed of energy efficiency improvements depends on a mix of policies, including: regulatory instruments such as efficiency standards, economic instruments such as energy taxes, and supportive instruments such as cooperative measures and capacity building, see (Tanaka, 2011) for a review. There may also be a preponderant role for international institutions in enabling technology diffusion (Suzuki, 2015).

Fossil fuel resources

This set describes the availability of coal and gas and the development of coal-to-liquids technologies. Again, two variants are considered: a first option corresponds to abundant coal and gas resources at relatively cheap cost and large market penetration of coal-to-liquids technologies (*high availability of fossil fuel resources*), the second option corresponds to scarcer and more expensive coal and gas resources, and limited market penetration of coal-to-liquids technologies (*low availability of fossil fuel resources*). The scenarios do not include variants on the oil price. The oil price is endogenous in the model and reflects tensions between supply and demand. It evolves as a function of the geological nature of world oil reserves, OPEC's influence, the inertia in the deployment of production capacities and agents' decisions. More details are available in the appendix.

Low carbon technologies

This set considers the speed of technical change (excluding energy efficiency improvements in productive sectors) in low carbon technologies for electricity generation (renewables and nuclear). Again, two variants are considered: early vs. late entry into the market, high vs. low learning-rates and high vs. low asymptote for the market share of those technologies, which taken together correspond to *high availability of low carbon technologies* vs. *low availability of low-carbon technologies*.

Table 1 summarizes the scenarios used in this study.

<i>Parameter family</i>		<i>Sector or technology</i>	<i>High</i>	<i>Low</i>
<i>Energy demand</i>	<i>Energy efficiency</i>	<i>Agriculture, industry, construction, services</i>	Slow induced energy efficiency improvement	Fast induced energy efficiency improvement
	<i>Development patterns</i>	<i>Transport, buildings, consumption of industrial goods</i>	Asymptotic catch-up of developing countries with the US development pattern	A less carbon-intensive development pattern
<i>Fossil fuel resources</i>		<i>Coal, gas</i>	Relatively abundant and cheap	Relatively scarce and expensive
		<i>Coal-to-liquids</i>	High penetration	Low penetration
<i>Low carbon technologies</i>		<i>Low carbon electricity technologies (renewables, nuclear)</i>	High availability Fast learning	Low availability Slow learning

Table 1: Definition of scenarios in terms of energy demand (high or low), availability of fossil fuel resources (high or low), and availability of low carbon technologies (high or low). Further information on specific parameter values are in the appendix.

Because our scenarios only span the first half of the century to focus the study on short to medium term transitions, the resulting temperature increase over the 21st century cannot be directly evaluated. Nonetheless, our scenarios can be related to 1.5°C scenarios as we place them on the map of carbon budgets until mid-century vs. carbon budgets until the end of the century (Figure 2). Our

four families⁶ of scenarios have cumulative carbon emissions over 2010-2050 of 950 GtCO₂, 1035 GtCO₂, 1124 GtCO₂ and 1215 GtCO₂, respectively⁷. From Figure 2, we can deduce that the first family of scenarios would be close to some 1.5°C scenarios from Rogelj et al. (2015) if cumulative carbon emissions after 2050 would be comprised between -400 and -600 GtCO₂. With similar cumulative carbon emissions after 2050, the second family of scenarios would be at the extreme edge of the 1.5°C scenarios previously assessed (in blue). The families of scenarios 3 and 4, extended with carbon budgets above -400 GtCO₂ would be similar to 2°C scenarios from Rogelj et al. (2015). The carbon budgets over 2010-2050 of families 3 and 4 are higher than mid-century carbon budgets of 1.5°C scenarios. Therefore, scenarios of families 3 and 4 may not be consistent with the objective of limiting the temperature increase to 1.5°C with a probability of at least 50%, or would require extremely high levels of negative emissions after 2050. There are strong limits to the feasibility of such high levels of negative emissions (Smith et al., 2016; Anderson and Peters, 2016). If evaluated against the new assessment of carbon budgets that are consistent with limiting warming to 1.5°C by Millar et al. (2017), our four families of scenarios would require cumulative emissions from 2050 to 2100 approximately between 0 and -200 GtCO₂, between -100 and -300 GtCO₂, between -200 and -400 GtCO₂ and between -300 and -500 GtCO₂, respectively, to be consistent with the 1.5°C objective. Note that the carbon budget values of Millar et al. (2017) are significantly higher than those from Rogelj et al. (2015). The difference arises from different definitions and methodologies between the two studies. First, Millar et al. (2017) use a Threshold Exceedance Budget whereas Rogelj et al. (2015) use the concept of Threshold Avoidance Budget⁸. Second, Millar et al. (2017) methodology estimates the relationship between cumulative CO₂ emissions and temperature increase with both warming and cumulative emissions from the present day onwards, instead of the earlier practice of using values from pre-industrial times. This new methodology is less influenced by possible bias in warming in climate models in the historic period, but it depends on the estimation of current warming compared to pre-industrial temperature. Millar et al. (2017) use the value of 0.93°C for present day warming, which is in the lower range of estimates, thus leading to a higher

⁶ One family corresponds to one global emission constraint with a peak at year 2016, 2020, 2025 or 2030 and eight different combinations of technico-economic parameters.

⁷ Non-CO₂ GHG gases and emissions from land-use change are not modeled explicitly in this version of the model. Cumulative CO₂ emissions over 2010-2050 are compared to CO₂ budgets from studies that account for the impact of non-CO₂ gases on warming. Implicitly, this means that we are assuming non-CO₂ gases emissions to be similar to the trends from those studies.

⁸ Threshold Exceedance Budget (TEB) and Threshold Avoidance Budget (TAB) are defined as follows : «TEB is the amount of cumulative carbon emissions at the time a specific temperature threshold is exceeded with a given probability in a particular multi-gas emission scenarios», «TAB is the amount of cumulative carbon emissions over a given time period of a multi-gas emission scenario that limits global-mean temperature increase to below a specific threshold with a given probability» (definition from Rogelj et al. (2016), which detail the different types of carbon budget concepts used and their implications). TEB is expected to be higher than TAB.

budget for remaining emissions. We may also compare cumulative CO₂ emissions until 2050 with cumulative emissions of scenarios that limit end-of-century radiative forcing to 1.9 W.m⁻², and consequently restrict median warming in the year 2100 to below 1.5°C, from the study by Rogelj et al. (2018). The latter reports cumulative emissions over 2016-2050 ranging from 525 GtCO₂ to 1025 GtCO₂. Given that cumulative emissions over 2010-2015 were roughly equal to 200 GtCO₂, the 2010-2050 cumulative emissions translate to 725-1225 GtCO₂. Our four families are within this range, with family 4 at the higher end of the range.

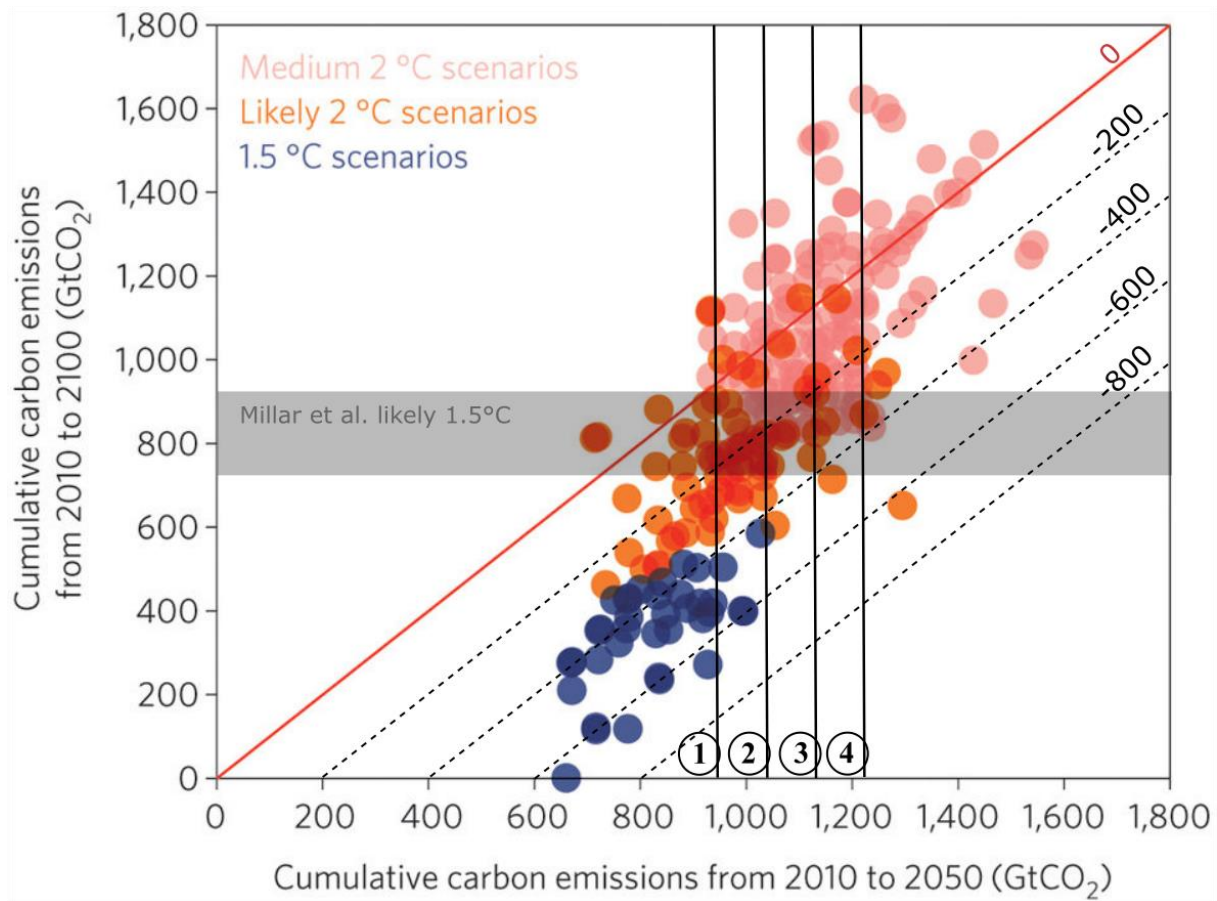


Figure 2: Mapping the location of the four scenario families of this study on the carbon budgets corresponding to 1.5°C and 2°C scenarios previously assessed in the literature. The figure is adapted from Figure 2 from Rogelj et al. (2015), where likely 2°C scenarios correspond to a 66% probability to remain below 2°C, medium 2°C scenarios to a 50% probability to remain below 2°C, and 1.5°C scenarios to a 50% probability to remain below 1.5°C. On the original figure, we map the cumulative carbon emissions from 2010 to 2050 of the four scenario families of this study (vertical lines labelled 1 to 4), and dashed lines parallel to the diagonal to materialize scenarios with cumulative carbon emissions from 2050 to 2100 equal to -200 GtCO₂, -400 GtCO₂, -600 GtCO₂ and -800 GtCO₂, respectively, from left to right (labelled on the right-hand side of the figure). The diagonal (in red) materializes scenarios with cumulative carbon emissions from 2050 to 2100 equal to zero. We also add the 2010 to 2100 carbon budgets of likely 1.5°C scenarios from Millar et al. (2017) (grey band).

In any case, bringing forward the peak of global emissions increases the probability to reach a given temperature target (1.5°C or 2°C) for given cumulative carbon emissions in the second half of the century. Said differently, bringing forward the peak reduces the efforts required in the second half of the century to reach a given target with a given probability, which can be interpreted as an insurance against the gamble that negative emissions may represent (Fuss et al., 2014). It should however be noted that even with no or little net negative emissions along an emission pathway,

negative emissions technologies may still be required - and may still represent a gamble - to compensate for remaining positive emissions.

3. Results

This section presents the importance of additional policies to improve energy efficiency and reduce energy demand across sectors in order to reach the 1.5°C objective (section 3.1) and highlights the effect of the date of the global peak of global emissions on the relative pace of decarbonisation of energy demand sectors (section 3.2).

3.1 High energy demand and the difficulty of reaching the 1.5°C objective

A first striking result is the fact that all scenarios become infeasible with a late peak in global emissions, whatever the assumptions on energy demand, on the availability of fossil fuels and on the availability of low-carbon technologies. This result shows that it will be impossible to achieve the 1.5°C target if emissions peak in 2030 or later, whatever the policies in place to lower energy demand in all sectors and to develop low carbon alternatives. In those cases, the carbon price required to decarbonize the economy and achieve the emission target increases at a pace that is deemed impossible in the real-world, leading to what we call an ‘infeasible scenario’. We define a scenario as infeasible in modelling terms when the carbon price required to meet the set emission constraint more than doubles from one year to the next at any date of the modelling horizon. This infeasibility criterion translates political and social concerns regarding the pace of increase in carbon prices that society is likely to withstand in reality. Indeed, such rapidly increasing carbon prices would lead to drastic reductions in household demand for energy and other goods to attain the carbon target, which are deemed unpalatable. Some modelling exercises have explored the feasibility of low carbon emissions pathways as a function of the availability and diffusion of low carbon technologies. For instance, Iyer et al. (2015) show that stringent climate change mitigation scenarios may become infeasible if the deployment of low-carbon technologies is constrained due to institutional, behavioural and social factors. Other studies have shown that improving energy efficiency could lift part of the decarbonisation effort, hence leading to lower carbon prices compared to scenarios assuming slow energy efficiency improvements driven by energy prices, see for instance Bibas et al. (2015).

The effect of the delay in the peak of global emissions on the pace of increase of carbon prices is apparent when examining feasible scenarios. In all feasible scenarios (i.e. scenarios with a peak in global emissions in 2016, 2020 or 2025), an early peak of global emissions leads to a faster increase of CO₂ prices at the beginning of the period (Figure 3). The pace of increase of CO₂ price in late-peaking scenarios (2020 and 2025 peaks) later catches up with the first family of scenarios (those peaking in 2016). Indeed, delaying the peak of global emissions leads to a faster increase of the carbon tax between 2040 and 2050, i.e. the end of the period considered in the analysis (cf. Figure 4). This result partly stems from the fact that the model does not use an optimization framework and has imperfect expectations (cf. section 2). If global emissions peak in 2016, carbon prices grow at an average yearly rate between 5% and 10% over the last decade of the period considered (2040-2050), compared with a yearly growth rate of nearly 15% over the same period if emissions peak in 2025. Note that a yearly growth rate of 15% over ten years is considerable and may well be considered infeasible depending on the particular institutional and socio-economic context. We should point out that the line between a feasible and an infeasible scenario is arbitrary, and the definition of what makes a scenario infeasible can be challenged.

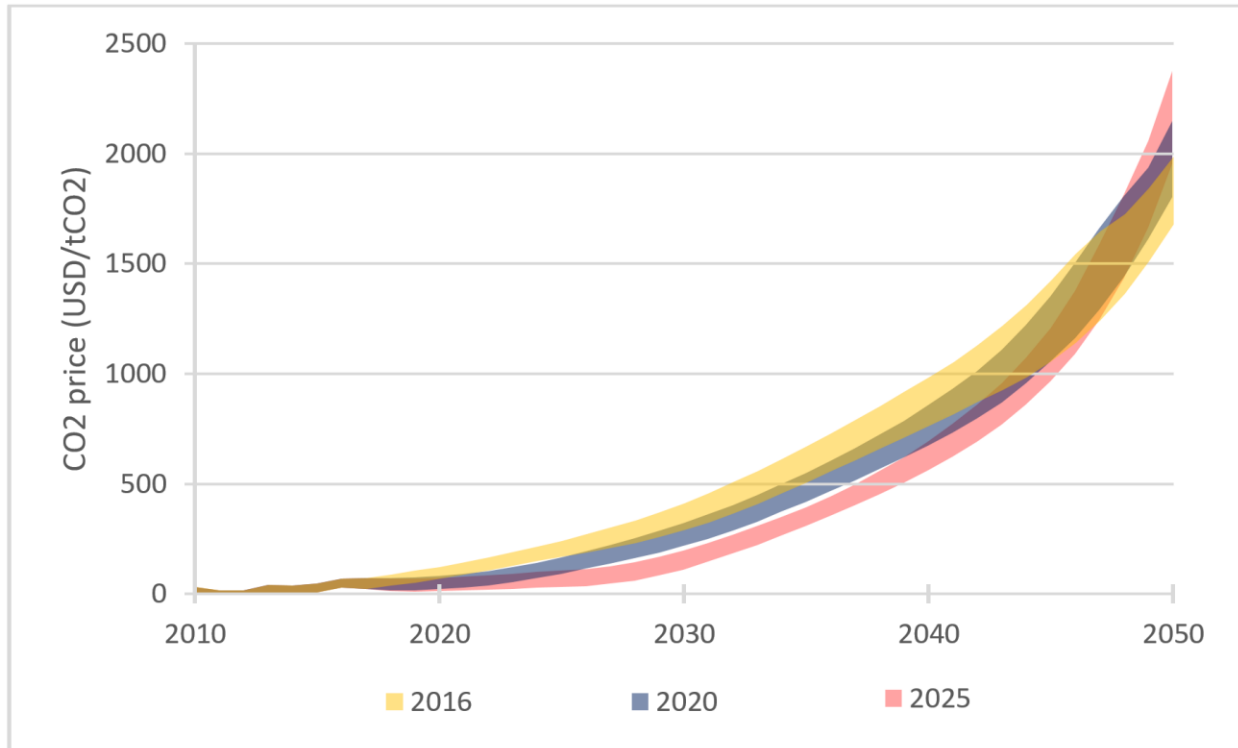


Figure 3: Ranges of CO₂ prices (USD/tCO₂) across scenarios over time by date of the peak of global emissions. The ranges for scenarios with a global peak of emissions in 2016, 2020 and 2025 are shown in yellow, blue and red, respectively.

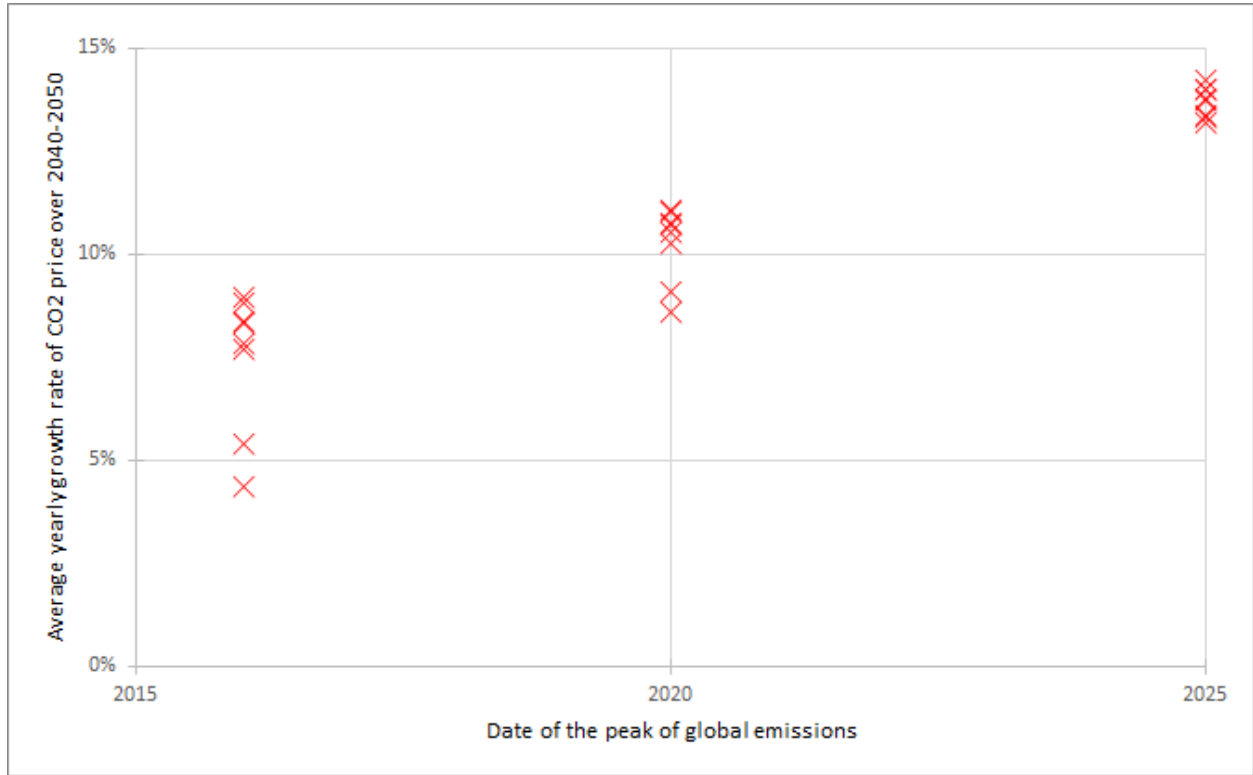


Figure 4: Average yearly growth rate of CO₂ price (%) over the 2040-2050 period (y-axis) as a function of the date of the peak in global emissions (x-axis) for all feasible scenarios⁹.

An important characteristic of the scenarios considered in this study is the level of energy demand as determined by sectoral energy efficiency and household consumption patterns. As seen on Figure 5, the level of carbon prices required over the period is higher in high energy demand scenarios, i.e. in scenarios that combine slow energy efficiency improvements in productive sectors (in particular industry) and energy-intensive lifestyles (i.e. a steady increase in car purchases, in living space per capita and in the consumption of industrial goods). The difference in the required carbon prices to achieve the same level of emissions between high and low energy demand scenarios is a measure of the contribution of the sector-specific policies in allowing for a smoother transition towards the 1.5°C objective. Comparing those results by type of scenarios (i.e. in comparable worlds in terms of the date of the peak and other scenario parameters) shows that the level of the carbon price required in high energy demand scenarios is between 25% and 50% higher in 2030 than in low energy demand scenarios. This result points out to the role of energy demand levers for the feasibility of stringent mitigation pathways. It shows that a uniform carbon price across sectors and regions is most likely to be insufficient to trigger emission reductions that are compatible with the 1.5°C objective. In

⁹ This figure is given in table format in the appendix (Table A.6).

other words, the 1.5°C objective will be very difficult to achieve without the sector-specific policies embedded in the definition of ‘low energy demand’ scenarios (cf. section 2.2) and that complement the uniform carbon price.

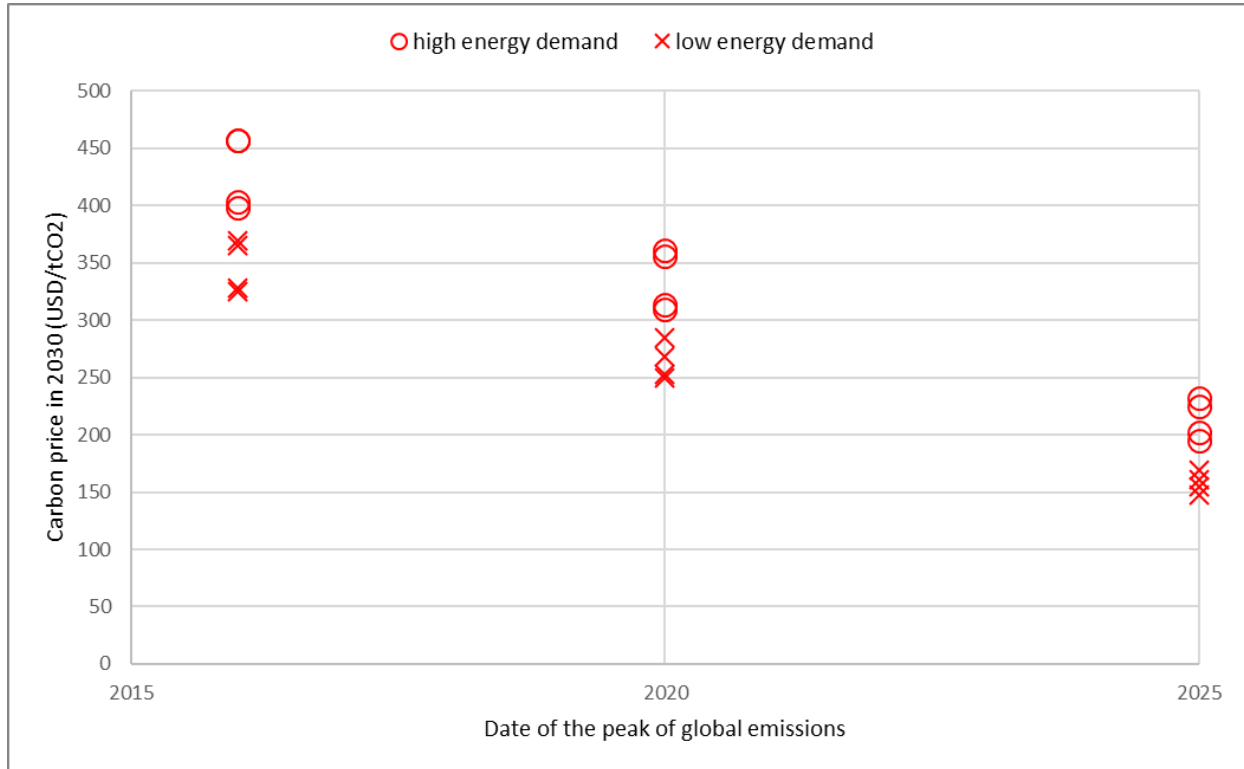


Figure 5: CO₂ price (USD/tCO₂) in 2030 (y-axis) as a function of the date of the peak in global emissions (x-axis) for low energy demand scenarios (crosses) and high energy demand scenarios (circles)¹⁰.

In order to grasp the meaning of the numbers presented in Figures 3, 4 and 5, we can compare these with announcements made by governments for the future increase in the taxation of carbon emissions. In 2017, the level of carbon prices worldwide ranged from less than 1 USD/tCO₂ to 126 USD/tCO₂ (World Bank and Ecofys, 2017). The French 2018 Finance bill has announced a raise in the carbon price from 30.50 euro/tCO₂ in 2017 to 44.6 euro/tCO₂ in 2018 and to 86.20 euro/tCO₂ in 2022. These levels are within the range of our estimates. However, the carbon price in 2050 commanded by 1.5°C scenarios as estimated by the model are of another order of magnitude. The levels of carbon price in 2050 are of the order of 1400-2000 USD/tCO₂ when global emissions peak relatively early, i.e. in 2015 or 2020. Those can be more readily compared with the estimates produced by other integrated assessment models. Clarke et al. (2014) synthesises the results of a

¹⁰ This figure is given in table format in the appendix (Table A.7).

wide range of global integrated assessment models that were used to assess the transition pathways to various levels of climate stabilization, with the most ambitious scenarios targeting to limit temperature increase to 2°C. The carbon prices in 2050 in our 1.5°C compatible scenarios are generally higher than the estimates summarised in Clarke et al. (2014) which show an upper bound of carbon prices in 2050 at around 1000 euros/tCO₂. Our results are consistent with those, as our emission trajectories are more ambitious than those of the scenarios presented in Clarke et al. (2014). Indeed, Clarke et al.’s 2°C scenarios correspond to RCP 2.6, with emissions in 2050 equal to 11.682 GtCO₂ (van Vuuren et al., 2007), which is almost twice the emissions in 2050 in our scenarios (6.55 GtCO₂).

3.2 Sectoral implications of shifting the peak of global emissions

In this section, we analyze the impacts of the timing of the peak of global emissions on the decarbonisation profiles at the sectoral level, distinguishing between the electricity, industry, transportation and residential sectors. Figure 6 shows sectoral emissions over time in the case of a global emissions peak in 2020 in the “low energy demand/high fossil fuel resources/high availability of renewable technologies” scenario. This provides an example to portray the typical decarbonisation profiles of the different sectors along a global decarbonisation pathway.

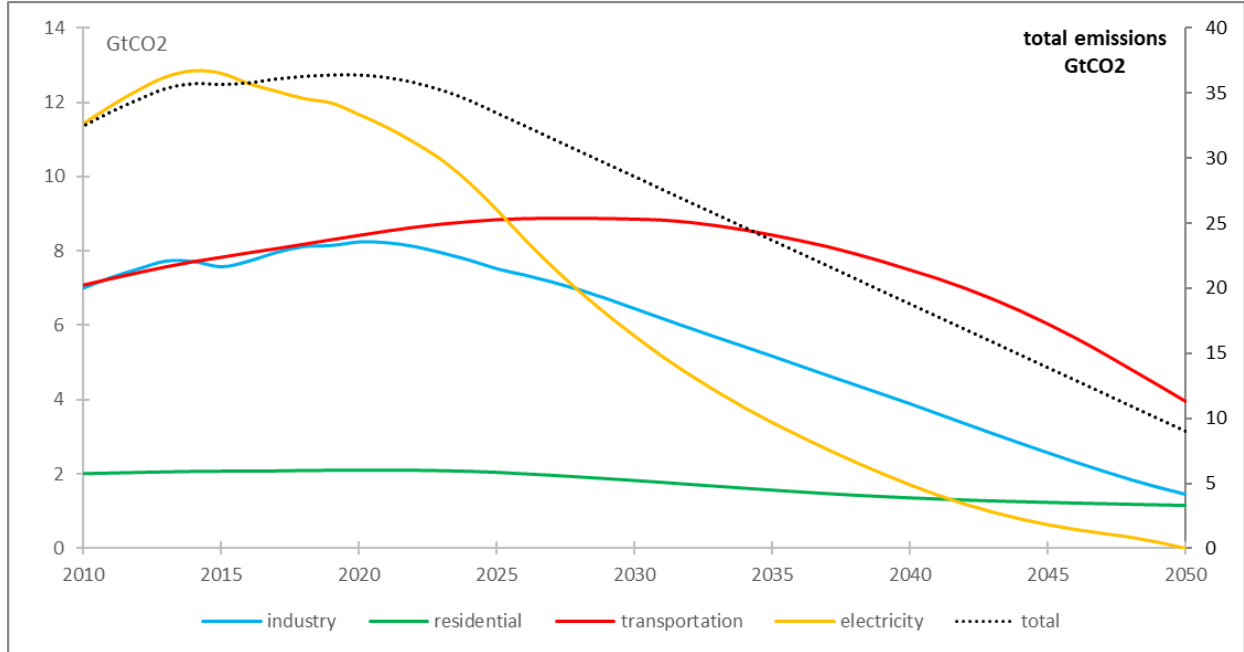


Figure 6: Sectoral emissions over time in the “low energy demand/high fossil fuel resources/high availability of renewable technologies” scenario with a peak of global emissions in 2020. Sectoral emissions are shown on the left y-axis, total emissions are shown on the right y-axis.

The peaks of sectoral emissions occur at very different dates. Emissions from the electricity sector peak first and before global emissions, whereas the peak of emissions from demand sectors occurs around or after the peak of global emissions¹¹. Among demand sectors, the peaks of the industry and residential sectors occur close to the global peak while the peak of the transportation sector is the most delayed. Also, the pace of decarbonisation after the peak is contrasted among sectors, with a more rapid decarbonisation for electricity generation - which represents more than 35% of CO₂ emissions at its peak - than for demand sectors. Decarbonisation is slower in demand sectors, although still steady for industry and transportation sectors, while the residential sector shows the slowest pace of decarbonisation. The early and fast decarbonisation of electricity is typically explained by the higher availability of cost-effective mitigation options, which makes it possible to fully decarbonize the electricity sector before 2050. The late peak for the transportation sector is due to the fact that decarbonisation is constrained by existing infrastructure and spatial planning (Edenhofer et al., 2014 p. 65)., and that the demand for mobility for passengers and freight is strongly coupled to GDP growth (Schafer and Victor, 2000). The relative inertia of the transport sector compared to the residential sector, with transport emissions in our results peaking later but

¹¹ Note that the results show direct emissions for the transportation and residential sector (i.e. excluding for instance the emissions associated with the production of electricity used for transportation). We account for both direct and indirect emissions in the industry sector.

decreasing at a faster rate after the peak than the emissions from the residential sector, may be specific to our model structure and/or the values of the parameters chosen in this study. Indeed, Figure 6.35 from Clarke et al. (2014) indicates that the relative inertia of the two sectors behave differently in other models. However, disentangling the reasons of the differences between our model’s results and other models’ is beyond the scope of this article and would require a rigorous diagnostic protocol similar to that of Kriegler et al. (2015), but with a sectoral disaggregation of results.

We analyse further how the sectoral decarbonisation profiles are modified when the global emissions peak is brought forward in time – to increase the chance to reach the 1.5°C target. We rely on three main indicators to synthesize the shape of sectoral emissions across scenarios: the date of the peak, the emission level at the peak and the decarbonisation rate after the peak. Figures 7, 8 and 9 respectively show the dates of the sectoral peaks, the absolute levels of the sectoral emissions at the peaks and the annual growth rate of sectoral emissions after the peak as a function of the date of the global peak (between 2016 and 2025).

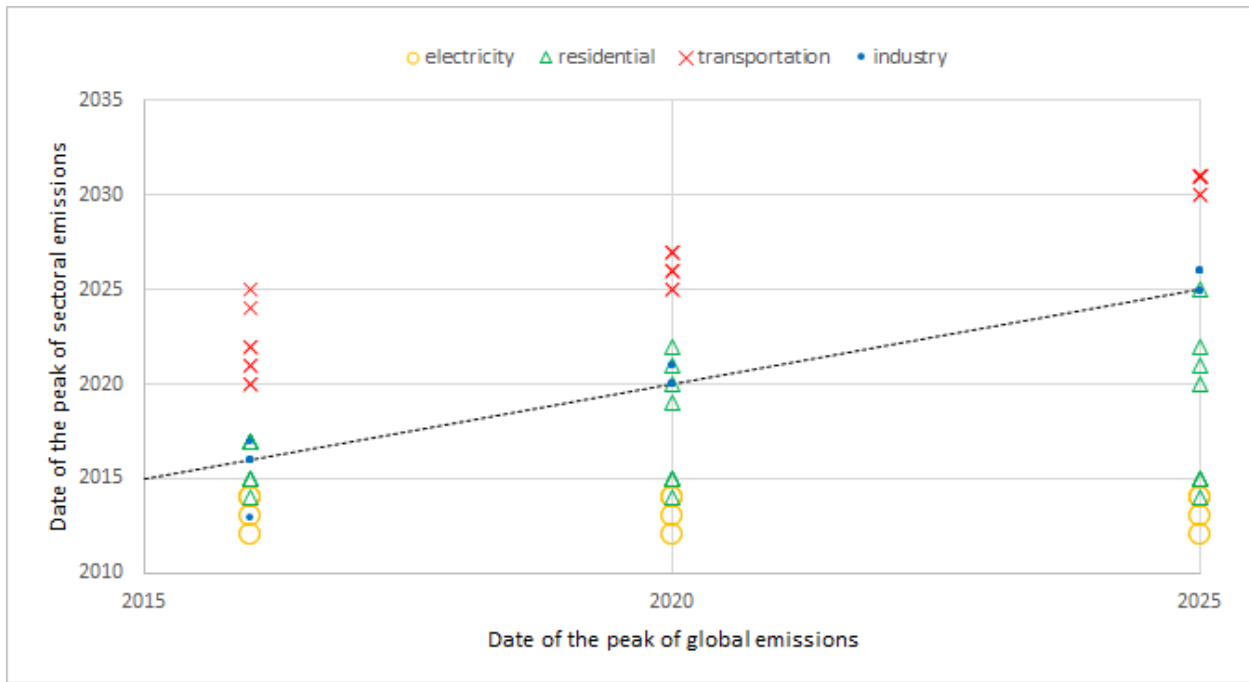


Figure 7: Date of sectoral emission peak as a function of date of global emission peak. Data points above the dashed line show cases where sectoral emissions peak after the peak in global emissions, while data points below the dashed line show cases where sectoral emissions peak before the peak in global emissions. Note that some points overlap¹².

¹² This figure is given in table format in the appendix (Table A.8).

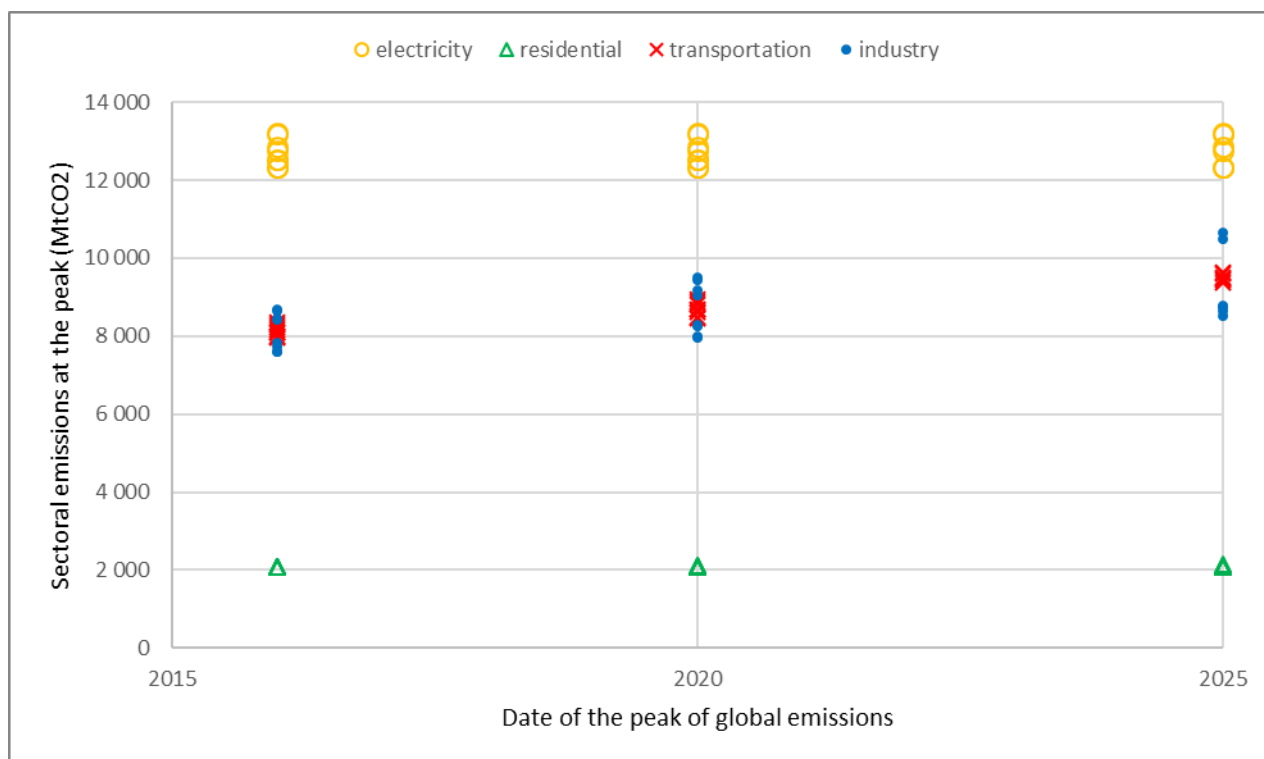
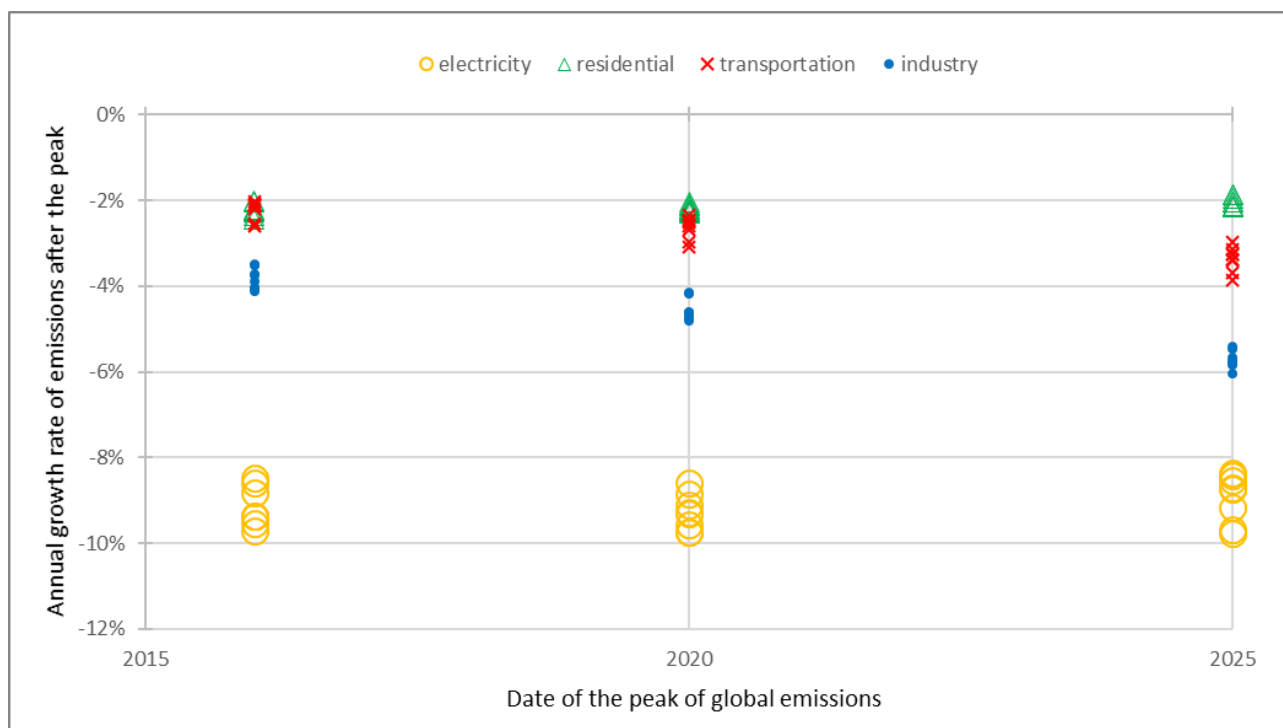


Figure 8: Level of sectoral emissions at the sectoral peak as a function of the date of the peak of global emissions¹³.



¹³ This figure is given in table format in the appendix (Table A.9).

Figure 9: Annual growth rate of sectoral emissions after the sectoral peak (until the end of the period) as a function of the date of the global emission peak¹⁴.

Table 2 shows the shifts in years of the sectoral peaks when the peak of global emissions is brought forward by 9 years (from 2025 to 2016) for all feasible scenarios.

<i>Scenario</i>									
<i>energy demand</i>	high	high	high	high	Low	low	low	low	
<i>fossil fuel resources</i>	high	high	low	low	High	high	low	low	
<i>renewables and nuclear</i>	high	low	high	low	Low	high	low	high	
Shift of the peak of sectoral emissions when bringing forward the peak of global emission by 9 years (from 2025 to 2016)									average over scenarios
<i>Industry</i>	-10	-10	-9	-10	-9	-13	-9	-9	-9.9
<i>Residential</i>	0	0	0	0	-3	-5	-4	-8	-2.5
<i>Transportation</i>	-10	-10	-10	-10	-9	-6	-9	-7	-8.9
<i>Electricity</i>	0	0	0	0	0	0	0	0	0

Table 2: Shift (in years) of the peak of sectoral emissions when bringing forward the peak of global emissions by 9 years for all feasible scenarios. Here we compare scenarios with a peak of global emissions in 2016 and scenarios with a peak of global emissions in 2025.

The results first show that the date of the peak of global emissions does not affect the date of the peak of emissions from the electricity sector: whatever the date of the peak of global emissions (between 2016 and 2025), the peak of emissions from the electricity sector occurs between 2012 and 2014 (Figure 7), the level of emissions at the peak reaches the same average value of 13-14 GtCO₂ (Figure 8) and the annual decline rate of emissions is high, at around 8-10% per year (Figure. 9). By contrast, the emission profiles of energy-demand sectors are significantly affected by the date of the global peak in general. Bringing forward the global peak leads to earlier sectoral emission peaks

¹⁴ This figure is given in table format in the appendix (Table A.10).

(Figure 7), lower emission levels at the peak (Figure 8) and a slower decarbonisation after the peak (Figure 9). However, looking more closely at the shape of emission reductions in the electricity sector, when the global peak is brought forward from 2025 to 2016, for the same average decline rate until 2050, we note a significant acceleration of emission reductions before 2030 and a deceleration afterwards. Indeed, the average decline rates of emissions from the electricity sector over the 2016-2030 period are 2.2%, 1.5% and 0.4% per year for a peak of global emissions in 2016, 2020 and 2025, respectively. This order is reversed after 2030, as the average decline rates of emissions from the electricity sector over the 2031-2050 period are 4.9%, 5.5% and 6.2% per year for a peak of global emissions in 2016, 2020 and 2025, respectively. We can therefore conclude that bringing forward the peak of global emissions implies a faster decrease in emissions from the electricity sector, and earlier and lower emission peaks in energy-demand sectors on average.

In addition, bringing forward the peak of global emissions has contrasted impacts among demand sectors. First, as shown in Table 2, when the peak of global emissions is brought forward by 9 years (from 2025 to 2016), the peak of emissions is shifted by 9.9 years and 8.9 on average in the industry and transportation sectors, whereas it is only shifted by 2.5 years in the residential sector. Second, bringing forward the global peak reduces the level of emissions at the peak for the industry and transportation sectors by 2 GtCO₂ on average (from 10 to 8 GtCO₂), whereas it remains steady at 2 GtCO₂ for the residential sector (Figure 8). Third, shifting the global peak reduces the pace of decarbonisation after the peak for the industry and transportation sectors, whereas it almost remains unchanged for the residential sector (Figure 9). Therefore, industry (and to a lesser extent transportation) is the key adjusting sector, whereas the residential sector does not contribute much to achieving an earlier peak of global emissions. This is mainly due to the strong capital inertia and limited potential of decarbonisation in this sector, which are captured in the model. Conversely, the emission profiles of the industry and transportation sectors adjust to mimic the shift in the global peak in terms of the date of the peak, the lower level of emissions at the peak and of the pace of decarbonisation after the peak.

One additional question is to what extent the assumptions about demand patterns affect the pace of decarbonisation of the demand sectors. First of all, the level of emissions at the peak for the industry sector is quite sensitive to the assumption about high or low energy demand – with a lower emission level under low demand, and all the more so as the global peak is delayed (see Figure 8). In addition, the assumption about energy-demand patterns affects the date of the peaks of the transportation and residential sectors. Under the assumption of high energy demand, the peak of the transportation sector is shifted by 10 years on average when the global peak is brought forward by 9 years, compared to only 8 years under the assumption of low energy demand. Conversely, the

peak for the residential sector is not shifted at all under the assumption of high energy demand, but shifted by 5 years on average under the assumption of low energy demand. These results show that the assumptions about energy demand patterns change the way demand sectors contribute to the early peaking of global emissions. When assuming low energy demand patterns (i.e. assuming additional energy efficiency policies to complement a carbon price), the industry sector provides significant emission reductions in the short term due to faster energy efficiency improvements, which allows for the emissions peak in the transport sector to be delayed by 2 years on average compared to the case assuming high energy demand patterns.

4. Conclusion

The modelling exercise highlights the scale of the impact of medium-term emission pathways compatible with the 1.5°C objective on the dynamics of sectoral emissions. We show that it is impossible to delay the peak of global emissions until 2030 while reaching a level of emissions in 2050 that would be compatible with limiting temperature increase to 1.5°C above pre-industrial levels. In those scenarios, the rapid increase in carbon prices would lead to drastic reductions in household demand for energy and other goods, which are deemed infeasible for political and social reasons. This result points out to the risk associated with delaying climate change policy. We concur with the assessment of Rogelj et al. (2015) that energy efficiency and stringent early emission reductions are key for limiting warming to below 1.5°C. Indeed, without specific policies targeted at improving energy efficiency across sectors (in addition to a carbon price), the level of carbon prices required to stay on a path compatible with achieving the 1.5°C target is significantly higher than in the case where such measures are implemented (i.e. in low energy demand scenarios). This result shows that a uniform carbon price across sectors and regions is most likely to be insufficient to trigger emission reductions that are compatible with the 1.5°C objective.

Bringing forward the peak of global emissions does not lead to a homothetic adjustment of all sectoral emissions pathways. It explains the faster decrease of emissions in the electricity sector (after an immediate peak in all scenarios), and earlier and lower emission peaks in energy-demand sectors on average. We find that demand sectors provide the larger part of the additional emission reductions needed to trigger an immediate peak of global emissions compared to a global peak delayed to 2025. Therefore, we conclude that more stringent policies in energy-demand sectors - industry and transportation especially - are needed in the short run to trigger an immediate peak of global emissions and increase the probability to meet the 1.5°C objective.

The contributions of demand sectors to achieving an early peak of global emission are quite contrasted. In all scenarios, the peak of emissions in the transportation sector occurs later than the peak of emissions of the industry and residential sectors. This is due to the fact that the decarbonisation of the transportation sector is constrained by existing infrastructure and urban forms, and that the demand for mobility and freight services is strongly coupled to GDP growth. Bringing forward the peak of global emissions has a larger impact on the date of the peak of emissions in the industry and transportation sectors than in residential sector due to even stronger capital inertia and limited potential of decarbonisation in that sector. The assumptions about energy demand patterns change the way demand sectors contribute to the early peaking of global emissions. When assuming low energy demand patterns (i.e. assuming additional energy efficiency policies to complement a carbon price), the fast decarbonisation of the industry sector allows for the emissions peak in the transport sector to be delayed compared to the case assuming high energy demand patterns.

We conclude that additional sector-specific policies aimed at improving energy efficiency and reducing the energy demand of all sectors of the economy are paramount to achieve the 1.5°C objective while keeping carbon prices to levels that may be considered as socially and politically acceptable. Whether or not the 1.5°C objective can be attained will depend on the emission pathway before 2050, and on the implementation of those policies to decarbonize all sectors of the economy.

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6. Appendix

6.1 Parameters

This section provides a description of the parameters used for each scenario. Note that this description is very similar in its formulation to Guivarch et al. (2015).

a) Energy demand

Energy efficiency improvements

In each sector, the region with the lowest energy intensity is defined as the leader and its energy efficiency is triggered by energy prices. After a delay, other regions catch up with the leader region. We build two hypotheses (see Table A.1) using the following parameters: maximum annual improvement in the leader's energy efficiency, other regions' speed of convergence (% of the initial gap after 50 years) and asymptotic level of catch up (% of the leader's energy efficiency).

	<i>Low</i>	<i>High</i>
Maximum annual improvement in the leader's energy efficiency	1.5	0.7
Other regions' speed of convergence (% of the initial gap after 50 years)	10	50
Asymptotic level of catch-up (% of the leader's energy efficiency)	95	60

Table A.1. Parameters for energy efficiency improvements

Development style of developing countries

This set describes either a mimetic development pattern for developing countries, which aim at adopting western lifestyles, or a less carbon-intensive development pattern. We take into account

infrastructure policies and the agents' preferences for automobile transport and spacious individual dwelling (see Table A.2).

		<i>Low</i>	<i>High</i>
transportation	motorization rate growth with GDP per capita	20% decrease w.r.t the value from IEA data (2008)	20% increase w.r.t the value from IEA data (2008)
Buildings	income elasticity of buildings stock growth	0.7	1
	asymptote to surface per capita in China and India	40 sqm	60 sqm
	start year and fuel price for a forced decline of oil consumption in this sector	2010 1000 USD/toe	2020 1300 USD/toe
Industrial goods	Household industrial goods consumption saturation level [min-max] (see Rozenberg et al., 2010)	[1-2]	[1.5-3]

Table A.2. Parameter options for development patterns of developing countries

b) Fossil fuel resources

The scenario alternatives on fossil fuel resources focus on the availability and prices of gas, coal and coal-to-liquids.

In the model, global gas production capacities match demand growth until ultimately recoverable resources enter a depletion process. Variations in gas prices are indexed on variations of oil prices via an indexation coefficient (0.68, see Equation 1) calibrated on the World Energy Model (IEA, 2007). When oil prices increase by 1%, gas prices increase by 0.68%. Two alternative assumptions are used in this price indexation. Under the assumption of “relatively abundant and cheap” fossil fuel resources, this indexation disappears when oil prices reach 80 USD/barrel: beyond this threshold, fluctuations in gas prices only depend on production costs and possibly on the depletion

effect. When depletion is reached, the price increases. Under the assumption of “relatively scarce and expensive” fossil fuel resources, gas prices remain indexed on oil prices regardless of fluctuations, but an additional price increase occurs when gas production enters its depletion phase. The price of gas in each region at year t is:

$$p_{gas}(t) = p_{gas}(t_0) \cdot \tau_{gas}(t) \quad (1)$$

where $p_{gas}(t_0)$ is the gas price in this region at year t_0 . As long as gas depletion has not started, $\tau_{gas}(t)$ in each region is:

$$\tau_{gas}(t) = 0.68 \cdot \left(\frac{1}{3} \cdot wp_{oil}(t) + \frac{2}{3} \cdot wp_{oil}(t-1) \right) \cdot \frac{1}{wp_{oil}(t_0)} \quad (2)$$

Where $wp_{oil}(t)$ is the world oil price at year t ; $wp_{oil}(t_0)$ is the world oil price at year t_0 . If depletion has started in this region, $\tau_{gas}(t)$ increases 5% each year, regardless of oil prices.

The oil market is modelled according to the following principles: (i) The OPEC can influence world oil prices before they approach a depletion constraint; (ii) Oil supply cannot fully adapt to demand due to the geological nature of world oil reserves, i.e. the amount of economically exploitable reserves and technical constraints leading to inertias in the deployment of production capacities; (iii) Oil demand depends on agents' decisions and on incentives aimed at increasing the production of alternatives to oil. The oil price reflects tensions between supply and demand:

$$p_{k,oil} = \sum_j pIC_{j,oil,k} \cdot IC_{j,oil,k} + \left(\Omega_{oil,k} \left(\frac{Q_{oil,k}}{Cap_{oil,k}} \right) \right) \cdot l_{oil,k} \cdot (1 + tax_{oil,k,w}) + \pi_{oil,k} \cdot \frac{Q_{oil,k}}{Cap_{oil,k}} \cdot p_{k,oil} \quad (3)$$

Regional prices $p_{k,oil}$ are obtained by adding average regional production costs and a margin that includes both Ricardian and scarcity rents. In equation (3), $IC_{j,oil,k}$ is the intermediate consumption of goods from sector j to produce a unit of oil and $pIC_{j,oil,k}$ is the intermediate consumption price for sector j for oil in region k . $Q_{oil,k}$ is the quantity of oil produced in region k . $\Omega_{oil,k}$ is an increasing function of the utilisation rate of production capacities $Cap_{oil,k}$ in region k . $l_{oil,k}$ is the quantity of labour per unit of oil produced in region k , $tax_{oil,k,w}$ is the labour tax rate in the oil sector in region k . $\pi_{k,oil}$ is the markup rate in the oil sector in region k . The swing producer anticipates the level of capacities to reach a predefined target on the basis of projections of total oil demand and production in other regions.

Coal is treated in a different way than oil and gas in the model because coal resources are plentiful, which prevents coal production from entering a depletion process before the end of the 21st century. We describe the price formation on the world coal market in a reduced functional form linking variations in price to variations in production. This choice allows us to capture the cyclic behaviour of this commodity market. Coal prices then depend on current production through an elasticity coefficient η_{coal} : tight coal markets exhibit a high value of η_{coal} (i.e. the price of coal increases if coal production increases). We make two assumptions for η_{coal} . Under the assumption of “relatively abundant and cheap” resources, the sensitivity of an increase in coal price to an increase in coal production is quite low, so that the increase in coal production can be absorbed without price fluctuations ($\eta_{\text{coal}}=1.3$). Conversely, the increase in coal prices is very sensitive to any increase in coal production under the assumption of “relatively scarce and expensive” resources ($\eta_{\text{coal}}=3$).

The variants on coal-to-liquids (CTL) govern its ability to penetrate energy markets (Table A.3, see Rozenberg et al., 2010 for details).

	<i>Low</i>	<i>High</i>
Oil price threshold for CTL production to start (USD/barrel)	200	120
Time scale of reactive anticipation for CTL production (years)	8	0
Maximum production growth in 2030, 2035 and 2050 (million barrels per day)	0.05	0.20
	0.10	1.5
	0.10	3

Table A.3. Parameter options for Coal-to-Liquid penetration

c) Low carbon technologies

Technologies penetrate markets according to their profitability, but are constrained by a maximum market share which follows an S-shaped curve (Grübler et al., 1999). We consider two alternatives for each group of technologies. The high availability assumption corresponds to a higher maximum market share, and faster diffusion than under the low availability assumption. The model also represents endogenous learning for some new technologies: the cost of the technology decreases with

the cumulative investment in that technology. This mechanism is governed by a learning rate, and two alternative values are considered for this learning rate.

Low carbon power generation technologies

The technologies considered are nuclear power and renewables. In the low availability assumption, it is assumed that the new generation of nuclear power plants is not available at all. The parameters are described in Table A.4.

		Start date	Bottleneck phase (years)	Growth phase (years)	Maturation phase (years)	Maximum market share at the end of the maturation phase (%)	Learning rate
Nuclear (new generation)	high	2001	15	75	25	20	n/a
	low	2001	15	75	25	1	n/a
Renewables	high	2001	2	65	25	99	Wind: 0.15 Concentrated solar power: 0.1 Central PV: 0.2 Rooftop PV: 0.25
	low	2001	3	65	25	50	Wind: 0.05 Concentrated solar power: 0.05 Central PV: 0.15 Rooftop PV: 0.15

Table A.4. Table Parameters options for low carbon electricity generation

6.2 Detailed result tables

This section provides the results of figures 4, 5, 7,8 and 9 in table format.

Energy demand	Fossil fuel resources	Low carbon technologies	Peak date	CO2 price growth rate
low	Low	high	2025	14.0%
low	Low	low	2025	13.7%
low	High	high	2025	14.0%
low	High	low	2025	14.2%
high	Low	high	2025	13.4%
high	Low	low	2025	13.3%
high	High	high	2025	13.8%
high	High	low	2025	13.2%
low	Low	high	2020	11.1%
low	Low	low	2020	10.8%
low	High	high	2020	11.0%
low	High	low	2020	10.7%
high	Low	high	2020	10.5%
high	Low	low	2020	8.6%
high	High	high	2020	10.3%
high	High	low	2020	9.1%
low	Low	high	2016	9.0%
low	low	low	2016	7.7%
low	high	high	2016	8.8%
low	high	low	2016	7.8%
high	low	high	2016	8.4%
high	low	low	2016	4.3%
high	high	high	2016	8.3%
high	high	low	2016	5.4%

Table A.6: Average yearly growth rate of CO2 price (%) over the 2040-2050 period as a function of the date of the peak in global emissions for all feasible scenarios (corresponds to figure 4)

Energy demand	Fossil fuel resources	Low carbon technologies	Peak date	CO2 price in 2030
low	low	high	2025	154.8
low	low	low	2025	160.9
low	high	high	2025	147.1
low	high	low	2025	169.5
high	low	high	2025	224.9
high	low	low	2025	194.5
high	high	high	2025	202.1
high	high	low	2025	232.3
low	low	high	2020	249.7
low	low	low	2020	268.3
low	high	high	2020	253.2
low	high	low	2020	284.8
high	low	high	2020	309.8
high	low	low	2020	356.2
high	high	high	2020	313.4
high	high	low	2020	360.9
low	low	high	2016	325.3
low	low	low	2016	365
low	high	high	2016	328.3
low	high	low	2016	369.2
high	low	high	2016	398.5
high	low	low	2016	457.5
high	high	high	2016	403.7
high	high	low	2016	457.5

Table A.7: CO2 price (USD/tCO2) in 2030 as a function of the date of the peak in global emissions for low energy demand scenarios and high energy demand scenarios (corresponds to Figure 5)

Energy demand	Fossil fuel resources	Low carbon technologies	Global emissions peak	Transportation	Industry	Residential	Electricity
low	low	High	2025	2031	2025	2025	2014
low	low	Low	2025	2031	2025	2021	2014
low	high	High	2025	2031	2026	2022	2014
low	high	Low	2025	2031	2025	2020	2014
high	low	High	2025	2031	2026	2015	2013
high	low	Low	2025	2030	2026	2015	2012
high	high	High	2025	2031	2026	2015	2013
high	high	Low	2025	2030	2026	2014	2012
low	low	High	2020	2027	2020	2022	2014
low	low	Low	2020	2027	2020	2020	2014
low	high	High	2020	2027	2020	2021	2014
low	high	Low	2020	2026	2020	2019	2014
high	low	High	2020	2026	2021	2015	2013
high	low	Low	2020	2025	2020	2015	2012
high	high	High	2020	2026	2021	2015	2013
high	high	Low	2020	2025	2020	2014	2012
low	low	High	2016	2024	2016	2017	2014
low	low	Low	2016	2022	2016	2017	2014
low	high	High	2016	2025	2013	2017	2014
low	high	Low	2016	2022	2016	2017	2014
high	low	High	2016	2021	2017	2015	2013
high	low	Low	2016	2020	2016	2015	2012
high	high	High	2016	2021	2016	2015	2013
high	high	Low	2016	2020	2016	2014	2012

Table A.8: Date of sectoral emission peak as a function of date of global emission peak (Corresponds to Figure 7)

Energy demand	Fossil fuel resources	Low carbon technologies	Global emissions peak	Transportation	Industry	Residential	Electricity
low	low	High	2025	9609	8643	2157	12770
low	low	Low	2025	9504	8781	2098	13170
low	high	High	2025	9619	8760	2114	12850
low	high	Low	2025	9460	8508	2082	13220
high	low	High	2025	9437	10660	2080	12320
high	low	Low	2025	9180	10110	2073	12510
high	high	High	2025	9372	10500	2082	12340
high	high	Low	2025	9102	9972	2072	12510
low	low	High	2020	8952	8275	2125	12770
low	low	Low	2020	8805	8004	2090	13170
low	high	High	2020	8868	8249	2106	12850
low	high	Low	2020	8688	7954	2077	13220
high	low	High	2020	8672	9496	2080	12320
high	low	Low	2020	8493	9162	2073	12510
high	high	High	2020	8622	9429	2082	12340
high	high	Low	2020	8438	9056	2072	12510
low	low	High	2016	8366	7822	2088	12770
low	low	Low	2016	8218	7614	2072	13170
low	high	High	2016	8288	7735	2085	12850
low	high	Low	2016	8143	7592	2068	13220
high	low	High	2016	8103	8683	2080	12320
high	low	Low	2016	7996	8443	2073	12510
high	high	High	2016	8090	8633	2082	12340
high	high	Low	2016	7957	8403	2072	12510

Table A.9: Level of sectoral emissions at the peak (MtCO₂) as a function of the date of the peak of global emissions (Corresponds to figure 8)

Energy demand	Fossil fuel resources	Low carbon technologies	Global emissions peak	Transportation	Industry	Residential	Electricity
low	low	High	2025	-3.1%	-5.7%	-2.1%	-8.4%
low	low	Low	2025	-3.4%	-5.9%	-2.0%	-8.7%
low	high	High	2025	-3.0%	-6.0%	-1.9%	-9.2%
low	high	Low	2025	-3.3%	-5.7%	-2.0%	-8.7%
high	low	High	2025	-3.4%	-5.8%	-1.9%	-9.8%
high	low	Low	2025	-3.9%	-5.5%	-2.2%	-8.5%
high	high	High	2025	-3.3%	-5.8%	-1.9%	-9.7%
high	high	Low	2025	-3.7%	-5.4%	-2.1%	-8.4%
low	low	High	2020	-2.5%	-4.8%	-2.2%	-9.3%
low	low	Low	2020	-2.7%	-4.7%	-2.3%	-9.3%
low	high	High	2020	-2.3%	-4.8%	-2.1%	-9.6%
low	high	Low	2020	-2.5%	-4.7%	-2.2%	-8.9%
high	low	High	2020	-2.6%	-4.6%	-2.1%	-9.7%
high	low	Low	2020	-3.1%	-4.2%	-2.3%	-9.1%
high	high	High	2020	-2.5%	-4.6%	-2.1%	-9.7%
high	high	Low	2020	-3.0%	-4.1%	-2.2%	-8.6%
low	low	High	2016	-2.1%	-4.1%	-2.0%	-9.4%
low	low	Low	2016	-2.2%	-4.1%	-2.2%	-8.8%
low	high	High	2016	-2.1%	-3.7%	-2.1%	-9.4%
low	high	Low	2016	-2.1%	-4.0%	-2.3%	-8.6%
high	low	High	2016	-2.1%	-3.9%	-2.2%	-9.5%
high	low	Low	2016	-2.6%	-3.5%	-2.4%	-9.4%
high	high	High	2016	-2.0%	-3.8%	-2.2%	-9.7%
high	high	Low	2016	-2.5%	-3.5%	-2.4%	-8.5%

Table A.10: Annual growth rate of sectoral emissions after the peak (until the end of the period) as a function of the date of the global emission peak (Corresponds to Figure 9)

6.3 References

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