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Emissions and system-level decarbonization pathways for global petrochemical production

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The petrochemical industry is responsible for 13% of global industrial and 3.5% of total greenhouse gas emissions, yet a globally consistent facility-level emissions inventory is lacking. Here we present a bottom-up assessment of historical, current and prospective emissions from 37,379 production facilities, covering 81 chemicals and 2,043 manufacturing processes. We estimate that petrochemical production emitted 2.0 ± 0.8 $GtCO_2e$ in 2023 and this could increase to 3.0 ± 1.2 $GtCO_2e$ by 2050 under a business-as-usual scenario. Emissions are highly concentrated, with 53% of 2023 emissions arising from 10% of facilities. Among primary chemicals, ethylene and ammonia were the largest emitters, at 290 ± 50 and 250 ± 50 $MtCO_2e$, respectively, in 2023. Our scenario analysis indicates that decarbonization efforts should prioritize the highest-emitting facilities through efficiency improvements, alternative fuels and feedstocks, alongside broad demand reduction and power grid decarbonization. The analysis provides insights for industry, researchers and policymakers to target effective decarbonization in the petrochemical sector.

Petrochemicals production has surged by 500% since 1980 to nearly one billion tonnes per year, driven by increased demand for chemical products[1]. The industry accounts for 30% of industrial energy use, 14% of global oil demand and 9% of natural gas demand[2,3]; in 2017, chemicals and their derivatives contributed over 7% to global GDP, amounting to US$5.7 trillion[4]. Plastics alone account for 420 Mt, while the remaining production consists of nitrogen fertilizers, fibres, rubbers, solvents, additives and explosives. These products are derived from eight main primary chemicals: ammonia, methanol, ethylene, propylene, butadiene, benzene, toluene and xylenes. The International Energy Agency (IEA) projects the production of primary chemicals will increase from 680 Mt in 2020 to 971 Mt in 2050, a compound annual growth rate of 1.3%[5,6].

At a moment when humanity has exceeded at least six out of the nine planetary boundaries[7], continued growth in petrochemical production, use and disposal risks exacerbating multiple environmental and human health pressures. For example, expansion of hydraulic fracturing to supply petrochemical feedstocks places additional demands on water and sand resources and contributes to habitat fragmentation[8–10]. Communities living near petrochemical production facilities may experience elevated cancer risks[11], while exposure to certain petrochemically derived chemicals has been

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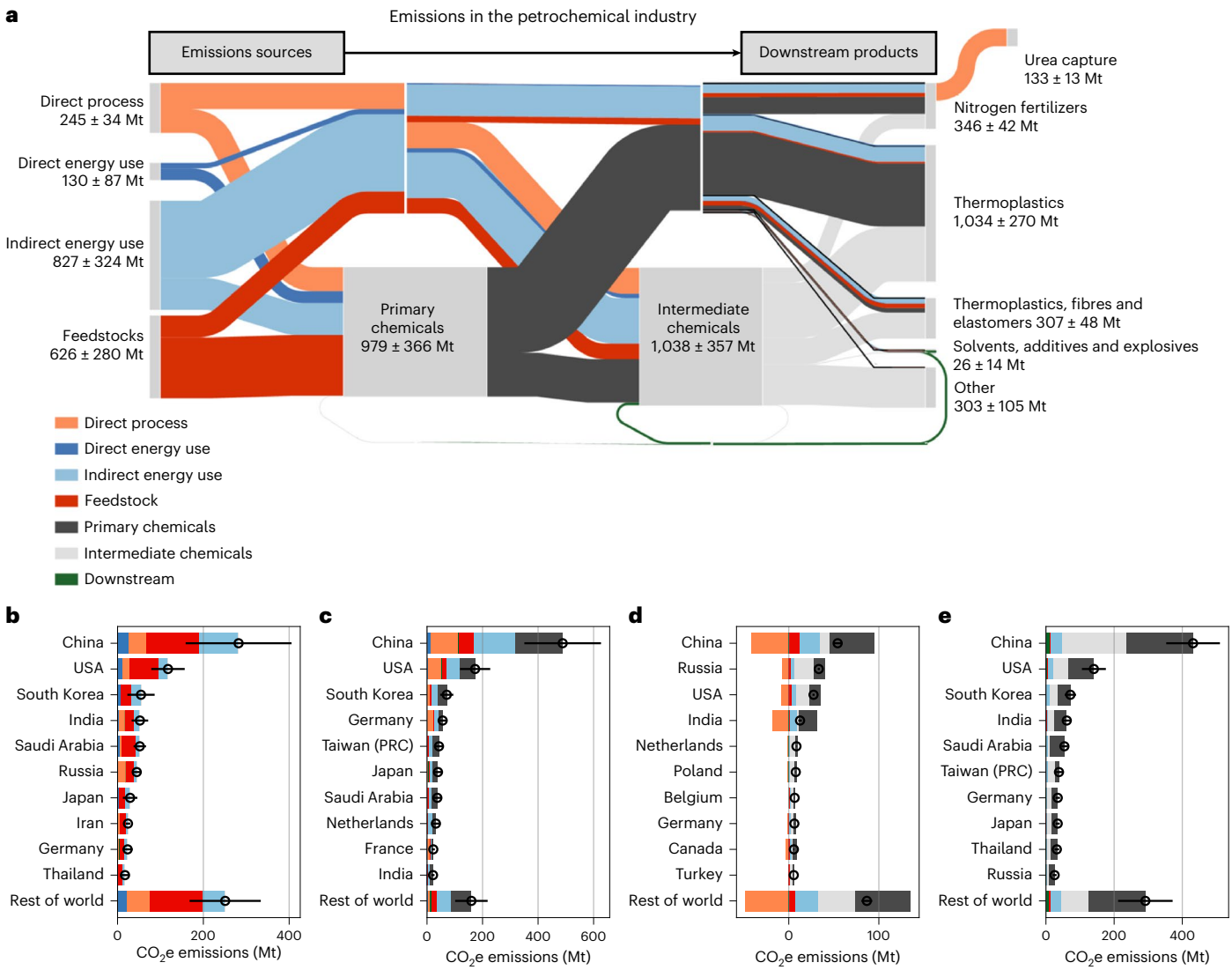

Fig. 1 | Global allocation of production of GHG emissions between product groups in 2020. a, Sankey diagram of production emissions in $MtCO_2e$, showing the flow of embodied emissions from primary to intermediate and downstream chemical products. The diagram represents emission burdens transferred between conversion stages, not carbon content in products. **b**–**e**, Top five emitting countries/regions per product group: primary chemicals (**b**), intermediate chemicals (**c**), fertilizers (**d**), thermoplastics (**e**). Error bars indicate the 95% confidence intervals as described in the Methods.

linked to endocrine disruption[12]. Plastic waste and microplastics are now pervasive throughout terrestrial and marine ecosystems, with documented impacts on food webs and increasing evidence of human exposure[13,14]. That being said, petrochemicals are used throughout modern industrial society and many applications currently lack readily deployable substitutes.

Given these broader environmental and societal impacts, we will focus on the potential impacts of petrochemical production on global greenhouse gas (GHG) emissions. Primary chemical production alone was responsible for about 925 $MtCO_2e$, or 13%, of global industrial GHG emissions in 2021[2,3]. Unlike other emissions-intensive industries, decarbonizing petrochemical production is challenged by fossil feedstock use, process emissions from chemical reactions, high degrees of process integration, slow infrastructure turnover (many decades), and a lack of commercialized alternatives for high-temperature heat processes.

Emissions associated with a given facility can be split between direct and indirect emissions. Direct emissions include on-site fuel combustion (direct energy use) and chemical reaction emissions (direct process). Indirect emissions include upstream extraction and processing emissions (feedstock) and upstream primary energy source combustion (indirect energy use). These emissions are calculated for each product, where emissions from upstream chemical feedstocks are denoted as embodied emissions. Together, these direct and indirect emissions constitute a cradle (upstream processing)-to-gate (finished chemical product) perspective. For a per-product view we can also include the embodied emissions of primary and intermediate chemicals (double counting upstream sources). This breakdown is illustrated in Fig. 1.

Decarbonizing petrochemical production requires a multifaceted approach, including: energy-efficiency improvements[15,16], use of alternative carbon feedstocks such as biobased materials and captured CO_2 (ref. 17), carbon-capture technologies[2,18,19], and switching to clean fuels for process heat, including electricity[20–24]. Existing reports provide some insights into reducing direct CO_2 emissions[3,6,25], but are mostly limited to specific developed countries and lack detail in distinguishing between emissions sources. The primary repository for global petrochemical emissions is the United Nations Framework Convention on Climate Change (UNFCCC) GHG database[26], which relies on self-reporting from country databases (for example,

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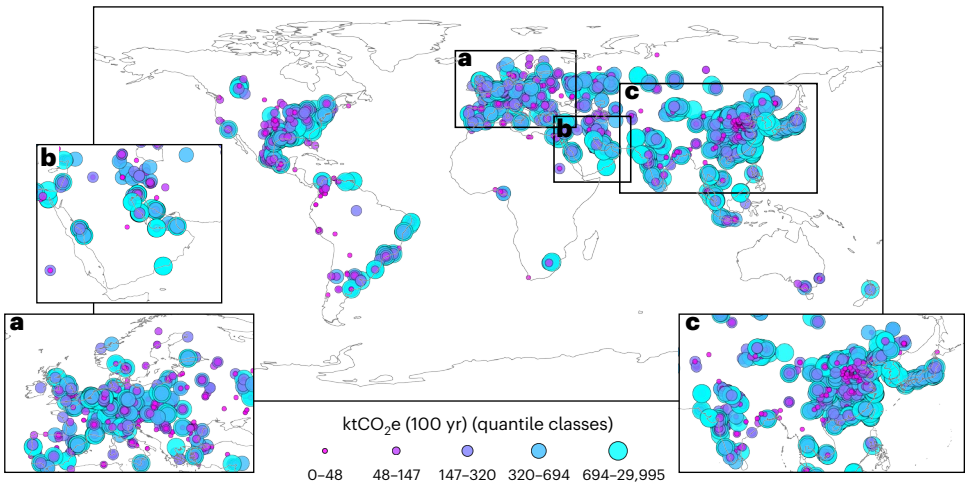

Fig. 2 | World map of carbon emissions from global petrochemical facilities in 2020. a, Europe. **b**, The Middle East. **c**, India and East Asia. Basemap from Natural Earth (https://www.naturalearthdata.com).

United States[27]); however, this approach leads to internal inconsistencies and offers limited breakdowns of emissions data (D. Malkowska et al., unpublished observations).

Actionable insights to decarbonize petrochemical production require more granular emissions estimates. Disaggregating emissions by product and process improves clarity on end-use markets, enabling accurate impact assessments of demand shifts. Country-level emissions coverage reveals equity issues and prioritizes efforts for policy change. Facility-level emissions data provide specific actionable insights, such as prioritizing action for individual plants, which are not achievable with generic forecasts.

This study provides an unprecedented global facility-level resolution for 37,379 facilities worldwide (Fig. 2), with records of historical, present and anticipated direct and indirect GHG emissions from petrochemical production (see Supplementary Table 7 for detailed information on the data availability for each facility). The analysis integrates resource flows, production volumes, underlying reaction and thermodynamic principles, and quantified uncertainties. Using a bottom-up approach, the study calculates total GHG emissions intensities for the production of 81 large-volume chemicals by summing the relevant emissions from 2,043 chemical manufacturing processes from 1978 to 2020. The analysis is informed by the IHS PEP Yearbook, a long-running database that covers process technologies for chemical production[28,29]. Production statistics are sourced from the Independent Commodity Intelligence Services (ICIS) Supply and Demand database, the International Fertilizer Association (IFA), and the Food and Agriculture Organization (FAO)[1,30,31]. Various emissions scenarios, from 2021 to 2050, are based on a mix of capacity and production projections from ICIS, IFA and FAO[1,30,31], and country-level electricity carbon intensity projections from the IEA[32]. Our more granular study helps to identify the most emission-intensive facilities, products, processes, materials, regions and production stages[33]. This will assist industry, researchers and policy interest groups in developing effective emission-reduction strategies. The complete analysis results are accessible via an interactive dashboard[34].

Results

Enabled by the product-, process-, and facility-level granularity of this study, this section presents the breakdown of emissions from petrochemical production emissions in 2020 and evaluates decarbonization pathways to 2050. The petrochemical industry converts hydrocarbon feedstocks into primary and intermediate chemicals, which are then used to produce downstream derivative products (Supplementary Information, section 1). Figure 1 shows how embodied emissions flow through this production network.

Global scale and composition of petrochemical emissions

The model estimates that the total cradle-to-gate GHG emissions of the global petrochemical industry were 1.8 ± 0.7 $GtCO_2e$ per annum in 2020 (the last year for which data are available), which is used as the reference year in this study. Figure 3 details the breakdown of emissions and shows the uneven spread across regions, products, emission sources and gases. China is currently the largest emitter, contributing 37% of the global total in 2020 (660 ± 260 $MtCO_2e$).

Most emissions from the sector are indirect, with 45% from indirect energy use (820 ± 320 $MtCO_2e$) and 34% from feedstock extraction and processing (620 ± 280 $MtCO_2e$). Globally, thermoplastics account for 75% of indirect emissions (1.3 ± 0.3 $GtCO_2e$) due to their common incineration. Carbon dioxide accounts for 74% (1.3 ± 0.7 $GtCO_2e$) of GHG emissions impact in the chemical industry over a 100-year time horizon. Methane (CH_4) and dinitrogen monoxide (N_2O or nitrous oxide) contribute 15% (0.3 ± 0.1 $GtCO_2e$) and 11% (0.19 ± 0.02 $GtCO_2e$), respectively. These gases are released in lower volumes than CO_2, but have much stronger global warming potentials, meaning their climate change contribution is still substantial. Over a 20-year time horizon, methane emissions are particularly impactful, responsible for 33% of global warming potential (0.8 ± 0.3 $GtCO_2e$).

The IEA estimated 'direct emissions' from the petrochemical industry in 2020 to have been 1.3 $GtCO_2e$, which excludes upstream electricity production[35]. As a comparison, our 2020 estimate excluding electricity is 1.6 ± 0.6 $GtCO_2e$. Despite a different methodology, the IEA's calculated value is within the uncertainty bounds of this study. Without a statement of their uncertainties, a direct comparison is challenging.

Extended Data Fig. 1 compares the granular coverage and breakdown of petrochemical emissions in this study with the more aggregated data from the UNFCCC. For Annex I parties after 2010, the total emissions from this study and the UNFCCC reports largely agree, but the UNFCCC data have detailed breakdowns for only a quarter of the countries and categories covered by this study. For non-Annex I countries, which include China, Saudi Arabia and India, the UNFCCC data are extremely incomplete, with at most 25% of petrochemical emissions accounted for and no breakdown provided.

Figure 3 shows that large uncertainties exist based on the facility-level analysis. Although our database lists 37,379 facilities,

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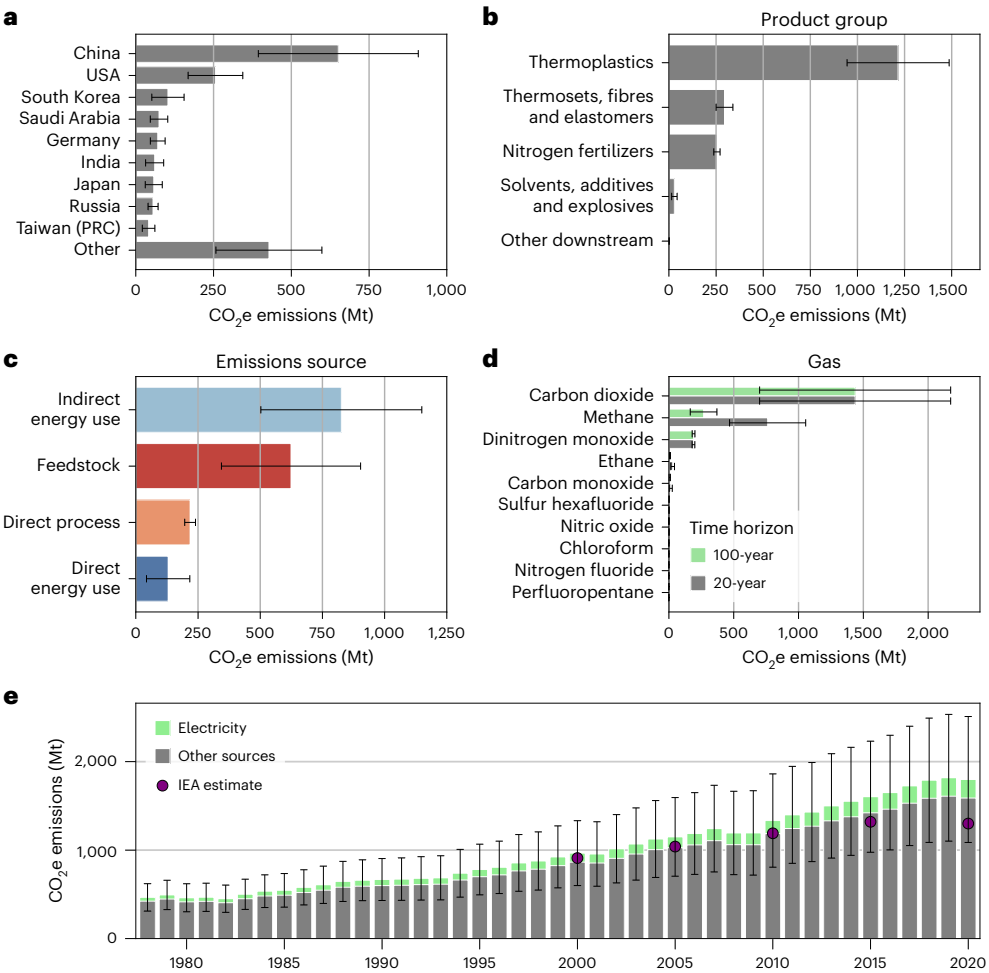

Fig. 3 | GHG emissions due to the production of downstream petrochemical products calculated across five dimensions. a–e, Emissions are calculated for regions (**a**), products (**b**), emissions sources (**c**), gas type (**d**) and year (**e**). Emissions associated with a given facility are split between direct and indirect emissions. Direct emissions include on-site fuel combustion (direct energy use) and chemical reaction emissions (direct process). Indirect emissions include upstream extraction and processing emissions (feedstock) and upstream primary energy source combustion (indirect energy use). Errors represent the propagated uncertainty estimates in the underlying data. CO_2e emission values are based on the IPCC AR5 global warming potential in 100 years[57], except for where 20 years is stated in **d**; error bars indicate 95% confidence intervals as described in the Methods. **a–d** are a snapshot of industry total emissions for the year 2020. **e** shows historical emissions calculated in this study and IEA estimated values for comparison. We include our value excluding electricity for comparison purposes with the IEA. See Supplementary Section 2.1 for product group definitions. An interactive dashboard detailing the full results of the study can be accessed via https://www.c-thru.org/emissions-dashboard[34].

publicly available information rarely specifies the exact manufacturing process used at each site and many facilities lack production data. Because many chemicals can be produced via multiple alternative processes, we can narrow down but cannot uniquely assign a specific process to each facility, as discussed in ref. 36.

Emissions are concentrated across countries, products and facilities

Extended Data Fig. 2 shows GHG emissions from petrochemical production across different countries between 1978 and 2050 and compares this trend with production mass and average emissions factors. The top nine countries emitted 63% of emissions in 1990, 76% in 2020 and 79% by 2050. This represents a great opportunity for policymakers, such as those within the UNFCCC, to target substantial emissions reductions with agreement from just a few countries. Under the base-case scenario, China, the United States and India together account for 63% of global production emissions in 2050.

Figure 1a shows that 83% (1.6 ± 0.5 $GtCO_2e$) of emissions attributed to downstream products are embodied emissions from upstream primary and intermediate chemical production. These values represent upstream process emissions allocated to downstream outputs based on material flows. This highlights that decarbonizing primary and intermediate chemical production should be the priority for reducing the overall carbon footprint of petrochemical products. Extended Data Fig. 3 shows the impact of individual primary chemicals.

Figure 1b–e shows that China dominates production emissions across all product groups. For methanol, China accounts for 65% ± 16% of emissions. Of these emissions, the majority (62% ± 12%) are concentrated in a single facility. Although if China and the United States were to adapt their policies, this could achieve large-scale emissions reduction across most product groups, fertilizer production will likely require broader international collaboration, particularly with Russia.

Reducing emissions from each source implies implementing changes at individual facilities. Figure 4 emphasizes the concentration of emissions among a subset of all facilities, with 10% of facilities responsible for 53% of emissions on a cradle-to-gate basis. Figure 2 shows the spatial breakdown of emissions associated with each facility in this analysis.

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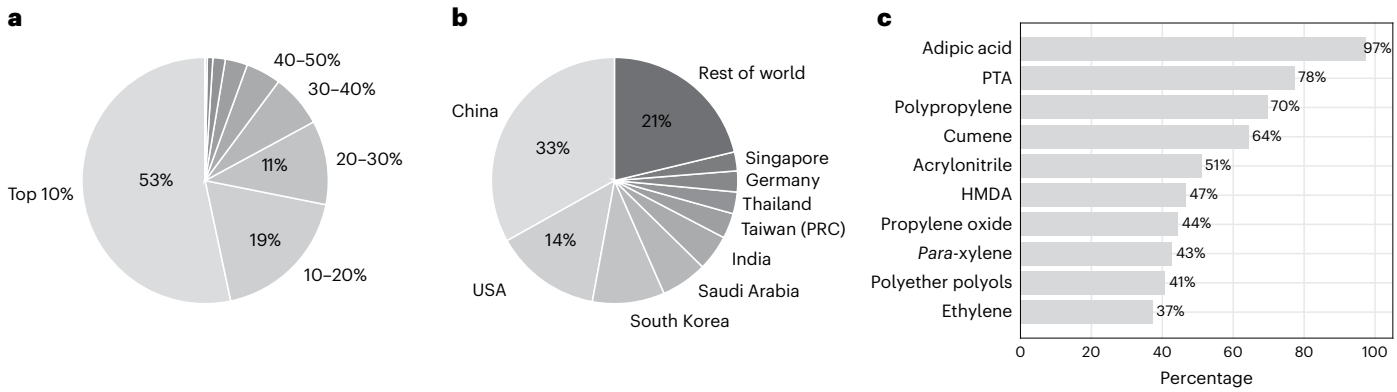

Fig. 4 | Concentration of emissions among facilities. a, The concentration of emissions, showing that 53% of emissions come from just 10% of facilities. **b**, The top 10% of emitting facilities by country/region. **c**, The percentage of facilities that produce each product that are included in the top 10% of emitters. PTA, purified terephthalic acid; HMDA, hexamethylenediamine.

Combined and prioritized decarbonization pathways to 2050

Under the business-as-usual scenario, global petrochemical production emissions increase to 2.3 ± 1.0 $GtCO_2e$ in 2030 and 3.0 ± 1.2 $GtCO_2e$ per annum in 2050. Extended Data Fig. 4 shows that these estimates are higher than the IEA forecasts[6].

Figure 5 compares pathways combining electricity-grid decarbonization, carbon capture and storage (CCS), feedstock substitution, and other mitigation measures. In all scenarios, multiple levers are required to reduce emissions. However, even under the highly optimistic scenario 2, which applies the IEA Sustainable Development Scenario for electricity generation, assumes complete deployment of CCS at eligible facilities, and assumes sufficient biobased feedstocks to replace fossil feedstocks, residual emissions remain in 2050.

The alternative scenarios presented in Extended Data Fig. 5 show that the effect of electrification depends strongly on the carbon intensity of electricity generation. Electrification reduces emissions after substantial grid decarbonization but can increase near-term emissions when deployed in regions with carbon-intensive electricity systems. The scenarios also show that demand reduction delivers larger emissions reductions than any single supply-side measure.

The impact of decarbonization solutions is modelled using an S-curve, as described in the Methods. Facility-level granularity allows roll-out to be modelled by facility rather than by aggregate emissions alone. The large disparity in emissions between facilities shown in Fig. 4 means that a prioritized roll-out can drastically accelerate industry decarbonization.

For example, 97% of adipic acid plants are within the top 10% of emitters. This is primarily due to the high N_2O emissions (190 ± 11 $MtCO_{2e}$ N_2O versus 15.6 ± 2.7 $MtCO_2$). Figure 5 shows the benefit of a prioritized roll-out versus an unprioritized roll-out for two decarbonization scenarios. Figure 5b,c shows that a prioritized approach could save 23 ± 3 $GtCO_2e$ by 2050 versus an unprioritized one. This advances the date at which emissions fall below 2020 levels from 2045 to 2025, providing an upper-bound scenario.

Discussion

Granular emissions data as a basis for targeted action

Accurate, granular emissions data are essential for identifying priority decarbonization targets in the chemical value chain. This study shows that a consistent, transparent methodology across production facilities can help accelerate progress towards net zero. Enhancing transparency over supply chains reveals opportunities to reduce emissions and collaborate with suppliers to implement sustainable practices; however, to reduce uncertainties and effectively track progress, reporting coverage and standards need to improve. Addressing emissions further upstream in the production process carries important implications for the industry. Prioritizing the most emissions-intensive facilities is crucial for rapid decarbonization. Despite the potential of electrification to mitigate emissions in the long term, premature implementation could exacerbate the issue, particularly in regions with high-emission-intensity grids.

Granular data can inform solutions for specific chemicals, emissions sources and facilities. For instance, our model indicates that the production of adipic acid is responsible for emitting 210 ± 14 $MtCO_2e$, primarily due to the direct release of N_2O during the manufacturing process. Leveraging existing catalysis techniques, such as metal and biological catalysts, could potentially reduce these emissions by approximately 90%[37,38]. Emissions are unequally distributed, with just 10% of facilities accounting for 53% of emissions. Prioritizing these facilities enables more effective decarbonization than a uniform approach.

Production-network integration constrains mitigation choices

The structure and integration of chemical production networks vary notably across primary chemicals: some facilities are highly integrated, as in the case of olefins and aromatics, which are precursors of thermoplastics, synthetic fibres, elastomers and various solvents, while others operate as standalone plants, such as ammonia and methanol. These differences strongly influence how readily plants can adapt to feedstock changes or pursue decarbonization strategies.

Olefins and aromatics are typically produced in integrated petrochemical complexes that share common feedstocks and utilities and produce many products. Olefins are derived primarily from the steam cracking of lighter hydrocarbons (for example, ethane and liquefied petroleum gas) and liquid petroleum fractions (for example, naphtha)[39]. During naphtha steam cracking, pyrolysis gasoline is formed and can be routed to an aromatics extraction unit. Hydrogen generated during catalytic reforming is also utilized in hydrocracking and hydrotreating processes[40]. These interlinked operations are optimized, making feedstock substitutions in one process difficult without inducing cascading impacts across others.

Unlike aromatics and olefins, ammonia and methanol are usually produced in standalone facilities. Ammonia production requires a source of hydrogen (commonly produced from steam methane reforming) for the Haber–Bosch process. Methanol routes vary widely, and we included 10 different routes in our analysis (Supplementary Table 2). The standalone nature of these plants makes them more amenable to disruptive feedstock transitions, such as the shift toward biomass gasification. Even the shift to autothermal methane reforming could be readily implemented and decrease emissions[41]. Additionally, there is important research in 'green' ammonia, which has the potential to use renewable energy to derive hydrogen via electrolysis.

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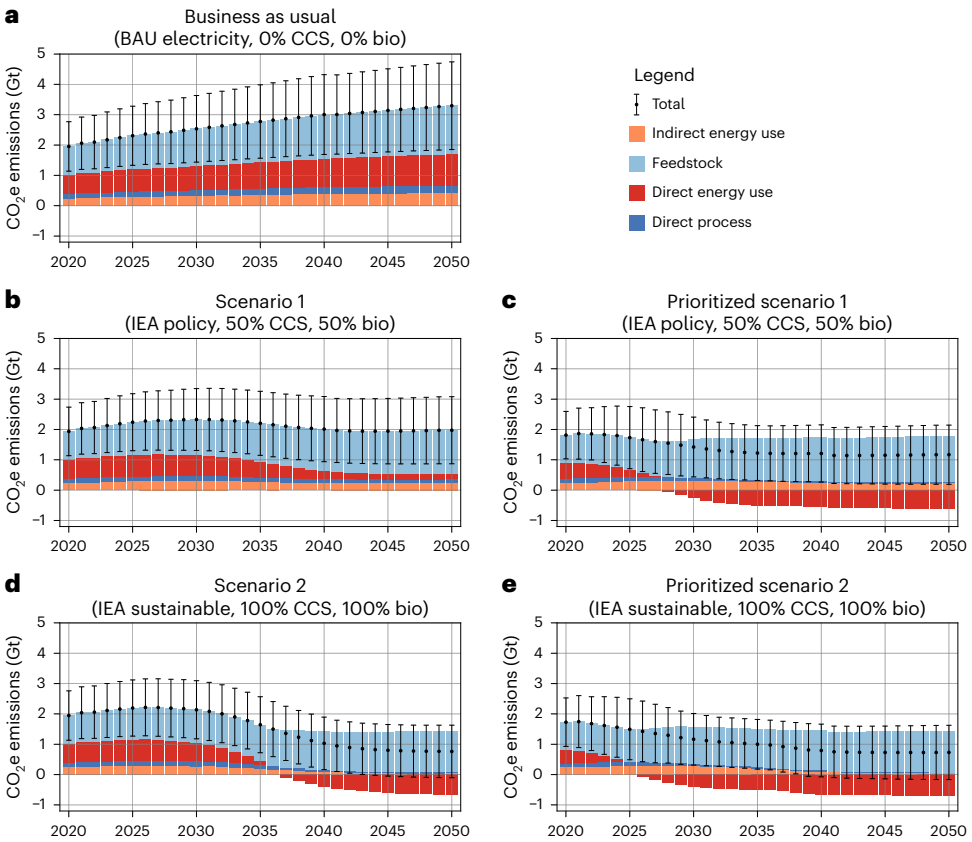

Fig. 5 | Future scenarios for petrochemical emissions from 2020 to 2050. **a**–**e**, The titles of each figure indicate the limits applied for roll-out by 2050: business as usual (BAU) (**a**), scenario 1 (**b**), prioritized scenario 1 (**c**), scenario 2 (**d**) and prioritized scenario 2 (**e**). Prioritized implies a prioritized facility roll-out, the alternative being a conventional scenario considering total emissions. The first term in parenthesis denotes the electricity scenario used. The second term in parenthesis denotes the level of carbon capture utilisation and storage (CCUS) achieved in 2050, here CCUS includes CCUS for direct energy use, CCUS for direct processes and N_2O abatement. The third term denotes the level of biofeedstocks achieved in 2050. Total emissions are presented as the mean with 95% confidence intervals as described in the Methods. Details for each scenario are provided in Extended Data Table 1.

Irrespective of feedstock integration, many chemical plants also integrate heat flows between unit processes for improved energy efficiencies at the plant level. For example, many chemical plants have complex heat networks that recover waste heat from some processes for use in other processes. Such heat integration can also make it difficult to upgrade one process unit without affecting others. For example, electrifying a combustion source in the interest of decarbonization will eliminate flue gas that may have been used to heat another process, triggering engineering changes to plant systems that may prove prohibitive. Furthermore, many chemical plants utilize combined heat and power systems for co-generation of heat and electricity, sometimes fuelled by feedstock by-products, which are expensive to replace with decarbonized options that would strand by-products and require extensive engineering changes in addition.

Among the eight major primary chemicals considered (Supplementary Fig. 30), ammonia and ethylene had comparable emissions in 2020, at 260 ± 50 $MtCO_2e$. However, their different production structures mean that similar emissions totals do not imply similar mitigation pathways. These process-level differences demonstrate why decarbonization measures cannot be applied uniformly across chemicals or facilities.

No single lever can deliver net-zero petrochemicals

In all scenarios considered in this study, a combination of the available levers is necessary for decarbonization. However, even under the highly optimistic scenario 2, which uses the IEA's Sustainable Development Scenario for electricity, assumes 100% roll-out of CCS and assumes sufficient biofeedstocks to replace all fossil feedstocks[42], emissions do not reach net zero by 2050. Extended Data Fig. 5 presents alternative scenarios showing that electrification may be viable in the long term once the electricity grid is decarbonized but, in the short term, could drastically increase emissions. These scenarios also indicate that demand reduction could be the most effective lever for achieving substantial emissions reductions.

Neither carbon capture nor alternative feedstocks are a silver bullet solution. From a technical perspective, CCS may be easier to implement than feedstock substitution because it requires fewer modifications to existing process pathways in a capital-intensive industry. However, geological storage requires suitable formations[43], and although many petrochemical facilities are located in oil- and gas-producing regions with such potential, major investments in transport and pipeline infrastructure would still be needed[44].

CCS primarily addresses direct process emissions. Urea is produced through the Bosch–Meiser process, which requires CO_2 at a stoichiometric ratio of 1 mole of CO_2 per mole of urea, thereby consuming a substantial share of the direct process CO_2 generated by ammonia production. The CO_2 utilized is usually generated on-site in ammonia plants from the water–gas shift reaction. Only the remaining direct emissions are therefore potentially available for geological storage. The amount of CCS required in the 100% scenario plateaus at 20 $MtCO_2$ per year by 2050. While this is consistent with projections of total global CCS capacity (1–16 $GtCO_2$ per year by 2050)[45], there remains considerable uncertainty, particularly given the approximately 80% failure rate of proposed projects[46].

Renewable carbon could contribute to chemical-sector decarbonization, particularly because upstream feedstock production is responsible for 34% of production emissions and the sector remains structurally dependent on carbon-containing feedstocks. Substituting conventional fossil feedstocks with renewable carbon sources could enable the use of biogenic carbon in chemical synthesis and, under favourable conditions, potentially deliver net-negative GHG emissions[2]. The use of limited biomass resources in long-lived or high-value chemicals may also create greater value per unit of biomass than their use as an energy source[47]. However, biobased feedstocks cannot be scaled to replace all fossil feedstocks without substantial ecological externalities.

However, biobased feedstocks cannot be scaled to replace all fossil feedstocks without substantial ecological and social consequences. Large industrial monocultures required for biomass feedstocks may contribute to biodiversity loss through habitat destruction and carbon emissions from land-use change, while increasing competition for land used to grow food[48]. Additionally, intensive agriculture can lead to soil depletion and water pollution through run-off from synthetic fertilizers[49,50]. Renewable carbon should therefore be deployed selectively in applications where carbon is required as a molecular feedstock and where its use provides the greatest climate and resource benefits.

Feedstock substitution must also account for the complex networks of co-products and interdependent production processes within the chemical sector. For instance, about 95% of butadiene is currently produced as a by-product of the steam cracking of naphtha to produce ethylene. The increased use of lighter gas feedstocks in US steam crackers and the adoption of methanol-to-olefins processes in China have reduced butadiene yields from existing production routes, even as global demand and production have continued to grow, driven predominantly by capacity expansion in China (Supplementary Fig. 27). Therefore, selective on-purpose butadiene production routes based on renewable feedstocks and decarbonized energy sources may be required[45]. Similar interdependencies occur throughout the sector and must be explicitly represented when assessing alternative feedstocks and future production pathways.

Electrification has an important role, but its feasibility depends strongly on process temperature. Low- and medium-temperature steam may be supplied by electrode boilers or high-temperature heat pumps with limited disruption, whereas high-temperature processes such as cracking may require major retrofits. Plants with combined heat and power systems are especially challenging because heat and power generation are coupled and often rely on by-product gases.

Mitigation measures may also extend to the substitution of downstream products. For instance, adipic acid is used mainly to produce nylon 6,6. In many applications, this material could be replaced by nylon 6, whose precursor caprolactam produces only about one-quarter of the N_2O emissions of adipic acid and can approach zero in the most advanced facilities[41,51]. Nylon 6 is also better suited to chemical recycling. However, such substitution would require broader changes in polymer specification and monomer supply chains.

Although CCS, electrification, feedstock substitution and process-specific abatement can all contribute to emissions reductions, none fully addresses the indirect emissions that dominate the sector's footprint. Demand reduction must therefore form an integral part of any credible pathway to net-zero petrochemicals.

Coordinating actions across value chains and regions

The concentration of chemical production emissions in the top-producing countries presents an opportunity for policymakers to target substantial emissions reductions with the cooperation of just a few key nations, especially China, the United States and India. It is important to note that this analysis does not consider the consumption side of petrochemical products, which often do not align with production patterns due to substantial imports from wealthier nations. The responsibility of emissions linked to products consumed by wealthier countries must be considered for equitable decarbonization. In addition to the upstream production emissions quantified here, downstream emissions related to chemical products, especially nitrogen fertilizers[52] and plastics[53], have increasingly become a challenge for the sector's low-carbon transition. The analysis presented here is a step towards a more granular understanding of chemical production in global energy and emission models. Future research can build on this to study the entire lifecycles of chemicals, including the impact of emissions on the use phase and end-of-life treatment. It will be important also to consider the non-climate environmental challenges associated with these downstream products, such as the health impacts of microplastic accumulation in food webs.

Coordinated efforts across both the chemical and energy sectors are required for any large emissions reduction by 2050. This entails supply-side decarbonization through a combination of efficiency enhancements, alternative feedstock utilization and carbon-capture technologies. Simultaneously, demand-side changes and policy measures promoting clean investments and international cooperation are essential. Further exploration at regional or individual plant levels can refine strategies customized to specific local contexts, including plant technologies, plant ages and the availability of renewable energy or raw materials. This can facilitate the swift implementation of the significant transformations necessary to meet ambitious mitigation targets and prevent increased GHG emissions beyond 2050.

Implications and future research

This analysis focuses on cradle-to-gate emissions from chemical production and does not quantify emissions occurring during product use or end-of-life treatment. These downstream stages are particularly important for nitrogen fertilizers and plastics, whose use and disposal can generate substantial additional GHG emissions[43,45]. Future research should connect the facility-level production model developed here with product stocks, international trade, consumption patterns and end-of-life pathways to evaluate the full lifecycle impacts of petrochemical products.

The study also focuses on climate impacts and does not quantify other environmental and health consequences, including toxicity, nutrient pollution, water use, biodiversity impacts and exposure to microplastics. Incorporating these indicators will be important because some climate-mitigation measures may shift burdens between environmental categories.

Further regional and facility-level analysis is also required to evaluate implementation constraints, including plant age, process configuration, heat integration, electricity-grid intensity, access to renewable resources, carbon-transport infrastructure and geological storage availability. Better disclosure of facility production volumes and technology routes would reduce uncertainty and enable the model to be updated as technologies and production networks evolve.

These extensions have the potential to support the development of transition pathways tailored to specific chemicals, facilities and regional conditions, while helping to identify where coordinated supply-side investment and demand-side intervention can deliver the fastest and most durable emissions reductions.

Methods

We develop a chemical-process-based emission assessment model on a cradle-to-gate basis to account for GHG emissions at each stage of chemical production from 1978 to 2020 in a similar way to that used in ref. 36. Our model ensures mass balance across chemical production processes and considers the variability in production quantity, feedstocks and process technologies used, to account for emissions at a facility (production pathway) scale. To calculate GHG emissions, we multiply the production mass for each facility ('Facility-level production estimation'), with the appropriate GHG emissions factors

('Facility-level emission intensity factor estimation'). The resulting emissions can be projected forward to 2050 using ICIS forecasts for petrochemical production capacities in the future[1], and estimated for different decarbonization strategies applied to production facilities ('Future projections and scenarios'). Our totals can also be compared with other emissions reporting databases, including the UNFCCC database ('Comparisons to other datasets'). Supplementary Fig. 1 shows a summary flowchart of our calculation methods. To validate the findings of this study, uncertainties were explicitly handled and propagated through the calculations. We define uncertainty hereinafter as the 95% confidence interval based on a normal distribution.

Facility-level production estimation

Production mass data for 81 large-volume chemicals and fertilizers are obtained from ICIS[1] and IFA[30] datasets from 1978 to 2020. Capacity data for 37,379 individual petrochemical manufacturing facilities are extracted from the ICIS Supply and Demand database[1]. The production data are broken down into product and type of technology (for example, naphtha steam cracking for ethylene). To attribute these data to individual facilities, an equal capacity-to-production ratio is assumed per country, product and technology type, as illustrated in Supplementary Section 2.2. Given that within a country emissions intensities from plants with the same technology will be very similar due to sharing an electricity grid and supply of feedstocks, this is a reasonable assumption and will not affect the results when facilities are aggregated.

Uncertainties in facility capacity and regional production are not explicitly stated in the data sources, but ICIS methodology states that uncertainties can be up to 10% for facility capacity[1]. In line with previous carbon budget studies and the Intergovernmental Panel on Climate Change (IPCC) guidelines for activity data, which suggest a 7% uncertainty[54,55], we define an uncertainty of 10% from the combination of facility capacity and regional production data.

Facility-level emission intensity factor estimation

To calculate the facility-level GHG emissions intensity factor (EF), we use two steps: calculating the EF associated with each of the 2,043 processes considered broken down into emissions sources; and assigning the appropriate EFs to each facility based on the information available about the technology used in the ICIS database[1]. The four emissions sources are defined as follows: upstream raw material extraction and processing, including fugitive emissions (feedstocks); upstream energy conversion for electricity and supply of utilities (indirect energy use); on-site combustion of fuels (direct energy use); direct process emissions resulting from chemical reactions (direct process). Note that upstream emissions are all emissions associated with feedstocks regardless of the physical location of the processing (off- or on-site). In the chemical industry, primary and intermediate chemicals are often used as feedstocks for other chemicals[56]. To avoid double counting, these inputs will not be considered as feedstocks but as 'primary chemicals' and 'intermediate chemicals'. These two categories will be counted if considering the cradle-to-gate emissions of an individual chemical but will be excluded when considering overall total emissions. Beyond production, emissions are released from the use phase of some petrochemicals (for example, application of fertilizers) and end-of-life product treatment (for example, incineration); these are excluded from the study.

Emission intensity factors are estimated for 2,043 chemical production processes and petrochemical production technologies, using the input/output process recipes in the IHS PEP Yearbook[28]. The IHS database contains process simulations and datasets that have been verified by industrial experts, which serve as the mass and energy balance data for this lifecycle modelling. From the outputs, CO_2e, global warming potentials are calculated following the 20-year and 100-year horizons published by the IPCC[57]. The overall EF for an individual process is calculated as an addition of the four lifecycle stages following equation (1).

$$\begin{aligned}\mathrm{EF}_{\mathrm{process}} = \mathrm{EF}_{\mathrm{feedstocks}} + \mathrm{EF}_{\mathrm{direct\ process}} \\ +\mathrm{EF}_{\mathrm{direct\ energy\ use}} + \mathrm{EF}_{\mathrm{indirect\ energy\ use}}\end{aligned} \quad (1)$$

The EFs of each lifecycle stage are calculated as follows.

'Feedstock' emissions, defined in equation (2) for the number F of feedstocks, originate from the sum of GHG emissions embedded in the supply chains of each feedstock used for a particular process. This is dependent on the EF of each feedstock, specific to the region of use extracted from ecoinvent 3.10[58], the quantity Q of each feedstock used according to the IHS process recipes and the total mass m_{product} of all output products produced following the recipe, typically 1 kg. In most cases, uncertainty is unspecified from ecoinvent and in that case, an uncertainty of 10% is attributed to feedstock EFs. IHS process recipes are subject to up to 5% uncertainty[59] which is used for Q.

$$\mathrm{EF}_{\mathrm{feedstocks}} = \sum_{f=1}^{F} \frac{\mathrm{EF}_f \times Q_f}{m_{\mathrm{product}}} \quad (2)$$

'Direct process' emissions originate from the chemical reactions involved in production. Stoichiometric ratios C, based on equations obtained from the IPCC[55] and process reactions from Levi and Cullen[56], determine the output quantity of GHG molecules released from a reaction compared to the output quantity of the desired atoms used in a process's products (for example, carbon, mitrogen). This assumes CO_2 is completely oxidized and that all nitrogen is emitted as NO_2. Data on other potential GHG emissions (methane) are not available and are assumed to be negligible. In equation (3), the stoichiometric ratio is $C = M_{\mathrm{GHG}}/M_{\mathrm{product}}$, where M defines the molecular mass and m_{input} is the mass of feedstock. Chemical reactions are well understood and combustion is optimized in industry, but 1% uncertainty in output values is considered to account for incomplete combustion in line with Levi and Cullen[56].

$$\mathrm{EF}_{\mathrm{direct\ process}} = \frac{m_{\mathrm{input}}}{m_{\mathrm{product}}} C \quad (3)$$

'Direct energy use' represents any CO_2e that originates from the on-site combustion of fuels to generate heat, or conversely any heat energy exported from exothermic processes. This is calculated as the sum of combustion emission factors, sourced from the IPCC and US Department of Energy[60,61] with uncertainties, for each energy source e multiplied by the consumption Q defined in units of energy calculated based on the mass inputs of fuels in the IHS process recipes[59].

$$\mathrm{EF}_{\mathrm{direct\ energy\ use}} = \sum_{e=1}^{E} \frac{EF_e \times Q_e}{m_{\mathrm{product}}} \quad (4)$$

The 'indirect energy use' contribution is calculated in a similar way to direct energy use, except here the energy source e, including electricity used on-site, is supplied from offsite power. EFs depend on regional energy mixes accounted for by using the CO_2e coefficients from ecoinvent 3.10[58] with uncertainties for feedstock EFs.

$$\mathrm{EF}_{\mathrm{indirect\ energy\ use}} = \sum_{e=1}^{E} \frac{\mathrm{EF}_e \times Q_e}{m_{\mathrm{product}}} \quad (5)$$

Chemical production processes often yield co-products alongside the product under consideration. To avoid double counting of emissions, total process emissions are allocated between co-products. In this study, we use mass allocation where the emissions are allocated to each product proportionally to their mass, relative to the entire mass of co-products. We choose mass allocation because we have the most

complete data for mass but this choice does not have an important effect on the results according to Cullen et al.[62]. Equation (6) defines the EF of each co-product c following allocation from the process EF calculated according to equation (1).

$$\mathrm{EF}_{\mathrm{co-product}} = \frac{m_c}{\sum_{c=1}^{C} m_c}\mathrm{EF}_{\mathrm{process}} \quad (6)$$

At this point we have an EF broken down into emissions sources for each of the 2,043 processes considered and for each country. These EFs incorporate the technology configuration available at the time the underlying data were reported: for most major processes, historical datasets specify when technologies such as feedstock changes or alternative pathways (for example, methanol to olefin) were adopted. This enables the process 'recipe' to reflect efficiency improvements and technological evolution over time. For countries or chemicals for which historical data are less granular, the best available EF is applied and assumed to remain constant over periods lacking additional information. Supplementary Fig. 29 illustrates an example of how carbon intensities evolve over time when sufficient data exist (ethylene production in China).

To be combined with production mass obtained above ('Facility-level production estimation'), the production of each product from each facility must be associated with one of these EFs. We implemented an automated algorithm matching each facility to the corresponding production processes based on its product, route and technology information from the ICIS database[1]. In instances when a unique match was not found, the mean EF of each possible corresponding process was taken. This lack of matching data is a significant source of uncertainty, which we explore further in Cullen et al.[36]. When a mean is taken, uncertainty is estimated as the standard deviation of process EFs excluding outliers beyond 3 s.d. from the mean. These outliers often represent unconventional processes not widely used outside of a laboratory environment and are therefore reasonable to exclude from the study. The result from the matching is an $\mathrm{EF}_{\mathrm{facility,co\text{-}product}}$ per emissions source.

In the exceptional case of ethylene production, additional feedstock ratio information from the ICIS database is used to reduce uncertainty by taking a weighted mean of possible processes. Processes p are grouped into their principal feedstock categories (for example, naphtha, methanol), and weighted according to the ratio r of each input feedstock category f, as shown in equation (7). In equation (7) EF_p is equivalent to the $\mathrm{EF}_{\mathrm{co\text{-}product}}$ corresponding to ethylene for each process from which ethylene is produced with feedstock f.

$$\mathrm{EF}_{\mathrm{facility,ethylene}} = \sum_{f=1}^{F}\left(r_f \times \frac{\sum_{p=1}^{P}\mathrm{EF}_p}{P}\right) \quad (7)$$

The output of equations (6) and (7) leads to individual cradle-to-gate emissions factors broken down into emissions sources and gases, for each product, for each year, from each facility. Given the production mass obtained above ('Facility-level production estimation') and the emissions factors for each facility and product, the corresponding GHG emissions can be simply calculated according to equation (8).

$$\mathrm{emissions}_{\mathrm{facility,product}} = m_{\mathrm{facility,production}} \times \mathrm{EF}_{\mathrm{facility,product}} \quad (8)$$

With emissions calculated for each facility, we can then aggregate to analyse trends across five dimensions: region, product, emissions source, gas and year. For aggregation into country emissions, we must consider the global nature of the petrochemical industry. Not all countries produce the primary and intermediate chemicals necessary for their downstream products, and therefore the trade of these products must be considered. This study does not explicitly map the trade of upstream chemicals but infers the import and export needs of each country based on the mismatch of the production mass of primary and intermediate chemicals with the input mass of these chemicals into downstream production. When input needs to downstream chemicals cannot be met by a country's production, imported primary or intermediate chemicals are assumed with EFs estimated as the global average for the product in question.

Future projections and scenarios

Given the methodology for estimating historical GHG emissions outlined above, we use forecasts of facility capacity and regional production from the ICIS database[1] and the FAO[31] to extrapolate our findings forward to 2050 in a business-as-usual scenario. Capacity forecasts from the ICIS database[1] rely on detailed knowledge of plans for the continuation, construction and decommissioning of production facilities, and on analysis interpreting future global petrochemical development[1]. The technology shift is reflected in the types of future plants that will exist but improvements in particular processes are not explicitly considered.

For the future decarbonization of the industry, this study identifies a set of mitigation options across the four main emissions sources.

In terms of feedstocks, the replacement of fossil-based hydrocarbons with biobased hydrocarbons, that is, extracted from plants, allows for a substantial reduction of emissions factors EF_f from equation (2). Emissions intensity factors from biobased feedstocks can be negative given the capture of CO_2 by plants. However, we should be cautious in viewing petrochemical feedstocks as a potential carbon sink because end-of-life treatment regularly involves incineration, which re-releases the captured carbon to the atmosphere. Conversion to biobased feedstocks is projected according to an S-curve implementation as defined in equation (9).

For direct process emissions, mitigation is achieved through the application of CCS and N_2O abatement. For chemical reactions emitting CO_2 the implementation of CCS can reduce emissions by up to 90% due to the efficiency of CCS methods[63,64]. This is in line with theoretically feasible capture rates and is perceived as a minimum to be considered 'abated'. Currently demonstrated capture rates are often lower (for example, 60%) because only process CO_2 is captured and not CO_2 in the flue gas created for heat and power production. For reactions emitting N_2O, primarily for producing adipic acid and nitric acid, catalysts can be used to abate the release of N_2O into the atmosphere with an efficiency of approximately 90%[65,66]. These two decarbonization solutions are jointly implemented in our scenarios with 90% efficiency according to the S-curve in equation (9).

Direct energy use emissions can be reduced via CCS applied to emissions from on-site fuel combustion. An alternative to reducing emissions from combustion is eliminating combustion by switching to electric methods of heating in the industry. To calculate the effect of electrification, we add the equivalent electricity to the energy supplied from the combustion of fuels. Emissions then depend on the EF_e of electricity in the country in question. The transition to electrified plants is implemented according to the S-curve in equation (9).

Finally, indirect energy use emissions are addressed through grid decarbonization. We use the IEA's policy and sustainable pathways for electricity emissions factors to 2050[32]. Additionally, to achieve a pathway to net zero it was necessary to implement an electricity decarbonization scenario that reaches a net-zero grid in 2050. This net-zero pathway has EF_e values from equation (5) reducing according to the S-curve defined in equation (9).

Typically, in scenario modelling, decarbonization options are rolled out based on gradually increasing the quantity of emissions covered by the solution. The granularity of this study allows us to base the roll-out of decarbonization solutions on the possibility of roll-out in the real world, which is done by facility. We will compare

the results from a typical 'emissions-based' scenario with the optimal 'facility-based' scenario, which assumes that facilities will be prioritized based on their impact on GHG emissions. Both these roll-outs follow an S-curve implementation rate. An S-curve is applied to estimate the growth of each technology given the end constraint set at 2050. The S-curve used, shown in equation (9), is initially designed for hydrogen production process ramp-up but is considered relevant in the context of scaling a process in the chemical industry[67].

$$x = \frac{1}{1 + e^{-b(y-M)}} \quad (9)$$

In equation (9), x is the penetration rate of the technology, y is the year from 0 to 30 in forecasting from 2020 to 2050, M is the mid-year of the forecast (set to 15), and b dictates the slope of the S-curve (set to 0.35). For the 'emissions-based' scenarios the penetration rate is applied to the total emissions. For 'facility-based' scenarios the penetration rate is applied to the number of facilities covered by the roll-out.

As an alternative solution to the supply-side options for decarbonization addressed above, this study also evaluates the impact of implementing a demand-side solution of reducing consumption by 50%. This reduction is also rolled out using the S-curve from equation (9).

Comparisons to other datasets

The IEA reports global estimates for 'direct' emissions from petrochemical production which do not include emissions from electricity generation[6]. These estimates can be directly compared to our cradle-to-gate values excluding the electricity share of emissions.

The UNFCCC emission data comprise anthropogenic emissions from sources, removals by sinks, activity data, and implied emission factors reported by signatory countries according to the methodologies agreed upon by the Conference of Parties[26]. Annex I parties are required to use the IPCC 2006 Guidelines for National Greenhouse Gas Inventories as a basis for their GHG emissions inventories, while non-Annex I Parties use the IPCC Revised 1996 Guidelines for National Greenhouse Gas Inventories. Category 2.B and its subcategories are related to emissions from the chemicals sector resulting from production emissions excluding those from upstream energy generation, which are accounted for in UNFCCC category 1. Therefore, UNFCCC estimates can also be directly compared to our cradle-to-gate values excluding the indirect energy use share of emissions, although a more exhaustive comparison study is being carried out by D. Malkowska et al. (D. Malkowska et al., unpublished observations).

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All data are publicly available; however, some data are proprietary. A user license from ICIS is required to access the underlying production data: https://www.icis.com/explore/services/analytics/supply-demand-data/. Source data are provided with this paper.

Code availability

Code and freely available data are archived at ref. 68. An interactive beta version dashboard detailing the full results of the study can be accessed at https://www.c-thru.org/emissions-dashboard (ref. 34).

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Extended Data Table 1 | Summary of scenarios and key assumptions

Scenario	Roll-out type	Electricity decarbonisation	Level of CCS achieved in 2050	Level of bio-feedstocks achieved in 2050	Demand reduction
Business-as-usual	–	Business as usual electricity	0%	0%	0%
Scenario 1	Unprioritised	IEA Stated Policy	50%	50%	0%
Prioritised scenario 1	Prioritised	IEA Stated Policy	50%	50%	0%
Scenario 2	Unprioritised	IEA Sustainable Development	100%	100%	0%
Prioritised scenario 2	Prioritised	IEA Sustainable Development	100%	100%	0%
Prioritised electrification	Prioritised	IEA Sustainable Development	100%	100%	0%
Prioritised net-zero electrification	Prioritised	Net-zero electricity	100%	100%	0%
Prioritised S1 & 50% demand reduction	Prioritised	IEA Stated Policy	50%	50%	50%
Prioritised S2 & 50% demand reduction	Prioritised	IEA Sustainable Development	100%	100%	50%

Here CCS includes CCS for direct energy use, CCS for direct processes and N_2O abatement. Demand-side solutions are considered, and the volume of petrochemical products produced is halved by 2050 in the scenarios with 50%. Our model contains five main parameters that can be varied. We have included nine of these scenarios below. First is the roll-out type, prioritised roll-outs prioritise the largest emitting facilities first, unprioritized are based upon emissions. Second, there is an assumption related to the carbon intensity of the grid, which is tied to the IEA scenarios[24]. The third and fourth are the assumptions related to the deployment of CCS and alternative feedstocks. The percentage indicates the amount of biobased feedstocks used or carbon emissions that are captured based on the 2050 demand. Lastly, a 50% demand reduction entails cutting the demand in half.

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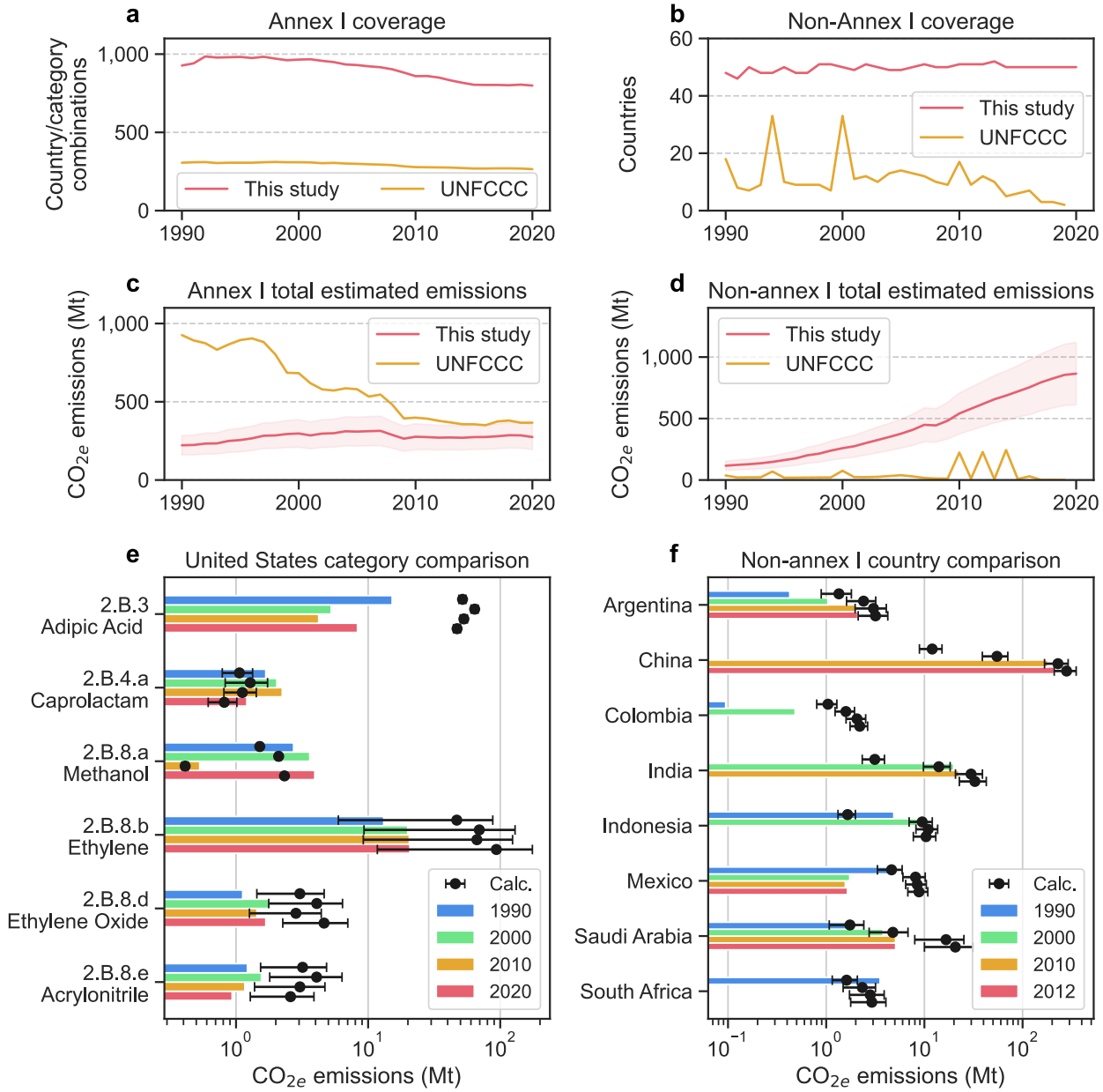

Extended Data Fig. 1 | Data comparison between this study and reports available from the UNFCCC database for Annex I parties (a,c,e) and non-Annex I parties (b,d,f). a) Annex I comprises 45 countries, with 81 possible products in this study although only a limited number of products are produced in each country in any given year. A higher number of product/country combinations indicates a more exhaustive breakdown of emissions into categories. **b**) Non-Annex I comprises all countries outside of the 45 Annex I parties, not all produce petrochemicals. **c**) Total emissions for UNFCCC category 2.B Chemical Industry for Annex I compared to this study. **d**) Total emissions for UNFCCC category 2.B Chemical Industry for non-Annex I parties. This is impacted by non-reporting by many countries as seen in b). **e**) Direct category comparison for the United States, an annex I party. **f**) Direct total comparison for non-Annex I countries for years with the most available data. Notes: In e) and f) 'Calc.' indicates calculated results from this study. Error bars indicate the 95% confidence intervals around the mean as described in the methods section. In subfigures c and d, uncertainties are depicted by the shaded areas around the mean representing the 95% confidence interval. For further discussion and comparison with the EU and across different gases see SI 3.1.

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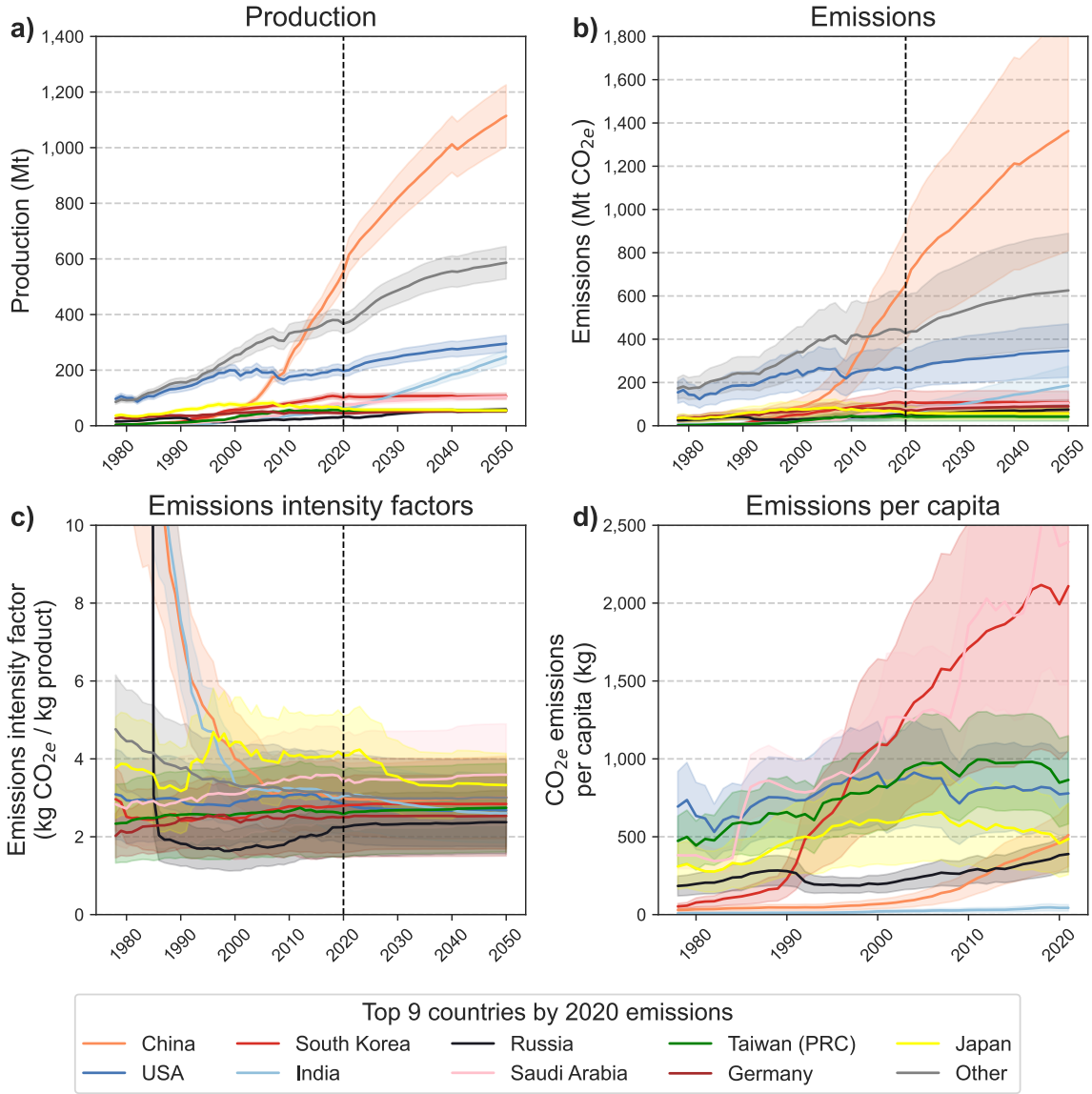

Extended Data Fig. 2 | Regional evolution of petrochemical production from 1978 to 2050, selected top 9 countries. a) annual production volumes of 81 chemicals sourced from ICIS, IFA and FAO data[6,23,24]; **b**) annual cradle-to-gate greenhouse gas emissions; **c**) calculated average emission intensity factors per kg product; **d**) evolution of per capita greenhouse gas emissions with populations from the World Bank[65] for 1978-2020. The dashed vertical line in plots **a**), **b**) and **c**) separates historical data to the left from projections on the right based on a business-as-usual scenario generated from ICIS future production projections[6]. Uncertainties are depicted by the shaded areas around the mean representing the 95% confidence interval. Summarised numerical data for these figures can be found in Section 3.2 of supporting information.

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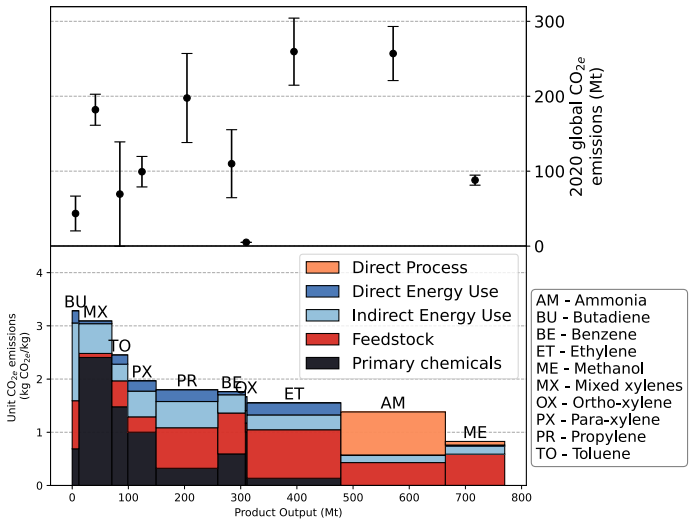

Extended Data Fig. 3 | Greenhouse gas emissions of eight primary chemicals for production in 2020. The lower half of the figure shows the average greenhouse gas emissions intensity (CO2e/kg product) of production broken down by emissions source. The x-axis shows the production output of each chemical (Mt). The area of each rectangle, also denoted by the values in the top half of the plot, indicates the total emissions of product production broken down by emissions source. Figures showing the forecasts for the years 2030, 2040, and 2050 can be found in SI 3.3. The IEA's ammonia roadmap[8] uses an emissions intensity factor of 2.4 kg CO2e/kg, which is much higher than the global average of 1.5 ± 0.3 kg CO2e/kg derived from this study, leading to a higher overall emissions estimate. The difference in emissions factors stems from our consideration of different possible technologies used. The IEA's estimation[66] is categorised by steam methane reforming, coal, and oil, each employing a single emissions factor. However, in practice, there are a number of different processes within each of these three routes, a complexity that our study addresses. Error bars indicate the 95% confidence intervals around the mean as described in the methods section.

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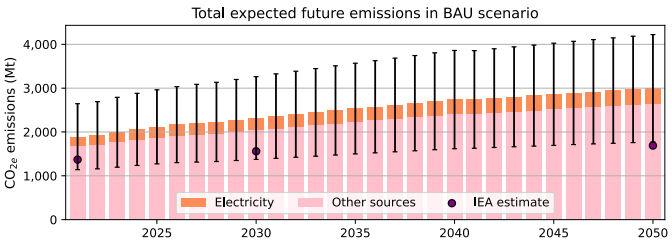

Extended Data Fig. 4 | Total expected future emissions from the petrochemical industry to 2050. Numerical values for each year are available in SI3.4. The IEA expect direct CO2e emissions to rise by 20% by 2030 and 30% by 2050[9]. As a comparison, our projections, excluding electricity, suggest a 32% rise by 2030 and a 72% rise by 2050. Based on the aggregated IEA modelling outputs available, we have not been able to find the specific reason for the difference. Error bars indicate the 95% confidence intervals around the mean as described in the methods section.

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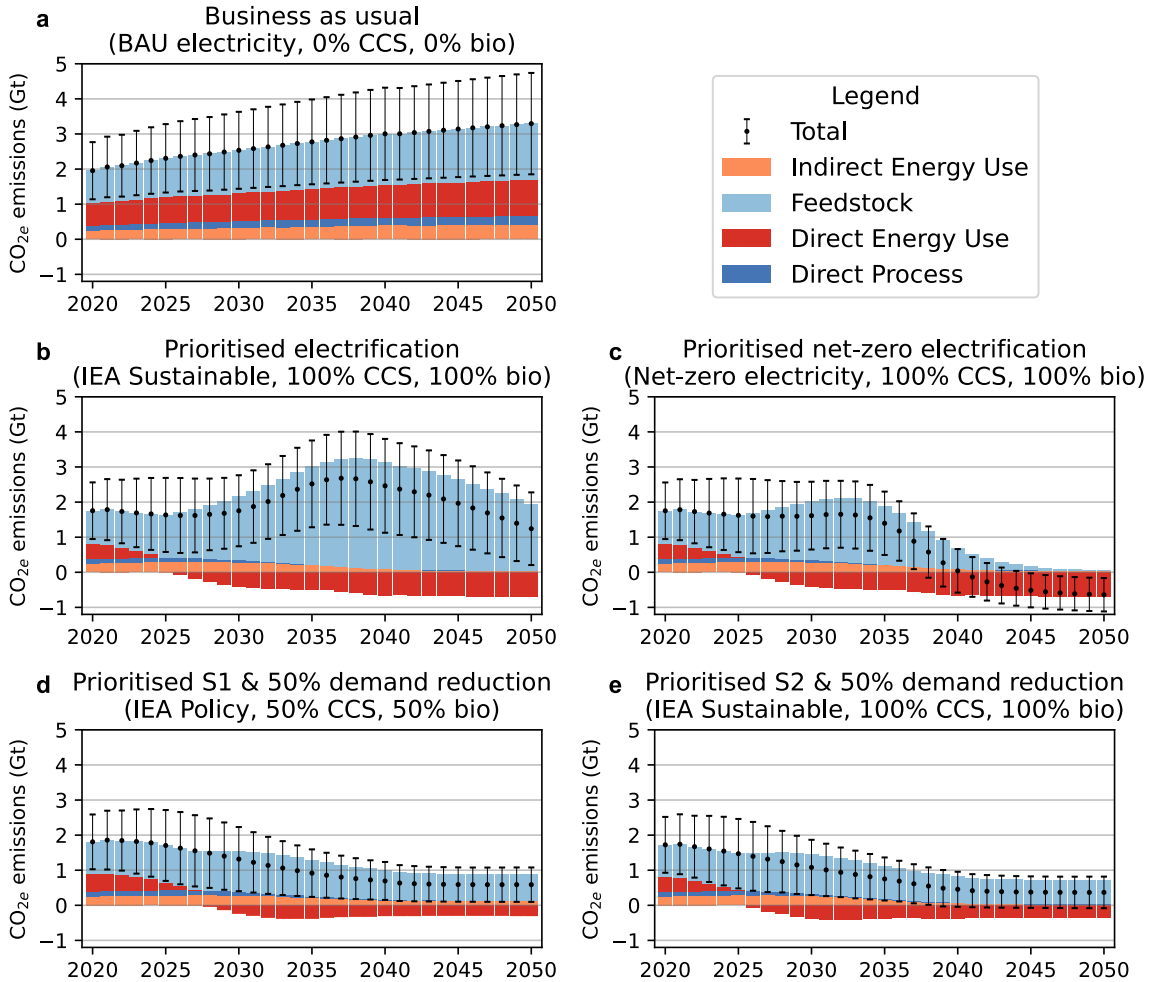

Extended Data Fig. 5 | Future scenarios for petrochemical emissions from 2020 to 2050. a-e, The titles of each figure indicate the limits applied for roll-out by 2050:business as usual (BAU) (a), prioritized electrification (b), prioritized net-zero electrification (c), prioritized scenario 1 and 50% demand reduction (d), and prioritized scenario 2 and 50% demand reduction (e). Prioritized implies a prioritized facility roll-out, the alternative being a conventional scenario considering total emissions. The titles in each figure indicate the limits applied for roll-out by 2050. Prioritised implies a prioritised facility roll-out, the alternative being a conventional scenario considering total emissions. The first term in brackets denotes the electricity scenario used. The second term in brackets denotes the level of CCUS achieved in 2050, here CCUS includes CCUS for direct energy use, CCUS for direct processes and N2O abatement. The third term denotes the level of bio-feedstocks achieved in 2050. Figures **d**) and **e**) present an alternative scenario where demand-side solutions are considered and the volume of petrochemical products produced is halved by 2050. Error bars indicate the 95% confidence intervals around the mean as described in the methods section. Details for each scenario are provided in Extended Data Table 2.

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