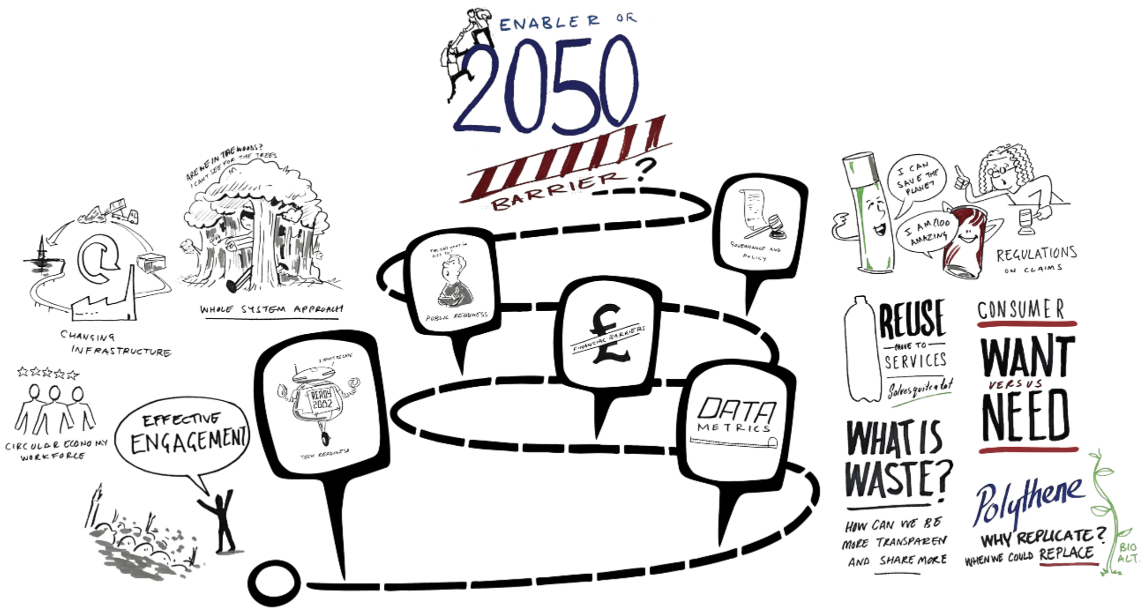
UKRI Interdisciplinary Centre for Circular Chemical Economy

NICER PROGRAMME

UK Research and Innovation

Circular Economy of Olefins Roadmap for the UK Executive Summary



Roadmap methodology and principles

To develop a roadmap for the circular economy of ethylene, we conducted interviews and workshops with stakeholders, for a holistic perspective on the barriers and enablers to a circular chemical economy and where we can accelerate change in the chemical sector. This included perspectives on the Technology Readiness Level (TRL) of different technologies and their potential within a UK context. The roadmap also draws on research conducted within the UKRI Interdisciplinary Centre for Circular Chemical Economy (CircularChem), that bridged three interconnected themes: (1) Key technologies to enable olefin production from alternative/recycling wastes streams and design more reusable chemicals via advanced catalytic processes; (2) Process integration, whole system analysis and value chain evaluation, and (3) Policy, society and finance.

Within the vision of the roadmap, there are four key principles which have been studied to enable the transition to a circular economy:

1) Promoting resource efficiency across the chemical supply chain. Existing frameworks such as the waste hierarchy should be applied as a priority to create sustainable resource flows of olefins. A system-wide approach is required to assess how best to implement new resource efficiency measures and compare their impact.
2) Reducing carbon emissions. The chemical sector is considered a ‘difficult to abate’ sector as fossil carbon is embedded in the production of platform chemicals and as an energy source. The roadmap utilises the learnings from the core themes and roadmap research to show viable technologies and effective decarbonising strategies which can effectively reduce emissions in the chemical sector.
3) Replacing petrochemical feedstocks and reduce waste. Utilising waste feedstocks such as captured CO_2, bio-based and composite waste can provide the pathways for sustainable olefin production. A suite of alternative production routes to olefins are presented with their viability compared to the business-as-usual production of olefins.
4) A whole systems approach. The complexity of transitioning from the current linear model to a circular model should not be underestimated. The roadmap encompasses the wider changes required in the chemical sector beyond new technology development such as: circular business models, economic, social and ethical considerations, societal acceptance, and political levers to transition to net zero in a timely manner.

Overall projections

Our projections for 2050 show that alternative feedstocks and production routes would ensure that the UK chemical sector can compete internationally while reducing our reliance on fossil ethylene by at least 2.6 Mt (from 4.1 Mt – BAU) to below 1990 levels. Deeper decarbonisation, through emerging Carbon Capture and Utilisation, and Storage (CCUS) technologies is expected to reduce fossil ethylene demand further by 2050. Hitting the targets set out in the roadmap for increased non-fossil ethylene production and reduced ethylene demand, through circularity, would maintain UK pro capita polymer production rates and enable a two-fold increase in the production of high value organic chemicals.

Assumptions of future demand

In 2023, the UK produced 2.79 Mt of olefins, including ethylene and propylene, with associated CO_2 emissions of 3.1 Mt (1.1 kg CO_2/ kg ethylene).[1] The per capita demand for plastics in the UK has levelled off and population is set to increase from 68 to 78 million by 2050 representing a 0.33% Compound Annual Growth Rate (CAGR) from 2023 to 2050.[2,3] Therefore, by 2050 the demand for ethylene for polymers is expected to grow from 1.53 Mt to 1.67 Mt if we maintain Business as usual (BAU). In contrast, the demand for high value chemicals is expected to double by 2050, in line with revenue growth objectives.[4] This would mean that ethylene demand for organic chemicals could increase from 1.26 Mt to 2.45 Mt (2.5% CAGR). Therefore, in a BAU scenario, total ethylene demand could rise to 4.13 Mt by 2050, resulting in emissions of 4.6 Mt CO_2.

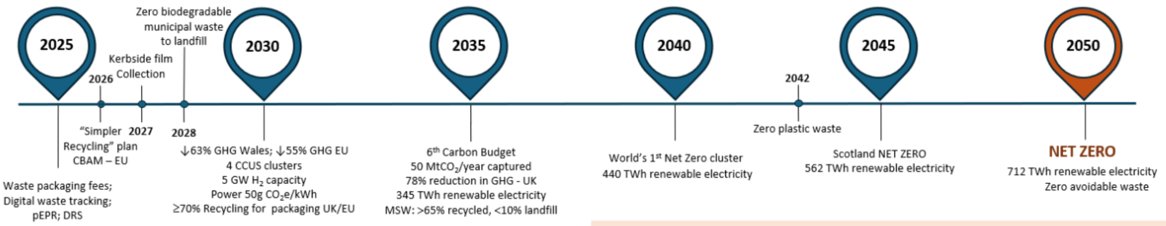
Non-fossil feedstocks and alternative production pathways

Non-fossil feedstocks, including biomass, plastic waste and CO_2, will be required for the UK chemical industry to meet its growth targets while simultaneously complying with our net zero obligations. This will require developing the infrastructure to collect, sort, process and convert waste streams, as well as designing materials that enable circularity. Rapid growth in the capacity/deployment of mature technologies to valorise available waste feedstock is needed as emerging technologies for processing innovative feedstocks, such as advanced recycling, 2nd generation bio-ethanol, and CO_2 reduction technologies, continue to be developed and scaled-up. Clear policies are needed to facilitate these transitions, including prioritised allocation of advanced feedstocks such as residual biomass for chemicals and fuels, improvements in waste collection and processing infrastructure, product legislation (such as Safe and Sustainable by Design), and data sharing requirements.

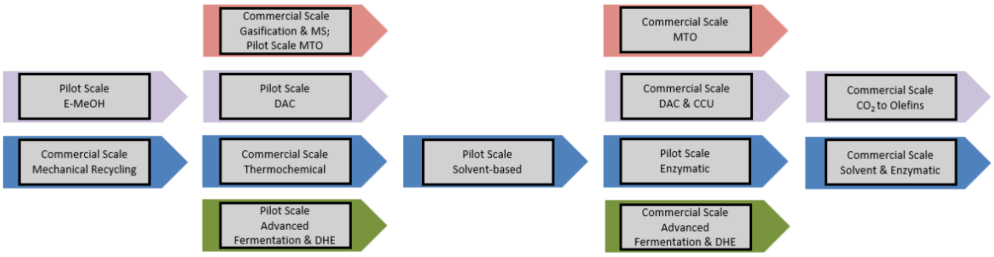
Roadmap assumptions and targets

UK Roadmap for a Circular Economy of Chemicals

Achieving net zero in the UK chemical industry will require a balanced approach, leveraging immediate emissions reduction potential while planning for long-term integration of sustainable practices across the sector



Timeline showing existing policy drivers and milestones for reduction of waste and CO2 emissions.

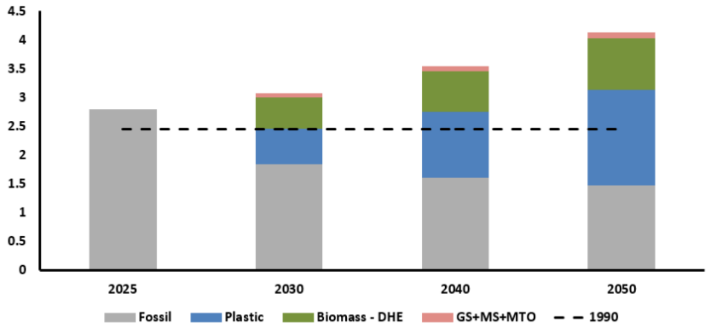


Technology development milestones for advanced recycling and carbon capture and utilisation to support reduction of waste and de-fossilisation of the ethylene supply chain. Estimates are representative of the UK chemical industry, considering feedstock availability, government targets and technology capacity.

The graph shows how the increasing demand for ethylene in the UK can be met with recycled carbon, initially from biomass and "visible polymers" (plastic waste) diverted from landfill and incineration.

Plastic waste is projected to grow from 5.59 Mt in 2022 to 6.24 Mt by 2035, potentially exceeding 7 Mt by 2050. Increasing reuse and recycling of this resource could reduce demand for fossil ethylene by 1.7 Mt by 2050 and curb associated scope 1 emissions.

Electrification of steam cracking could reduce process emissions by 90%. This will require a reliable supply of renewable electricity and green hydrogen.



30% of available residual biomass (non-energy crops) will go to chemicals from 2030, increasing to 50% by 2050 at a CAGR of 2.5%.

Not all polymers can be recovered, and some scope 3 product emissions will still need to be mitigated.

The remaining fossil ethylene demand (projected 1.5 Mt in 2050) requires incentives for CCU, including cheap renewable power and H_2, and/or CO_2 credits. Significant energy inputs (86-124 TWh) would be required to produce CO_2-derived ethylene using current technologies. However, based on high learning rates efficiency improvements are expected which would improve viability, while direct conversion to high value chemicals is expected to reduce ethylene demand further.

The projections in our roadmap show non-fossil ethylene increasing with recycled carbon, initially focusing on biomass and visible polymers (plastic waste), as waste is diverted from landfill and incineration. Key targets are given in the timeline, along with enabling policies on the way to Net Zero. These include Extended Producer Responsibility for Packaging (pEPR) legislation and the "Simpler Recycling" plan in the short-term, and targets for eliminating avoidable plastic waste and carbon capture in the long-term.

In 2022 5.59 Mt Plastic waste was generated in the UK of which 0.88 Mt (16%) was sent to mechanical recycling in the UK, 0.75 Mt (13%) was exported, 2.30 Mt (41%) went to Energy from Waste (EfW) and 0.35 Mt (22%) was sent to landfill.[5] In line with the British Plastics Federation (BPF) "desired scenario", plastic waste will continue grow to 6.24 Mt by 2035 if recycling and reuse increased from current levels, down from 8 Mt in the BAU case, as demand grows and an increasing number of products reach their end of life.[5] Projecting from 2035 to 2050, total plastic waste could reach 7.08 Mt. Under the BPF "desired scenario", by 2035 mechanical recycling rates increase (39%) along with chemical recycling (6%) and reuse (13%), as plastic waste is diverted from going to EfW (26%) and landfill (4%).[5] We assume that recycling and reuse levels continue to increase gradually, reaching zero plastic waste to landfill and phasing out EfW by 2050. Assuming an overall recycling yield of 45% from mechanical and chemical recycling, across the different polymer types, if plastic waste grows at a faster rate than polymer demand (0.85% vs 0.33% CAGR), that recycling rates increase as outlined above, and that there is sufficient demand reduction from reuse, then fossil ethylene demand for plastic polymers could approach zero by 2050. Increasing reuse and collection, and recirculating carbon from visible polymers will reduce fossil demand and associated scope 1 emissions. However, not all polymers can be recovered, and some scope 3 product emissions will still need to be mitigated.

We target an increase in bio-ethylene production capacity from residual biomass to 0.6 Mtpa by 2030, reaching 0.98 Mtpa by 2050 (2.5% CAGR). The residual biomass categories considered were the biodegradable portion of municipal solid waste (6.3 Mtpa - 5 GJ/t NCV), straw and dry agricultural residues (10.6 Mtpa – 19 GJ/t NCV), and sustainably available wood (2.5 – 19 GJ/t NCV). [6] Our projections assume that 30% of available residual biomass (non-energy crops) is diverted to chemicals by 2030, increasing to 50% by 2050 at a CAGR of 2.5%.[7] While overall residual biomass may stay the same, the increased proportion diverted to chemicals may come from reduced demand from other sectors like energy, as electrification increases. By 2050, innovative biomass feedstocks like sewage sludge and algae (not included in our projections) are expected to become viable for commercial bio-ethylene production.[4,7] Bio-ethylene may be obtained from Municipal Solid Waste (MSW) via gasification to syngas followed by the Methanol to Olefins (MTO) process. In our roadmap, 0.052 Mtpa bio-ethylene production capacity from MSW is targeted by 2030, reaching 0.085 Mtpa by 2050 (2.5% CAGR), assuming an overall yield of 10% (100g ethylene/ kg dry biomass). [8] The target for bio-ethylene from agricultural residues and sustainably available wood is ambitiously set to 0.55 Mtpa by 2030, rising to 0.90 Mtpa by 2050 (2.5% CAGR). This assumes an overall yield for the cellulosic ethanol production and dehydration of ethanol pathway of 14% (140g ethylene/ kg biomass).[9]

Future fossil ethylene demand and carbon emissions

Lower demand for fossil ethylene, will result in associated emissions reduction from steam cracking of fossil feedstocks of 2.9 Mt CO_2 annually, by 2050. Circularity is expected to reduce scope 1 and 3 emissions, for example through increased reuse and plastic waste recycling rates, as well as direct emissions for energy intensive processes like Poly(ethylene terephthalate) (PET) production. However, carbon emissions from some alternative routes, including the cracking of pyrolysis oil co-feed, will still need to be mitigated, and without significant disruption in technology or UK demand, some fossil ethylene may still be required in the future (estimated 1.5 Mt by 2050, 1.7 Mt CO_2). While electrification of steam cracking could reduce process emissions by up to 90%,[10] deeper decarbonisation can be achieved by artificially accelerating the carbon cycle, using captured CO_2 as a feedstock through biomass and emerging CCUS technologies. This will require a reliable supply of renewable electricity and green hydrogen.

Impact and emerging technologies

By 2050, diverting the projected 7 Mt of plastic waste away from energy from waste (0%) and landfill (0%), through increased rates of reuse (20%) and mechanical (55%) and chemical (20%) recycling, could reduce demand for fossil ethylene by 1.6 Mt along with the associated scope 1 emissions. Chemical recycling includes thermal processes, like pyrolysis, and emerging solvent-based and depolymerisation technologies, like methanolysis and hydrogenolysis. Polyethylene (PE) pyrolysis has been shown to be cost competitive with naphtha cracking in Europe (~half the cost), and potential cradle-to-gate net negative emissions when accounting for avoided emissions from naphtha cracking to give ethylene and byproducts.[11] However, pyrolysis oil is typically converted to ethylene via conventional steam cracking by co-feeding small quantities with fossil feedstocks. Therefore, specialised crackers are needed, and pyrolysis oil must be upgraded to meet specifications to further defossilise ethylene production using this route. Solvent-based and depolymerisation chemical recycling technologies are currently being commercialised, however further technological developments are needed for improved handling of the range of plastic waste streams.[12] Higher efficiencies, together with the use of renewable energy, would also reduce the environmental impact of these pathways and improve their commercial viability and emissions savings potential in comparison with virgin polymer production.[13] The bio-ethylene production target of 0.98 Mtpa by 2050 would displace fossil ethylene demand and enable the valorisation of residual biomass from agricultural residues and sustainably available wood together with the biomass fraction of MSW, in line with government targets to eliminate biodegradable waste to landfill by 2028. Bio-ethylene from advanced bioethanol, via dehydration of ethanol, is not yet cost competitive,[14] unlike bio-ethylene from primary bioethanol[15]. However, both pathways have the potential to be carbon negative, when sequestered CO_2 is accounted for. Investments in advanced bioethanol production could be accelerated in the short-term by targeting low-volume high-value chemicals. The MSW-syngas-methanol-olefin route, via gasification+methanol-synthesis+MTO was found to have lower a lower global warming potential (GWP) than ethane steam cracking, both with and without retrofitted CCS technology. This route also provides a reduction 1 and 2 CO_2 emissions when MSW is diverted from incineration. Production costs are currently uncompetitive (0.23-0.39 USD/kg_{MSW}).[16] However, we expect that technological improvements, lower renewable energy costs and economies of scale would make this route viable by 2050. In the short-term, specialised chemical production from syngas, including methanol which has a higher market price than ethylene, as well as sustainable fuel targets could drive investments. The remaining fossil ethylene demand (projected 1.5 Mt in 2050) requires incentives for CCU, including cheap renewable power and green hydrogen, and/or carbon credits. Significant energy inputs (86-124 TWh) would be required to produce CO_2-derived ethylene using current technologies making it uncompetitive with fossil-ethylene, albeit potentially carbon negative (up to -3.3 tCO_2-eq using the MS+MTO pathway).[1] However, based on high learning rates, efficiency improvements are expected which would improve viability, while direct conversion to high value chemicals is expected to reduce ethylene demand further.

Recommendations

To achieve net zero emissions in the UK chemical industry by 2050, several key strategies and actions are required.

Government can create the conditions for defossilising the chemical industry through ***policies that enable circularity*** including feedstock allocation, infrastructure development, product legislation and data reporting requirements. Much of the legal framework is in place or incentivising the transition but how the sector will adapt while facing global competition and geopolitical uncertainty is unclear. ***Collaboration and communication*** with stakeholders, e.g. Safe and Sustainable by Design (SSbD) requirements and green sector jobs, would ensure that policy decisions deliver impactful and fair outcomes for industry and the general public. Significant ***private and public sector investments*** are urgently needed to support the commercialisation of circular production pathways in the UK, including developing recycling infrastructure and technologies, non-fossil ethylene production (e.g. via bioethanol and methanol routes), and CO_2 utilisation technologies (moving from CCS to CCUS).

Industry must act to ***improve transparency around the sustainability and safety of their products***, processes and supply chains to government and consumers, through data reporting, labelling and advertising claims. ***Collaboration with the government and other stakeholders*** is crucial to identify and address the needs that the government can support in facilitating the transition to circular and sustainable business practices and identify opportunities for innovation and growth. This includes strategies for managing costs for the chemical sector and sharing data in ways that preserve competitiveness. Industry needs to be ***proactive in adapting*** to the upcoming changes needed to comply with UK sustainability goals and the requirements of our export markets. This includes ***designing materials for circularity*** to reduce demand for virgin fossil resources and being flexible towards the best available carbon feedstocks and technologies. Businesses need to ***bridge the knowledge gap*** with investors to respond to new demands and opportunities. They would also benefit from ***working with higher and further education*** providers, e.g. by contributing to green sector jobs awareness and upskilling/reskilling programmes, to ensure that the labour market is well equipped for the future.

Achieving net zero in the UK chemical industry will require a balanced approach, leveraging immediate emissions reduction potential while planning for long-term integration of sustainable practices across the sector.

Key Actions:

1. ***Technological advancements:***
    - Implement carbon capture and storage (CCS) in existing industrial clusters
    - Develop and deploy step-change technologies for decarbonization
    - Transition to renewable energy sources and green hydrogen for power and feedstock

2. ***Circular economy and sustainable feedstocks:***
    - Increase use of bio-based feedstocks and advanced recycling
    - Design materials for circularity to reduce demand for virgin fossil resources
    - Source 80% of carbon requirements from sustainable, non-virgin fossil sources by 2050

3. ***Policy and regulatory framework:***
    - Establish outcome-oriented regulations to drive innovation
    - Implement data-driven policy measures to support industry transition
    - Create a long-term industrial strategy for the chemical sector

4. ***Infrastructure development:***
    - Build infrastructure for collecting, sorting, and processing waste streams
    - Expand renewable electricity generation capacity
    - Develop hydrogen production and distribution networks

5. ***Collaboration and investment:***
    - Foster close cooperation between government and industry
    - Secure significant investments in new technologies and infrastructure
    - Support the development of large-scale demonstrator plants for sustainable chemicals

The full roadmap will be available at a later date. The DOI is https://doi.org/10.57711/ttmv-cq24

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