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

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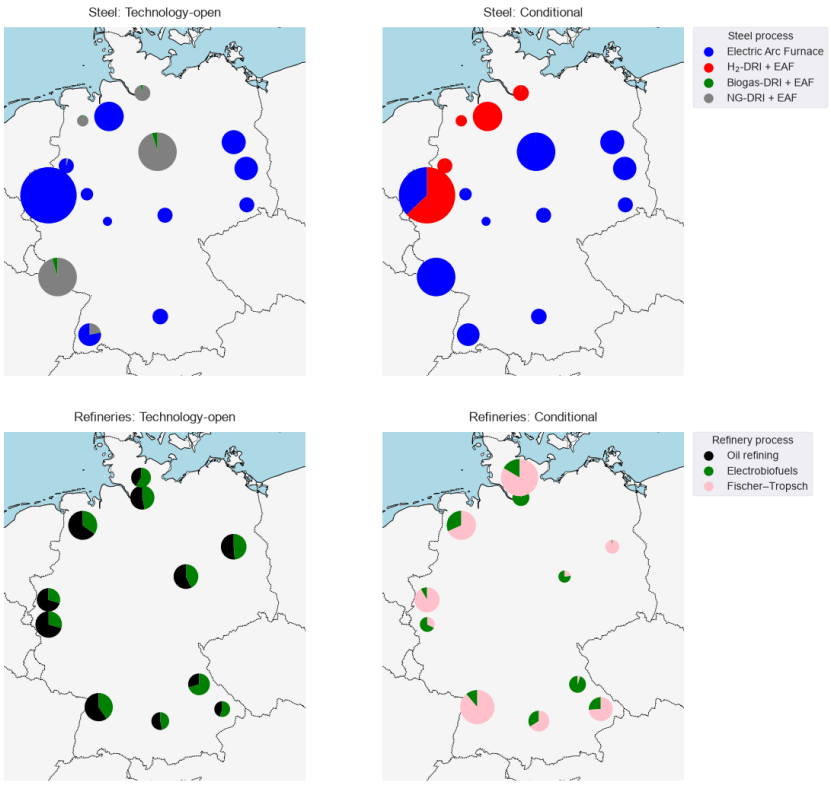
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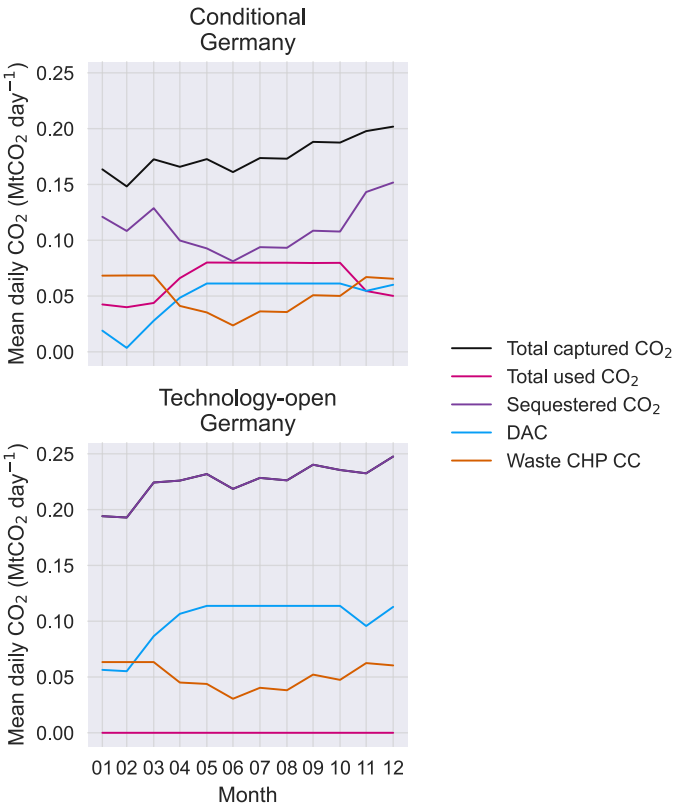
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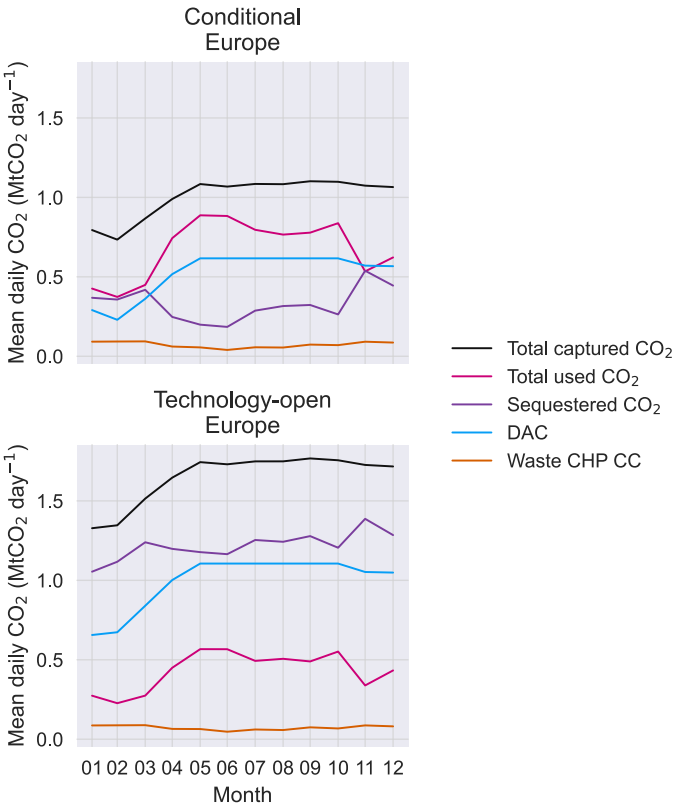
Supplementary Figures



Supplementary Figure 1 Steel plants and refineries in Germany in the modelled cases. DRI, direct reduction of iron. NG, fossil gas. EAF, electric arc furnace.



Supplementary Figure 2 Monthly captured CO_2 balance in Germany. Mean daily captured CO_2 per month, aggregated over all nodes in Germany. DAC, direct air capture. CHP, combined heat and power.



Supplementary Figure 3 Monthly captured CO_2 balance in Europe. Mean daily captured CO_2 per month, aggregated over all nodes in Europe. DAC, direct air capture. CHP, combined heat and power.

Supplementary Tables

Supplementary Table 1: Studies that vary the availability or use of CO_2 storage, CCU or carbon dioxide removal. Rows give the study design and the reported effects on industry, refineries and fuel production, the energy system, CO_2 infrastructure and system costs. "Not represented" means that the study does not report results for that dimension. Storage in Mt CO_2/a. CC, carbon capture. CDR, carbon dioxide removal. DAC, direct air capture. BECC, bioenergy with carbon capture. DRI, direct reduction of iron. FT, Fischer-Tropsch. H_2, hydrogen. HVC, high-value chemicals. RE, renewable energy. SMR, steam methane reforming.

Study	Study design	Industry	Refineries and fuels	Energy system	CO_2 infrastructure	System costs
Shu et al. [1]	• Germany to 2045, no or limited energy imports • Storage lowered stepwise from 379 to 118 • Fixed industry emissions, no CO_2 transport	• Fixed sites, no route switch, optional CC at steel and cement • High-temperature heat only from methane	• Not represented	• Least cost: CCS at cement, steel and gas power plants, 251 Mt CO_2/a DAC • Least storage: battery electric vehicles, synthetic methane, wind and solar at poor sites	• Not represented	• +105 % at 118 versus 379 • 81 % of the increase below 141
Seibold et al. [2]	• PyPSA-DE, brownfield, 2025, 2035 and 2050, 89 nodes • 60 CO_2 pipeline topologies versus no network, storage 100 in 2035	• Endogenous steel and cement routes at plant level • Early CO_2 network keeps gas-based DRI with CC in 2050	• No refinery sites • Without network, captured CO_2 used locally for methanol	• Early CO_2 network keeps blue hydrogen and delays electrification	• Network mainly used by process emissions, cement and BECC • Corridor North Rhine-Westphalia to the Netherlands most valuable	• 2035: network saves 22 b€/a for German consumers • 2050: pathway without early network cheaper
Brazzola et al. [3]	• Aviation only: fossil kerosene with DAC and storage versus FT fuel from DAC CO_2 • Energy and CO_2 storage as exogenous prices	• Not represented	• Compares CCU fuel with fossil fuel and CCS	• Not represented	• Not represented	• Fossil kerosene with CCS mostly cheaper • CCU fuel cheaper at low electricity or high fossil prices

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Table 1 continued

Study	Study design	Industry	Refineries and fuels	Energy system	CO_2 infrastructure	System costs
Hofmann et al. [4]	• Europe, storage 200 to 1,000, with versus without CO_2 network • Exogenous industry demand	• All process emissions captured at every storage level	• More storage: fewer FT fuels, more fossil oil • H_2 shifts from electrolysis to SMR with CC	• More storage: less H_2 and RE, more gas in CHP and heating	• Network from inland sources to the North Sea • High storage: concentrated CCS, low storage: distributed CCU	• Highest storage: −13 % • CO_2 network: −1.6 %
Hofmann et al. [5]	• Europe, 90 regions, 3-hourly, storage 200 to 800 • Endogenous H_2 and CO_2 networks, exogenous industry	• Fixed emissions and demands, only CC endogenous	• No refinery sites • More storage: fossil fuels with CCS replace FT fuels	• More storage: fossil fuels remain in aviation, heating and gas CHP • Less H_2 and RE	• CO_2 network capacity quadruples, H_2 network halves • DAC near the coast offsets fossil emissions	• −9.1 % from 200 to 800 • Shadow price 225 to 51 €/t CO_2
Millinger et al. [6]	• Europe, net-negative target, storage 600 to 2,400, net-zero case 140 • Endogenous biomass and process heat	• Small share of biomass for process heat with CC	• Large biomass share in biorefineries	• Fossil fuel use rises from 0.1 to 3.7 PWh/a with storage • Little change above 1,200	• Not represented	• Not reported as a function of storage
Yeates et al. [7]	• CO_2 network for exogenous sources and sinks • Cement and lime always, steel and coal power optional	• Steel plants change routing and raise flows	• Not represented	• Coal and lignite plants change routing and raise flows	• Isolated sites have high connection costs • Sink location changes routes	• Largest increase with fossil power plants
Homaei et al. [8]	• European power sector, 2020 to 2060 • CCS restricted by fossil investment or geography	• Not represented	• Not represented	• Base case 2050: 21 % of power from fossil fuels with CCS • Restricted CCS: 38 % more solar, 33 % more wind	• About 1.5 Gt CO_2/a captured • Transport and storage not modelled	• Restricted CCS: +6 %

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Table 1 continued

Study	Study design	Industry	Refineries and fuels	Energy system	CO_2 infrastructure	System costs
Holz et al. [9]	• Europe to 2050, scenarios without, costly and affordable CCS • Sites and CO_2 infrastructure at about 200 km resolution	• Sites represented, no technology choice	• Not represented	• Affordable CCS: coal and gas CCS • Without CCS: more RE and flexibility	• Spatial infrastructure, routing not reported	• Affordable CCS: −4 %
Raillard-Cazanove et al. [10]	• Industry only, six European countries, 2015 to 2050 • Unlimited storage, with versus without e-fuels	• National, not site level • Without e-fuels, hydrogen-based DRI replaces blast furnaces with CCS	• E-fuels use captured industrial CO_2 • Without e-fuels, more storage	• Not represented, e-fuels use 56 % of H_2	• Not represented	• Not reported
Grant et al. [11]	• Global integrated assessment, with versus without CDR, 1.75 and 2 °C	• Without CDR, more demand reduction in industry	• Not represented	• Without CDR, faster electrification, 60 % more electricity in 2050	• Not represented	• Without CDR, 3 % instead of 1 % of GDP
Bindl et al. [12]	• CDR limited to 25 or 50 % of the cost-optimal level	• Not represented	• Not represented	• Less CDR requires earlier emission reductions	• Not represented	• CDR shortfall raises costs or makes targets infeasible • Less CDR, fewer stranded assets
Kalweit et al. [13]	• Europe, 39 nodes, storage minimised within 1 to 5 % cost slack, from 200 • No H_2 or CO_2 network, exogenous industry	• Slightly more biomass CC for industrial heat	• Less storage: up to 77 Mt CO_2/a more for FT, less fossil refining • No refinery sites	• Less storage: natural gas falls from 179 to 65 TWh/a, more biomass boilers and electrolysis	• No network • Storage down to 96 at 5 % slack	• Storage of 163, 129 and 96 at 1, 3 and 5 % higher costs

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Table 1 continued

Study	Study design	Industry	Refineries and fuels	Energy system	CO_2 infrastructure	System costs
Glaum et al. [14]	• PyPSA-Eur, 100 regions, 2030 costs, net zero • Methanol backstop without H_2 and methane networks, storage 200, 400 or unlimited	• H_2 only within industrial clusters for steel, ammonia and methanol • Methanol supplies 76 % of HVC	• No refinery sites • Methanol-to-kerosene replaces FT fuels without H_2 networks	• Methanol mainly from biogenic carbon, no DAC with medium biomass • Unlimited storage: more fossil oil and gas with CCS, less methanol	• Unlimited storage: about 500 • Without CO_2 network: +1.7 %	• Backstop: +2.4 % • Unlimited storage: −7.6 %
Schreyer et al. [15]	• REMIND, eight EU regions, five-year steps to 2050 • Storage cap 2,000 versus 110, regional caps, no CO_2 transport	• Steel routes endogenous but not reported • Least cost: fossil fuels remain in chemicals	• No refinery sites • Low cap: more than 1,000 TWh/a of e-fuels	• Fossil primary energy −90 % versus −99.5 % • Similar electrification, difference in residual hydrocarbons	• Capture 440 versus 260 Mt CO_2/a • Storage about 400, limited by scale-up costs	• Marginal abatement cost 460 to 630 €/t CO_2 • Consumption losses rise much less
This study	• Europe with Germany at NUTS2, endogenous steel, cement and HVC routes, refineries at their sites, CO_2 network • Conditional (120) versus technology-open storage	• Technology-open: gas-based DRI with CC in German steelmaking • Cement and HVC routes unchanged	• Conditional: seven German refineries become CO_2 sinks for FT fuels • Technology-open: fossil refining with CC	• Fossil oil and gas 1,430 versus 39 TWh/a (−97 %) • Conditional: 32 % more wind and solar	• Network capacity halves, corridors largely shared • Seasonal flow reversal in Germany	• Conditional: +2.8 % • Reverses at 2022 gas prices

Supplementary Note 1: CO_2 network detailed results

Total pipeline length in Europe is 12,364 km in the technology-open case and 13,136 km in the conditional case, of which 9,146 km follow identical corridors. Corridors are counted as active above a capacity of 10 t CO_2/h. Network capacity falls from 10.2 Mt CO_2/h·km in the technology-open case to 5.1 Mt CO_2/h·km in the conditional case. Of this difference, 2.9 Mt CO_2/h·km result from lower capacity on shared corridors and 2.7 Mt CO_2/h·km from corridors that exist only in the technology-open case, while new corridors in the conditional case add 0.4 Mt CO_2/h·km.

In Germany, the network capacity on shared corridors is 2.9 Mt CO_2/h·km in the technology-open case and 2.5 Mt CO_2/h·km in the conditional case. Corridors with a length of 771 km (0.45 Mt CO_2/h·km) exist only in the technology-open case, and corridors with a length of 712 km (0.16 Mt CO_2/h·km) only in the conditional case. Without cross-border pipelines, the German network is 5,396 km long in the technology-open case and 5,337 km in the conditional case.

In the technology-open case, CO_2 captured in Germany joins inflows from Switzerland, Austria, Poland, Belgium and France. Part of it is stored at sites in northern Germany, and a major corridor continues through Denmark to storage sites elsewhere in northern Europe. Germany is a transit country and a net exporter of 3.0 Mt CO_2/a. In the conditional case, CO_2 is used at three refinery sites in the south of Germany, one in the west and three in the north close to the storage sites. Germany becomes a net importer of 8.6 Mt CO_2/a, and no CO_2 is exported to Denmark.

In both cases, BECC occurs only at nodes without refineries. Where biomass is available near a refinery, it is transported to that refinery and converted into electrobiofuels.

Supplementary Note 2: Model details

Energy system model configuration

The energy system model, extended with the industry and refinery model, is built with PyPSA-Eur version 2025.07.0. It uses the generation, conversion and storage technologies of PyPSA-Eur for electricity, hydrogen, methane, liquid fuels and heat, with the following settings.

- No imports of hydrogen, hydrogen-based carriers or solid biomass into Europe are allowed.
- Transmission grid expansion is limited to 1.5 times the current total volume (length times capacity) of all AC lines and DC links.
- No new nuclear capacity can be built.
- **Biomass potentials:** ENSPRESO database [16], low scenario (`ENS_Low`), reference year 2030, residual biomass only, without dedicated energy crops (for example miscanthus, switchgrass, willow, poplar, rapeseed and sugar beet) and without biomass imports.
- **Technology and fuel costs:** Investment costs, fixed and variable operating costs, efficiencies and lifetimes of all energy system technologies are taken from the PyPSA `technology-data` package, version 0.13.3, for the target year 2050, with a societal

discount rate of 2 % and a default discount rate of 7 % where no technology-specific rate is given. Fuel costs are given in Supplementary Table 2. Marginal costs of wind and solar generation are set to 0.01 to 0.015 €/MWh.

- **CO_2 storage:** Regional storage potentials from the CO_2StoP project (offshore only, conservative estimate). Storage capacity costs 87 €/t CO_2 per year, the upper end of the range of 40 to 87 €/t CO_2 estimated for offshore transport and storage in Germany in the initial deployment phase [**?**].

Supplementary Table 2 Fuel and feedstock costs for the target year 2050. Costs are taken from the PyPSA `technology-data` package, version 0.13.3, except for municipal solid waste, whose cost is set separately in the model. Costs refer to the thermal energy content of the fuel.

Carrier	Model name	Cost (€/MWh)
Biogas	`biogas`	62.4
Crude oil	`oil primary`	52.9
Fossil gas	`gas`	24.6
Nuclear fuel	`nuclear`	3.4
Solid biomass	`solid biomass`	13.6
Municipal solid waste	`municipal solid waste`	0.016

Data sources and assumptions

- **Industrial production routes.** Steel: scrap-based electric arc furnace (EAF), hydrogen-based direct reduction with EAF, blast furnace with basic oxygen furnace (with optional capture) and methane-based direct reduction with EAF. Cement: ordinary Portland cement (CEM I) and cements with clinker substitutes (CEM II variants), whose process heat demand, process emissions and raw material costs scale with the clinker content, and capture of process emissions. High-value chemicals (HVC): naphtha steam cracking, electrified steam cracking, methanol-to-olefins, and mechanical and chemical (pyrolysis-based) recycling.
- **Secondary materials.** Secondary steel is available at 31.23 Mt/a, calculated from the stock-flow model in the Supplementary Information of ref. [17].
- **Industrial material demand.** Production of steel, cement and HVC is taken from the AIDRES database and assigned to the nearest NUTS2 node. HVC demand is derived from the naphtha demand of the chemical sector divided by the specific naphtha demand per tonne of HVC from JRC-IDEES, and the remainder is treated as other chemicals. Refinery locations are also taken from the AIDRES database.
- **Industrial energy and process parameters.** Energy and feedstock intensities, process heat temperature levels, process costs and raw material prices for steel, cement and HVC are taken from JRC-IDEES, Fraunhofer ISI and the literature. A full overview of parameters and sources is given in ref. [18].
- **Plastic waste and recycling.** National plastic waste flows are based on the PlasticsEurope circular economy report [19]. Of the 5.419 Mt/a of post-consumer

plastic waste collected and sorted, 3.68 Mt/a are available for chemical recycling, comprising waste currently sent to energy recovery or landfill and process losses from mechanical recycling. A further 1.05 Mt/a of recycled plastic is represented as mechanically recycled HVC. These quantities are kept constant until 2050, without improvements in collection or recycling rates. Material yields, waste input and electricity demand of mechanical and pyrolysis-based chemical recycling are taken from the Supplementary Information of ref. [20]. Investment costs for mechanical recycling are calculated from the recycling facilities reported in ref. [21], and the investment cost and 20-year lifetime of the pyrolysis plant are taken from ref. [22]. The investment cost of chemical recycling also includes the downstream electric steam cracker [23].

- **Other demand.** Apart from steel, cement and HVC, the remaining industrial subsectors, buildings, transport and other demand enter the model as exogenous demand time series for electricity, hydrogen, methane and process heat derived from JRC-IDEES.
- **Storage potentials.** The conservative CO_2StoP estimate allows about 2 Gt CO_2 of offshore storage in Germany over 25 years and about 60 Gt CO_2 in Europe. For Germany, this value lies between the technical potential of about 6.5 Gt CO_2 and the prudent offshore potential of about 1 Gt CO_2 estimated by Gidden et al. [24], which additionally excludes areas for environmental, seismic and population-related risks. Under such a precautionary limit, German storage would constrain the technology-open case more strongly than the conditional case. For Europe, Gidden et al. estimate a prudent potential of 39 Gt CO_2, of which 22.5 Gt CO_2 lie in basins with existing oil and gas infrastructure (Supplementary Table 5 in ref. [24]).

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