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Reserving carbon storage for unavoidable emissions replaces fossil fuels with carbon cycles in climate-neutral scenarios

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Article

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Reserving carbon storage for unavoidable emissions replaces fossil fuels with carbon cycles in climate-neutral scenarios

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Abstract

European climate-neutrality strategies rely on geological carbon storage but leave open which emissions can use it. A conditional approach reserves storage for unavoidable emissions, such as from cement and waste incineration, whereas a technology-open approach allows it wherever it lowers costs. Here we compare both approaches in climate-neutral scenarios of a European energy and industry model with regional detail for Germany, endogenous industrial processes, refineries and CO_2 pipelines. In the technology-open approach, the system keeps fossil oil and gas and stores four times the unavoidable emissions. In the conditional approach, fossil fuel use is 97 % lower, steelmaking moves away from fossil gas and refineries turn from emission sources into sinks. Pipeline routes barely change, but capacity halves. System costs rise by 2.8 %, mostly for wind and solar expansion. This cost gap shrinks with higher fossil prices, more biomass or costlier direct air capture. The conditional approach is far less exposed to fossil price shocks, which sharply raise fuel costs in the technology-open approach.

Keywords: carbon capture and storage, carbon capture and utilisation, energy system modelling, industry defossilisation, CO_2 infrastructure

1 Introduction

Carbon capture and storage (CCS) is widely seen as part of climate-neutral energy and industry systems, but it remains contested which emissions should have access to geological storage [1–3]. Two positions dominate the debate. The conditional [2] or society-driven [3] perspective reserves CCS by regulation for emissions considered technically unavoidable, such as process emissions from cement production and emissions from waste incineration, and excludes CCS where mitigation alternatives exist. In contrast, the technology-open [2] or market-driven [3] perspective allows storage for all emissions, limited only by geological storage potentials.

The choice matters beyond the amount of CO_2 stored. It decides which fossil fuels in energy and industrial processes remain, by how much renewable electricity, hydrogen and synthetic fuels they are replaced, and how much CO_2 transport and storage infrastructure is built. Clear rules on which emission sources can use storage are a precondition for industry, energy system and infrastructure actors to choose which transformation options to invest in [3, 4]. Political climate and carbon management strategies do not specify which emissions are eligible to remain [1, 3, 4]. European and German strategies focus on hard-to-abate emissions, but the EU strategy also mentions remaining fossil emissions [5, 6] and the German storage law only excludes coal-fired power plants from storage [6]. National long-term low-emission development strategies submitted under the United Nations Framework Convention on Climate Change use no consistent definition of residual emissions, and most do not specify from which sectors they would originate [4]. Research does not show a clear picture either. Model-based studies differ in whether and by how much CO_2 storage is limited, so that European storage in these studies ranges from about 110 Mt CO_2/a to about 1.5 Gt CO_2/a [7–14].

Arguments exist for both positions. Technology-open access avoids excluding cost-effective options, keeps flexibility while technologies develop, allows retrofitting existing plants and spreads infrastructure costs over more users [1]. Conditional access limits continued fossil fuel use. Lower fossil fuel use reduces exposure to fossil price shocks, as in the European gas crisis of 2022 and after the closure of the Strait of Hormuz in 2026 [15, 16]. Further arguments for conditional access are the slow development of CO_2 injection capacity [1, 17, 18], the need to preserve storage for net-negative emissions [19], and risks related to infrastructure leakage with local consequences for health and the environment [20] which also affect public acceptance of CCS [21, 22].

The role of carbon sequestration affects industry processes relying on carbon as feedstock, refineries producing carbon-containing fuels, and the energy system and infrastructure providing electricity, hydrogen and heat for these processes and for technology alternatives. Previous research has shown that an integrated analysis of carbon flows in these sectors is necessary to represent their interconnection and competition for limited resources [13, 23]. Furthermore, an integrated European perspective is relevant, because countries exchange CO_2 and energy in an interconnected system. At the same time, regional resolution is necessary to capture how regions with different industrial structure, distance to CO_2 storage sites and renewable resources are affected, and how the capacity and routes of CO_2 networks change.

Model-based studies have analysed the effect of varying the amount of CO_2 sequestration, focusing either on the energy system [8–10, 24, 25], on CO_2 infrastructure [7, 26], or on an interconnected system but without the regional and infrastructure detail [13]. The energy system studies find that less storage leads to more carbon capture and utilisation (CCU), more hydrogen and renewable electricity, less fossil fuel use and higher system costs or marginal abatement costs [8–10, 24, 25, 27], see Supplementary Table 1 for details on the studies. However, these studies keep industry emissions fixed, and mostly consider storage levels above unavoidable emissions. CO_2 network studies vary the set of captured sources [7, 26] or the network topology [14] and do not optimise the network, energy system and industry jointly. System studies incorporating both industry and energy system technologies have low spatial and temporal detail and do not model CO_2 transport between regions [13]. Yet high spatio-temporal resolution is essential when studying highly renewable energy systems, to represent grid bottlenecks and wind and solar variability [28]. It therefore remains open how the storage rule changes industrial production routes, refinery operation and CO_2 infrastructure when these are optimised together with the energy system at regional resolution.

In this work, we compare the conditional and the technology-open rule in a climate-neutral European energy and industry system. To capture both the interconnected European carbon and energy flows and the regional effects at acceptable computational cost, we model Germany in high spatial and industrial detail and the other European countries in lower detail. Germany is a suitable case study because of its large energy- and carbon-intensive industry and dispersed refineries, its sequestration potentials in the North Sea, and its central location in Europe, which makes it a relevant region for CO_2 and energy transport. Similar conditions exist in other industrial regions of Europe, so the mechanisms identified for Germany are transferable to these regions. Fuel use, storage and costs are considered at the European level.

We extend the sector-coupled model PyPSA-Eur [29] with Germany resolved at NUTS2 level, where steel, cement and HVC plants and refineries are kept at their current sites with endogenous production routes. The other European countries are single nodes with endogenous refineries. All countries can be linked by electricity, hydrogen, methane and CO_2 networks, and the energy system is optimised at 6-hourly resolution. Storage is capped at 120 Mt CO_2/a, the level of unavoidable emissions plus a margin, in the conditional case and limited only by geological potential in the technology-open case, with all other assumptions identical.

We analyse how the storage rule changes industrial production routes, refinery operation, the energy system and the CO_2 network. Under conditional access, refineries turn from CO_2 sources into sinks for synthetic fuel production, and steelmaking switches from fossil gas to hydrogen. The CO_2 network therefore keeps most of its corridors but needs less capacity. Higher fossil prices, more biomass and costlier direct air capture (DAC) narrow the cost gap. The technology-open system remains highly exposed to fossil price shocks.

2 Results

2.1 Carbon cycles replace carbon storage in the conditional case

Fig. 1 shows the carbon flows of the entire European system for both cases. The flows run from carbon sources on the left through conversion and use to capture and then to sequestration or utilisation on the right. The two cases differ in how carbon moves through the system. In the technology-open case, a large part of the carbon flows in one direction: fossil carbon enters the system, its emissions are captured at point sources or balanced by DAC and bioenergy with carbon capture (BECC), and the captured CO_2 ends in geological storage. In the conditional case, fossil carbon almost disappears from the system, and carbon cycles characterise the system: CO_2 emitted from biogenic and synthetic fuels is captured at point sources or from the atmosphere and converted into new fuels and chemicals.

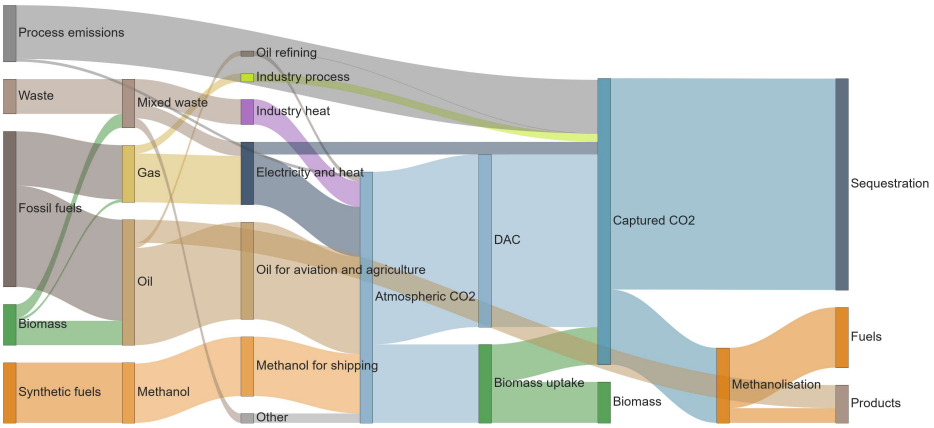
Total capture amounts to 602 Mt CO_2/a in the technology-open case and 367 Mt CO_2/a in the conditional case. In the technology-open case, 444 Mt CO_2/a, or 74 % of captured CO_2, are stored, and the remaining 158 Mt CO_2/a are converted into methanol. In the conditional case, storage reaches the cap of 120 Mt CO_2/a, equivalent to 33 % of capture, while 247 Mt CO_2/a, or 67 %, are utilised. Methanol production uses 158 Mt CO_2/a in both cases, the additional utilisation in the conditional case consists entirely of Fischer-Tropsch synthesis using 89 Mt CO_2/a.

In the technology-open case, Europe uses 1,430 TWh/a of fossil oil and gas. Fossil oil supplies part of the liquid fuels, and fossil gas supplies space heating, power generation and gas-based steelmaking (Industry process in Fig. 1a). Where CO_2 is emitted at large point sources, such as refineries and steel plants, it is captured. Where it is emitted in dispersed form, as from gas boilers in buildings, aviation and agricultural machinery, it is released to the atmosphere and balanced by DAC and BECC. Most of the captured CO_2 is sequestered, while carbon also cycles through biofuel and methanol production and use.

In the conditional case, fossil fuel use falls by 97 % to 39 TWh/a, consisting entirely of fossil gas, and the system is characterised by carbon cycles rather than linear flows. Captured CO_2 is combined with electrolytic hydrogen to produce Fischer-Tropsch products for aviation, agricultural machinery and the chemical industry, as well as methanol for HVC. Biomass is used to produce biofuels and biomethane, and some of the conversion processes are equipped with carbon capture for the carbon that is not converted into fuel. Fuel carbon returns to the atmosphere on combustion and is taken up again by biomass or DAC. In heating, fossil gas boilers and gas combined heat- and power plants (CHP) are replaced by electric heating. All these changes lead to a higher electricity demand, either directly or indirectly through a higher hydrogen demand supplied by electrolysis. In this system, geological storage balances process emissions from cement industry. In both cases, HVC are produced from methanol based on captured CO_2, and carbon from oil is stored in products.

The two cases use biomass for different purposes. Both consume 555 TWh/a of solid biomass, but the technology-open case uses only a small part of the biogas potential, 6 TWh/a compared with 172 TWh/a in the conditional case, because fossil gas with

a



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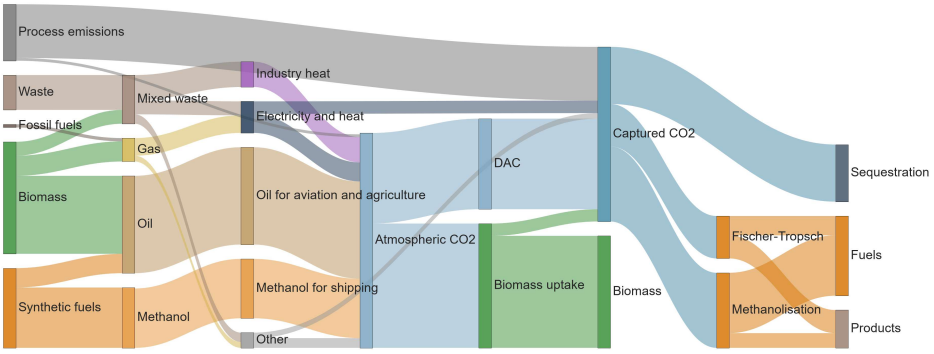

Fig. 1 European carbon flows in the technology-open and the conditional case. **a**, Technology-open case. **b**, Conditional case. Flow widths are proportional to the carbon flow in Mt CO_2/a. Carbon enters on the left and passes through conversion processes. In the middle of the diagram, carbon is released to the atmosphere or withdrawn from it by direct air capture (DAC) and biomass uptake. On the right, captured CO_2 is converted into synthetic fuels or chemical products, or stored geologically. Converted synthetic fuels, products and biomass form a cycle because they become a carbon source for the system.

CCS is cheaper and enabled by larger CO_2 storage. In the technology-open case, part of the solid biomass supplies industrial process heat, and the largest part is converted into biofuels with carbon capture, where a large share of the biogenic carbon is captured and stored rather than converted into fuel. Biomass therefore provides negative emissions that offset fossil emissions, and supplies part of the liquid fuels. In the conditional case, biogas replaces fossil gas, and most of the solid biomass is converted into electrobiofuels, in which added hydrogen allows most of the biogenic carbon to end up in the fuel. Biomass therefore mainly replaces fossil oil and gas with

biogenic fuels, and BECC captures 26 Mt CO_2/a compared with 79 Mt CO_2/a in the technology-open case.

DAC is deployed at large scale in both cases, but with different functions. In the technology-open case, DAC mainly offsets fossil emissions that are too dispersed for capture at the source. In the conditional case, DAC mainly supplies the carbon needed for synthetic fuels. Overall, European DAC falls by 48 %, from 363 to 190 Mt CO_2/a.

2.2 German industry leaves fossil fuels in the conditional case

The shift from storage to use changes individual industrial sites in Germany. In steelmaking, gas-based direct reduction with carbon capture in the technology-open case is replaced by hydrogen-based direct reduction in the conditional case. Additionally, both cases use recycling of steel with electric arc furnaces to the full potential defined by scrap availability. Cement and HVC production use the same routes in both cases. Cement plants capture their process emissions and use partly biogenic waste for process heat, and HVC are produced from methanol that is synthesised outside Germany at nodes with better conditions for wind and solar power. Additionally, mechanical and chemical plastics recycling are used to the full potential defined by availability of suitable fractions of the waste. Coal-based steelmaking or cement production with carbon capture is not used at all.

Refineries change their net-zero strategy from CCS to CCU and therefore switch from being sources to sinks of CO_2. In the technology-open case, German refineries process fossil oil, and emissions from refining processes are captured. In the conditional case, refinery sites produce Fischer-Tropsch fuels and use 23.4 Mt CO_2/a of captured CO_2. The refineries thus turn from CO_2 sources into CO_2 sinks, and they are the only sites in Germany where captured CO_2 is used. For site-specific transformation of steel and refinery processes see Supplementary Fig. 1.

2.3 CO_2 networks share corridors but differ in capacity

Figs. 2 and 3 show the CO_2 network in Germany together with the sources and sinks of captured CO_2. The network has similar routing, but the capacity changes. Counting internal pipelines and cross-border connections, the German network has a similar length in both cases, 6,687 km in the technology-open case and 6,548 km in the conditional case, and 5,136 km of it follow identical corridors. Its network capacity, defined as the sum of pipeline capacity times length over all pipelines, is, however, 38 % smaller in the conditional case. The complete European network shows the same pattern: its length is similar in both cases and most of its corridors are shared, but its network capacity in the conditional case is half that of the technology-open case.

Three factors explain why the networks of both cases share most of their corridors in Germany. First, several capture sources exist in both cases and have to be connected to CO_2 storage sites. Capture of industrial process emissions from cement and steel takes place at the same locations and is concentrated in north-western Germany, whereas capture at waste-fired CHP plants is spatially dispersed. Second, DAC adds little transport demand in either case, because it is located close to the northern storage sites and to wind resources. The higher DAC deployment in the technology-open case

therefore does almost not affect the network. Third, refinery sites are connected to the network in both cases, as CO_2 sources in the technology-open case and as CO_2 sinks in the conditional case. Differences in routing arise from sources that exist in only one case, such as gas-based steel plants with carbon capture in the technology-open case, and from the different sources and locations of BECC. In the technology-open case, part of the CO_2 captured in Germany and imported from other countries is exported for storage in northern Europe. In the conditional case, the German storage sites take up the CO_2 captured in Germany and imported and no CO_2 is sent to northern countries.

The difference in network capacity arises mainly from the change of refineries from CO_2 sources into CO_2 sinks. In the technology-open case, refineries and gas-based steel plants capture fossil CO_2, and all CO_2 captured in Germany flows north, either to German storage sites or on to storage elsewhere in northern Europe. In the conditional case, these fossil sources disappear, and refinery sites in the south, west and north of Germany use captured CO_2 for Fischer-Tropsch synthesis. These additional sinks reduce the network capacity because less CO_2 has to be transported north.

In the conditional case, the use of CO_2 at refineries also changes the operation of the network over the year. In summer, low-cost renewable electricity lowers the cost of electrolytic hydrogen, so Fischer-Tropsch synthesis runs at higher output and draws CO_2 towards the refineries. In winter, fuel synthesis declines, while waste-fired CHP plants run more to meet heat demand and capture more CO_2, which is transported north for storage. Several German corridors therefore carry flows in both directions over the year (Fig. 2). In the technology-open case, flows run towards storage throughout the year. The seasonal patterns are shown in Supplementary Figs. 2 and 3.

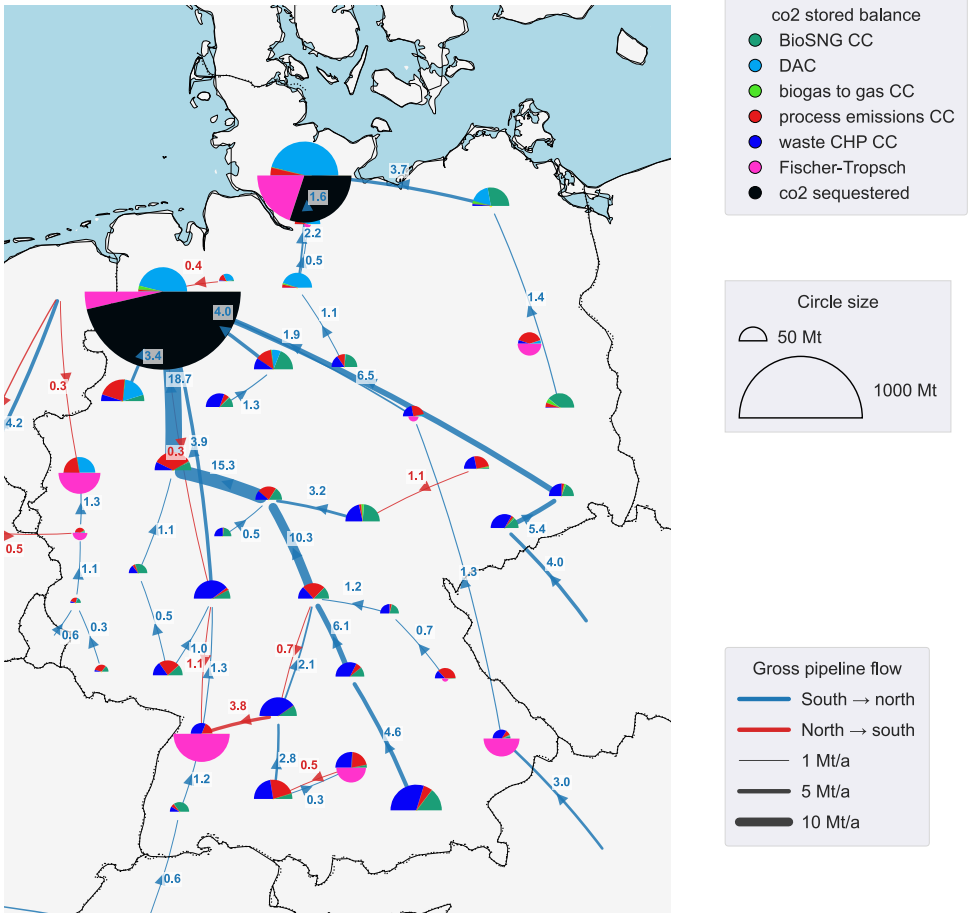

Fig. 2 Annual flows of captured CO_2 in Germany in the conditional case. Arrow widths and numbers indicate the annual amount of CO_2 transported in each direction. The upper half of each circle shows the CO_2 captured at the node, and the lower half shows the CO_2 used or stored at the node. CC, carbon capture. BioSNG CC, production of bio-synthetic natural gas with carbon capture. DAC, direct air capture. CHP, combined heat and power.

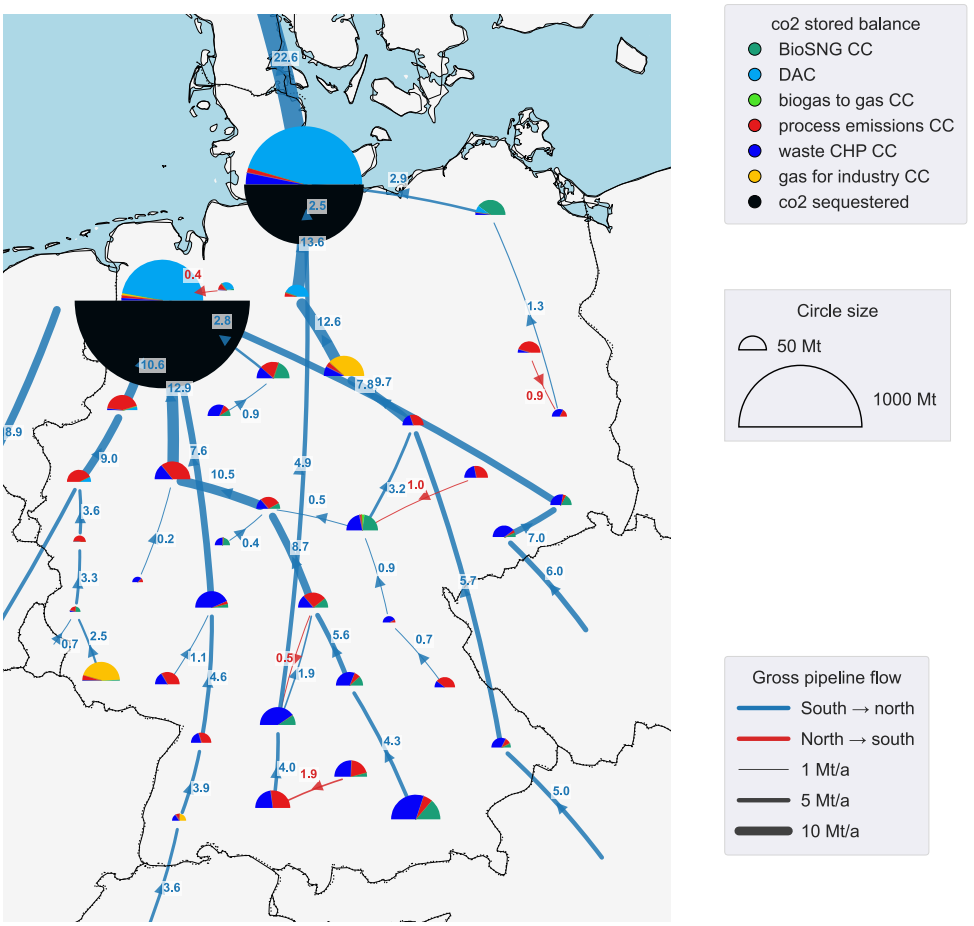

Fig. 3 Annual flows of captured CO_2 in Germany in the technology-open case. Arrow widths and numbers indicate the annual amount of CO_2 transported in each direction. The upper half of each circle shows the CO_2 captured at the node, and the lower half shows the CO_2 used or stored at the node. CC, carbon capture. BioSNG CC, production of bio-synthetic natural gas with carbon capture. DAC, direct air capture. CHP, combined heat and power.

2.4 Higher investments replace fossil imports in the conditional case

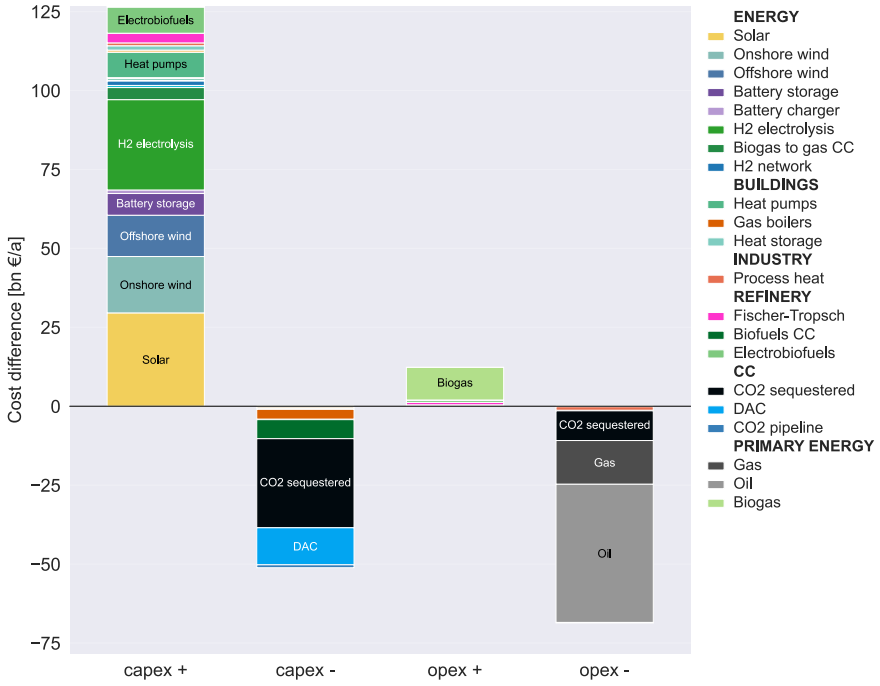

Fig. 4 Difference in annualised system costs between the conditional and the technology-open case, split into capital and operating costs. Positive values indicate higher costs in the conditional case. CC, carbon capture. DAC, direct air capture.

Measured by total system costs, the technology-open case is the cheaper option. The conditional case costs 19.4 b€/a more, which corresponds to 2.8 % of total annual European system costs. The net difference results from two much larger shifts in opposite directions, higher annualised capital costs and lower operating costs in the conditional case (Fig. 4).

In the conditional case, the additional capital costs arise mainly from electricity generation, electrolysis and synthetic fuel plants. The electricity needed for synthetic fuels, electric space heating and hydrogen-based steelmaking exceeds the electricity saved through lower DAC deployment. Meeting this demand requires 32 % more wind and solar capacity in the conditional case. Wind and solar generation account for the largest increase in annualised capital costs, at 60.5 b€/a. The substitutions also require plants producing hydrogen and synthetic fuels. Electrolysis accounts for 28.6 b€/a of additional annualised capital costs, followed by electrobiofuels and Fischer-Tropsch synthesis at the refineries. Part of these additional investments is offset by lower carbon management costs, mainly for geological storage and DAC, while the smaller CO_2 network contributes very little to the savings.

In the technology-open case, operating costs are dominated by fossil fuel imports. Europe imports 1,430 TWh/a of fossil oil and gas, at a cost of 58.6 b€/a. In the conditional case, fossil imports fall to 39 TWh/a and their cost to 0.9 b€/a. Nearly all costs of the conditional case are thus capital costs.

Although total system costs differ little, the marginal abatement cost of CO_2, given by the shadow price of the net-zero constraint, differs much more between the cases. For Europe, it rises from 237 €/t CO_2 in the technology-open case to 411 €/t CO_2 in the conditional case, an increase of 74 %. The shadow price reflects only the most expensive abatement options, which only make up part of the system, and the increase is therefore larger than the system cost increase.

2.5 More biomass or costlier air capture narrow the cost gap

Biomass serves two functions in the energy system. It is a source of non-fossil carbon that can be converted into fuels and chemicals, and, when its carbon is captured with BECC, it withdraws CO_2 from the atmosphere. In this second function, BECC can replace DAC, but it is less flexible in location, because capture is bound to the sites where biomass is available and converted. Additional biomass replaces costly synthetic fuels in the conditional case and cheaper fossil fuels with CCS in the technology-open case, so we test how higher biomass potentials affect the cost gap.

The reference case uses the low scenario of residual biomass potentials from the ENSPRESO database[30], with 841.3 TWh/a in Europe, including the biomass fraction of municipal solid waste, and the sensitivity analysis uses the medium scenario, with 1,547.6 TWh/a on the same basis, so almost doubled. Additional biomass lowers system costs in both cases, but less in the technology-open case, so the cost gap narrows from 2.8 to 1.3 %. In the conditional case, biomass replaces all Fischer-Tropsch fuels. The additional biogas replaces hydrogen-based steelmaking and part of the electric heating by biogas boilers, so wind and solar capacity is reduced by 13 % compared with low biomass availability. In the technology-open case, biofuels with carbon capture replace part of the fossil oil and part of DAC, and sequestration and fossil fuel use decrease but remain substantially higher than in the conditional case. More biomass increases BECC and reduces DAC in both cases. Collecting CO_2 from dispersed biomass conversion plants expands the network in these cases. With more biomass, network capacity rises by about 61 % in the technology-open case and 67 % in the conditional case.

Another relevant technology in both systems is DAC. DAC has not yet been deployed at scale, so its future costs are uncertain. Because DAC mainly offsets dispersed fossil emissions in the technology-open case and mainly closes the CO_2 cycles of synthetic fuels production and use in the conditional case, higher DAC costs affect the two cases differently. We test how the cases are affected by doubled DAC investment costs. With doubled DAC investment costs, the cost gap narrows to 1.7 %. In the conditional case, DAC capacity is reduced by only 17 %, mainly because fuel production changes from Fischer-Tropsch synthesis to electrobiofuels, which reduces capture requirements. Fossil gas use remains at the same level as the reference case. In the technology-open case, DAC falls more strongly, by about one third, for two reasons. First, BECC replaces part of DAC. Second, fewer fossil emissions have to be offset,

because biogas replaces part of the fossil gas and biofuels replace part of the fossil oil. The biomass for these biofuels is shifted from industrial process heat, which is instead supplied by electricity. Fossil fuel use in the technology-open case falls in both sensitivities, but remains substantially higher than in the conditional case. It falls from 1,430 TWh/a in the reference case by 16 % with more biomass and by 23 % with costlier DAC, compared with 39 TWh/a in the conditional case, and storage remains more than three times as high as in the conditional case. With more biomass or costlier DAC, biogas and biofuels replace part of the fossil fuels and BECC replaces part of DAC, but most fossil fuels remain in the system. The general difference between the two cases thus persists under higher biomass potentials and higher DAC costs.

2.6 Cost gap closes when oil and gas prices rise jointly

The cost advantage of fossil fuels with CCS over CCU and biogenic fuels depends on fossil fuel prices, which are 24.6 €/MWh for fossil gas and 52.9 €/MWh for crude oil in the reference case. Long-term projections of these prices are uncertain, and higher fossil prices narrow the cost gap between the cases. We therefore raise the oil and gas prices separately and jointly and optimise both cases with the higher prices, until the break-even prices are reached, at which the storage cap in the conditional case no longer binds and both cases yield the same system.

When the price of one fuel is increased, the system is built substituting with the other fuel that still has a lower price (Fig. 5). With a higher oil price, fossil gas replaces oil in the technology-open case, and oil is no longer used above 1.4 to 1.5 times the reference oil price. With a higher gas price, oil and biogas replace fossil gas, which is no longer used above 2.4 to 2.5 times the reference gas price. As long as one fossil fuel remains cheap, using it with CCS is less expensive than replacing it with electricity, hydrogen or synthetic fuels, and the cost advantage of the technology-open case persists. When both prices rise together, switching to a cheaper fossil fuel is no longer possible. Fossil fuels with CCS then lose their cost advantage, and the cost-optimal system of the technology-open case approaches that of the conditional case, with electrified heating, hydrogen-based steelmaking and synthetic fuels from captured CO_2. The break-even prices lie at 1.5 times the reference oil price and 2.45 times the reference gas price.

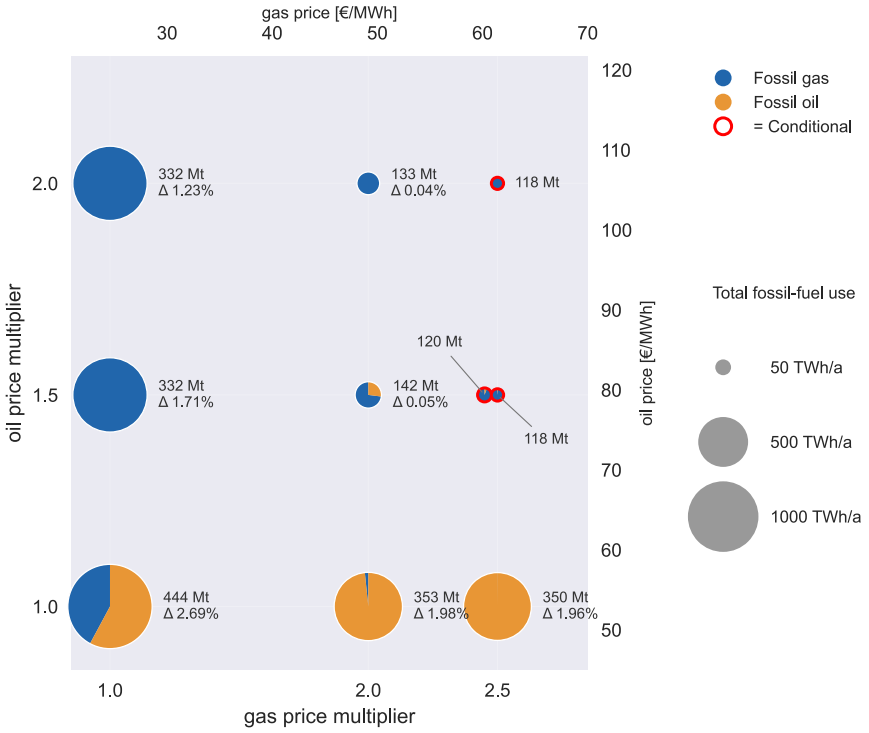

Fig. 5 Fossil oil and gas use in the cost-optimal technology-open case at increased fossil fuel prices. Prices are given as factors of the reference prices of 24.6 €/MWh for fossil gas and 52.9 €/MWh for crude oil. Labels next to the circles indicate the annual CO_2 sequestration in the technology-open case and its system cost advantage relative to the conditional case.

2.7 Technology-open case is exposed to fossil price shocks

The price increases tested so far are known when the system is planned. Fossil fuel prices can, however, also rise unexpectedly after the system has been built, when capacities and infrastructure can no longer adapt. A system that depends on fossil fuel imports is exposed to such shocks, as the European gas price crisis of 2022 and the rise in fossil fuel import costs after the closure of the Strait of Hormuz in 2026 showed. To illustrate the effect that such a price shock would have on either system, we apply the average prices of 2022 to the unchanged fuel consumption, 132 €/MWh for gas at the Dutch Title Transfer Facility (TTF) hub, and 55.05 €/MWh for Brent crude oil. In the technology-open case, buildings are heated with gas boilers, part of the electricity is generated in gas-fired power plants and steel is produced from gas, so fossil fuel expenditure more than doubles, from 58.6 to 125.1 b€/a. In the conditional case, almost no fossil fuels are used, and fuel expenditure rises by only 4.1 b€/a. At 2022 prices, the technology-open case therefore costs 43.1 b€/a more than the conditional case, instead of 19.4 b€/a less.

This estimate is approximate, because it applies annual average prices and does not account for adjustments in dispatch. However, most of the fossil fuel use in the

technology-open case occurs in aviation, gas boilers and gas-based steelmaking, and this consumption cannot change without new equipment or demand reduction. Only gas-fired CHP plants, which account for 14 % of fossil gas use and run at average capacity factors of 9 %, could partly reduce their output. The estimate is therefore an upper bound, but likely close to the cost increase of a re-optimised dispatch. These high costs arise because the capacities were optimised for lower expected prices. For comparison, we optimise under anticipated 2022 prices. In this case, the technology-open case would use no fossil gas but 917 TWh/a of crude oil and would remain 1.7 % cheaper than the conditional case optimised with the same prices.

3 Discussion

The technology-open and the conditional case translate the debate on access to geological storage into two different net-zero systems that result under opposing rules. With unrestricted technology-open access, fossil fuels remain in energy system and industry, their emissions are captured at refineries and steel plants or offset by DAC and BECC, and high sequestration volumes and large DAC capacities result, at lower total system costs. Under conditional access, electrification, electrolytic hydrogen and carbon cycles replace almost all fossil fuels at 2.8 % higher system costs, which consist almost entirely of investment in renewable electricity, hydrogen and carbon cycling instead of recurring fuel imports. The small cost gap thus buys lower fossil fuel dependence.

Energy system studies with exogenous industry that vary CO_2 storage limits find, as here, that more storage keeps fossil oil and gas in the system and replaces hydrogen, synthetic fuels and part of the wind and solar capacity [8–10, 24]. Sequestration in the technology-open case is close to the levels of about 440 Mt CO_2/a found by Schreyer et al. [13] and 500 Mt CO_2/a found by Glaum et al. [25]. Homaei et al. [12] find 1,524 Mt CO_2/a, but assume higher capture rates and do not model CO_2 infrastructure. Schreyer et al. [13] find marginal abatement costs rising from 460 to 630 €/t CO_2 for a fossil phase-out, a much larger increase than in total system costs, as in this study. Shu et al. [27] find that system costs double when storage is reduced in Germany, which they model without cross-border energy exchange and with synthetic methane as the only climate-neutral option for high-temperature industrial heat. The much smaller cost increase here indicates that European energy and CO_2 exchange and the option to switch industrial production routes keep the cost of restricting storage access low.

In addition to these studies focusing on the energy system, we find that the storage rule changes steel production, the role of refineries and the CO_2 network. Under conditional access, German steelmaking switches from gas-based to hydrogen-based direct reduction. Refineries turn from CO_2 sources into sinks, a change that CO_2 network studies with predefined capture sources [7, 26] cannot represent. Our results confirm findings that CO_2 networks to be cost-optimal across sequestration levels [24], and additionally show that the corridors are robust at the two sequestration levels, but that network capacity decrease with additional CCU at refineries.

Higher fossil fuel prices narrow the cost gap between the two cases, as found for synthetic versus fossil aviation fuels by Brazzola et al. [31]. More biomass or costlier

DAC also narrow the cost gap, but most fossil fuel use remains in the technology-open case. Millinger et al. [9] also find that additional biomass lowers system costs more under tighter storage limits. A system built for high fossil fuel use such as the technology-open case is exposed to unexpected fossil fuel price shocks, consistent with the exposure of European industry to price shocks found in [32]. The additional investment in the conditional case therefore reduces the exposure to fossil fuel markets during shocks such as those of 2022 and 2026.

Both cases require the scale-up of technologies that operate only at small scale today, but the risks of delayed scale-up lie in different technologies. European injection capacity is currently below 3 Mt CO_2/a [33], and the Net-Zero Industry Act targets 50 Mt CO_2/a by 2030 [34]. The technology-open case relies on large volumes of storage and DAC, which are at an early stage. The conditional case requires less storage and DAC, but more electrolysis and fuel synthesis, while its largest additional investment goes into wind and solar power, which are already deployed at large scale. CO_2 storage and related infrastructure also face risks that the optimisation does not quantify, such as concerns about the long-term stability of storage sites and leakage [8, 20], public scepticism towards CO_2 storage [21, 22] and civil-society positions that prioritise direct emission reductions [2, 3, 31].

Lower annual sequestration also makes geological storage last longer. The offshore storage potential from the CO_2StoP project, which is used in the model, amounts to about 60 Gt CO_2 in Europe. If annual sequestration remained at the level of the net-zero systems, this potential would be filled within about 136 years in the technology-open case and 503 years in the conditional case. With the prudent European limit of 39 Gt CO_2 proposed by Gidden et al. [35], these periods shorten to about 88 and 325 years. Lower sequestration also preserves storage for the net-negative emissions needed to return warming to 1.5 °C after an overshoot [19]. A system with lower annual sequestration therefore leaves future generations both storage capacity and the choice of how to use it, for example for net-negative emissions or for emissions that are still unavoidable then, as argued by Gidden et al. [35].

Germany serves as a case study for the regional effects. Similar effects can be expected in other countries with inland industrial sites and refineries, where using captured CO_2 at refineries would also shorten transport distances and reduce the required network capacity. Where industrial clusters lie closer to storage sites, this reduction would be smaller. Seasonal variations in CO_2 flows arise wherever capture at waste-fired CHP plants follows heat demand while fuel synthesis follows renewable generation. The argument on price risk applies mainly to fossil fuel importers.

Several assumptions limit these results. Unavoidable emissions and the demand for carbon-based products are exogenous. Demand reduction through circularity in the chemicals sector, lower industrial production, less air travel, material efficiency and reuse could change the role of CCS and CCU in both cases and are not considered as strategies here. Imports of hydrogen and synthetic fuels into Europe are excluded, although they can lower net-zero system costs [36], especially in the conditional case with high synthetic fuel use. Only two sequestration levels are compared. Near-optimal [10] or Pareto-front [27] methods could show at which sequestration level a model with endogenous industry changes most and where the solution space is

flat. Resolving only Germany at NUTS2 level simplifies renewable resources, emission sources, storage locations and transport distances elsewhere. The greenfield formulation excludes existing assets, and pathways could show how industrial sites and CO_2 networks change roles over time, such as refineries turning from CO_2 sources into sinks, and how CCS performs as a transitional option. Carbon removal options additional to geological sequestration are not included, which has been shown to impact results [10, 37].

The results have implications for policymakers, infrastructure planners, industry and modellers. First, current strategies and laws largely correspond to the technology-open case [2, 3, 5, 6]. We show that defining which emissions can use storage also decides on future fossil fuel imports and exposure to price shocks, on production routes at industrial sites and refineries, and on their role in the CO_2 network. Second, a CO_2 network is built in both cases and is therefore a no-regret option. Its corridors hardly depend on the storage rule, but its capacity does, and because CO_2 is transported across Europe, its planning needs coordination at least at the European level. Third, broad electrification and a large expansion of wind and solar power are no-regret options under either storage rule. Fourth, a storage rule set today decides how long geological storage lasts and how much of it remains for net-negative emissions later in the century. Fifth, carbon management strategies need to be assessed considering industrial transformation, energy supply and CO_2 infrastructure together, and considering regional detail as well as European connected systems.

4 Methods

4.1 Model overview

The model builds on the sector-coupled European energy system model PyPSA-Eur [**?**], version 2025.07.0, and on its module for energy-intensive industry by Burghardt et al. [23]. In that module, the production routes of steel, cement and HVC are decision variables that are optimised together with the energy system. For the present study, the model is extended in two ways. Germany is divided into its NUTS2 regions with industrial plants and refineries at their sites, and the whole European energy system is optimised.

The model covers the energy demand of all sectors. Exogenous demands are given for electricity, heating in buildings, land transport, aviation, shipping, agriculture and industry. These demands are met by technologies whose capacities and operation are optimised. In buildings, the heat demand is fixed, whereas the heating technologies, such as heat pumps, resistive heaters, gas boilers and district heating, are optimised. Because these technologies link electricity, heat, hydrogen, methane, liquid hydrocarbons, methanol, solid biomass and CO_2, all sectors are coupled and compete for the same resources. Land transport is fully electrified and shipping uses methanol by assumption, while aviation and agricultural machinery use oil products from fossil, synthetic or biogenic sources.

The model minimises total annual system costs of a climate-neutral system in the target year 2050. These costs consist of annualised investment costs, fixed and variable operating costs and fuel costs. Costs, efficiencies and lifetimes of the technologies are

taken from the technology-data package [**?**], version 0.13.3, for 2050. The optimisation follows an overnight, greenfield approach, in which all capacities are built for the target year. All parameters and data sources are listed in Supplementary Note 2.

Separate net-zero constraints on CO_2 emissions apply to Germany and to Europe as a whole, reflecting national and European climate targets. Both constraints cover CO_2 emissions from fuel combustion and industrial processes, including aviation and shipping, but not other greenhouse gases or emissions and removals from land use. Within the one-year horizon of the model, carbon bound in newly produced chemicals is counted as a sink, and carbon in waste is counted as emitted when the waste is incinerated. Over several years, these two flows form a carbon cycle, in which products return as waste and their carbon is emitted or captured at waste incineration.

4.2 Industry and refineries

Steel, cement and HVC are produced at the sites of existing plants, with production volumes fixed at current levels. Each site can choose among production routes that differ in their demand for energy carriers, process heat, feedstocks and raw materials, in their process emissions and in their investment and operating costs. Steel can be produced by scrap-based electric arc furnaces, by direct reduction of iron with hydrogen or fossil gas, or by blast furnaces with optional carbon capture. Cement can be produced with lower clinker shares and with capture of process emissions. HVC can be produced by fossil gas-based or electrified steam cracking, from methanol, or by mechanical and chemical recycling. The operating costs of the production routes include the costs of raw materials. The recycling routes are limited by the availability of secondary materials. Process heat is represented at three temperature levels following Millinger et al. [9], extended by heat from coal with carbon capture, hydrogen and direct electric heating.

Refineries remain at their current sites, but these sites can be transformed. Liquid fuels and naphtha can be produced by fossil refining with optional carbon capture, by Fischer-Tropsch synthesis, as biofuels or as electrobiofuels, in which hydrogen is added so that all biomass carbon ends up in the fuel. All of these fossil, synthetic and biogenic processes can be built only at the current refinery sites, but their output is not fixed at current levels and adapts to the demand for refinery products. This demand is exogenous for aviation and agricultural machinery and endogenous for the chemical industry, where it depends on the chosen HVC routes. Methanol can be produced at any node.

In this study, the site-level representation of industry and refineries is applied to Germany only, although the model can be configured to represent all countries at site level. The other European countries also have refineries with endogenous production routes. Because each of these countries is represented by one node, its refineries are aggregated at that node instead of being represented at individual sites. The industry of these countries and the other industrial subsectors in Germany are represented by exogenous demands for electricity, feedstocks and process heat.

4.3 Spatial and temporal resolution

The model covers European countries and is solved for one year at 6-hourly resolution, which gives 1,460 time steps, with weather data from 2013. Germany is represented by its 38 NUTS2 regions and every other country by one node. Each node contains its own subsystem for supplying, converting, storing and transporting energy and CO_2. Wind and solar potentials and capacity factors, demand time series, biomass potentials and geological storage potentials are resolved at these levels.

The spatial resolution is a trade-off between regional detail, the representation of the interconnected European system and computation time. Regional detail is needed to resolve the flows of energy and CO_2 between industrial sites, refineries, storage sites and renewable resources. The European system has to be represented because countries exchange energy and CO_2 and share storage sites. Resolving all European countries at NUTS2 level with endogenous industry and 6-hourly resolution would make the optimisation problem too large to solve, so the regional detail is limited to one country. Germany is suited to this role because it combines a large energy- and carbon-intensive industry, refineries dispersed across the country, access to storage sites in the North Sea and a central location in the European flows of energy and CO_2.

Transmission of electricity and pipeline transport of hydrogen, methane and CO_2 between nodes are optimised. Solid biomass and municipal solid waste can be transported by road within Germany, and biogas can be upgraded and transported through the methane network. These transport options have investment and operating costs. Liquid hydrocarbons and methanol are transported between nodes without costs or capacity limits, because transport infrastructure for liquid fuels exists and their high energy density makes transport costs per unit of energy negligible (see [8]). Fossil oil and fossil gas are the only energy carriers that can be imported into Europe. Hydrogen and synthetic fuels cannot be imported from outside Europe.

4.4 Carbon capture, utilisation and storage

CO_2 can be captured at industrial plants, refineries and power and CHP plants, from biomass conversion processes and from the atmosphere by DAC. BECC comprises capture in the production of bio-synthetic natural gas (BioSNG), in biogas upgrading, in biomass-to-liquid and biomass-to-methanol plants, in hydrogen production from solid biomass, in solid biomass CHP plants for district heating and in the supply of industrial process heat from solid biomass at all three temperature levels. The capture rate is 95 % for industrial process emissions and 90 % for combustion processes, such as in waste-fired CHP plants. DAC consumes electricity and low-temperature heat, and has an annualised investment cost of 0.58 M€/a per t CO_2/h of capture capacity. Captured CO_2 can be either stored in geological formations or used to produce synthetic fuels and chemicals by Fischer-Tropsch synthesis, methanolisation and methanation. The carbon in synthetic fuels returns to the atmosphere when the fuels are combusted. Geological storage is limited to offshore sites. Regional storage potentials follow the conservative estimate of the CO2StoP project [38]. Storage costs and potentials are given in Supplementary Note 2.

4.5 Storage rules in the two cases

The two cases differ only in the annual amount of CO_2 that can be stored in Europe. All other assumptions, including storage costs and potentials, are identical. In the technology-open case, the regional storage potentials are the only upper bound on storage. CCS can therefore be combined with any CO_2 source, including fossil fuels, wherever it lowers total system costs.

In the conditional case, storage is reserved for emissions that cannot be avoided with current technology. Instead of defining eligible sources, a single annual storage cap applies to Europe as a whole. The cap is derived from net unavoidable emissions. Process emissions amount to 111 Mt CO_2/a, mostly from cement production. For Germany, they are calculated with the least emission-intensive production route at fixed production volumes, and for the other countries, they are exogenous. Emissions from non-biogenic waste add 31 Mt CO_2/a, and the carbon bound in newly produced chemicals subtracts 31 Mt CO_2/a, because the carbon stored in new products is assumed to equal the carbon in newly generated waste in the target year. Net unavoidable emissions are thus 111 Mt CO_2/a. The cap of 120 Mt CO_2/a adds a margin, which keeps the problem feasible and shows which emissions are the most expensive to abate, because these use the additional storage. The cap applies only to storage, so the capture and use of CO_2 are unrestricted in both cases.

4.6 Sensitivity analyses

For the biomass sensitivity, the low scenario of residual biomass potentials from the ENSPRESO database of the European Commission's Joint Research Centre [30] is replaced by the medium scenario, both for the reference year 2030. For the DAC sensitivity, the investment costs of DAC are doubled.

For the fossil price sensitivity, oil and gas prices are raised separately and jointly as multiples of the reference prices, and both cases are optimised again with the higher prices. To find the break-even prices, the prices are raised step by step, each time to the level at which the additional fuel costs of the technology-open case at unchanged capacities and dispatch would equal its cost advantage, until the storage cap in the conditional case no longer binds. For the 2022 price crisis, the average 2022 prices of fossil gas at the TTF hub and of Brent crude oil are applied to the fuel consumption of both reference systems without new optimisation, so the systems cannot adapt to the higher prices. For comparison, both cases are also optimised with the 2022 prices, which represents anticipated price increases.

Use of AI. During the preparation of this work, the authors used AI (ChatGPT, Claude) for improving language. They reviewed and edited the content afterward and take full responsibility for the content.

Data availability. All input data used in this study are from publicly available sources. The input data and the model results supporting the findings of this study have been deposited at Zenodo (https://zenodo.org/records/24321880).

Code availability. The model code, an extended version of PyPSA-Eur, is available on GitHub (https://github.com/INATECH-CIG/regional_carbon_flows) and archived at Zenodo (https://zenodo.org/records/24321880).

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