

The refinery of the future

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Fossil fuels—coal, oil and gas—supply most of the world's energy and also form the basis of many products essential for everyday life. Their use is the largest contributor to the carbon dioxide emissions that drive global climate change, prompting joint efforts to find renewable alternatives that might enable a carbon-neutral society by as early as 2050. There are clear paths for renewable electricity to replace fossil-fuel-based energy, but the transport fuels and chemicals produced in oil refineries will still be needed. We can attempt to close the carbon cycle associated with their use by electrifying refinery processes and by changing the raw materials that go into a refinery from fossil fuels to carbon dioxide for making hydrocarbon fuels and to agricultural and municipal waste for making chemicals and polymers. We argue that, with sufficient long-term commitment and support, the science and technology for such a completely fossil-free refinery, delivering the products required after 2050 (less fuels, more chemicals), could be developed. This future refinery will require substantially larger areas and greater mineral resources than is the case at present and critically depends on the capacity to generate large amounts of renewable energy for hydrogen production and carbon dioxide capture.

Population growth and the increasing consumption associated with a higher standard of living have led to increasing anthropogenic carbon dioxide (CO₂) emissions that cannot be absorbed by the natural geological and biological carbon cycles. Because these emissions change Earth's climate with adverse effects such as more frequent and severe droughts, heatwaves and rainfall, the aim is to reduce CO₂ in the atmosphere (about 424 ppm in May 2023 (ref. 1)), as set out in the Paris Agreement and the Kyoto Protocol^{2,3}. Applicable to us is the European Climate Law, which provides a legal framework for the rapid reduction of CO₂ emissions and targets an economy that is carbon-neutral by 2050 (ref. 4). Because a large fraction of current CO₂ emissions arises from the production and use of energy, achieving this ambitious goal will probably involve an energy system based largely on renewable electricity, with a prominent role for solar photovoltaics (PV) and wind power^{5–7}.

But there are less obvious solutions for how to reduce the emissions of refineries, which—at present—process fossil-based resources to make our transport fuels, performance chemicals and monomers for polymer production. Transport fuels, which are the main products of today's refineries and contribute about 25% of present-day CO₂ emissions, can—in part—be replaced through transport electrification. But electrification will not be feasible for all transport modes and there will be an increasing need for chemicals and polymers as both the world population and the material needs of developing countries grow. Developing alternative, carbon-neutral refining concepts that focus on sustainability and circularity will thus be essential for transitioning towards a carbon-neutral economy in 2050. The key questions that need to be answered for a carbon-neutral refining concept are as follows. (1) What carbon input will replace the fossil-based resources to enable a carbon-neutral refinery? (2) Can science and technology progress rapidly enough so that we can replace in time existing conversion processes with more sustainable alternatives? (3) Are available energy,

materials and land resources sufficient for designing and constructing carbon-neutral refineries? (4) What are the costs associated with building future refineries and how can we make them economically and socially viable?

In this Perspective, we attempt to provide some answers to the questions above by sketching a possible roadmap towards a refinery of the future. We do this using order-of-magnitude calculations for a single refinery plant that we assume to be located in Europe. We first discuss the necessary building blocks for the anticipated refinery concept. We then evaluate the required land and offshore area, resources and investments costs and consider the necessary scientific and technological developments that are needed to make this all possible. We also highlight some possible show-stoppers, which include the need for large amounts of renewable energy and so-called critical chemical elements to construct all the necessary hardware.

Building blocks of a refinery of the future

Crude oil refining as we know it today took off in the early 1900s because petroleum-based products were increasingly used for transport⁸. Large-scale chemical processes, such as cracking, hydroprocessing, isomerization, reforming and alkylation, were developed to allow crude oil refineries to produce ever more complex product slates that included transport fuels (that is, gasoline, kerosene and diesel), heating oil and later on also petrochemicals such as ethylene, propylene and benzene, toluene and xylenes^{9–13}. Today's refinery and associated petrochemical complex produce essentially all transport fuels and the essential raw materials for polymers (plastics, resins, fibres), detergents, coatings, construction chemicals and medicine. Along with changes to the product slate, economy of scale and process integration led to the construction of ever larger petrochemical complexes and refineries¹⁴.

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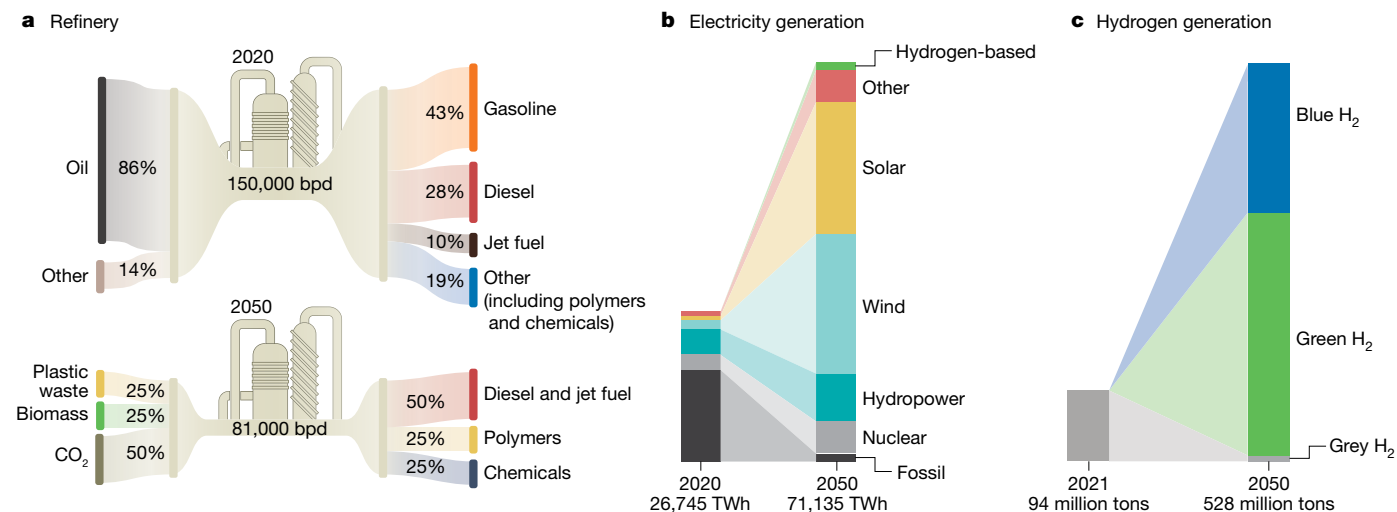


Fig. 1 | The anticipated refinery of 2050 compared with the refinery of 2020. **a**, The carbon input stream changes from mostly oil in 2020 to CO₂ and agricultural and municipal waste, including biomass and plastics, in 2050. The ‘Other’ in the 2020 input comprises other liquids, such as fuel ethanol, hydrocarbon gas liquids and blending components. The output changes from mostly transport fuels with a main gasoline component in 2020 to a 50%/50% mixture of fuels (limited to diesel and jet fuel) and chemicals and materials, including performance chemicals and polymers. The average size of the proposed 2050 refinery is most probably smaller than the 2020 refinery in terms of carbon molecules processed. The 2020 numbers originate from the

US Energy Information Administration¹⁵⁷. **b**, Changes in electricity generation capacity by source for 2020 and 2050 (projected), based on 2021 data of the IEA¹⁵⁸. It is projected that electricity production will almost triple in the next 30 years from about 26 terawatt-hours (TWh) to about 70 TWh. **c**, Projection of the development of hydrogen generation based on IEA data (2021 data from ref. 159, projected 2050 data from ref. 158). Grey hydrogen, hydrogen produced from hydrocarbons without carbon capture and use/storage; blue hydrogen, hydrogen produced from hydrocarbons with carbon capture and use/storage; green hydrogen, hydrogen made with electrolysis using renewable electricity.

Although historically the share of petroleum-derived chemicals was roughly 5–10% in volume of all refinery products, their importance in the product slate is increasing: recent developments suggest that the share of chemicals (such as propylene, an important polymer precursor) may reach 30% and beyond and that the oil-to-chemicals approach could become viable in well-integrated oil refinery complexes¹⁵. But irrespective of the nature of the refinery output, most of the carbon atoms that enter a refinery at present will eventually be emitted as CO₂. This is because, even though only a small portion of the carbon atoms emitted as CO₂ is lost in the refining process, most products are either burnt as transport or heating fuels or are incinerated after being transformed into chemicals or materials and then used. If we could convert some or all of this emitted CO₂ back into useful products, we could substantially contribute to a carbon-neutral society. For this reason, we analyse in this Perspective the options for using CO₂ as the carbon source for transport fuels and considering plastic waste and biomass (that may already contain desired chemical features) as raw materials for producing polymer monomers and chemicals.

Changes in the carbon streams

Although refineries of today convert mostly crude oil, we predict a gradual change to the refinery input stream so that only CO₂ and agricultural and municipal waste (which includes biomass and plastics) are used in 2050 (Fig. 1a). Refinery output streams are also expected to change substantially in response to transport electrification and use of fuel cell vehicles, which could largely eliminate the demand for gasoline products by as early as 2050. It is expected that a few modes of transport, such as long-distance aviation and heavy and marine transport, will still require high-energy-density hydrocarbon fuels (although these might be gradually replaced by an alternative liquid energy source, such as ammonia or methanol). These shifts are expected to limit future demand for hydrocarbon fuels to about one-third of the transport fuels that are produced today¹⁶.

The anticipated changes in the transport sector imply that we only need a relatively small part of the present-day refinery to satisfy the future demand for hydrocarbon fuels (Fig. 1a). Although we expect that most of the naphtha (the crude oil fraction processed at present into gasoline and H₂) will no longer be needed, there are other valuable refinery cuts (that is, crude oil fractions such as asphalt, bitumen, lubes and benzene, toluene and xylenes) that are not directly linked to fuel production and will need to be obtained from other carbon sources, such as from agricultural and municipal waste. Using these materials as alternative refinery input streams may seem straightforward, but will be challenging when considering that present-day refineries have evolved into highly integrated units that ensure optimal operation of the refinery as a whole, with complex interlocking of processes that supply and require heat and interlocking of processes that generate and use particular molecules and thereby avoid waste. The result is a highly optimized and very efficient overall processing system, and future refineries that use different input streams will have to be redesigned to integrate the new conversion processes to ensure that they reach the same degree of optimization while also avoiding unnecessary waste streams.

Current and new refinery schemes

At the end of 2018, there were 615 crude oil refineries in the world, with a combined refining capacity of roughly 92 million barrels per day (bpd)¹⁷. This equates to an average single refinery, based on crude oil processed, having a capacity of about 150,000 bpd, or about 20,700 tons per day (based on 7.25 barrels per ton). We will consider several scenarios for how such an average-sized single refinery, projected to use no crude oil while meeting the demands of 2050, could operate in the future. Box 1 summarizes the assumptions underpinning the 2050 refinery concept, with one key point being that it needs to produce only one-third of the hydrocarbon fuels that are generated in a refinery at present. This amounts to approximately 5,600 tons per day of hydrocarbon fuels. Extrapolating current trends in the amount of chemicals versus

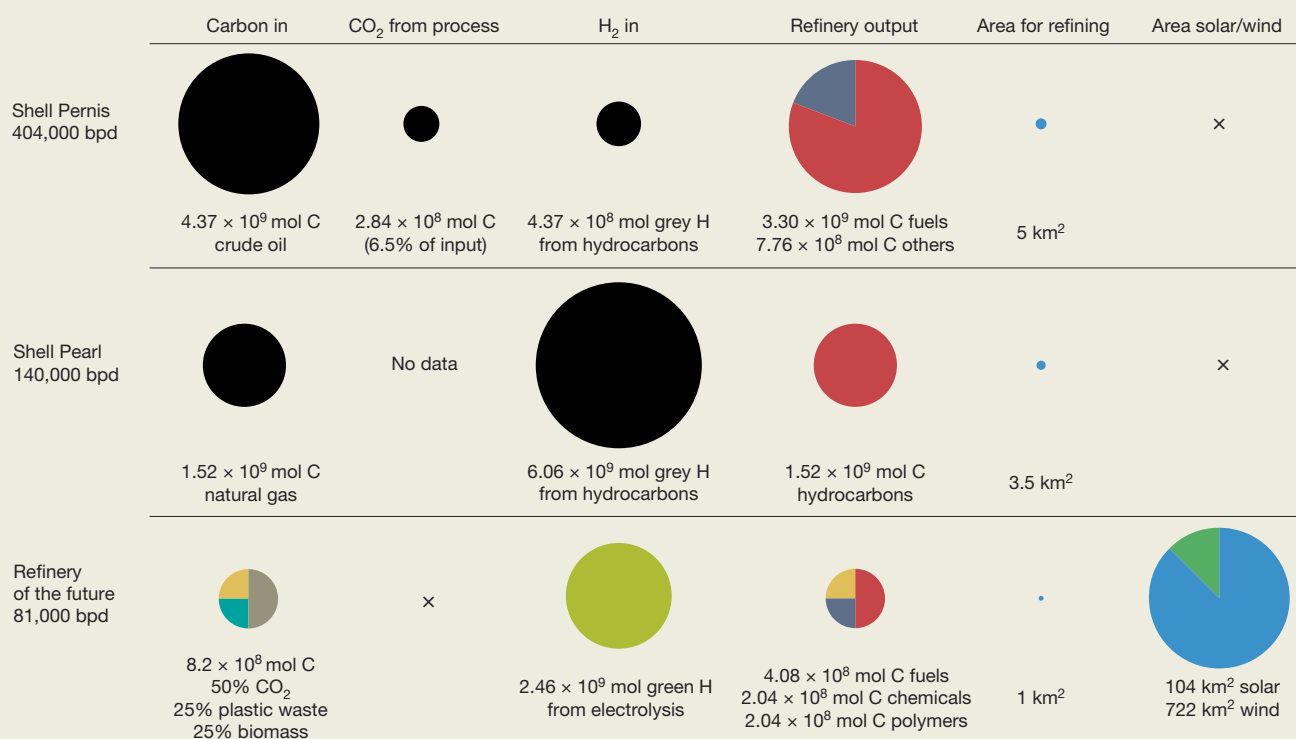
Box 1

Assumptions for designing hydrocarbon fuel production in the refinery of the future

- The average refinery size is about 150,000 barrels per day (bpd), of which 81% results in transport fuels.
- Our future refinery produces only one-third of the hydrocarbon transport fuels required today, or about 40,500 bpd. This equates to about 5,600 tons per day.
- Only carbon from CO₂ goes into the 40,500 bpd of hydrocarbon fuels produced, which requires 18 kilotons (kt) (or 4.1 × 10⁸ mol) of CO₂ per day.
- The overall conversion of CO₂ into hydrocarbons follows $n\text{CO}_2 + 3n\text{H}_2 \rightarrow (-\text{CH}_2)_n + 2n\text{H}_2\text{O}$. This requires 3 mol of H₂ per mol of C entering the refinery, which translates into 2.4 kt (or 1.2 × 10⁹ mol) H₂ per day.
- H₂ will be produced from electrolysis. This requires 5.5 gigawatts (GW) of electricity, which is to be generated from both wind power and solar photovoltaics (PV) to solve intermittency issues.
- CO₂ capture requires an extra 0.3 GW for capture from a concentrated source such as flue gas or 1.5 GW for direct air capture.
- We need areas of 104 km² for solar PV panels and 722 km² for 328 wind turbines (situated offshore or on land) if solar and wind power each contribute 50% to the electricity for H₂ generation.
- We estimate costs of 5–10 billion euros for solar PV and 3–6 billion euros for wind turbines for this scenario, as well as notable pressure on resources, including some critical raw materials.
- H₂ has to be stored for several days following production (for example, approximately 10 kt for 4 days).

Scenarios

Several scenarios have been calculated to compare the raw materials use (carbon and hydrogen) for the refinery operations and land area for typical refineries. The following existing refineries/complexes were used: Shell Pernis, the largest refinery in the Netherlands, at 404,000 bpd (ref. 17), and Shell's Pearl GTL (gas-to-liquids) complex in Qatar, at 140,000 bpd (ref. 37). More details can be found in the Supplementary information (Supplementary Table 1 and Supplementary Fig. 1).



materials versus fuels produced, we assume that the 2050 refinery will produce an equal quantity of chemicals and polymers (that is, 2,800 tons each per day of chemicals and polymers). Because we aim for overall carbon neutrality even though the hydrocarbon fuels generated in the refinery will be burnt and emit CO₂ when used, the carbon feedstock processed in our future refinery cannot include fossil fuels and should instead comprise a mixture of CO₂ and waste. We opt for CO₂ as the carbon source for fuel production because the required fuels are long-chain linear hydrocarbons that can easily be made from CO₂ through syngas routes that are established industrial processes. Chemical considerations also suggest biomass as a good carbon source

for chemicals because we can then make efficient use of the chemical functionalities already present in this raw material, and that plastic waste would be a good carbon source for producing monomers that can be polymerized to generate new materials. Figure 2 sketches the use of CO₂, biomass and plastic waste as carbon sources and the conversions expected for the refinery of the future.

Need for increased carbon capture

The CO₂ required for future fuel production needs to be captured from either high-concentrated flue gas emitted from blast furnaces or during

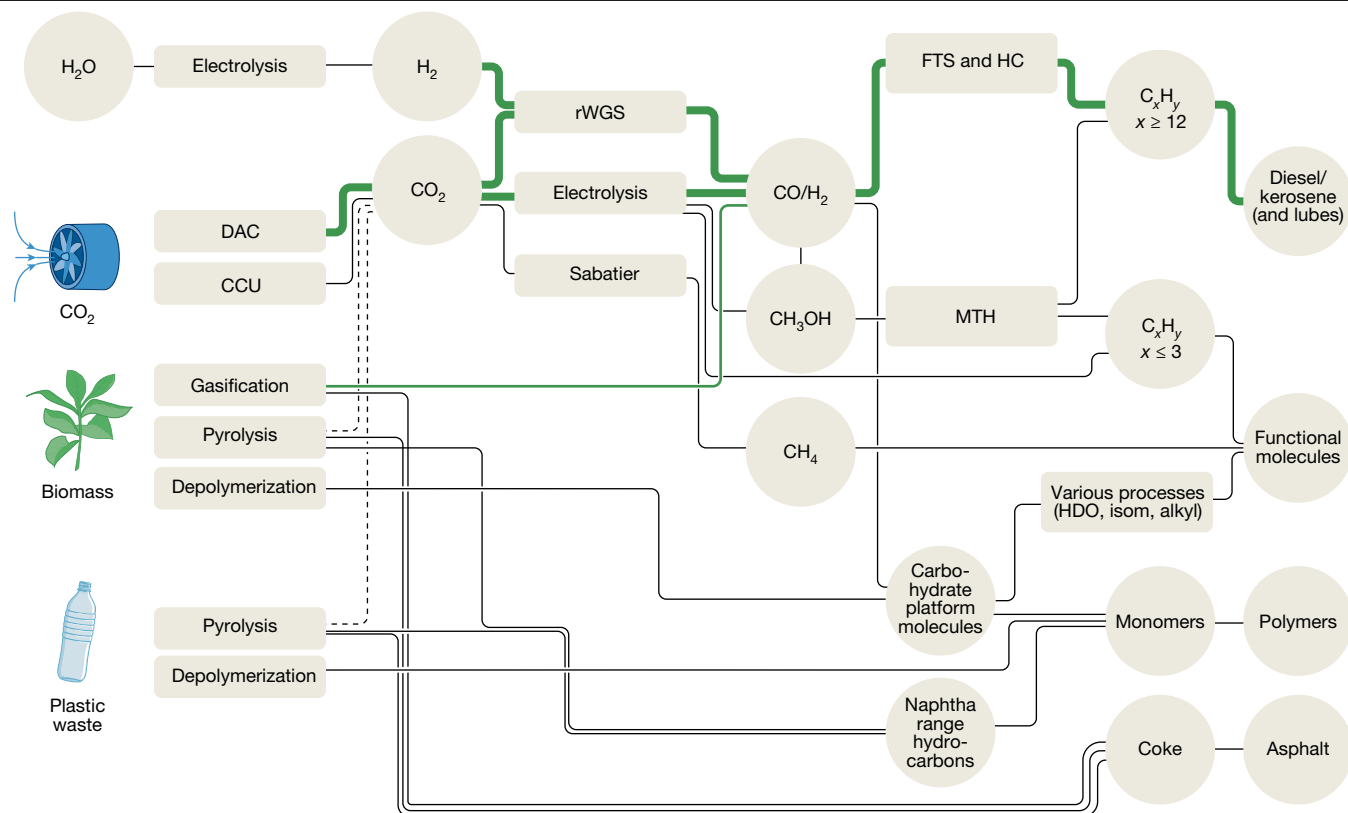


Fig. 2 | Overview of the various conversion processes in the refinery of the future. The starting materials are CO₂, biomass and plastic waste. The last two are taken as showcase examples of agricultural and municipal waste. The green process line shows the main process route for converting CO₂ to hydrocarbon fuels advocated in this Perspective. The dashed lines indicate that biomass and plastic waste conversion may produce CO₂ that can be used in the fuels train.

Functional molecules are aromatics, oxygenates, amines, for example. Polymers are not necessarily produced in the refinery but are added in the process flow to clarify the plastic waste-to-polymers concept. alkyl, alkylation; CCU, carbon capture and utilization; isom, isomerization; MTH, methanol-to-hydrocarbons; FTS, Fischer–Tropsch synthesis; HC, hydrocracking; HDO, hydrodeoxygenation.

cement production or other CO₂-intensive activities that may remain in place in 2050, or be obtained as one of the by-products of the processing of agricultural and municipal waste inside the refinery itself (a variation on the conventional high-concentrated point sources), or be pulled from the surrounding air by means of direct air capture (DAC). Capture from point sources (post-combustion capture) is much more energy-efficient than DAC, simply because much less volume needs to be treated to obtain the same amount of CO₂ and extraction from a more concentrated source is less demanding. CO₂ capture from point sources is typically stored, not used as we propose here, and is already performed at the multimillion tons per year scale¹⁸.

CO₂ capture uses absorption by liquids such as amines or ionic liquids or by solids such as activated carbon, zeolites, hydrotalcites, metal-organic frameworks or K₂CO₃ supported on alumina¹⁹. Although the field is rapidly growing²⁰ and has seen substantial reductions in energy requirements¹⁸, opinions diverge about the overall impact of CO₂ capture and especially about whether DAC is a viable CO₂ mitigation option in view of its energy and materials requirements^{21–23}. Climeworks, one of the companies involved in DAC for storage, is operating ORCA, a 4,000 tons per year DAC demonstration project in Iceland²⁴ (for context, our refinery would need 18,000 tons per day or 6,570,000 tons per year). Carbon Engineering, another company in the DAC field, states developing DAC and associated fuels synthesis in the million tons per year range²⁵. Some reviews summarize developments and challenges associated with DAC technology^{26,27}, and one study has evaluated the factors limiting the rate at which developed technologies can be scaled up²¹. For our refinery, challenges with CO₂ capture are mitigated because it can be a combination of point source capture (from plastic waste and biomass conversion in the refinery) and DAC.

CO₂ and CO conversion

Once captured, we need to convert CO₂ into hydrocarbons^{28–31}, which requires about three times as much energy (for H₂ generation and CO₂ capture) as is generated when using the fuel³². Thermodynamically, this approach is not an ideal choice. But as stated above, some liquid hydrocarbon fuels will be needed for long-distance flying, trucking and marine shipping, for which H₂, CH₃OH and NH₃ are not (yet) appropriate fuel choices³³. For this reason and because CO₂ has to be removed to reduce its concentration in the atmosphere to climatically less disruptive amounts, we are of the opinion that it is better to directly use captured CO₂ (carbon capture and utilization (CCU)) than to store it in the long run (carbon capture and storage (CCS)), despite the high direct cost involved.

The hydrocarbons in the C₁₂–C₁₆ range needed as diesel and jet fuel can be produced efficiently using a combination of Fischer–Tropsch synthesis (FTS) and hydrocracking (HC), both established technologies that have been proved well beyond the required scale^{34,35}. FTS produces a mixture of mostly linear hydrocarbons following the Anderson–Schulz–Flory distribution, and this mixture can then be cracked/oligomerized/alkylated into the required carbon range³⁶. FTS starts from synthesis gas, a mixture of CO and H₂ conventionally made from hydrocarbons³⁷ (as in the Shell Pearl complex described in Box 1). We anticipate that the refinery of the future will generate synthesis gas either through a process known as reverse water gas shift (rWGS) that uses CO₂ and hydrogen produced by electrolysis or by electrocatalytic reduction of CO₂ to CO, as depicted in Fig. 3. That this approach is technically viable was illustrated by producing synthetic jet fuel from captured CO₂ and green H₂ using a process combining rWGS, FTS and HC^{32,38}.

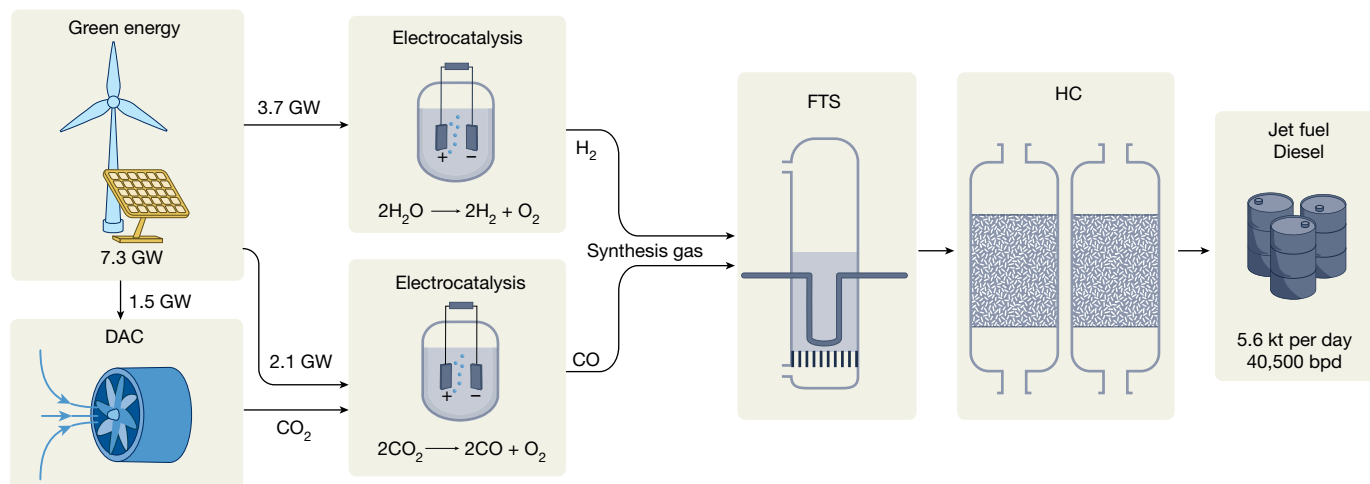


Fig. 3 | A scenario for hydrocarbon fuels production processes in the refinery of the future. This scenario for the process uses hydrogen from water electrolysis and CO from electrocatalytic reduction of CO₂ (from DAC) to make synthesis gas (a mixture of CO and H₂), which is then converted to the desired mixture of hydrocarbons. The FTS process starting from CO requires only two

molecules of H₂ per C atom, so only 3.7 GW of power is needed, instead of the 5.5 GW mentioned previously. However, to replace the third H₂ molecule mentioned previously, an extra 2.1 GW is needed for the electrocatalytic reduction of CO₂, which is not 100% efficient.

(all established industrial processes), with Shell and KLM announcing successful use of 500 l of such fuel for a flight from Amsterdam to Madrid.

It should be noted that synthetic jet fuel cannot be produced from long-chain paraffins such as FTS products alone, but also requires aromatics. We can easily produce these either as a by-product of plastics cracking or lignin deconstruction or also on purpose using methanol to hydrocarbons or methane to aromatics processes that are available already and are part of our refinery complex design (vide infra).

The successful demonstration of jet fuel production from CO₂ illustrates that some of the process technology needed for the anticipated refinery of the future is already available, but we need to emphasize that all conversion processes need to be developed with the whole refinery concept in mind to ensure maximum carbon-atom and energy efficiency. That is, individual processes should not be developed and optimized in isolation; instead, process intensification and process integration will be paramount, so that no carbon and no energy is wasted. In that regard, present-day refineries offer a very high benchmark in overall system optimization. However, this requirement should not prevent the development of promising new technologies that do not yet offer the desired efficiency or compatibility with existing refinery processes.

Among the conversion processes we expect for the refinery of the future, sketched in Fig. 2, one of the first chemical reactions is the rWGS (CO₂ + H₂ → CO + H₂O) that converts CO₂ into CO (refs. 39,40) for syngas production. This conversion requires a third of the total amount of H₂ needed for the overall synthesis of hydrocarbons and, for one refinery, the production of this H₂ by electrolysis would use about 1.8 GW of electrical power. This thermochemical CO production route might, in the future, be replaced by direct electrochemical reduction of CO₂ to CO (refs. 41–44) (as pictured in Fig. 3) that, if carried out with the same efficiency as water electrolysis to produce H₂, would consume roughly 2.1 GW (Fig. 3). CO production directly from CO₂ would thus use more energy than needed to generate the H₂ for CO production through the rWGS process (2.1 versus 1.8 GW). However, the thermocatalytic process also requires energy to run the endothermic reaction and to heat and compress the process gases, which would probably result in comparable overall energy requirements. It is also worth considering that the electrolysis of water to produce H₂ and the CO₂RR share the oxygen-producing half-reaction. Because this generated oxygen is not needed, there might be scope for lowering the overall energy

requirements of the processes and for generating useful products by replacing this half-reaction with less energy-demanding selective oxidation reactions, such as oxidation of methanol or glycerol to formic acid^{45,46}, oxidation of hydroxymethylfurfural to furandicarboxylic acid or the conversion of sorbitol to aldoses, ketoses and aldonic acids⁴⁶.

Electrocatalytic CO₂RR can produce CO and also more complex molecules such as alcohols, aldehydes and hydrocarbons in the C₁–C₃ range⁴², but we are not aware that it has been used to generate diesel-range hydrocarbons. Although the CO₂-to-CO conversion can be performed through both electrocatalytic and thermocatalytic routes, the production of long-chain hydrocarbons is thus probably best done through FTS, which requires synthesis gas (a CO and H₂ gas mixture). The CO component is accessible not only through rWGS and CO₂RR but also through methods such as dry methane reforming⁴⁷ (that is, CO₂ + CH₄ → 2H₂ + 2CO) or CO₂ methanation using the Sabatier reaction⁴⁸ followed by partial oxidation of CH₄ (that is, CO₂ + 4H₂ → CH₄ + 2H₂O followed by 2CH₄ + O₂ → 2CO + 4H₂). These chemical routes typically co-produce the H₂ needed for FTS. If the CO:H₂ ratio needs to be adjusted or when using CO from CO₂RR, the required extra H₂ could be generated not only through H₂O electrolysis but also CH₄ pyrolysis⁴⁹ (that is, CH₄ → C + 2H₂) that retains the carbon as a solid, that is, the process avoids CO₂ emissions and could therefore serve as a possible intermediate solution for large-scale H₂ production while transitioning from fossil to renewable energies. As a further benefit, the required CH₄ is not only available from natural gas but can also be generated through anaerobic digestion of agricultural and municipal waste and then integrated into chemical H₂ production schemes.

Further flexibility for future fuel production could arise from using methanol (CH₃OH) as the starting material for the methanol-to-hydrocarbons (MTH)⁵⁰ process, which is very versatile and can generate paraffins, olefins and aromatics^{51–53}. The methanol could be generated through the conventional methanol synthesis route that uses synthesis gas or possibly through electrocatalytic CO₂RR. As well as conversion into hydrocarbon fuel, methanol itself could be used as a fuel in fuel cells or even as an additive to gasoline for internal combustion engines.

Industry has developed gas-to-liquids (GTL) technology that uses chemical routes we have just discussed for converting natural gas through synthesis gas and H₂ into a wide range of liquid products that would otherwise be made from oil. GTL generates lower CO₂ emissions but at present makes only a very minor contribution to global

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liquid hydrocarbon production. Increasing this contribution offers an important intermediate step towards more sustainable refineries. Ultimately, however, our refinery of the future will generate liquid hydrocarbon fuels through routes that only use renewable energy, CO₂ and water. This so-called power-to-liquids concept^{54–57} can tap into existing industrial processes developed for GTL and needs to combine these with efficient CO₂ conversion strategies to develop technology options for making carbon-neutral hydrocarbon fuels.

Biomass-to-chemicals conversion

The carbon coupling processes for converting CO₂ and CO described above mainly produce linear hydrocarbons, so other feedstocks are needed to make products such as bitumen, asphalt and lubes that are derived from crude oil at present. Plant-derived biomass is an obvious choice and available in the form of oils and fats (for example, triglycerides), sugar-containing biopolymers (for example, starch, hemicellulose and cellulose) and aromatics-containing biopolymers (that is, lignin), with each of these three classes requiring specific processes for valorization^{58–60}.

The thermal and catalytic conversion of agricultural waste into fuels and chemicals has been studied extensively^{61–64}. Biomass has been added as a co-feedstock in conventional refinery processes^{65–67}, sometimes together with plastic waste⁶⁸, and biomass was the basis of the first generations of biodiesel (for example, the fatty acid methyl esters (or FAME) biodiesel and deoxygenated fatty acids).

Oils and fats contain the long linear hydrocarbon chains desired for diesel fuels and these can be retrieved by removing the glycerol and carboxylic acid groups using hydrodeoxygenation (HDO). HDO of renewable fats and oils followed by isomerization is the basis for the NExBTL biodiesel production processes developed by the oil and refining company Neste and partners. One of their plants in Rotterdam, the Netherlands, produces approximately 800,000 tons of diesel-type molecules per year, or about 2.2 kilotons (kt) per day, which matches closely in scale, but not in application, with our target of 2.8 kt per day of chemicals from biomass in the anticipated refinery concept⁶⁹.

Biomass in the form of sugar-containing biopolymers such as starch or lignocellulose is typically deconstructed using processes such as pyrolysis or solvolysis⁷⁰. Processing sometimes takes into account the range of chemical functionalities present in the feedstock^{71–74}, with a combination of methods such as aqueous-phase reforming, hydrogenation/hydrogenolysis and dehydration used to generate the desired products⁷⁴. That said, most of the processes now under development simply target biomass conversion to hydrocarbon fuels⁷⁵, even though a wide range of platform molecules could, in principle, be made, such as succinic acid, furanics, hydroxypropionic acid, glycerol, sorbitol, xylitol, levulinic acid, isoprene, lactic acid and ethanol (these have been identified⁷⁶ as the top 10 biomass-derived platform molecules). Ethanol, for instance, can serve as a gasoline additive or be converted into diesel and jet fuel⁷⁷. The (partial) removal of oxygen implies that CO₂ is a by-product of biomass conversion to chemicals⁷⁸, which will lower the carbon atom efficiency and thus the maximum yield of these processes. Economic viability is also affected because H₂ is often needed to perform the conversion reactions^{79,80}.

Lignin, the third type of biomass, was long treated as a low-value by-product of biorefineries and the pulp and paper industry and used as low-grade fuel. It can be converted to valuable aromatics, however, and its lower oxygen and higher aromatics content compared with cellulose and hemicellulose make it an interesting starting material for the production of chemicals. But lignin is structurally complex and difficult to process: although the bonds between the building blocks of the celluloses are fairly uniform, those in lignin vary considerably and make it challenging to develop efficient depolymerization strategies. The structural and bonding complexity of lignin also mean that exploratory research on model compounds can be challenging to extrapolate, as

model compounds will often not capture the key challenges of working with real-world lignins. However, integrated routes for lignin valorization are emerging and slowly transitioning lignin from being regarded as a low-grade fuel to an interesting raw material for various applications^{59,60}.

Plastic-waste-to-polymers conversion

About 368 million tons of polymers are produced each year (ref. 81), of which almost 80% ends up as plastic waste⁸². Polymers are produced by combining monomers that are the direct product of refinery and petrochemical processes. The combination or polymerization of monomers is itself not necessarily a refinery process but can be performed in petrochemical plants associated with refineries.

The most efficient way to close the polymer–carbon cycle is to recycle polymer-containing waste using mechanical or (our preferred option) chemical processes. In chemical recycling, the waste material is depolymerized into its constituent monomers, which can then be repolymerized to create a fully circular polymer technology. Concern over plastic pollution has highlighted the need for recycling, with chemical recycling receiving increasing attention^{83–86} and some large plastic producers and chemical manufacturers announcing recycling pilot projects^{87,88}. One of the challenges in the field is, however, that the percentage of plastics recycled is still very low in many countries^{89–91}. But recycling and disposal schemes are emerging and can be compared using an index that considers economic, environmental and energy-related parameters⁹² (with mechanical recycling, in the form of incorporation of plastics into construction materials, scoring highly among available strategies).

Polymers differ with respect to their ease of recycling. For example, polyolefins, such as polyethylene and polypropylene, constitute around 55% of the global production volume of polymers and are challenging to depolymerize to their monomers (ethylene and propylene). They are most often subjected to a combination of pyrolysis and cracking^{93,94} that produces a mixture of naphtha-range molecules, considerable amounts of aromatics and heavy polyaromatic molecules, that is, a product that is more suited for producing fuels than monomers⁹⁵. Moreover, recycling that combines pyrolysis and cracking is not 100% carbon-atom-efficient⁹⁶. By contrast, chemical recycling of polymers such as polyethylene terephthalate, polystyrene and polymethylmethacrylate through depolymerization to their monomers seems technically possible, although—again—is not 100% carbon-atom-efficient⁹⁷. Solvolysis as the most efficient recycling route for polyethylene terephthalate, for example, still generates more than 30% of the CO₂ emissions associated with incineration⁸⁹. This highlights the need for considerable process developments to limit by-product and CO₂ production during the plastic-waste-to-polymers conversion processes to be installed in the refinery of the future.

Biomass and plastic waste conversion

The anticipated 2050 refinery uses 18 kt of CO₂ (4.1×10^8 mol C) to produce hydrocarbon fuels and another 4.1×10^8 mol C derived from biomass and plastic waste to produce chemicals and materials such as polymers. We therefore have to consider the effectiveness of waste and biomass conversion when designing an integrated refinery process. If we assume that the conversions are initially 50% effective for example, then we would obtain not only the 4.1×10^8 mol C required for the chemicals and polymers production chain but also 4.1×10^8 mol C in the form of by-products that we will assume to be (or converted to) CO₂. The 50% effective biomass and plastic waste conversion thus produces exactly the amount of CO₂ needed for the production of hydrocarbon fuels, in a form and location in which it can be captured efficiently from high-concentration-process flue gas inside the refinery itself (that is, the CCU mode of operation).

However, we expect that the conversion of agricultural and municipal waste would reach higher efficiencies in the future so that the CO₂

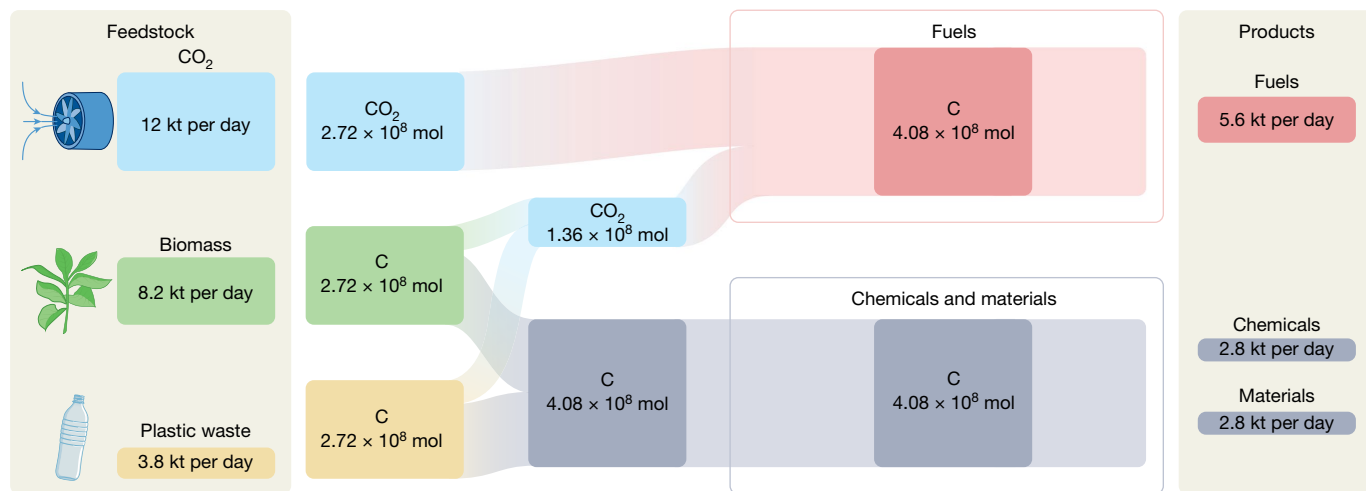


Fig. 4 | Integration of the carbon streams in the refinery of the future. The conversion of biomass and plastic waste is not 100% effective. At an assumed 75% efficiency for both, the conversion of biomass and plastic waste would produce a carbon stream (presumed to be CO₂) equivalent to one-third of the carbon required for the fuels train, next to the 4.1×10^8 mol C required for the chemicals and polymers train. As well as this carbon, the refinery would remove 12 kt per day of CO₂ from the atmosphere by means of DAC. Combustion of the hydrocarbon fuels would generate 18 kt of CO₂, so this particular scenario is not yet carbon-neutral (although it would lower overall CO₂ emissions from fuels by two-thirds). Increased efficiency in the biomass

and plastic waste conversion, or a lower contribution of biomass and plastic waste conversion to the system, will improve these numbers. No carbon is lost in this scheme. The differences between input tons and output tons are caused by the different molecular weights on the input molecules: CO₂ has a weight of 44 g mol^{-1} , biomass is assumed to be $(\text{CH}_2\text{O})_n$, at 30 g mol^{-1} C, and polymers, as well as all the products, are assumed to be $(\text{CH}_2)_n$, at 14 g mol^{-1} C. At 100% efficiency for the conversion of biomass and plastic waste, the process would use 18 kt of CO₂ (4.08×10^8 mol C), 6.2 kt of biomass (2.05×10^8 mol C) and 2.8 kt of polymers (2.05×10^8 mol C).

input stream can be supplemented with DAC. Although DAC will require extra electricity, it moves operation of the overall refinery towards being carbon-neutral or carbon-negative (illustrated in Fig. 4 for an anticipated biomass and plastic waste conversion efficiency of 75%).

If the efficiency for biomass and plastic waste conversion is lower than 50%, more CO₂ is produced in the refinery than the hydrocarbon fuels chain can handle and the excess CO₂ would have to be captured and stored (that is, CCS mode of operation). Coupling the CCU and CCS modes would be a way to create a carbon-negative refinery scenario.

Process integration and energy needs

The various processes that convert feedstocks and generate fuels, chemicals and materials will need to be integrated into the refinery of the future. They can be described as follows (with processes posing the main technical challenges in bold):

- Hydrocarbon fuels production:

Hydrogen production

Carbon capture → rWGS and/or CO₂RR → FTS → HC

- Biomass conversion:

Biomass → **Depolymerization** → Raw material pool (and excess CO₂ to CCU or CCS)

- Plastic waste conversion:

Plastic waste → **Depolymerization** → Raw materials pool (and excess CO₂ to CCU or CCS)

- Chemicals and polymers production:

Raw materials pool → value-added products, such as chemicals and polymers

- Crossovers

Some products from biomass and plastic waste conversion can be used as fuels

Some routes resulting from CO₂-derived synthesis gas can produce platform materials en route to functional chemicals

A large part of the future refinery's energy demand is for H₂ synthesis and CO₂ capture, but running the refinery processes also requires

energy—reactors will have to be heated to process temperature, gases will have to be compressed to increased pressures and the thermodynamic heat of reaction will have to be provided for endothermic processes (such as rWGS or biomass/plastic pyrolysis). This energy will have to be generated from electricity or by heat integration of the refinery processes (for instance, FTS and methanol synthesis are strongly exothermic). We have carried out thermodynamic heat of reaction calculations (provided in the Supplementary information, Supplementary Table 2) that indicate that the process energy will be about 10–15% of the energy required for H₂ synthesis and CO₂ capture. But ultimately, the refinery's energy requirements will depend on the refinery concept, which should target an integrated design allowing for the most efficient flow of energy and molecules through the anticipated refinery, rather than focus on individual process solutions.

Process developments and scale-up

We list in Table 1 the main processes required for our refinery of the future. Some of the conversion processes are already available at the commercial scale (for example, FTS, HC, rWGS, methanol synthesis, MTH and olefin polymerization). All of these processes have been demonstrated at >1 ton per day capacity, but may need further development. For example, impurities present in CO₂ gas streams and in the biomass and plastic waste may deactivate existing catalysts, so feedstock pretreatment or the development of more resilient catalysts may be required to handle the new range of feedstocks. We consider such process development to be relatively straightforward compared with the substantial scale-up efforts required for some of the other processes listed in Table 1.

Ensuring that electrolysis and CO₂ DAC technologies are available at the scale at which the refinery of the future would need will be particularly challenging. However, 2050 is still many years ahead and exponential technological development, for which capacity doubles every 2 years as with Moore's law for computing, is not uncommon^{98–100}. If this holds true, a scale-up factor of 32,768 is possible in 30 years and the required scale of DAC capacity could be reached in roughly 22 years.

Table 1 | Scale-up required for the main conversion processes

Process	Reactant(s)	Product	Present scale	Desired scale	Estimated scale-up required
DAC of CO ₂	CO ₂ in air (400 ppm)	Concentrated CO ₂	11 tons per day (ref. 24)	18 kt per day	1,636×
CO ₂ capture at stationary sources	CO ₂ in flue gas	Concentrated CO ₂	5,500 tons per day (ref. 18)	18 kt per day	3.3×
Electrolysis	Water	Hydrogen	8 tons per day (ref. 153)	2.4 kt per day	300×
Electrocatalysis	CO ₂	CO	25 tons per day in 2030 (ref. 154)	18 kt per day	720×
FTS	CO/H ₂	Long-chain hydrocarbons	20,000 tons per day ^a	5.6 kt per day	Industrially available
MTH	CH ₃ OH	Olefins, paraffins, aromatics	2,300 tons per day ^b	2.8 kt per day	Industrially available
HC	Hydrocarbons	Hydrocarbons of desired range	16,000 tons per day ^c	5.6 kt per day	Industrially available
rWGS	CO ₂	CO		18 kt per day	Industrially available
Depolymerization	Plastic waste	Monomers	500 tons per day (ref. 82)	2.8 kt per day	5.6×
Polymerization	Monomers	Polymeric hydrocarbons		2.8 kt per day	Industrially available
Depolymerization	Biomass, including agricultural waste	Platform molecules	400 tons per day (ref. 155)	6.2 kt per day	15.5×
Synthesis and conversion	Biomass, including agricultural waste	Platform molecules	280 tons per day (ref. 156)	2.8 kt per day	10×

Present scale is based on existing technology. Data are for one refinery. Commercial processes in operation at present refineries/complexes: ^aShell, Ras Laffan, Qatar. ^bJiangsu Sailboat Petrochemical Company, Lianyungang, China. ^cMarathon Petroleum Corporation, Garyville, LA, USA.

This assumes, of course, that all necessary materials and financing are available.

The scale-up factor for DAC of 1,636 may seem daunting, particularly when considering that it accounts for only the CO₂ need of one of 615 refineries. But the factor is based on Climeworks' ORCA unit that was built in 2021 and is capturing 4,000 tons per annum (or 11 tons per day) of CO₂ (ref. 24). Climeworks recently announced a breakthrough on project Mammoth with a CO₂ capture capacity of 36,000 tons per annum or close to 100 tons per day, making it nine times larger than ORCA¹⁰¹ and reducing the scale-up challenge to a factor of about 180 in just 2 years. The Haru Oni project in Chile, co-founded by Siemens Energy, ExxonMobil and others, will produce methanol from captured CO₂ and green hydrogen. It aims to reach by as early as 2027 a production capacity that is one-fifth the capacity of our refinery (8.6 × 10⁷ mol C per day), using DAC, power from wind turbines and methanol-to-gasoline technology^{102,103}. These developments make us optimistic that, in principle and with sufficient support, the technologies needed for the refinery of the future can be developed to the desired scale before 2050.

Land and offshore area requirements

The main power consumption of the proposed refinery is for water electrolysis to produce H₂. H₂ is needed for making synthesis gas used in FTS to produce hydrocarbon fuels and in more limited amounts in other processes such as HC that establishes the correct carbon length distribution in the hydrocarbon fuels. We are considering H₂ made 'on purpose' for the anticipated 2050 refinery. An abundance of H₂ may also become available as a means of intermediate storage of energy^{104,105} from inherently intermittent sustainable power generation technologies (solar PV and wind power), to address Richard Smalley's 'terawatt challenge' that calls for a transition from the approximately 14 TW power generated in 2003 from fossil fuels to the 30–60 TW power that will be needed in 2050 and should be generated using renewables^{5,6} (Fig. 1b). Although H₂O electrolysis is an established technology, the scale-up from present-day 10–100 MW units to the future multiple-GW-scale units is still a great challenge, even when taking expected cost reductions into account¹⁰⁶.

The H₂ and energy demand of the refinery concept can be appreciated when considering that the overall reaction for hydrocarbon fuels production is essentially $n\text{CO}_2 + 3n\text{H}_2 \rightarrow (-\text{CH}_2)_n + 2n\text{H}_2\text{O}$, meaning that at least three molecules of H₂ are required per molecule of CO₂. Given

the fuel production rate we are targeting, we thus need to produce (store/transport) 2.4 kt (or 1.2 × 10⁹ mol) of H₂ per day. The production of H₂ requires 50–58 kWh per kg H₂ (ref. 107) or 1 MW for roughly every 18 kg H₂ produced per hour, which equates to 5.5 GW of electrical power needed to produce 2.4 kt H₂ per day. This electricity must be produced fossil-free and thus primarily from wind power or solar PV. Considering day/night and seasonal cycles for a northwest European location that is at a higher latitude compared with the USA, we assume for PV a capacity factor of 12% (on the low side of the 10–21% window reported by the International Energy Agency (IEA)¹⁰⁸ and in line with PV potential studies for countries in Europe^{109–111}). An evaluation of present-day wind turbine technology in the UK¹⁰⁹ and the USA¹¹² has indicated capacity factors between 30% and 35%, although newer turbines claim 60% capacity factors¹¹³. Because of the difference in intermittency of wind and solar energy, we choose to split the energy source used to meet the refinery requirement 50/50 between wind and solar, so we need 2.75 GW from each.

This implies that we need 104 million m² of solar panels (delivering 220 W m⁻² peak power and with 12% capacity factor) and about 328 windmills (assuming that the newest wind turbines produce 14 MW each at 60% capacity factor) to generate the overall power of 5.5 GW required for making hydrogen; that is, alongside our refinery itself occupying an area of perhaps 1 km by 1 km, we need a solar panel park of 10.2 km by 10.2 km and a windmill park of 28 km by 28 km (which, if on shore, could also readily house the required DAC units). An artist's impression of the whole refinery complex is depicted in Supplementary Fig. 1. These numbers do not take into account the energy needed for DAC (which could reach 1.5 GW if all carbon used in our refinery were obtained by means of DAC using current technology) nor the energy needed to run the processes in the refinery. To put the required infrastructure into perspective, the 5.5 GW needed to produce H₂ for one of our anticipated refineries of the future is comparable with the European Green Deal target of "installing at least 6 GW of renewable H₂ electrolyzers in the EU by 2024"¹¹⁴ for primary energy provision, and the 475 GW needed just to produce H₂ for 86 western European refineries with a current capacity of around 13.6 million bpd¹⁷ is about 12 times more than the European Green Deal target of "40 GW of renewable H₂ electrolyzers by 2030"¹¹⁴.

CO₂ DAC using present technology requires between 0.32 and 4.73 MWh per ton of CO₂ (ref. 115). The energy needed to capture CO₂ from concentrated stationary sources compares at the very low end

of that range¹¹⁵, whereas the Climeworks technology needs a medium energy input of 2 MWh per ton CO₂ (ref. 116). This suggests that DAC requires about five times more energy than capture from concentrated stationary sources and that capturing all the CO₂ needed in one future refinery with present DAC technology would use 1.5 GW of electrical power. The present Climeworks DAC collector units can capture approximately 230 kg per day per unit^{101,117}. To capture the required 18 kt per day, we would need 79,000 units. If clustered in blocks of 24 (a stack of four containers with six units each), we would need 3,285 blocks, or five rows of 8 km each, presumably spaced apart by at least 500 m.

Cost requirements

We calculated installation costs for the electricity generation and electrolyzers to produce the hydrogen required. Given the considerable disagreement in the literature about cost estimates for PV and wind power^{7,118–122}, we can only provide a rough estimate for these costs in 2050. With available numbers (see Supplementary Information, Supplementary Table 4) and assuming that prices will drop as technologies develop and are scaled up, we estimate a range of 5–10 billion euros for the manufacturing of the required solar cells, 3–6 billion euros for the manufacturing of the required wind turbines and about 1.0–2.5 billion euros for the electrolyzers^{123,124}, or 9–18.5 billion euros in total. As well as this, we expect the investment costs for the refinery installations to be on the order of 5 billion euros (see Supplementary information). These costs do not cover the infrastructure for transporting or storing energy or H₂ or maintenance of the solar panels and wind turbines. We assume that the refinery would mainly need to store H₂ (used at a rate of 2.4 kt per day). If we assume that we need enough H₂ to cover several days (say, 4 days), we will need a storage facility for about 10 kt of H₂. This is similar in scale to the ConocoPhillips Clemens Terminal storage facility in Texas, USA used for underground H₂ storage in salt caverns for more than three decades. Investments for these types of storage facilities seem to be two orders of magnitude lower than the costs required for the manufacturing of solar cells and wind turbines¹²⁵. However, the required geological features may not be available at all sites at which future refineries might be constructed.

There are of course alternatives to solar and wind power for generating the electricity needed in H₂ production, with nuclear power a natural choice. France is producing about 70% of its power from nuclear reactors that typically have capacities between 0.9 and 1.3 GW (ref. 126). For one refinery, we would thus need about five of these to produce the required 5.5 GW of electricity, at an estimated cost of 20–40 billion euros (refs. 127,128).

Resources

As well as the direct costs, the refinery of the future also has notable resource implications, illustrated by an EU Joint Research Centre evaluation of the raw materials requirements for solar PV and wind power technologies¹²⁹. Wind turbines require large amounts of relatively abundant concrete and steel and substantial amounts of critical raw materials¹³⁰, such as aluminium, chromium, manganese, nickel, zinc and the rare earths dysprosium, neodymium, praseodymium and terbium. Solar PV cell construction uses concrete, steel and glass and critical elements such as aluminium, indium, gallium and germanium. We should also consider that developing the electrolyzers needed for our refinery may encounter materials availability issues, as the supply of the required iridium, scandium, yttrium and platinum may become critical¹³¹. The quest to replace fossil fuels may thus trigger undesired challenges in other critical raw materials cycles¹³², even for metals as abundant as iron, copper, nickel and aluminium. More background information can be found in the Supplementary information (Supplementary Tables 5 and 6).

In terms of its input stream, assuming 100% conversion efficiency, the anticipated refinery of the future will use 6,200 tons of agricultural waste and sustainable-resourced and certified biomass and 2,800 tons of plastic waste every day. Globally, for 615 refineries, these numbers translate to 1.4 Gt of biomass and 628 Mt of plastic waste that are needed per year. A report by Imperial College London Consultants¹³³ suggests that the available sustainable-resourced biomass in Europe alone (which would house 86 of the 615 refineries) would be between 1 and 1.3 Gt in 2050, of which 539–915 Mt would be available for energy applications. So there should, in principle, be sufficient biomass for the proposed refinery scenario. Polymer production is projected to triple in 2050 compared with 2014 (ref. 134), reaching a level of 950 Mt. To meet refinery needs, we would need to recycle two-thirds of that production, which is still a challenge given the efficiencies of the current chemical recycling technologies.

Challenges towards a carbon-neutral future

A carbon-neutral future with CO₂ emissions balanced by CO₂ uptake is an ambitious goal that requires not only technological developments affecting sectors such as the chemical industry and transport but also targeted and sustained policies and public support.

Technical challenges

The steps that can be taken to decarbonize electricity production and a large part of the transport sector are relatively clear. But realizing the proposed 2050 refinery concept will be a more demanding task, given the complexity of the feedstocks, processes and products that are involved and considering the necessary process and technology innovations and scale-up of existing technology that are required. Key technical challenges need to deliver:

- Technologies for CO₂ DAC are required on a scale of approximately 20 kt per day for a single refinery.
- Electrocatalytic CO₂ activation and conversion processes need to be efficient, selective, use earth-abundant elements as catalysts and ultimately produce molecules more complex than CO (at a scale of approximately 20 kt per day for a single refinery).
- Large-scale reactors need to be electrified to lower the CO₂ footprint of endothermic production processes^{135–137}; such process electrification might be compatible with existing refineries and could serve as an intermediate solution for lowering refinery CO₂ emission.
- Electrocatalytic CO₂ conversion and H₂ production are both accompanied by O₂ formation at the anode, which should be replaced by reactions (such as oxidation of molecules derived from agricultural and municipal waste) that generate useful products¹³⁸.
- Carbon-efficient processes are needed for making chemicals from biomass and agricultural waste and for recycling of plastic and municipal waste; this will require new catalytic technologies that should be based on earth-abundant elements.
- A considerable infrastructure needs to be developed to ensure sufficient solar PV and wind power generation capacity (about 6–7 GW per refinery).
- Effective and reliable energy storage techniques are needed to store excess energy during peak solar PV and wind power production.
- Green H₂ generation capacity needs a substantial scale-up to meet future refinery demand and be based on electrolyser technology that uses stable electrodes composed of earth-abundant elements; in the interim, H₂ can be generated through processes such as biomethane pyrolysis^{139–141} that yields solid carbon and thereby avoids CO₂ emissions.

The sheer scale of the transformation needed to realize a carbon-neutral chemical industry, in terms of the technology and process developments and associated material demands, is staggering. After all, the chemical and petrochemical industry transforms 1.6 billion tons

of raw materials every year (677 Mt of fossil feedstock, 274 Mt of water and 686 Mt of secondary reactants) into 821 Mt of primary products and 815 Mt of secondary products (such as CO₂, CH₄ and H₂O)¹⁴². On top of this, complexity needs to be considered as the industry produces hundreds of different products that are used in all parts of modern society, supplying, for instance, plastics, fibres and fertilizers that are indispensable for our economy. These products are the result of highly complex, interdependent process flows and we cannot simply drop in a new conversion process but need instead a systems approach to devising solutions^{137,142–144}. As an intermediate solution, renewable electricity could be used to replace combustion-based electricity and, in some cases, provide process heating, thereby reducing emissions of current refineries. This concept has been described in general for several endothermic reactions¹⁴⁵, such as CO₂ reforming of methane or rWGS¹⁴⁶, methane steam reforming^{147,148} and propane dehydrogenation¹⁴⁹. A large-scale demonstration plant for electrically heated steam cracking furnaces is under construction at BASF's site in Ludwigshafen, Germany¹⁵⁰ and another at Coolbrook's Brightlands Chemelot Campus in the Netherlands¹⁵¹. Of course, local circumstances will dictate whether green electrons are best used for heating or for electrochemical processes.

Economic challenges

We argue that it should be technically possible to build in 2050 a carbon-neutral refinery that converts CO₂ and municipal and agricultural waste into hydrocarbon fuels, chemicals and the many man-made materials that are indispensable to modern life. However, each of the new refineries requires investments on the order of 14–23 billion euros, with 65–80% of this sum covering costs directly related to hydrogen generation. Just replacing all 615 refineries now operating over the next 25+ years would require investments on the order of 320–520 billion euros per year for each year until 2050. To put this into perspective, our new refineries would use a total of 4.3 TW of electrical power in 2050. The terawatt challenge^{5,6} assumes that we will need 30–60 TW of non-fossil power in 2050 to supply the world's energy needs, or roughly ten times the requirements for refinery replacement.

As well as the substantial financial investments, large land or off-shore areas will be needed to site the solar panels and/or wind turbines required to supply the refineries with electrical energy. In fact, even nuclear energy may have to be used to meet the immense electricity demand of the future refineries. Construction of the solar cells and wind turbines will also require large amounts of materials and metals, many of which are critical minerals. Solving the fossil fuel challenge may therefore trigger other undesired cascades of raw materials issues.

Long-term societal commitment

To deliver the large-scale science and technology developments required for a refinery of the future, it will be essential to have in place adequate policies and a long-term support and financing framework that fosters discovery and innovation and enables the necessary demonstration projects. Support should also include economic drivers that encourage a move to carbon neutrality, such as a form of carbon tax, and a removal of barriers that prevent the adoption of low-carbon technologies (such as infrastructure or subsidies on fossil fuels)^{104,152}.

We have mentioned our optimism that science and technology can ultimately deliver the solutions for moving society towards carbon neutrality but recognize that the magnitude of the transition that is needed, in terms of investments, critical raw materials and required areas for electricity generation, is unprecedented. After all, we need to replace infrastructure and processes built and improved over more than a century and that today turn cheap fossil fuels into the large number of products that satisfy the needs of modern society. The changes required of the chemical industry, and of other industry sectors, can thus be expected to fundamentally transform the world economy and

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Additional information

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