The last use of fossil fuels?
Making chemicals without oil and gas
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green alliance...

Methodology

Our independent analysis for our report builds on existing academic and policy literature, and includes new calculations. This methodology explains how we estimated figures for different feedstock options.

Estimated land use, energy demand, carbon emissions and feedstock availability for different carbon-based chemical feedstocks

Fossil fuels

Energy demand: As a sort of 'business as usual' baseline, we estimate the energy consumption of an electrified UK chemical industry that continues to use fossil fuels as feedstocks in a steam cracker process. A 1Mt per annum capacity steam cracker is estimated to require 7TWh of energy per year, (according to P Coenen, October 2021, 'E-Crackers – sustainability developments in steam cracker technology from an industry perspective', Institute of Sustainable Process Technology). Some efficiency can be expected from an electrified cracker over a conventional one, but we assume this is roughly cancelled out by the energy penalty of running a carbon capture process on the flue gas. CCS would be required to eliminate the unavoidable process emissions inherent in steam cracking, regardless of the heat source.

The UK's 2.695Mt per annum steam cracking capacity might, therefore, need approximately 18.9TWh per year of clean electricity. By 2050, the total electricity demand on the UK grid is expected to be somewhere in the range of 500 to 900TWh a year (see S Dossett and L Hardy, January 2023, 'The building blocks of a secure 2035 zero carbon power system', Green Alliance briefing). An electrified steam cracking process producing the same volume of ethylene as today would therefore consume between two and four per cent of the UK's electricity in 2050.

Residual emissions: In the Climate Change Committee's (CCC's) sixth carbon budget, under the 'balanced net zero pathway', the grid carbon intensity in

Great Britain will fall to 2gCO_2e per kWh in 2050. At this intensity, 18.9TWh would be responsible for 0.04MtCO_2.

On top of this, there is the embedded fossil carbon inside chemical products, some of which is released to the atmosphere at the end of life of the products. Detergents and many consumer goods are deliberately designed to break down and release CO_2, whilst plastics and other polymers are often incinerated.

SystemIQ (*Planet positive chemicals*, 2022) suggest, in figure 15, that 11 per cent of non-ammonia (ie carbon-based) chemicals leak directly into the environment. These will be detergents, surfactants, some fibres and solvents etc. SystemIQ assumes that 29 per cent of non-ammonia chemicals accumulate in the global economy. These can be things like long-lived plastics used in construction. SystemIQ assumes that, after a long lifetime, they will usually end up in landfill and, therefore, will not be released to the atmosphere. The remaining 60 per cent of chemicals will go to either recycling, landfill or incineration.

To estimate the relative breakdown of these different end of life routes in the UK, we refer to tables 11 and 13 of the 'UK statistics on waste', available from the Department for Environment, Food and Rural Affairs (Defra). Assuming that all carbon-based chemical products used in the UK that are not already leaked to the environment are classified either as 'plastic waste' or they make up roughly 14.5 per cent of the waste classified as 'household and similar waste' (see information below on plastic wastes), we calculated that, in 2018, 22 per cent of plastic and chemical product waste went to landfill, 37 per cent was recycled, and 40 per cent was incinerated with or without energy recovery.

Combining these numbers with those from SystemIQ (2022), we estimate that, in the UK:

- 11 per cent of all chemical products are leaked into the environment
- 29 per cent are locked away in the economy
- 24 per cent are incinerated
- 13 per cent are landfilled
- 22 per cent are recycled

Therefore, if all the ethylene produced in UK steam crackers was used to make all the chemical products used and discarded in the UK under current practices, we estimate that approximately 35 per cent of the embedded carbon from the fossil feedstock would be emitted as CO_2 at end of life. These estimates are approximate. The fraction of emitted embedded carbon could be reduced through increased recycling rates, and by retrofitting carbon capture and storage (CCS) technology onto some suitably located incineration facilities.

Ethylene has a carbon content of 0.857 by mass, and the UK can produce 2.695Mt of ethylene per year. A total of 0.81Mt of carbon might, therefore, be released each year, which converts to 2.99MtCO_2. Adding the 0.04MtCO_2 from the consumption of electricity in the electrified steam crackers brings this to 3.03MtCO_2.

In the CCC's sixth carbon budget, under the 'balanced net zero pathway', in 2050 the UK could have 97MtCO_2 of residual emissions that would need to be drawn down through carbon dioxide removal activities (the CCC assumes most of this will be via bioenergy and carbon capture and storage techniques (BECCS) and natural land carbon sinks, as well as a small amount of direct air carbon capture and storage technology (DACCS)).

An electrified but fossil feedstock based chemical industry might, therefore, be generating around three per cent of the UK's residual emissions in 2050. If these emissions were to be removed via DACCS, consuming 0.99MWh of electricity per tonne of CO_2 removed (see below on e-chemicals), this would require an additional 3TWh or 0.3-0.6 per cent of the UK's expected electricity supply in 2050.

Recycled plastic waste

Energy demand: We estimate the scale of energy needed to replace the fossil feedstock consumption of all three UK steam crackers with a mixture of mechanical recycling and some form of chemical recycling, using otherwise unrecyclable plastic waste. To do this, we looked at two studies: R Meys et al, 2021, *Science*, vol 373, pp 71-76, and H Jeswani et al, 2021, *Science of the total environment*, vol 769, 144,483.

In table S1 of their supplementary materials, R Meys et al (2021) estimate the predicted production volumes of different types of plastics in 2050. We add these together to find that the total production they are modelling in their analysis is around 1,400Mt of product. In figure 2 of the same study, the approximate minimum energy needed in the recycling pathway is shown as 11PWh. Comparing these two numbers gives an estimate of 7.85MWh per tonne of product, on average, for the recycling pathway. This includes both mechanical and chemical recycling. Scaling this up to produce the 2.695Mt of output from the UK's three steam crackers results in an energy demand of approximately 21.2TWh.

H Jeswani et al (2021) conduct lifecycle analyses for chemical recycling and show in figure 7 an estimated 16GJ of energy is consumed to produce one tonne of virgin grade LDPE (an ethylene-based plastic). 16GJ is 4.4MWh, and scaling this up to the UK's ethylene capacity of 2.695Mt, we find a total energy demand of 12.0TWh.

More efficient chemical recycling processes may be developed over time, but this gives a reasonable estimate of the scale of energy required at present. As above, we can compare these numbers with the expected total electricity demand on the UK grid in 2050 (500 to 900TWh). Replacing fossil feedstocks in the UK's production of ethylene with recycled plastics could, therefore, need one to four per cent of the UK's 2050 electricity supply.

Residual emissions: To estimate the residual carbon emissions of a system using recycled plastics as feedstock, we again use analysis by R Meys et al (2021). As shown in their figure 1, a global system based on the recycling pathway still results in around $2GtCO_2$ per year, due to residual wastes that cannot be recycled going to incineration. Dividing this by the total modelled production (1400Mt) gives approximately $1.4tCO_2e$ per tonne of product, on average. Scaling this up to the UK's ethylene production capacity gives $3.85MtCO_2e$. This is about four per cent of the UK's expected residual emissions needing to be removed in 2050 according to the CCC's 'balanced net zero pathway'.

However, relative to a linear pathway in which a significant amount of plastic waste is incinerated without CCS (a reasonable assumption since most current incinerators are not close to planned CO_2 transport and storage networks), the recycling pathway would represent a significant reduction in emissions. The estimated residual emissions could be traded off against the reduced emissions from incineration, as H Jeswani et al (2021), show in their lifecycle analysis of chemical recycling.

Supply of plastic waste: To supply the UK's three steam crackers with sufficient feedstock from plastic waste, we argue that the UK would need to import plastic waste from overseas. In table 3 of H Jeswani et al (2021) it is suggested that 1.23t of pyrolysis oil is needed to produce one tonne of ethylene, and that 1.41t of mixed plastic waste is needed to produce one tonne of pyrolysis oil. Therefore 1.73t of mixed plastic waste would be needed to produce one tonne of ethylene and, at the scale of the UK's production of ethylene, that means 4.67Mt of mixed plastic waste would be required each year.

To understand how this compares to current UK production of plastic waste, we again use Defra's 'UK statistics on waste'. Table 9 shows that the UK produced 222.2Mt of total waste in 2018. Figure 4 shows that 0.84 per cent of this was classed as plastic waste, but we expect some fraction of the 12.85 per cent that is 'household and similar waste' to also be plastic.

Within Defra's 'detailed dataset', and filtering for 2018, the 'Waste from households' tab suggests a recycling rate of 45 per cent. The 'Packaging' tab shows a recycling rate of 62.1 per cent.

Therefore, using a reverse calculation, we assume that approximately 72 per cent of household waste is packaging. Separately, 2,361kt of plastic packaging was recorded, of a total of 11,836kt. Thus, 20 per cent of the packaging recorded was made of plastic. If 72 per cent of household waste is packaging, and 20 per cent of packaging is plastic, then we estimate that roughly 14.5 per cent of household waste is plastic. As a result, 1.86 per cent of all waste could be considered to be household plastic waste, on top of the 0.84 per cent which is other plastic waste, totalling 2.7 per cent. We note that this may be an underestimate given that some household waste may be plastic but not from packaging.

So the UK produces approximately 6Mt of plastic waste per year, with much of this coming from imported products. This number is consistent, if a little higher than, the estimate found in the UK resources and waste strategy (2018), which says on page 22 that the UK uses five million tonnes of plastic a year. This total is just about enough to feed the UK's three steam crackers via chemical recycling, but only if all the waste is treated via chemical recycling. Instead, most plastic waste should be recycled mechanically and, therefore, some plastic waste or pyrolysis oil would need to be imported to feed the UK's steam crackers.

Biomass

Energy demand: P Gabrielli et al, 2023, *One Earth*, vol 6, pp 682-704, estimate that the electricity required to convert biomass into plastic is around 13MWh per tonne of product. A majority of this is to supply some extra hydrogen needed to complement that already present in the biomass. They assume that any process heat required is generated by burning the biomass feedstock itself.

If the UK's 2.695Mt annual ethylene production capacity was solely used to produce plastics, and was to be replaced by a biomass feedstock, 35TWh of electricity would be required each year. This is four to seven per cent of the UK's expected electricity demand in 2050.

Land use requirements: We use several sources to estimate a range of values for the possible scale of land use needed to supply biomass as a chemical feedstock in the UK.

P Gabrielli et al (2023) estimate that producing one tonne of plastic from short rotation coppice biomass would require roughly 3,000m^2 of land, or 0.3ha. Therefore, to provide enough feedstock to produce the equivalent of the UK's three steam crackers would need approximately 8,000km^2 of land, or 800,000ha.

To compare, we also ran a separate calculation using the government's bioethanol yields for different crops. In Defra's 'Area of crops grown for bioenergy in England and the UK: 2008-2020', annex A contains the conversion factors in the second column of the table below. Average harvest yields for each crop are also shown below with the relevant source for each.

Crop	Bioethanol yield in litres per tonne	Average yield in tonnes per hectare	Harvest yield source
Sugar beet	101	75	Our world in data
Wheat	367	8.1	'Cereal and oilseed rape production', 2023, Defra
Barley	317	6.1	'Cereal and oilseed rape production', 2023, Defra
Corn	418	10	Estimated from other European countries via Our world in data (UK data not available)

Using the above, an ethanol yield in litres per hectare was derived, and an average value of 4,100l/ha across the four crops taken. Using the density of ethanol (0.789kg/l) this results in an ethanol yield of 3.27t/ha. V Zacharopoulou and A A Lemonidou, 2018, *Catalysts*, vol 8, article 2, suggest that ethanol can be converted to ethylene with a yield of 99 per cent per carbon atom, which is 61 per cent by mass. Therefore, approximately 1.66t of ethanol are required for one tonne of ethylene. For the UK's 2.695Mt annual ethylene production capacity to be replaced by a bioethanol conversion route, 4.47Mt per year of bioethanol would be required. If this came solely from an equal split of the crops listed above, this would require 1.36mha.

The UK's total land used for agriculture is 17.2mha, according to Defra's 'Agriculture in the UK evidence pack', September 2022, although only 6.1mha is croppable. Thus, the two estimates above would require 13-22 per cent of the UK's croppable agricultural land, if all ethylene was derived from crops. Using agricultural residues and biomass wastes instead of crops would require much less land area.

Residual emissions: If it can be assumed that any process emissions and any wider impact on emissions, for example from land use change or the use of fertiliser, is roughly offset by the fraction of biogenic carbon locked away in long lived chemical products or in landfill, the only source of emissions would be from the electricity used. In this case, in 2050 when the grid has a carbon intensity of 2gCO_2e per kWh (CCC sixth carbon budget), using 35TWh of electricity would result in around 0.07MtCO_2, or about 0.1 per cent of the residual UK emissions requiring removal in 2050.

Alternatively, R Meys et al (2021) consider the biomass pathway to have global residual emissions of 0.5GtCO_2e, on average, and as little as 0.2 GtCO_2e for low grid carbon intensities. Again, using the estimate that their pathways consider a total demand of 1,400Mt in 2050, this equates to an average of 0.357tCO_2e per tonne of product. Scaling this up to the total UK production of ethylene, this would be 0.96MtCO_2 annually, or about one per cent of residual UK emissions in 2050.

Therefore, we consider that the biomass route might result in 0.1-1 per cent of the UK's residual emissions in 2050. If upstream emissions could be reduced, for example through using truly sustainable waste biomass feedstocks, it is possible that this route could become carbon negative.

Biomass supply and competition: Above, we show that 4.47Mt per year of bioethanol might be required to replace the ethylene production of the UK's three steam crackers with a biomass based route. That is 5.7bn litres of bioethanol per year. Below we convert this to energy units, purely for comparison with other studies exploring the availability of biomass. The discussion below continues to focus on biomass primarily as a green carbon feedstock, not an energy source for production processes.

In annex A of Defra's 'Area of crops grown for bioenergy in England and the UK: 2008-2020', the government assumes bioethanol has an energy density of 23.6MJ per litre. Using the conversion of 0.2777kWh to 1MJ, we find a total biomass demand in energy terms of 37TWh per year.

Alternatively, P Gabrielli et al (2023) estimate that one tonne of plastic would require 3.63t of biomass. Using the ethanol yields above, on average, whether the feedstock is woody or comes from traditional food crops like corn or wheat, the conversion rate from feedstock to ethanol is 23.7 per cent by mass. Therefore, a tonne of plastic would need about 0.86t of ethanol (plus some additional hydrogen). To match the UK ethylene production capacity (2.695Mt) would require 2.32Mt of ethanol per year. Converting this to energy terms as above results in 19TWh per year.

To compare this with the expected domestic supply of biomass, we looked at four different estimates: modelling by 3Keel on behalf of RSPB ('Biomass for energy: a framework for assessing the sustainability of domestic feedstocks', 2022), the CCC's sixth carbon budget, modelling by the Supergen Bioenergy Hub (A Welfle, et al, 2020, 'UK Biomass availability modelling: scoping report'), and the 2023 Biomass Strategy from the Department for Energy Security and Net Zero (DESNZ). The 3Keel modelling and some of the Supergen modelling both ultimately use the government's own 'UK and global bioenergy resource model' (2017). The following are estimates for domestic biomass availability in 2050 via the four sources.

(TWh)	3Keel/RSPB	CCC Balanced Net Zero Pathway	Supergen Bioenergy Hub (Table 10)	DESNZ 2023 Biomass Strategy
Domestic supply	278	166	123	106
...of which wastes and residues	101	109	107	N/A

In defining wastes and residues, we exclude biogas but include biogenic municipal solid waste, agricultural residues, waste bioethanol, forest residues and waste wood. It is important to highlight that different biomass supply models can provide quite different results, depending on the assumptions about price, competition and strictness of sustainability criteria. Estimates of waste resources are generally more consistent across models whereas supply from crops, forestry and forest residues can be much more varied.

Across this range of estimates, therefore, we calculate that a demand of 19-37TWh for chemical production in the UK would represent 7-35 per cent of expected domestic supply in 2050. Looking only at the potential supply from waste and residue streams, this fraction is 20-40 per cent.

In table 9 of the Supergen study, estimates are supplied for the potential demand for bioenergy for different end uses, including transport (surface transport, aviation and shipping), which, in 2050, might require 150TWh, or over three times as much as the chemical sector. In the CCC's sixth carbon budget (figure 3.5i) it is estimated that the electricity sector might require 65TWh of bioenergy, or about twice as much as the chemical sector.

E-chemicals

Energy demand: P Gabrielli et al (2023) model an e-chemical route using electricity, carbon dioxide captured directly from the air (DAC) and green hydrogen to produce plastic. They suggest that 0.65t of hydrogen and 3.55t of CO_2 are required per tonne of plastic. In their modelling, they assume that this would require 32MWh of electricity to generate the hydrogen, and 3.5MWh of electricity to capture the carbon. We note that this assumes that one tonne of CO_2 can be captured via DAC with 0.99MWh of electricity, which is an ambitiously high efficiency but may be possible if the heat requirements are met using a 400 per cent efficient electric heat pump. Other studies, including R Meys et al (2021) and SystemIQ's report (2022) expect one tonne of CO_2 to require 1.3-2 MWh of energy. Therefore, the figure from P Gabrielli et al, can be considered to be an optimistic best case scenario.

P Gabrielli et al (2023) also include 6.85MWh of electricity and 4.18MWh of heat for the process of combining the hydrogen and CO_2 into a plastic polymer, via methanol and a methanol to olefins process. Assuming all heat requirements are met via a heat pump, the total electricity required to produce one tonne of plastic is estimated to be 43.3MWh. Producing a tonne of ethylene rather than refined plastic may require a fraction less energy, but given the highly optimistic DAC energy efficiency, we assume this roughly balances out.

The total electricity demand in a situation where all of the UK's ethylene production capacity is replaced by this e-chemical route would be 117TWh, or 13-23 per cent of the UK's predicted electricity demand in 2050.

Land use requirements: We estimate how much land would be required if all this electricity were to be provided by onshore wind power. RenewableUK calculate an average onshore wind load factor of 26.34 per cent for the five years from 2018 to 2022, based on data from DESNZ. To supply 117TWh of energy over the course of a year would therefore need 51GW of onshore wind.

P Enevoldsen and M Z Jacobson, 2021, *Energy for sustainable development*, vol 60, pp 40-51, estimate that onshore wind in Europe has a spatial energy density of 19.8MW per km^2. Alternatively, in the CCC's sixth carbon budget, a spatial energy density of 5.1MW per km^2 is used. Therefore, we consider a range of values from the CCC's estimate at the low end, to P Enevoldsen and M Z Jacobson (2021) at the high end. Therefore, the total area needed would be 2,500-9,900km^2, or 250,000-990,000ha. However, only about one per cent of the actual land footprint of onshore wind is taken up by the turbines, with the rest able to sustain other uses such as agriculture, according to the Energy and Climate Intelligence Unit. Accounting for this, we find the onshore wind needs of this e-chemical route are equivalent to about 0.01-0.06 per cent of total agricultural land in the UK.

Offshore wind is more likely to supply the bulk of electricity in the UK as the grid decarbonises, and although it has a higher average load factor (40.58 per cent), its spatial density is lower (5.0-7.2MW per km^2), so around 4,500-6,600 km^2 would be needed to supply this electricity from offshore wind.

Residual emissions: In theory, the only emissions relating to this e-chemical production are those arising from the generation of the electricity. Currently, offshore wind has a carbon footprint of around 11gCO_2e per kWh, according to the Offshore Renewable Energy catapult. This will fall as the entire economy decarbonises and, as mentioned above, the CCC's sixth carbon budget 'balanced net zero pathway' sees the UK grid reach a carbon intensity of 2gCO_2e per kWh by 2050.

If delivering 117TWh, these carbon intensities equate to 0.23-1.28MtCO_2e per year, or 0.2-1.3 per cent of residual UK emissions in 2050.

However, this process also draws down carbon from the atmosphere and, as discussed above, some of the embedded carbon in chemicals can be locked away in long lasting products or in landfill. The carbon content of ethylene by mass is 85.7 per cent (two carbon atoms, four hydrogen atoms), and, therefore, the equivalent amount of embedded CO_2 is 3.15t per tonne of ethylene, since one tonne of carbon generates 3.67t of CO_2.

If, as above, 65 per cent of the ethylene produced in the UK ends up in long lasting products, is recycled or is locked away in landfill, an e-chemical route has the potential to draw down 5.4MtCO_2. The net result, accounting for the emissions arising from electricity generation, is -4.2 to -5.3 MtCO_2 per year. This would mean sequestering four to five per cent of the UK's expected residual emissions in 2050.

It is worth noting that this e-chemical route can only result in reduced overall emissions compared to continued use of fossil feedstocks (if electrified and adapted with CCS), at low grid carbon intensities. R Meys et al (2021) indicate that this route may result in lower emissions at intensities below 100gCO_2e per kWh, but suggest that to be cleaner than the recycled plastic waste pathway, or the biomass pathway, an intensity of less than 8gCO_2e per kWh is required. The current UK grid has a carbon intensity of 150gCO_2e per kWh.