Speed of technological transformations required for distinct climate ambitions in Europe

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Abstract

Europe’s contribution to global warming will be determined by the cumulative emissions until climate neutrality is achieved. In this paper, we investigate alternative transition paths under carbon budgets corresponding to temperature increases between 1.5 and 2\textdegree C. We use PyPSA-Eur-Sec, an open model of the sector-coupled European energy system with high spatial and temporal resolution. All the paths entail similar technological transformations, but the timing of the scale-up of important technologies like water electrolysis, carbon capture and hydrogen networks differs. Solar PV, onshore and offshore wind become the cornerstone of a net-zero energy system enabling the decarbonisation of other sectors via direct electrification (e.g. heat pumps and electric vehicles) or indirect electrification (e.g. using synthetic fuels). For a social cost of carbon (SCC) of 120\texteuro/tCO\textsubscript{2}, transition paths under 1.5 and 1.6\textdegree C budgets are, respectively, 8\% and 1\% more expensive than the 2\textdegree C-budget because building assets earlier costs more. They also require a faster ramp-up of new technologies before 2035. For a higher SCC of 300 EUR/tCO\textsubscript{2}, the 1.5\textdegree C-budget is cost-optimal. Moreover, we discuss the strong implications of the SCC and discount rate assumed when comparing alternative paths. We also analyse the consequences of different assumptions on the cost and potential of CO\textsubscript{2} sequestration.

1. Introduction

Sustained high global annual CO\textsubscript{2} emissions are quickly depleting our carbon budget, \textit{i.e.}, the cumulative emissions that will enable us to remain below a certain temperature increase. On top of that, estimating the carbon budget is subject to significant uncertainties in the evaluation of the transient climate response to cumulative emissions or the potential impacts of Earth system feedbacks such as permafrost thawing [1]. A cautious approach would entail reducing emissions as fast as possible. In Europe, climate ambition has risen in recent years with examples such as the 55\% greenhouse gas (GHG) reduction commitment for 2030 [2], the European Green Deal [3], and aggressive reduction targets in some member states [4, 5]. Still, a large gap exists between globally committed emissions reductions and those necessary to fulfil the Paris Agreement [6].

Some of the authors have recently shown that, for a carbon budget corresponding to 1.75\textdegree C temperature increase, it is beneficial to follow an early and steady decarbonisation path in Europe, in which emissions are strongly reduced before 2030, compared to delayed action that requires more abrupt and expensive transformations mid-century [7]. Here, we go one step further by investigating the consequences of transforming the full sector-coupled European energy system with different cumulative emissions corresponding to various temperature increases. There are two main benefits to Europe achieving net-zero emissions while using a lower carbon budget. First, ceteris paribus, the probability to remain below a certain temperature increase is higher, or the associated temperature increase is lower, see Fig. 1. Second, for the same global budget, reducing cumulative emissions in Europe enables higher emissions in other regions compensating for Europe’s higher historical emissions.

On the one hand, Integrated Assessment Models (IAMs) have traditionally been used to assess transition paths under strict carbon budgets [10, 11]. The term IAM covers a wide variety of models including a global representation of energy, economy, climate and land. Generally, IAMs suffer from a low spatial and temporal resolution that prevents the representation of energy networks and the variability of wind and solar, although some efforts to improve these limitations are ongoing [12–14]. On the other hand, Energy System Models (ESMs) with higher spatial and temporal resolution, as well as detailed representations of power networks [15–18] and storage [19, 20] are used to investigate power system transformations, but by focusing on regions and particular years, they miss long-term global interactions with climate and technological learn-
Figure 1: Temperature increase for distinct carbon dioxide budgets in Europe from 2020 (6.4% of global emissions allocated to Europe based on an equal per-capita distribution). Confidence intervals are indicated by different shadings. For 1.7°C and 67% confidence interval, the figure also shows the European budgets assuming a fair distribution that compensates for historical emissions, and an unfair distribution that assumes the prevalence of historical splits among regions (5.5% [8] and 11% [9] of global emissions allocated to Europe, respectively). In this work, we use PyPSA-Eur-Sec, an open model of the sector-coupled European energy system with uninterrupted 3-hourly resolution for a full year and a 37-nodes network, Fig. 2. The model comprises the electricity, heating and land transport sectors used in [7, 21]. Moreover, it is extended to include the transformation of industry, industrial feedstocks, shipping and aviation, the use of biomass and a detailed accounting of carbon capture, use, and storage (CCUS), as well as demand-side efficiency improvements in buildings. Our model outperforms most IAMs by including higher time and spatial resolution. This captures the variability of wind and solar, the presence of heating demand peaks and dark doldrums (i.e., periods with low wind and solar generation), and the role of storage at different time scales. This, together with detailed modelling of electricity and hydrogen grids, is crucial to dimension flexibility needs to balance variable renewable generation. Moreover, we include a more detailed breakdown of industry, e.g. by modelling the option of direct reduced iron (DRI) in steel manufacturing.

We model the transformation of the European energy system using a myopic approach in 5-years steps from 2020 to 2050 assuming different carbon budgets. We relate the climate and economic consequences, and evaluate when key new technologies emerge under distinct budgets. We show that, regardless of the budget, similar technological transformations take place, but the 1.5 and 1.6°C-budgets require most of them to be accomplished already by 2035. We extend the existing literature by providing three main novelties. First, the use of a highly resolved model. Second, the comparative analysis of transition paths for Europe under carbon budgets corresponding to temperature increases discretised by a tenth of a degree. Third, the inclusion of a sensitivity analysis to the cost and potential of CO₂ sequestration.

Figure 2: The networked model comprises 37 nodes, one per region of countries belonging to separate synchronous zone. The size of the circles represents today’s electricity demand in the residential and services sector. HVAC/HVDC transmission capacities among countries are shown in grey/red. Renewable resources are aggregated to the smaller regions shown on the map. The green shades represent the annual capacity factor for onshore wind in the different regions. Equivalent information for solar PV and offshore wind is depicted in Fig. S10-11.

2. Results

2.1. Deadlines for the required technological transformations

Fig. 3 gathers the occurrence of some key transformations under distinct carbon budgets. By definition, lower carbon budgets require reaching net-zero emissions earlier. For 1.5°C, reducing total emissions below 5% of 1990 level is already needed in 2040, see also Fig. S1. The time step at which electricity generation is almost fully renewable precedes the system-wide decarbonisation by 5 to 15 years. For 1.5 and 1.6°C-budgets, it would be optimal to fully decarbonise the electricity generation already in 2030, which highlights how challenging the low-emissions budgets are. Electricity generation is the first sector to undergo a deep transformation, see also Fig. S15. This was expected since renewable technologies, mainly solar photovoltaics, onshore and offshore wind are already competitive on a levelised basis with fossil-fueled generators.
Regardless of the budget, all the paths entail strong electrification of other sectors with non-biomass renewable electricity supplying more than 55% of final energy demand in 2050. The 1.5 and 1.6°C-budgets achieve more than 40% of renewable primary energy in 2030, a target that has been recently proposed by the European Commission [26]. However, those two budgets see a dramatic ramp-up of technologies, particularly solar PV, wind and electrolysis, between 2025 and 2035, see Fig. S13 and S14. In particular, the 1.5°C budget requires around 500 GW/a of newly installed wind and solar in that period, casting doubts on the feasibility of that specific transition path. The system finds it cost-effective to build a hydrogen network that enables exchanges among countries, Fig. S30.

Reducing emissions in the heating sector is harder, mainly due to the strong seasonality in heating demand [7]. The system uses three strategies to decarbonise this sector. First, heat pumps and electric resistors are used to supply heating demand. Second, in urban areas, district heating systems enable the use of large heat pumps together with biomass CHP units and gas boilers to ensure heating supply in the winter. When the system approaches net-zero emissions, waste heat output from the Fischer-Tropsch process dumped into district heating systems can cover up to 20% of the demand in those areas. Third, in regions without district heating systems, gas boilers are used at peak demand times to backup the heat pumps that cover the main supply. The share of consumed gas that has fossil, biogas or synthetic origin evolves throughout the transition paths, Fig. S26. The share of technologies providing heat in every time step are shown in Fig. S20-24.

Between 2030 and 2040, significant production of electrolytic H2 is cost-effective for scenarios below 1.9°C. Initially, the production H2 of is used for seasonal balancing of power generation, see Fig S32. As the Fischer-Tropsch technology is installed, H2 is consumed to produce synthetic hydrocarbons reaching a demand of 1700 TWh/a when all the hydrocarbons consumed in the model are synthetically produced. None of the transition paths installs capacity to produce blue H2 via steam methane reforming with carbon capture (SMR-CC), see Fig. S25. The production of H2 switches straight from SMR to electrolysis. The production of synthetic hydrocarbons starts as soon as the electricity generation is fully decarbonised in every budget.

Direct air capture (DAC) capacity is only installed for carbon budgets corresponding to temperature increase below 1.7°C. The model finds it more cost-effective to capture CO2 from (i) process emissions (which in 2050 represents 155MtCO2/a, Fig. S7), (ii) biomass and methane used in the industry, and (iii) biomass burnt in CHP units, see also Fig. 4. With the reference cost assumptions, sequestering CO2 underground is economically preferable and it occurs earlier than building Fischer-Tropsch capacities that transform the captured CO2 into synthetic hydrocarbons. The 200MtCO2/a potential for CO2 sequestration assumed for Europe is fully utilised as soon as it becomes cost-effective. A sensitivity analysis for CO2 sequestration is conducted in Section 2.2. The transition paths under 1.5 and 1.6 °C budgets require a large deployment of Negative Emissions Technologies (NET) between 2030 and 2045. This is because they achieve carbon neutrality by 2040 and 2045, respectively. However, the exogenously defined transformation of land transport and shipping still include significant emissions at that time, which need to be compensated by NETs. This example illustrates the consequences for the system if the decarbonisation of some sectors lags behind the global CO2 reduction targets.

In 2015, Europe imported 6000 TWh/a of oil [27]. More stringent carbon budgets reduce Europe’s external dependency earlier. The reasons are twofold: first, efficiency measurements and direct-electrification reduces the demand for oil and methane; second, as CO2 emissions are constrained, the upgrade of biogas into methane and the production of synthetic oil become cost-effective, see Fig.
Electricity generation is decarbonised first, followed by the heating and industry sectors, and finally, aviation. In our analyses, the shares of road transport and shipping that gets electrified or transformed into using hydrogen are exogenously fixed, Fig. S8.

The required CO₂ price, which is an output of the model, increases as CO₂ emissions allowance are reduced, see Fig. S17. For the 1.5°C-budget, a sharp increase of CO₂ price, reaching 370 €/tCO₂, is required to incentivise the extremely fast build-up of a carbon-neutral system by 2035. The 1.6°C carbon budget requires a smoother ramp-up in CO₂ price that stabilizes towards the end of the transition at around 270 €/ton CO₂. Higher carbon budgets require an increase of CO₂ price in 2050 to force carbon neutrality. Compared to our previous analysis [7], we found that similar CO₂ prices are required by mid-century, even though in this work we included a broader representation in the model of NETs such as carbon capture in the industry and CHP units, carbon sequestration, and carbon use in the Fischer-Tropsch process. The assumed cost and potential of CO₂ sequestration also affect the required CO₂ price, as discussed in Section 2.2. It is important to realize that, by setting up a CO₂ cap in every time step, instead of assuming a CO₂ price that steadily increases throughout the transition, the model avoids the large use of carbon dioxide removal as discussed by Streffler et al. [28].

Currently, only large emitters are included in the European Emissions Trading System (ETS), but extending this mechanism to other sectors has also been proposed [26, 29]. In the light of this discussion, it is interesting to realize that, for low carbon budgets, ETS-sectors tend to reduce emissions earlier than non-ETS sectors, see Fig. S16. This highlights the need for stronger incentives to reduce emissions in non-ETS sectors. In our modelling approach, this is indicated by the high CO₂ price required towards the end of the transition paths, but in reality, the policy implementations can vary and include other alternatives such as subsidies for emissions-free technologies and transformation deadlines including banning of emitting technologies.

2.2. Sensitivity to CO₂ sequestration cost and potential
So far, we have followed a conservative approach imposing a CO₂ sequestration potential for Europe of 200 MtCO₂/a, and a cost for sequestration and transport of 20 €/tCO₂. The high uncertainties associated with those assumptions and the full deployment of the potential shown in Fig. 4 motivates a sensitivity analysis. We conduct it here for the 1.7°C-budget. Fig. 5 shows the amount of CO₂ sequestered in 2050 under different assumptions. As the potential is increased, the system finds it optimal to sequester up to around 950MtCO₂/a. This could reduce the annualised system cost by 10%, and it would also impact the required CO₂ price, see Fig. S28 and S29.

Figure 4: Sequestration and use of CO₂ in the system (top) and technologies capturing CO₂ (bottom) for the distinct carbon budgets. CC stands for carbon capture.

S26-S27.

In all the alternative transition paths, the order of sectoral emissions reductions is maintained, see Fig. S15.
When lower costs are assumed, the sequestration rate increases slightly up to 1,150 Mt CO$_2$/a. On the contrary, if the transport and sequestration of CO$_2$ ends up being more expensive than initially estimated, this results in a lower optimal sequestration rate, *e.g.* for a fivefold increase in cost, the maximum CO$_2$ sequestration rate is approximately 600 Mt CO$_2$/a.

**Figure 5:** Sensitivity Analysis: CO$_2$ sequestered underground per year at the end of the transition for the 1.7°C-budget. Results are shown as a function of the assumed CO$_2$ sequestration cost and potential.

### 2.3. Additional sensitivity analysis

In this section, we briefly discuss the implications of some of the assumptions. We start by discussing the constraints on the networks expansion. The previous analysis assumed no expansion of transmission links among countries, besides those already planned in the TYNDP [30]. The build-up of a greenfield hydrogen network among countries, which was cost-effective in all the transition paths, was also included, see Fig. S30. On the one side, for the 1.7°C-budget, allowing the expansion of the power grid up to twice today’s volume reduces the system cumulative cost by 2%. As previously shown, the cost benefits of grid expansion [15] are reduced when the additional local flexibility provided by sector coupling is included in the model [21]. On the other side, disabling the build-up of the hydrogen network (*i.e.* hydrogen is produced and consumed locally) only increases the cumulative system cost by 0.5% and does not result in significant changes on the key transformation indicators, Fig. 3. These two examples illustrate the consequences of the optimal solution being “flat”. This means that alternative solutions, in which the deployment of some technologies is different, can still achieve a cost close to the minimum. Detailed analyses of the near-optimum solution space for the European power system have been recently presented [31–34].

Previous analyses assumed exogenous reduction in space heating due to building retrofitting whose cost is not included. To evaluate this assumption, we implemented a sensitivity run were the extension of investment in building retrofitting is endogenously calculated as described in [35]. For the 1.7°C, this strategy is gradually implemented throughout the path as it becomes cost-effective, see Fig. S34.

CO$_2$ capture on biomass burnt in CHP plants or the industry sector shows significant deployment when the system approaches net-zero emissions, Fig 4, but this technology is controversial due to the uncertain costs, land use and environmental impacts [11, 36, 37] . We run a sensitivity analysis disallowing CO$_2$ capture from biomass. The cumulative system cost is roughly the same, but the system deploys direct air capture to achieve the required negative emissions, Figs. 3 and Fig S31.

### 2.4. Cumulative system costs

**Figure 6:** Cumulative system cost for different carbon budgets and discount rates (indicated in the legend). A social cost of carbon of 120 €/t CO$_2$ is assumed. Equivalent results for other social costs of carbon are shown in Fig. S18 and S19.

Figure 6 depicts the cumulative system cost for transition paths using distinct carbon budgets and social discount rates. The assumed discount rate has a higher impact on the calculation than the carbon budget in every path. As expected, higher discount rates make the transition look less expensive by reducing the weight of future costs. Fig. 6 also shows that the required investments for distinct climate ambitions are not that different. Lower budgets require an earlier build-up of new assets, which due to the exogenous evolution of costs assumed, results in a more expensive transition. For a detailed description of cost components throughout the system transformation see Fig. S12.

For a 2% discount rate, the 1.5 and 1.6°C budgets, respectively, 8% and 1% more expensive than the 2°C budget. These percentages are 5% and -1% when a 6% discount rate is used. The implications of the assumed discount rate have been extensively discussed by other authors, see [38–40] and Supplemental Materials. For transition paths with perfect foresight and negative emissions, Emmerling *et al.* [39] found that reducing the discount
rate from 5% to 2% more than doubles the required CO\textsubscript{2} price in 2020, more than halves the carbon budget overshoot and increases significantly the investments in renewable energy. Our approach, based on myopic optimisation, is less impacted by the assumed discount rate, but still, this parameter has a large influence when computing the cumulative system cost. The selection of a discount rate higher than zero is based on the assumption that economic growth will continue. Based on this, historical growth rates are typically assumed. In [7], we selected 2% for the comparison based on the average growth rate of 1.6% over the past 20 years in the European Union. Temporal preferences are also claimed as an argument to support high discount rates. However, it is important to recognize the impacts in terms of inter-generational burden-sharing of this argument, as mitigation and adaptation costs in the short and long term will be paid by different groups of people.

Another parameter with a strong impact is the assumed social cost of carbon (SCC), which represents the economic cost caused by an additional tonne of carbon dioxide emissions or its equivalent. Widespread SCC estimations can be found in the literature caused by the uncertainties associated with climate change together with the high sensitivity to some modelling assumptions [41–47]. Alternative transition paths are commonly compared without including the SCC. This can create a distorted image since a significant part of the cost in high emissions scenarios is neglected. We have considered here a SCC of 120 €/tCO\textsubscript{2} [48]. Fig. S18 and S19 show, respectively, the cumulative system cost for a SCC of 75 and 300 €/tCO\textsubscript{2}. The former represents the recommendations by the Danish Economic Council of Environmental Economics [49]. For the latter, the transition under 1.5°C already results less expensive than for the 2°C budget. It must be noted that a SCC of 300 €/tCO\textsubscript{2} is lower than the SCC estimated by the German Environmental Agency with 0% time preference (680 €/tCO\textsubscript{2}) [50] and similar to recent recommendations by the European Commission (250 and 800 €/tCO\textsubscript{2} in 2030 and 2050 respectively) [51]. Moreover, considering the risk associated with climate tipping points could increase the SCC by up to a factor of 2 [52]. On top of that, the co-benefits of reducing CO\textsubscript{2} emissions in Europe due to avoided premature mortality and morbidity due to air pollution, reduced lost workdays and increased crop yields are estimated in the range of 125–425 €/ton CO\textsubscript{2} [53].

We believe that Fig. 6 provides a useful decision map where the costs of distinct climate ambitions in Europe are compared including not only those cost components associated with a profound transformation of our energy system but also those related to the avoided CO\textsubscript{2} emissions. Together with Fig. 1, it enables comparing the alternative budgets related to different temperature increases, confidence intervals and Europe’s share of global emissions, while not losing sight of the strong impacts of exogenous assumptions such as the discount rate or the SCC.

Before concluding, we briefly mention the main limitations of our study in this paragraph. First, we have assumed an exogenous transformation of land transport and shipping, since there is inertia in stock turnover that limits the transformation speed. This has important implications, particularly for the 1.5°C and 1.6°C budgets, which require offsetting the emissions from these sectors when net-zero emissions are imposed. Second, we have assumed that the cost evolution of different technologies is exogenous, i.e., no endogenous learning effects are considered. By doing that, we have assumed that global learning, driven by globally installed capacities, will determine the future costs of technologies, but we do not represent possible local learning.

3. Conclusions

In this work, we have investigated the transformation of the European energy system between 2020 and 2050 under distinct carbon budgets corresponding to various temperature increases between 1.5°C and 2°C. We found that all the transition paths experience similar technological transformations, but they occur at different points in the future. The system begins decarbonising electricity generation by installing solar PV, onshore and offshore wind capacities. This triggers strong electrification of other sectors such as heating, where large capacities of heat pumps are installed. Renewable electricity is also used to produce hydrogen via electrolysis, displacing the current production via steam methane reforming (SMR). A hydrogen network interconnecting the countries, co-optimised with the rest of the system, appear after 2035. None of the transition paths installs capacities of SMR with carbon capture, casting doubts on the relevance, from a system perspective, on the blue hydrogen strategy. When the system approaches net-zero emissions, electricity is also used to produce synthetic oil via the Fischer-Tropsch process, enabling the decarbonisation of the aviation and industry sectors. Carbon budgets corresponding to 1.5°C and 1.6°C require that the most significant technological transformations are fully accomplished by 2030, which shows how challenging these budgets are.

The system installs negative emission technologies (NETs) to offset process emissions from the industry. NETs are also needed when the transformations of land and maritime transport lag behind the CO\textsubscript{2} reduction targets. First and foremost, CO\textsubscript{2} is captured from point-source emitters including process emissions and biomass burn in the industry and CHP units. For the 1.5 and 1.6°C-budget, direct air captured is also extensively used. The 200 MtCO\textsubscript{2}/a assumed as CO\textsubscript{2} sequestration potential is completely deployed when the system approaches net-zero emissions. After that, the Fischer-Tropsch process is used to convert CO\textsubscript{2} into synthetic fuel. The impacts of uncertainties
in CO₂ cost and potential are investigated via sensitivity analysis. For optimistic cost and potential assumptions, up to 1,150 Mt CO₂/a are used. On the contrary, when the cost of CO₂ transport and sequestration is assumed to be 100 €/tCO₂, the use of CO₂ sequestration is reduced and the full potential is not deployed.

When comparing alternative climate ambitions, the cumulative system cost is typically employed to assess the alternatives. However, the high impact of uncertain exogenous assumptions, such as the social cost of carbon (SCC) or the discount rate, on these estimations requires careful evaluation. Here, we found that for a 2% discount rate and SCC of 120 €/tCO₂, the 1.5° and 1.6°C-budgets are 8% and 1% more expensive respectively, relative to the 2°C budget. However, for a SCC of 300 €/tCO₂, the 1.5° budget is cost optimal. These simulations suggest there is only a small cost to ambitious emissions reduction. In this case, following the precautionary principle and pursing an ambitious path, given the high uncertainty about the potential impact of climate change, would come with little cost penalty. This would not only allow a lower contribution of Europe to temperature increase but could also offset higher emissions in other world regions, compensating for unfair historical emissions.

4. Methodology

We model the transformation of the European energy system under six different carbon budgets corresponding to a temperature increase between 1.5 and 2°C, with 67% confidence, see [54] and Supplemental Materials. The share of the global carbon budget allocated to Europe is estimated assuming an equal-per capita distribution [8, 9]. Fig. 1 shows alternative relations between Europe carbon budget and temperature increase when (i) the historical responsibilities of every region are taken into account [8], (ii) splitting is proportional to historical emissions in every region [9], and (iii) different confidence intervals for temperature increase are considered [54].

The available carbon budget is distributed throughout the path assuming an exponential decay and forcing net-zero CO₂ emissions in 2050, Fig. S1. Nevertheless, it is worth mentioning that the EU commitment of net zero-GHG in 2050 could require net negative CO₂ emissions by mid-century. A myopic approach is used in 5 years time steps from 2020 to 2050. In essence, for every time step, the total system cost is minimised subject to a CO₂ constraint determined by the exponential decay, but without any information regarding the future. Contrary to assuming perfect foresight, the myopic approach provides a more expensive solution. However, it captures better shortsighted decisions by policymakers and investors, and it is less impacted by the assumed social discount rate. Technologies installed in previous time steps remain in the system and contribute to the total system cost until they reach the end of their lifetime. For every time step, the open energy model PyPSA-Eur-Sec [55] including 37 nodes, network modelling and uninterrupted 3-hour resolution for a full year is used. Generation, storage, energy conversion, and transmission capacities are optimised assuming a long-term market equilibrium, as well perfect competition and foresight. PyPSA-Eur-Sec includes the electricity, heating, land transport, aviation, shipping, industry sectors and a detailed representation of the carbon cycle, Fig. 7. The sectors are described in detail in the Supplemental Materials and a summary is provided below.

Electricity can be produced by solar PV, onshore and offshore wind, open (OCGT) and combined-cycle gas turbines (CCGT), nuclear, coal, lignite power plants, and combined heat and power (CHP) units using biomass or gas. The solar and wind resource are represented by 370 regions, each of which is connected to one of the 37 nodes in the network. Electricity can be stored in batteries or H₂ storage (underground in salt caverns or overground in steel tanks). Reservoir, run-of-river hydro and pumped hydro storage (PHS) capacities are fixed exogenously. The existing and planned transmission capacities are modelled using linear power flow. H₂ can be produced using electrolysery and by steam methane reforming (SMR) with or without carbon capture. A H₂ network can be built to connect countries if it is cost-effective.

Heating demand can be supplied by heat pumps, heat resistors and gas boilers and stored in thermal energy storage. Costs and properties of these technologies vary depending on if they are installed in a high-density population area, where district heating systems are assumed,
or in low-density population areas where only individual solutions are considered. In the former, heat can also be provided by CHP plants. Efficiency gains due to building retrofitting are exogenous, see Fig. S3 and [35].

CO₂ can be captured from exhaust gases (CHP plants, SMR or process emissions in the industry) or by direct air capture (DAC). Captured CO₂ can be used to produced synthetic methane via the Sabatier reaction or synthetic hydrocarbons via the Fischer-Tropsch process. It can also be sequestered underground with a maximum potential of 200 MtCO₂/a, which is conservative but enough for capturing process emissions. Cost assumptions for different technologies are taken from DEA [56]. Future cost evolution of different technologies is exogenous to the model [56]. Efficiencies, lifetimes, maximum potential for renewable technologies are described in the Supplemental Materials. Based on the JRC database [57], we follow a conservative approach in which only biomass that is not competing with crops is accounted as solid-biomass potential and can be used in the industry or burnt in CHP plants. Biogas is upgraded into biomethane.

In the industry sector, the production of materials (such as steel, cement, chemicals) in every node is assumed to remain constant. A detailed analysis is carried out in every industrial subsector to model the most probable transformations. The general approach includes the electrification of some industrial process, and the use of methane and biomass for high and mid-temperature process heat, respectively. A comprehensive description of all the industrial transformations assumed is included in the Supplemental Materials. In every time step, the percentage of steel that is produced via direct reduced iron (DRI) is fixed exogenously and so is the supply of aluminium from scrap metal. The model determines endogenously how the hydrogen demand is supplied (either using electrolyser, SMR or SMR with CC) and whether the methane and hydrocarbons have fossil, synthetic or biogas origin. All hydrocarbon feedstocks are also accounted for in the model.

Road and rail transport transformation is exogenously fixed using a path that ends with 85% of land transport electrified and 15% using fuel cells in 2050. Half of the existing EVs in every time step are assumed to do smart charging and enable vehicle-to-grid operation. Shipping transformation is also exogenous and follows a path that entails full conversion to hydrogen in 2050. Aviation consumes kerosene whose origin (fossil vs. synthetic) is endogenously determined. The possibility of importing synthetic fuels to Europe is not modelled. The agriculture sector is not included in the model and it is assumed that emissions from this sector are offset by the LULUCF sector.

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