A Sustainability Journey:

A Perspective on Best Available Carbon (BAC) as Feedstock for the Chemical Industry

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Planetary Health Under Threat

The health of the planet we all call home is under threat, with Earth's natural systems and boundaries increasingly breached on a daily basis.[1] Human health and well-being are intricately linked to the health of the planet, which is under threat from reduced air and water quality, climate change, biodiversity loss, and pollution from toxic materials.[2] At our present consumption rate, by 2050 three planets will be required to meet both our resource needs and to absorb our society's waste.[3]

The climate emergency is one of the greatest societal challenges of our time, caused primarily by the human induced release of fossil-derived greenhouse gases into the atmosphere – with carbon dioxide (CO_2) making up ~70% of all emitted GHGs.[4] As GHG emissions continue to rise, so too does the temperature of the planet, causing wildfires, flooding, food scarcity, disease outbreaks and droughts.[5]

Global emissions of climate changing fossil GHGs must therefore be reduced by significant volumes, as quickly as possible.[6]

Carbon and Chemicals

Chemicals play a crucial role in modern life, and we are likely to encounter them every day - from the chemicals used at work, to products found at home e.g., paints, detergents, and pesticides for use in the garden.[7] The chemical industry provides us with goods that we often take for granted and it is an essential part of the UK economy.

Currently, roughly 90% of the feedstocks used to make chemicals worldwide are derived from fossil resources, such as crude oil, natural gas and coal.[8] As such, the chemicals and plastics sectors are responsible for up to 10% of global GHG emissions[9, 10], and given that emissions resulting from the use of fossil carbon are the main cause of anthropogenic climate change, there is a very real need to significantly reduce the impact of these industries on the planet. While the UK rightly emphasises the reuse and avoidance of fossil-based feedstocks, the chemicals and materials industries are inherently reliant on carbon-based feedstocks. Unlike the energy sector, the chemicals sector cannot be "decarbonised" - instead, this industry must be "defossilised".

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[1] Stockholm Resilience Centre, Planetary boundaries, https://www.stockholmresilience.org/research/planetary-boundaries
[2] United Nations, Transforming our world: the 2030 Agenda for Sustainable Development, https://sdgs.un.org/2030agenda
[3] United Nations, Goal 12: Ensure sustainable consumption and production patterns, https://www.un.org/sustainabledevelopment/sustainable-consumption-production/
[4] Centre for Climate and Energy Solutions, Global Emissions, https://www.c2es.org/content/international-emissions/
[5] US Dept. of Commerce - NOAA, Climate change impacts, https://www.noaa.gov/education/resource-collections/climate/climate-change-impacts
[6] United Nations, For a liveable climate: Net-zero commitments must be backed by credible action, https://www.un.org/en/climatechange/net-zero-coalition
[7] Health and Safety Executive, Why chemicals matter, https://www.hse.gov.uk/chemicals/why.htm
[8] Renewable Carbon Initiative. RCI carbon flows report – Compilation of supply and demand of fossil and renewable carbon on a global and European level, https://renewable-carbon.eu/publications/product/therenewable-carbon-initiatives-carbon-flows-report-pdf/
[9] The Royal Society, Defossilising the chemical industry, https://royalsociety.org/news-resources/projects/defossilising-chemicals/
[10] Bauer, F., Kulionis, V., Oberschelp, C., Pfister, S., Tilsted, J. P., Finkill, G. D., & Fjäll, S. (2022). Petrochemicals and Climate Change: Tracing Globally Growing Emissions and Key Blind Spots in a Fossil-Based Industry. (IMES/EESS report; Vol. 126). Lund University.

Hidden Emissions

The chemicals and downstream manufacturing industries use fossil carbon in three ways: (1) as a source of fuel for industrial heat and steam, and in the supply of electricity, (2) as a transport fuel to move raw materials and products from location to location, and importantly, (3) as a source of carbon atoms, in the form of feedstocks from coal, crude oil, and fossil (natural) gas to produce the tens of thousands of chemicals manufactured by the chemical industry.

It is widely recognised that the combustion of carbon as fuel, during transportation and manufacturing processes, results in the production of CO_2 (a greenhouse gas), with well-known and studied implications for climate change.[11] Less recognised however, are the CO_2 emissions associated with the use of carbon within manufactured products. This is known as 'embedded carbon emissions'[12] and includes carbon that is released during the production of raw materials, through processing and transformations, and from the disposal of products after their use. In the context of the petrochemical industry, the carbon emissions associated with the use of carbon as a material vastly outweighs its use as fuel.

Best Available Carbon for a More Sustainable Carbon Economy

Sustainability isn't a destination, it's a journey. Therefore, the concept of sustainable carbon is not a concrete definition of what carbon source is the most sustainable, but rather a developing and constantly evolving view of what would be described as 'Best Available Carbon' (BAC). BAC means the available carbon that could be used in manufacturing, which minimises GHG emissions and any other negative impacts on the environment, whilst also importantly maintaining the economic and technical viability of specific manufacturing processes. Although the focus is placed on CO_2 emissions, the careful management of carbon is required to avoid undesirable and unintended knock-on consequences in other areas of planetary health, such as water availability, air and water pollution, toxicity and biodiversity.[13,14] The idea of BAC sits within the established concept of 'best available techniques' (BAT)[15], where advanced and proven techniques are used for the prevention and control of industrial emissions and wider environmental impacts caused by industrial installations. These available technologies have been developed to a scale that enables their implementation under economically and technically viable conditions. In a similar way, the concept of BAC should consider the economic and technical viability of the carbon sources required for specific manufacturing processes.

Any view of carbon sustainability and 'best available carbon' sits within a consideration of carbon cycles, climate change, and the need to maintain a balance of carbon (in various forms) across the planet's geosphere, biosphere, atmosphere and hydrosphere. The use of fossil resources extracted from the geosphere, ultimately results in the transfer of carbon in the form of CO_2 into the atmosphere and hydrosphere, which cannot then be easily returned to the geosphere [Figure 1].

This transfer of carbon lies at the heart of climate change, with increasing concentrations of CO_2 ultimately ending up in the Earth's atmosphere.

Given the importance of petrochemicals and derived materials, around 96% of all globally manufactured goods are understood to contain petrochemical products. It is therefore unrealistic to

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[11] United States Environmental Protection Agency, Climate Change Indicators: Greenhouse Gases, https://www.epa.gov/climate-indicators/greenhouse-gases

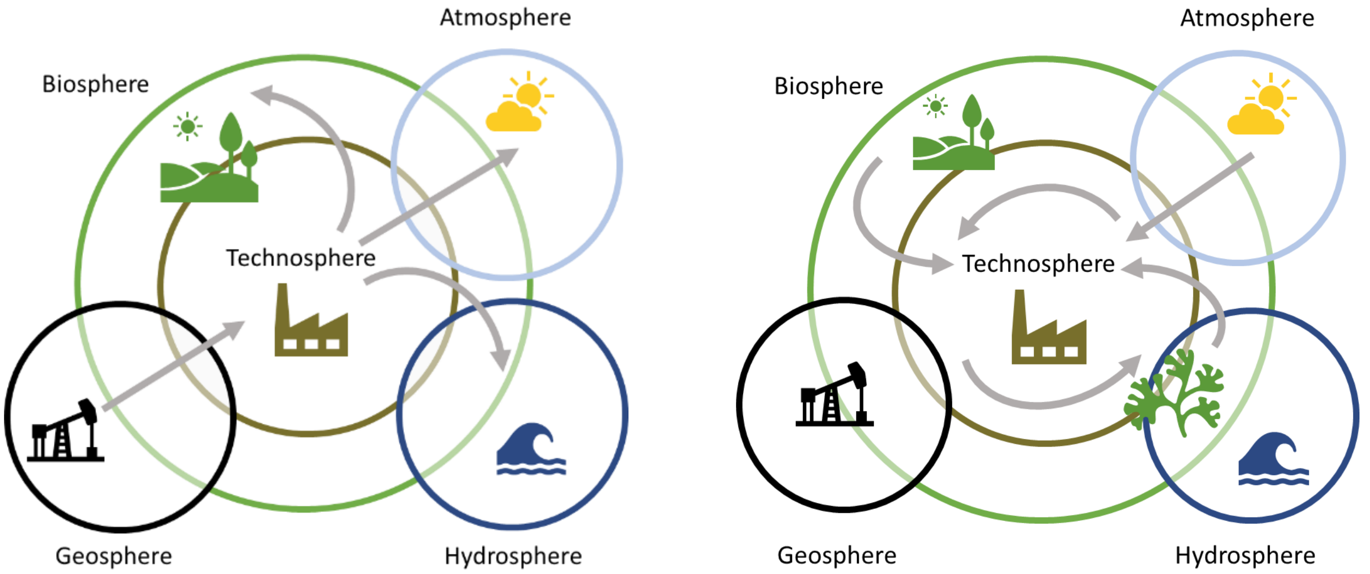
[12] E3G, Embodied carbon emissions: meaning and measurements, https://www.e3g.org/news/embodied-carbon-emissions-meaning-and-measurements/

[13] Arodudu, O., Holmatov, B. & Voinov, A. Ecological impacts and limits of biomass use: a critical review. Clean Techn Environ Policy 22, 1591–1611 (2020).

[14] Organisation of Economic Co-operation and Development, Carbon Management: Bioeconomy and Beyond, https://www.oecd.org/innovation/carbon-management-bioeconomy-and-beyond-b5ace135-en.htm

[15] HM Government, Best available techniques: environmental permits, https://www.gov.uk/guidance/best-available-techniques-environmental-permits

expect that any significant reduction in petrochemical use will take place in the near future, regardless of how desirable it would be. On the contrary, the production of petrochemical-derived goods is in fact expected to increase significantly over the coming decades.



Current carbon flow based on the extraction of fossil resources

Future carbon flow based renewable carbon used in a circular economy

Figure 1. Current and future carbon flows

Petrochemical production takes place at large scale through mature value chains that are inextricably linked to the refining of fossil oil and gas. The scale and value of petrochemical production means that any change to established processes and raw materials will inevitably be a slow one. Therefore, it is foreseeable that fossil resources will continue to be the predominant source of carbon for the manufacturing of chemicals and materials for several decades to come.[16]

The development and deployment of carbon capture and storage (CCS) technologies[17] can, to an extent, mitigate the fossil GHG emissions resulting from petrochemicals production. However, carbon leakage during CCS means that fossil carbon will continue to enter the atmosphere. It is also worth noting that the carbon emissions associated with the production of specific chemicals can be significantly influenced by feedstock choice (e.g. emissions associated with coal based methanol production can be three times higher than typical processes based on natural gas).[18] Fossil carbon could therefore be a BAC source in the near- to medium-term, however, targets for reducing its use through research and technology development are essential.

Fortunately, alternative carbon sources also exist, and alternative carbon flows can be envisaged where carbon moves from the atmosphere (either directly, or via the biosphere) into the technosphere, where it is recycled as part of a circular economy. In addition to fossil carbon, BAC can be derived from three other sources, the atmosphere (atmospheric carbon), the biosphere (biogenic carbon) and the technosphere (recycled carbon) [Figure 2]. These alternative sources offer the opportunity to reduce, and even halt the extraction of fossil resources, preventing any additional fossil-derived GHGs from entering the atmosphere. The use of these resources means that carbon remains above ground, creating a circular carbon economy where feedstocks are regrown (as biomass from the biosphere),

[16] The International Energy Agency, The Future of Petrochemicals, https://www.iea.org/reports/the-future-of-petrochemicals
[17] The International Energy Agency, Carbon Capture, Utilisation and Storage, https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage

recycled, captured and utilised (as carbon in multiple forms from the technosphere), or extracted (as CO_2 from the atmosphere).

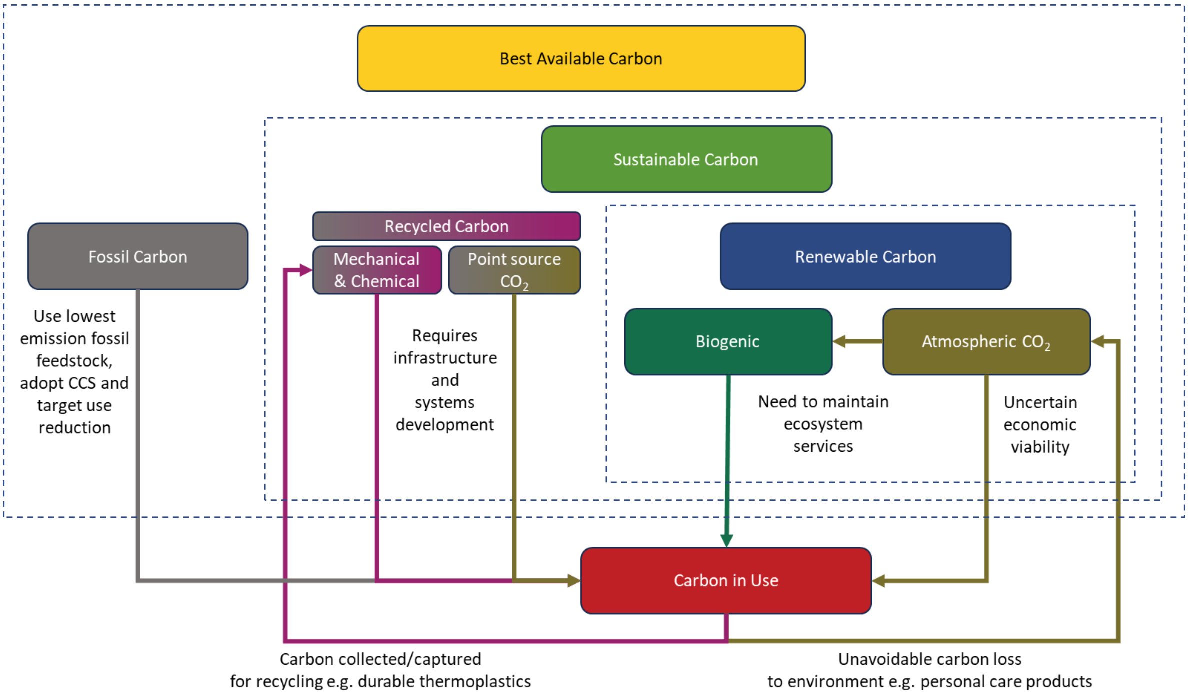


Figure 2. Best Available Carbon

Significant quantities of carbon reside in the millions of tonnes of products that are already traded and used within the global economy, with ~400 million tonnes of plastics entering the economy each year.[19] This carbon represents the potential from the recycling of chemicals and materials. Mechanical recycling reduces demand for virgin polymers, however when mechanical recycling is not possible, chemical recycling allows for the deconstruction of polymers back to starting feedstocks (e.g., chemical monomers or chemical feedstocks) which can then be turned back into useful chemicals. Although ideally avoided, technospheric carbon can be combusted or oxidised through chemical or biological processing, but carbon capture and utilisation (CCU) provides a means of preventing GHG emissions from entering the atmosphere and keeps carbon circulating throughout the economy.

Each form of recycling has its own merits and disadvantages and requires systemic approaches to ensure that the right feedstocks are used for different products and materials. Technospheric (recycled) carbon is widely accepted as a BAC category which will grow in importance.

However, despite the desire to develop a circular economy[20] no recycling system can run perpetually, and the loss of some carbon via oxidation to CO_2 to the atmosphere is inevitable. Additionally, not all chemical products can be recovered and recycled, as large volumes of carbon are lost during use (e.g. personal care, household cleaning products and total loss lubricants). Therefore, the chemical industry will require virgin (make-up) carbon, either extracted from the atmosphere or sourced in the form of biomass.

In terms of biomass, the use of carbon contained within the biosphere predates human civilisation, with plant and animal materials being used to construct shelters and provide clothing. The development of new chemistry, and in particular industrial biotechnology[21], results in increased

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[19] Plastic Europe, Plastics – the fast Facts 2023, https://plasticseurope.org/media/plastics-europe-launches-the-plastics-the-fast-facts-2023/

[20] Anne P.M. Velenturf, Phil Purnell, Principles for a sustainable circular economy, Sustainable Production and Consumption, Volume 27, 2021 Pages 1437-145.

[21] Industrial Biotechnology Leadership Forum, A National Industrial Biotechnology Strategy to 2030, https://www.bioindustry.org/resource-listing/a-national-industrial-biotechnology-strategy-to-2030.html

opportunities to utilise biomass for the production of biochemicals and synthetic materials. The challenge in using biomass feedstocks, however, lies in ensuring that the volumes harvested do not damage our ecosystems' ability to maintain their regulating and cultural services. Sustainably managed biogenic carbon constitutes an important renewable carbon source.

The final category of BAC is atmospheric carbon, where CO_2 is extracted through direct air capture (DAC). While the direct capture of atmospheric CO_2 essentially provides an unlimited supply of carbon for manufacturing, the effort, energy and financial cost of recovering such a dilute source of carbon from the atmosphere raises questions around the commercial viability of its use, and whether/when it could be a considered a BAC source.[22, 23] Furthermore, the conversion of CO_2 into the wide spectrum of chemicals currently manufactured by the chemical industry will require access to large volumes of low-cost, low-carbon electricity, which for the foreseeable future could instead be used in more efficient ways.

Assessing Best Available Carbon

Determining what constitutes BAC requires the careful consideration of multiple factors, addressing economic, environmental and social sustainability. Technoeconomic appraisal and lifecycle analysis are necessary to assess the range of impacts associated with each carbon source.

Each carbon source is chemically different, ranging from reduced fossil hydrocarbons, to oxidised carbon in CO_2. Furthermore, biogenic carbon encompasses many forms, both chemically and physically - available as vegetable oil, carbohydrates, or as various components within lignocellulosic materials. Physically, biogenic carbon may be associated with high moisture materials, such as animal and food wastes, or may be available as relatively dry material, such as cereal grains. The appropriateness of each carbon source must be evaluated against its intended product and the subsequent conversion processes expected to be used.

BAC may also vary by geographic location. This is because the availability and impacts of a specific carbon source may vary by region, particularly if considering the use of biogenic carbon. Accessing biomass may be restricted by competing land requirements (e.g. for food or feed), or it may be constrained by environmental factors such as the need for irrigation. The use of CO_2 feedstock is likely to be reliant on the availability of low cost, low carbon, renewable energy, and the availability of renewable electricity can vary by region (both due to a region's ability to generate electricity, in addition to its electricity demand).

Final Remarks

The petrochemical industry is a significant global consumer of carbon and a notable producer of carbon emissions contributing to climate change. The majority of the petrochemical industry's fossil carbon emissions do not result from energy consumed by the industry for the production of its products, but in the sourcing and disposal of its raw materials and products respectively. The disposal and treatment of petrochemical products is to a large extent beyond the control of the industry; however, the industry does have a level of control over the choice of its raw materials.

Through consideration of BAC there is the potential for the industry to make a progressive move towards more sustainable carbon choices.

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[22] Katrin Sievert, Tobias S. Schmidt, Bjarne Steffen. Considering technology characteristics to project future costs of direct air capture. Joule, 2024; DOI: 10.1016/j.joule.2024.02.005

[23] The International Energy Agency, Capturing CO2 from the air can support net zero goals, https://www.iea.org/reports/direct-air-capture-2022/executive-summary

Through the use of BAC, the carbon intensity of products can be reduced, and the use of sustainable non-fossil carbon eliminates the possibility of fossil carbon emissions being generated at the end of a product's life.

Given that around 96% of all manufactured goods are currently reliant on chemicals[24,25], when chemical products inevitably become more sustainable in the future, there will be a huge multiplier effect, with downstream products benefiting considerably. The chemical industry could therefore be a hidden climate hero, as it has the potential to act as a key enabler for the defossilisation of many other industries.

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[24] American Chemistry Council, 2019 Guide to the business of chemistry, https://www.americanchemistry.com/chemistry-in-america/data-industry-statistics/resources/2019-guide-to-the-business-of-chemistry
[25] Science Based Targets, Chemicals, https://sciencebasedtargets.org/sectors/chemicals

Recommended reading

The Future of Petrochemicals, The International Energy Agency, https://www.iea.org/reports/the-future-of-petrochemicals.

Catalysing change: Defossilising the chemical industry, The Royal Society, https://royalsociety.org/-/media/policy/projects/defossilising-chemicals/defossilising-chemical-industry-report.pdf

Carbon Management: Bioeconomy and Beyond, Organisation of Economic Co-operation and Development, https://www.oecd.org/innovation/carbon-management-bioeconomy-and-beyond-b5ace135-en.htm

How to Enable the Transition From Fossil to Renewable Carbon in the Chemical and Material Sector, The Renewable Carbon Initiative, https://renewable-carbon-initiative.com/media/press/?id=527

Planet Positive Chemicals, Systemiq, https://www.systemiq.earth/wp-content/uploads/2022/09/Main-report-v1.20-2.pdf

Glossary

Atmosphere - the layer of gases, known collectively as air, retained by Earth's gravity that surrounds the planet and forms its planetary atmosphere.

Atmospheric Carbon – carbon contained with CO_2 extracted from the atmosphere.

Best Available Carbon (BAC) - the available carbon which is the best for preventing or minimising emissions and impacts on the environment.

Biogenic Carbon – carbon present in biomass.

Biomass - all materials of biological origin, apart from fossil materials and/or those incorporated into geological formations.

Biosphere - the part of the Earth, including air, land, surface rocks, and water, within which life occurs and the total sum of living organisms. These life processes require energy, mostly in the form of solar radiation which is converted to biomass by photosynthesis.

Carbon Capture and Storage - capturing CO_2 at emission sources, such as oil refineries and chemical plants, then transporting and storing it underground.

Chemical Recycling – an umbrella term (sometime used interchangeably with advanced recycling or non-mechanical recycling) for a suite of technologies which allow for the reuse of polymers which can't be recycled with mechanical technologies. Technologies include purification (dissolution), depolymerisation and thermal (pyrolysis/gasification) processes.

Direct Air Capture - technologies that extract CO_2 directly from the atmosphere.

Fossil Carbon – carbon stored in fossil resources.

Fossil Resource - biomass that has undergone transformations over periods of millions of years. Resource is found within the geosphere.

Geosphere - also referred to as the lithosphere, it is the solid outer layer of the Earth with an average thickness of around 75 km. It comprises the Earth's crust and the solid or outer part of the Earth's mantle. The geosphere contains deep storage of carbon in the form of fossil fuels like oil, coal and natural gas.

Recycled Carbon – Carbon recovered from economic activities within the technospheric, includes carbon in chemicals produced through chemical recycling and carbon contained in point source captured CO_2.

Technosphere - The technosphere or anthroposphere is the part of the environment that is made or modified by humans for use in human activities and its interaction with the Earth's and extra-terrestrial systems.